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APORTACIONES DE LA SÍNTESIS EMERGÉTICA A LA EVALUACIÓN MULTI-ESCALAR DEL EMPLEO DE LOS SERVICIOS DE LOS ECOSISTEMAS A TRAVÉS DE CASOS DE ESTUDIO

Pedro Luis Lomas Huertas

Tesis Doctoral

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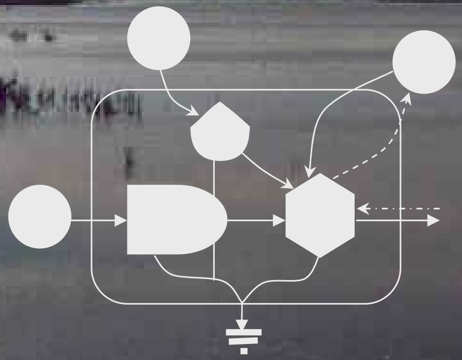

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Memoria presentada para optar al grado de Doctor en Biología por
Pedro Luis Lomas Huertas

Bajo la dirección de:

Carlos Montes del Olmo
Catedrático de Ecología
Departamento de Ecología
Universidad Autónoma de Madrid

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En este momento en que la agricultura como actividad productiva está comenzando a desaparecer de Europa, quiero dedicar esta tesis a los campesinos, verdaderos economistas ecológicos del planeta, y en especial a mis padres, cuyo esfuerzo y sacrificio me han dado oportunidades que ellos ni siquiera soñaron.

“- Gato de Cheshire, ¿podrías decirme, por favor, qué camino debo seguir para salir de aquí?
- Eso depende en gran medida de a dónde quieres ir, -dijo el Gato.
- ¡No me importa mucho a dónde...! -dijo Alicia.
- Entonces, no importa mucho el camino que tomes -dijo el Gato.
- …Siempre que llegue a alguna parte – añadió Alicia como explicación.
- ¡Oh, siempre llegarás a alguna parte –aseguró el Gato -, si caminas lo suficiente!”.

(Alicia en el País de la Maravillas. Lewis Carroll).

“No se puede resolver un problema pensado del mismo modo que cuando lo creamos”.

(Albert Einstein).

“Un enunciado lógicamente correcto adquiere su verdad del contenido de verdad del sistema al que pertenece”.

(Albert Einstein).

“Puesto que el proceso económico consiste materialmente en una transformación de baja en alta entropía, es decir, en desechos y, dado que esa transformación es irrevocable, los recursos naturales han de constituir necesariamente parte de la noción de valor económico; y, puesto que el proceso económico no es automático, sino deseado, los servicios de todos los agentes humanos o materiales, pertenecen también a la misma faceta de esa noción. Por otro lado, habría que resaltar que sería totalmente absurdo pensar que el proceso económico existe solamente para producir desechos. La conclusión irrefutable de todo ello es que el verdadero producto de ese proceso es un flujo inmaterial, el placer de vivir. Ese flujo constituye la segunda faceta del valor económico”.

(La ley de la entropía y el proceso económico, 1971. Nicholas Georgescu-Roegen).

“The growth of civilization on the nonrenewable reserves of the earth is surging to a climax of information miracles, stormy economics, turbulent populations, concentrated wealth, and bewildering complexity. Although the future is always masked by the oscillations of smaller scale, the empower of society may be at climax in transition to times of receding energy”.

(Environment, Power and Society for the twenty-first century: the hierarchy of energy, 2007. H.T.Odum).

“Desde hace ya más de treinta años el “problema ambiental” ha venido suscitando la necesidad de establecer circuitos de información sobre la dimensión física y territorial de las actividades económicas ordinarias que el análisis monetario dominante ignora, para hacer que la sociedad pueda rediseñar, a la luz de esta nueva información, las reglas del juego económico que condicionan valores y precios. Sin embargo esta necesidad de información no ha sido satisfecha: la información monetaria sigue siendo la única que se utiliza de forma sistemática para orientar la gestión”.

(Raíces económicas del deterioro ecológico y social: Más allá de los dogmas, 2006. J. M. Naredo).

AGRADECIMIENTOS

Lo cierto es que no resulta fácil escribir este apartado sin caer en la más lamentable de las cursilerías, y sin olvidarse de alguien que en algún momento pudo ser clave para avanzar, así que vaya por delante mi agradecimiento a todos los que han podido contribuir de cualquier manera a que esta tesis doctoral haya finalizado.

En primer lugar quisiera agradecer a mi director de tesis, Carlos Montes, la oportunidad de poder trabajar y pertenecer a este grupo de investigación, así como de involucrarme en tantos y tantos proyectos a lo largo de todos estos años. Cómo no, tengo que destacar la ayuda en el plano académico y personal del profesor Sergio Ulgiati, ahora en la Universidad de Nápoles, y en su momento mi referencia en la Universidad de Siena. Sus impagables ayuda, conocimientos y cercanía fueron imprescindibles tanto para poder afrontar el trabajo de esta tesis como para poder abrir puertas. También en Nápoles, Pier Paolo Franzese, cuyos consejos han servido para darle mayor robustez a las síntesis emergéticas de esta tesis, y que ha hecho un enorme esfuerzo por ayudarme. En Siena también quiero mencionar a Simone Prata, con el que tuve la oportunidad de compartir casa y tantas charlas sobre medio ambiente, sociedad y política en Italia, entendiendo mejor nuestros nexos Mediterráneos en todos los ámbitos; así como al PBC, el asturiano que me salvó de las contradas y el orgullo senese, que ahora disfruta de la tortilla de patata y el sol de Castellón.

En el que finalmente acabó auto-denominándose Laboratorio de Socio-Ecosistemas, ese lugar no siempre del todo bien entendido en la segunda planta del edificio de Biológicas, tengo que destacar la presencia de mis compañeros de fatigas, Diego (el primero, que luchó por los montes de Guadarrama a pesar el Parque Nacional), Erik (cuya aportación crítica e ideas han contribuido tanto al debate entorno a los temas de los que trata esta tesis como a otros que están relacionados con la misma), Berta (que resistió hasta el final y pudo terminar su tesis a pesar de todas las dificultades), Carla (de vuelta por tierras chilenas en la búsqueda de un poco de luz y calor), PedroZ, emigrado a la Complutense en busca de algo digno, que junto con Sergio (que buscó y rebuscó un hueco en Barcelona para poder integrarse en la Economía Ecológica a lo grande y convertirse en estrella de la música) contribuyeron tanto al debate como a materializar parte de los datos que se usarían para Doñana; y tantos otros que pasaron en algún momento por el despacho, tanto los que se fueron (Carmen Coleto, Marisa Pascual, Máximo Florín, etc.) como que se han ido incorporando (Marina, Sandra, Elisa, Nacho, etc.). También tengo que agradecer el buen clima alejado de otras disputas que, en general, ha existido entre los investigadores dentro del departamento, y las horas y horas que hemos pasado juntos, tanto en la universidad como fuera de ella. Diego García, David, Jorge, Íker, Pablo Acebes, Pablo

Manzano, Carmen, Susana, Paloma, y tantos y tantos otros que están o se fueron a buscar mejor vida en otro lugar.

Muchos han sido también las personas que desde el mundo académico o profesional me han ayudado aquí en España. Quiero mencionar especialmente a Óscar Carpintero, por sus desinteresados consejos en relación con la toma y fiabilidad de los datos que he manejado, y su apertura sobre la síntesis emergética; a Antonio Gómez Sal, por sus sugerencias y críticas en relación al Mediterráneo y a los paisajes culturales; a Sergio Álvarez, por su apoyo a la hora de entender mejor la síntesis emergética. También tengo que mencionar a Francisco Borja, Marisol Manzano, Carlos Fernández Delgado, Pablo García Murillo, y Pilar Drake, de distintos centros y universidades andaluzas, que me ayudaron a entender mejor la estructura y el funcionamiento de los ecosistemas de Andalucía y Doñana a distintas escalas. Por otro lado, tengo que agradecer a Antonio Pulido y Carlos Llano, del CEPREDE que tanto me ayudaron con el asunto del comercio. A la Federación de Arroceros de Sevilla, por su diligencia y colaboración, a Leandro del Moral, que como buen científico tuvo el tiempo y la paciencia de sentarse conmigo a hablar sobre el agua en los arrozales de Doñana, y también a Juan Requejo, que puso su granito de arena en cuanto a fuentes de información sobre el arroz. También a la Consejería de Medio Ambiente de la Junta de Andalucía y a la Fundación General de la UAM, sin cuya financiación hubiera sido imposible realizar esta tesis.

Al personal de las bibliotecas de tantos y tantos centros (Biblioteca Nacional, INE, Ministerio de Medio Ambiente, Ministerio de Economía, Ministerio de Agricultura, Pesca y Alimentación, Centro Documentación Estadística UAM, bibliotecas de Ciencias, Económicas, Filosofía, etc.), que se volvió literalmente loco intentando ayudarme a encontrar los datos que necesitaba para los resultados de la tesis, y me permitió valorar (más allá de lo crematístico) su labor, así como lo injusto que sería que se nos obligase a pagar por los préstamos en las bibliotecas.

Mis compañeros de piso y amigos, tanto en “La Comunidad” como en “Cevasalandia”, nos entendiésemos a veces mejor a veces peor, me hicieron crecer tanto en lo académico como en lo personal. Mario, una persona coherente y un huracán cuyas iniciativas llegaron a derribar gobiernos…..; Edu, al que conocí literalmente en la calle, defendiendo lo de todos, y con el que tantos buenos ratos, académicos y personales, he podido pasar mochila a las espaldas por todo el mundo; y Pablo, que trajo un poco de aire fresco a aquel piso cargado de tanto academicismo, y del síndrome de los “papers”. Mis amigos, a lo largo y ancho de toda la geografía manchego-internacional, a los que siempre he procurado volver durante todos estos años y con cuya fiel amistad he contado en todo momento, a pesar de la distancia, especialmente a Manolo, Dani, Eugenio, Luisa y Alfredo, que siempre estuvieron ahí, y a los que no se sabe ya dónde están ahora y que se fueron… a veces demasiado pronto.

A Íker Dobarro, que desde que volvimos de la tierra de los cruces inquietantes y las maniobras manuales a cada momento procura beber cerveza poco cool y desconfía de las costureritas y el vino aguado, y que ha sido uno más de la familia a lo largo de estos años, desde ese oasis de la repúblika de puente vallekas puerto, desde donde partirá hacia tierra de exiliados en breve con Fabi y la pequeña Ainhoa (o Ainoha). Del chiscón a Pachuka, andale guey….

Capercaillie, Kepa Junkera, Oskorri, Betagarri, Negu Gorriak, Kortatu, La Mala Rodríguez, Lúnasa, Kila, Ludovico Einaudi, Alasdair Fraser, Skyedance, The Chieftains, Rosendo, Banda Bassotti, Asian Doub Foundation, Hechos Contra el Decoro, La Musgaña, Madredeus, Dulce Pontes, Kroke, Fanfare Ciorcalia, 99 Posse, Mariza, Canti in Asociale, Têtes raides, Noir Desir, Zebda o Modena City Ramblers, entre otros muchos, pusieron banda sonora a varios años de tesis. Sin ellos también hubiera sido imposible terminar el trabajo.

Y finalmente, y por ello sí más importante, quiero agradecer, por una parte, el apoyo incondicional de mi familia española a la que debo todo (mis padres Carmen y Luis, mi hermano Jesús, Marta, Super-Sergio y la princesa, Ángela) y el buen recibimiento y cariño de toda mi familia italiana, desde la piccolina Isabella, pasando por Marta y sus besos, Matteo “el supremo”, Mario, Antonella, Vittorio, Paola, Elisabetta, Beniamino hasta nonna Gemma, guarda come ti dico…..a pesar de venir a ser una confirmación relámpago de las más que proféticas palabras aquellas de Enzo Tiezzi….tú ya sabes; y por la otra, creo que no tengo palabras para agradecer a Monica lo que ha hecho, tanto en lo personal como en lo académico, metiéndome en el cuerpo el ánimo para terminar la tesis, y ayudándome a entrar siempre en alfa tras la crisis. Hai fatto un po’ la brava……Pero espero que el día a día de todos los años que vendrán, y todo lo que haremos que suceda en este tiempo, sirvan para compensar, de algún modo, estas torpes palabras que no sirven para expresarlo todo.

RESUMEN

Existe un interés creciente en reincorporar el papel de los ecosistemas a la toma de decisiones económicas, puesto que se considera que el divorcio entre el crecimiento, que ha acaparado el debate dentro de la ciencia económica, y los ecosistemas, que son el objeto de la mayoría de los esfuerzos de conservación, es una de las causas primordiales de la pérdida de biodiversidad que vivimos actualmente en el marco del cambio global. La síntesis emergética es una metodología que se inscribe en este intento de reconectar el ser humano y la naturaleza, partiendo desde una base ecológica y termodinámica.

En esta tesis doctoral se han utilizado 4 casos de estudio con series históricas de síntesis emergéticas de diversos socio-ecosistemas mediterráneos a distintas escalas con el objetivo de estudiar las aportaciones clave de esta metodología a la comprensión, cuantificación, valoración y evaluación de los servicios de los ecosistemas. No en vano, los sistemas mediterráneos han sido ejemplos milenarios de la relación ser humano-naturaleza, que hoy se denomina sistemas socio-ecológicos, y los casos de estudio elegidos representan ese carácter mediterráneo dentro del contexto europeo.

Los resultados de esta tesis doctoral muestran que, a través de una potente base modelística, la síntesis emergética aporta una visión desde el punto de vista del proveedor de los servicios de los ecosistemas, que captura en términos puramente físicos el coste ecológico total del uso del capital natural por parte de la sociedad. Los indicadores emergéticos, provenientes de la mezcla de información de distinta naturaleza procedente de diferentes bases de datos, incorporan estructuralmente la variable temporal a través de la transformicidad y la emergía específica, estudiando sus cambios a través de series históricas de indicadores, y son contexto-dependientes, es decir, su significado varía de acuerdo con la fase del ciclo adaptativo en la que se encuentre el socio-ecosistema. Además, la perspectiva física que aportan sirve para entender las relaciones a distintas escalas espaciales, y entre socio-ecosistemas, mostrando explícitamente las desigualdades, desventajas, y otros aspectos de esta dimensión.

Así, la síntesis emergética forma parte de los métodos que investigan los costes físicos del uso del capital natural *desde la cuna hasta la tumba* y *desde la tumba hasta la cuna*. El papel concreto que juega la síntesis emergética dentro de este conjunto de metodologías, en un marco multi-criterio de evaluación, es el de introducir en el cómputo de costes del uso del capital natural para la satisfacción de necesidades humanas aquellos costes físicos que se derivan de los ecosistemas y su base biogeofísica. Para que la síntesis emergética pueda tener un papel significativo en la toma de decisiones relativa a las relaciones ser humano-naturaleza es necesario utilizar estas propiedades del método para complementar otras metodologías dentro de un marco multi-criterio.

ABSTRACT

There is an increasing interest in reintegrating ecosystem services into the economic decision-making, assuming that the divorce between economic growth, leading focus of the economic dedication, and ecosystems, subject of major conservation efforts, is one of the main reasons for biodiversity loss. Emergy synthesis is a methodology oriented to this purpose on ecological and thermodynamic basis.

In this document, 4 case studies of emergy synthesis historical series from some Mediterranean social-ecological systems at different scales have been used to study key contributions of emergy to understand, quantify, valuate and assess ecosystem services. Not in vain, Mediterranean systems of human and nature have been ancient examples of this relationship, recently labelled social-ecological systems, and the study cases chosen are representative of this Mediterranean nature.

Results show that emergy synthesis uses a powerful modelling basis and adopts a donor-side approach to ecosystem services in order to capture environmental costs of natural capital use by society. By means of the emergy concept and through the integration of data bases with different nature, it is possible to derive emergy indicators. These indicators include time through the use of transformity or specific emergies and allow studying temporal changes of natural capital use by emergy historical series. Emergy indicators are context-dependent, therefore, their meaning changes in accordance with the adaptive cycle phase of the social-ecological system. Furthermore, the physical nature of emergy indicators allows exploring relationships at different scales or between social-ecological systems connected.

Emergy synthesis is one of the methods oriented to study physical costs of natural capital use *from cradle to grave*, and *from grave to cradle*. Under a multi-criteria framework, the specific role played by emergy synthesis within these methodologies is to capture biogeophysical costs derived from ecosystem services. For emergy to have a significant role on decision making associated to human-nature relationships, it is necessary to exploit the emergy properties mentioned before under a multi-criteria framework.

ÍNDICE GENERAL

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LISTA DE ARTÍCULOS

La presente tesis se compone de los artículos que se enumeran a continuación. Todos los artículos se reproducen en la sección de resultados, bajo los derechos correspondientes a las respectivas publicaciones, y en el orden en que se exponen a continuación.

I.

Lomas, P.L., Cialani, C., Ulgiati, S. 2007. Emergy analysis of nations: Lessons learned from historical series. Chapter 39 in: Brown, M.T., Bardi, E., Campbell, D. E., Comar, V., Huang, S., Rydberg, T., Tilley, D., Ulgiati, S., editors. 2007. Emergy Synthesis 4: Theory and applications of the emergy methodology. Proceedings of the 4th Biennial Emergy Conference. Center for Environmental Policy, University of Florida, Gainesville. 483 pp.

II

Lomas, P.L. Gómez-Baggethun, E., Montes, C., Gómez-Sal, A. (manuscript). Investing in eco-cultural capital to deal with a changing world: Lessons from the Mediterranean Basin. Enviado a Ecology and Society.

III

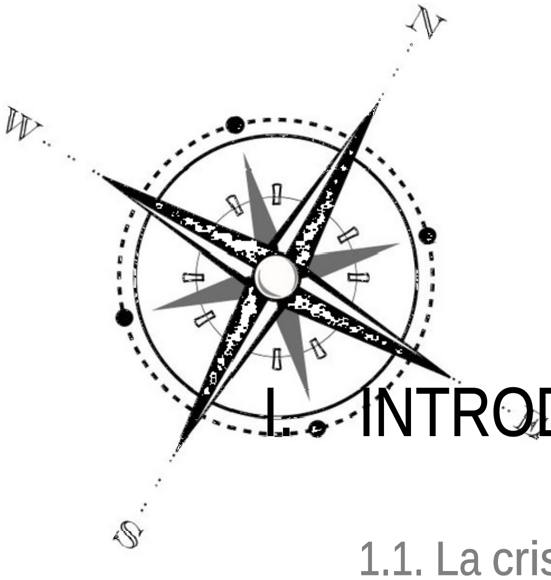
Lomas, P.L., Álvarez, S., Rodríguez, M., Montes, C. 2008. Environmental accounting as a Management tool in the Mediterranean context: The Spanish economy during the last 20 years. Journal of Environmental Management, 88: 326-347.

IV

Lomas, P.L., Montes, C. (manuscript). Multi-scalar assessment of the decoupling processes between local economic activities and natural capital by means of emergy synthesis. Andalusia (S Spain) as a case study. Manuscrito en revisión.

V

Lomas, P.L., Montes, C. (manuscript). Agricultural systems and wetlands conservation: The case of rice cultivation in the Guadalquivir marshes (SW Spain). Manuscrito en revisión.



I. INTRODUCCIÓN

1.1. La crisis: El cambio global y los modelos de “gestión de nuestra casa”.

Que vivimos tiempos de Cambio Global es algo prácticamente indudable. La creciente influencia de nuestra especie sobre los procesos biogeofísicos desde una escala local hasta una escala global es un fenómeno ampliamente documentado (Steffen *et al.*, 2005; Duarte *et al.* 2006). Si bien el cambio es consustancial a la propia naturaleza de los sistemas complejos, la situación que vivimos en la actualidad tiene, al menos, dos particularidades reconocidas frente a otros cambios sufridos a lo largo de la historia geológica del planeta:

- En primer lugar, la gran velocidad a la que se está produciendo, sin antecedentes conocidos. Desde que en los años 40, Vladimir Vernadsky (1945) ya advirtiera de un mundo en el que los principales ciclos biogeoquímicos del planeta, a los que denominó biosfera, estarían parcialmente controlados por la especie humana, por nuestra esfera cultural o noosfera, mucha ha sido la literatura que ha mostrado el control que ejerce la especie humana sobre los mismos, lo que ha permitido conocer tanto los cambios que hemos realizado en la superficie terrestre (Foley *et al.* 2005) como nuestra apropiación a escala planetaria de los productos de la fotosíntesis, del agua, etc. (Postel *et al.* 1996; Vitousek *et al.* 1986, 1997; Jackson *et al.* 2001; Rojstaczer *et al.* 2001; Imhoff *et al.* 2004), y también determinar qué efectos han tenido estos cambios sobre nuestro bienestar, y qué escenarios se vislumbran ante esta situación (MA, 2005).

- En segundo lugar, la causa común de la mayoría de estos cambios, nuestra especie, su crecimiento y su patrón de uso de la naturaleza, es decir, la administración que de “nuestra casa” estamos haciendo. La relación entre la actividad humana y el cambio global es tan evidente que se ha llegado a acuñar un nombre para una nueva era geológica, el Antropoceno, cuya particularidad sería que las riendas de los principales procesos biogeoquímicos que determinan el funcionamiento del sistema Tierra estarían, al menos en parte, en nuestras manos como especie (Crutzen & Stoermer, 2000; Steffen *et al.* 2007; Zalasiewicz *et al.* 2008), y por lo tanto, esto nos trasladaría en gran parte la responsabilidad de administrar bien “nuestra casa”.

El filósofo griego Aristóteles señalaba que la “administración de la casa” era el objeto de la *oikos-nomia* (Economía) en la Política (*Capítulos III, IV y VIII del Libro I*), ligándola al valor de uso de los objetos (o aptitud de los objetos para satisfacer necesidades humanas). Ésta se distinguía de la Crematística o “acumulación de riqueza”, ligada al valor de cambio (o relación de intercambio entre mercancías). Sin embargo, paradójicamente, y a pesar de que el origen de la disciplina económica estuvo inicialmente unido a esta “administración de la casa” a la que se refería el filósofo griego, la versión de la misma que ha acabado predominando es la que, parafraseando aquella frase célebre del despotismo ilustrado francés, “gestiona la casa, pero sin la casa”.

Así, el modelo sobre el que está construida la actual ciencia económica dominante es un modelo circular del flujo de la renta y los bienes y servicios (Figura 1.1.), centrado en dos componentes: las empresas o productores y los hogares o consumidores. Las empresas son fuente de bienes y servicios, y los hogares de capital (dinero, trabajo, etc.), que se intercambian. Así, la teoría del productor es la que pretende explicar cómo las empresas (los productores) deciden la cantidad de bienes a producir, y la teoría del consumidor es la que pretende explicar cómo los hogares (los consumidores) deciden la cantidad de bienes que consumen. El resultante sería la abstracción denominada mercado, que con una serie de asunciones, permitiría abordar la toma de decisiones a partir de un análisis de los costes y los beneficios monetarios de un determinado proceso, decisión, producto, etc.

En Naredo (2003) se puede encontrar un lúcido análisis de cómo a lo largo de su historia la ciencia económica ha ido reduciendo su objeto de análisis, desde el conjunto de toda la ecosfera hasta simplemente aquella parte de la ecosfera apropiable, directamente útil al ser humano y que se puede intercambiar y reproducir masivamente, es decir, aquella que dispone de una estructura de mercado como la que hemos visto, dejando fuera la mayoría de “la casa” que esta ciencia pretendía gestionar, y ciñendo el campo de la economía y sus mecanismos de análisis a la mera acumulación de riquezas y su estudio.

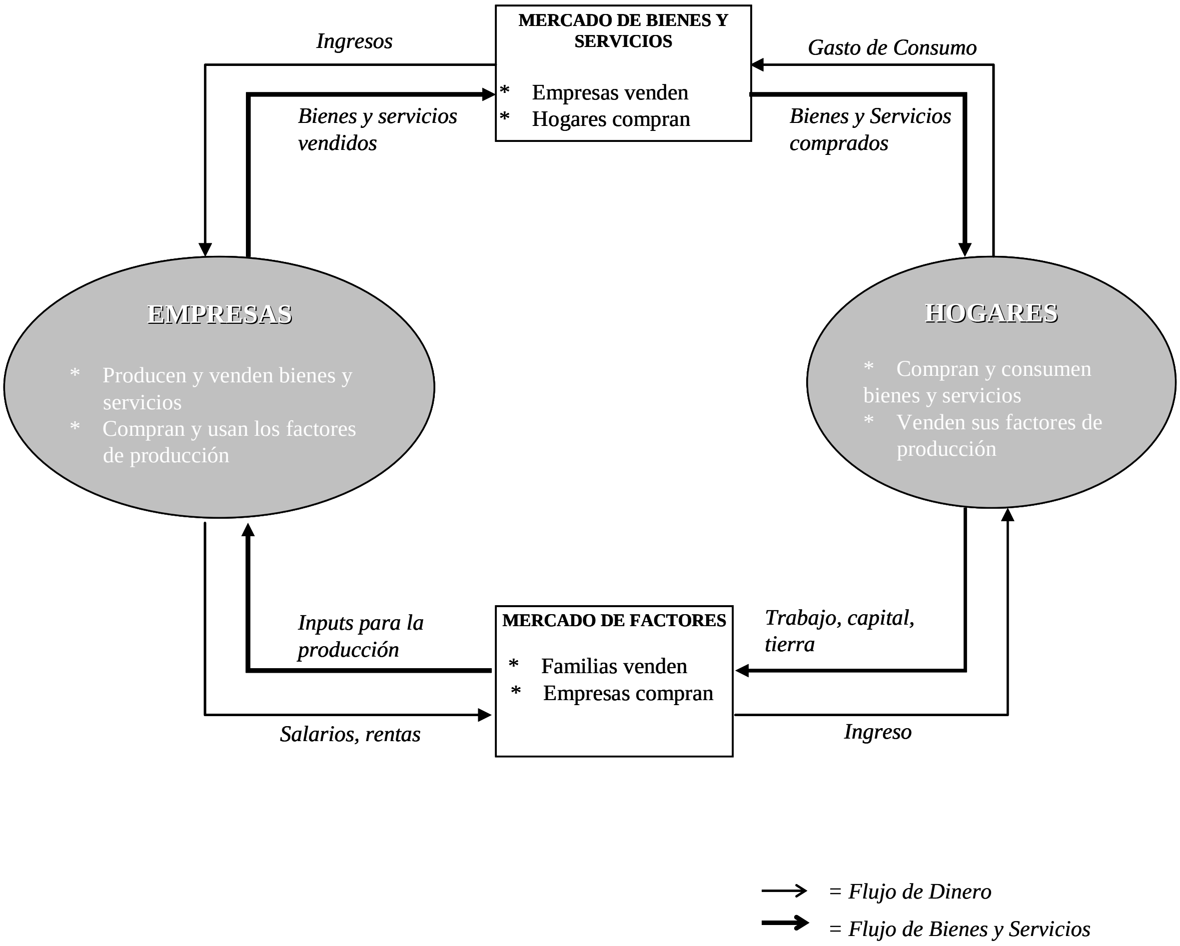


Figura 1.1. Esquema del funcionamiento de la Economía dentro del paradigma dominante, con el flujo circular de renta y bienes y servicios.

Así, la esfera de la economía era una esfera más junto a la ecológica y a la social, separadas entre sí, y pretendiendo maximizar su organización individual a costa de las demás (Figura 1.2a); los economistas se ocupaban fundamentalmente de la Economía, los ecólogos de la Ecología, y distintos científicos sociales de las cuestiones sociales.

Pero hacer operativa esa alianza no era tan sencillo, había que incorporar, de algún modo, los recursos que proporcionaba la naturaleza dentro del modelo circular de la economía. La naturaleza es considerada entonces como algo externo “a la casa”, una economía externa cuya interacción con el sistema económico había que hacer compatible con el crecimiento económico (el aumento de los agregados macroeconómicos), y por tanto incorporar al modelo de “gestión de la casa” actual para poder seguir manteniendo su racionalidad sin que ésta peligrase (Naredo, 1996).

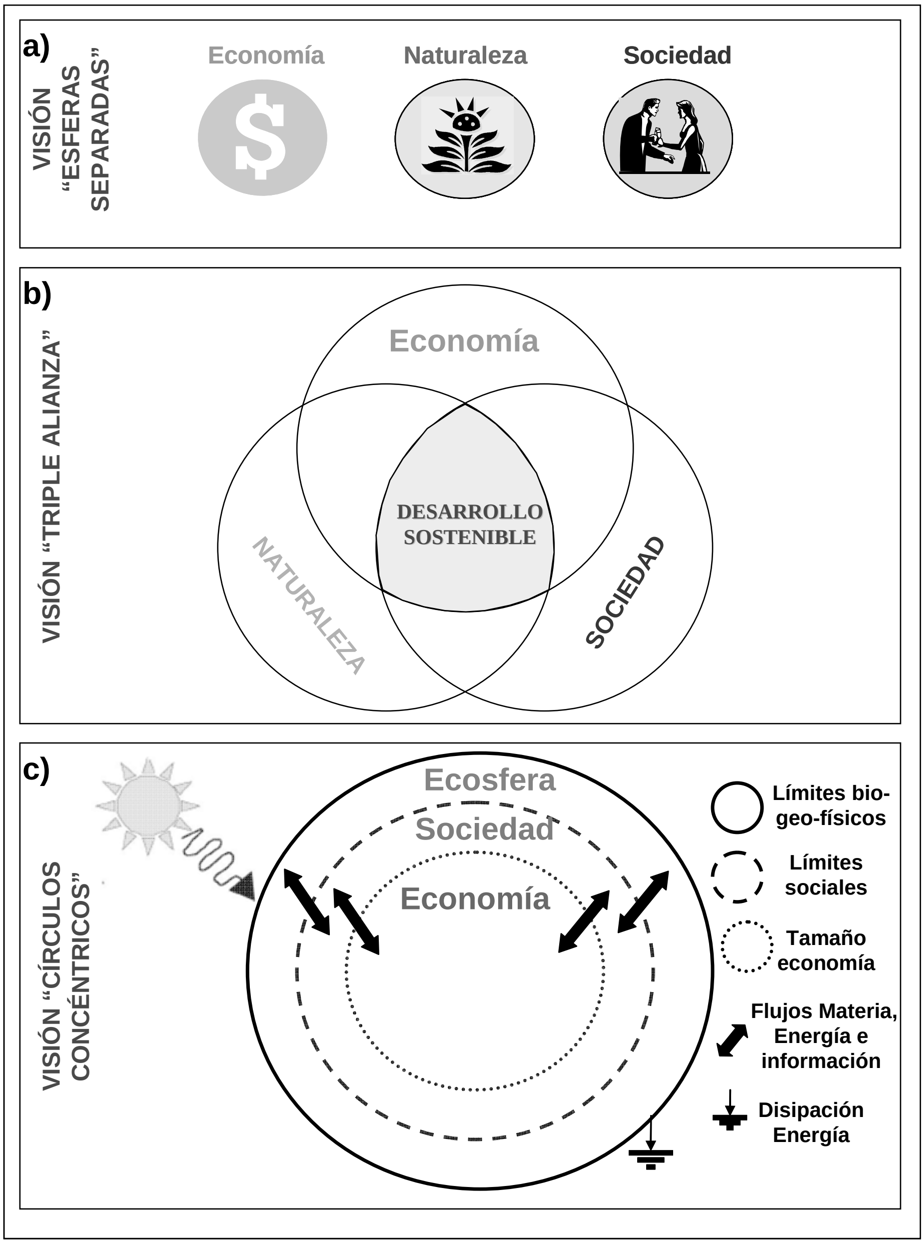


Figura 1.2.- Distintas visiones de las relaciones ser humano-naturaleza: (a) Esferas separadas; (b) Triple Alianza; (c) Círculos concéntricos.

A. Marshall acuñó este concepto de economía externa (Marshall, 1890) para referirse al efecto que sobre el precio de un determinado bien tenían otros mercados u otros factores ajenos al propio mercado del bien. Esta línea de argumentación sería continuada por un discípulo de Marshall, A.C. Pigou (1920), que defendía la aplicación de mecanismos de subvenciones e impuestos para resolver la problemática que suponían estos mercados externos, y más tarde, ya centrándose en los entonces denominados recursos naturales, por R. Coase (1960), que abogaba por la asignación de derechos de propiedad de los bienes para su asignación eficiente (en un sentido paretiano[1]) dentro del mercado. Se consolidaba así la idea de la naturaleza como una *externalidad* que había que internalizar dentro del mercado.

Es a partir de estas dos décadas cuando comienzan a usarse los términos económicos “bienes y servicios” aplicados a los beneficios que ofrecía naturaleza al ser humano como bienes y servicios ambientales, servicios ambientales, de los ecosistemas o de la naturaleza (Westman, 1977; Ehrlich & Ehrlich, 1981; De Groot, 1987; Daily, 1997). El argumento que se adoptaría desde esta aproximación al problema es que, frente a lo que sucede con los denominados bienes económicos, los “bienes y servicios” que aportaba la naturaleza a la economía, y que no están contenidos en el mercado, eran externalidades que no poseían precio (serían bienes libres, en la jerga económica), de tal modo que el efecto de su presencia o de su carencia se dejaba sentir sobre los mercados sin una contrapartida monetaria que permitiese computarlos y regularlos dentro de este marco. El resultado, de acuerdo con esta perspectiva, sería el de una asignación ineficiente (en un sentido paretiano) de los recursos, es decir, la problemática ambiental que actualmente sufrimos, de acuerdo con esta visión del problema (Costanza *et al.* 1997; Heal *et al.* 2005). La consecuencia inmediata de la aproximación adoptada bajo esta filosofía es la de tratar de encontrar modos de “internalizar las externalidades”, es decir, de poner precio a estos beneficios de la naturaleza, de tal modo que puedan ser incluidos en el actual marco de toma de decisiones coste-beneficio monetario, para así ser tomados en consideración. Algunos de los primeros intentos de llamar la atención sobre esta problemática dentro de la Economía Ambiental se inscriben en esta línea, siendo Costanza *et al.* (1997) y Balmford *et al.* (2002) los ejemplos más citados.

Así, a los denominados valores de uso directo (el beneficio o coste ligado a mercancías reales) se incorporan los de uso indirecto y los de no uso (Krutilla, 1967; Pearce & Turner, 1990; Pearce & Wardford, 1993) mediante multitud de métodos de cuantificación, orientados a conocer la disposición a pagar por el servicio o a ser

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[1] En Economía el concepto de eficiencia se refiere a la relación entre el precio de un determinado bien o servicio y el de los recursos utilizados para producirlo. La eficiencia económica pone de relieve entonces la relación entre el coste y el beneficio (monetarios ambos) de la producción. Es más, habitualmente cuando hablamos de Eficiencia en términos económicos nos estamos refiriendo a la denominada *Eficiencia en sentido de Pareto*, que caracterizaría aquella relación de costes y beneficios monetarios en la que se cumple que no es posible beneficiar monetariamente a más elementos de un sistema sin perjudicar a otros.

compensado por su pérdida (la demanda) y el posterior cálculo del excedente del consumidor para conocer el beneficio o el coste monetario correspondiente (Van Den Bergh, 2002). Así se construye el "verdadero valor", el Valor Económico Total o TEV, en sus siglas en inglés (Pearce & Turner, 1990; Turner *et al.* 2003). Lo que no es susceptible de valoración monetaria se denominan valores intrínsecos, y se inscriben en el campo de la ética ambiental, dejándolos aparte. La evaluación es, por tanto, monocriterio, siendo el criterio de valoración el coste o beneficio monetario "calculado adecuadamente" (con una muestra de población suficiente, con una escala adecuada, con mayor participación, a través del método acertado, etc.) de los servicios de los ecosistemas.

A pesar de la fuerte discusión científica que se está produciendo al respecto (e.g. Spash, 2008), y de la mercantilización de los servicios de los ecosistemas que bajo el manto de estos métodos se está a veces promoviendo (una revisión de esta idea se podrá consultar en el próximo número especial de la revista Ecological Economics sobre el pago por servicios ambientales, en el artículo de N. Kosoy & E. Corbera (2009) sobre el concepto de fetichismo de la mercancía aplicado a los servicios de los ecosistemas o en el de Gómez-Bagghetun *et al.* (*in press*) sobre la historia de los servicios de los ecosistemas, o en Spash (2008)) estos mecanismos de reduccionismo monetario están siendo ampliamente adoptados por la comunidad científica, y llevados ya a la arena política, especialmente desde la aparición del denominado Informe Stern (2006) sobre los costes monetarios del cambio climático, que ha propiciado la aparición de un informe análogo relacionado con la biodiversidad, con el nombre de "Economía de los ecosistemas y la biodiversidad" o TEEB (The Economics of Ecosystems and Biodiversity), en sus siglas inglesas (EC, 2008), donde se llega a afirmar que conservaremos la naturaleza cuando los beneficios (monetarios) de conservarla sean mayores que los de destruirla, llevando esta lógica a su punto más álgido.

1.2. La oportunidad: La Economía Ecológica, reconectando la "gestión de la casa" con "la casa".

Frente a esta visión donde la naturaleza continúa siendo una entidad periférica, una "externalidad", que hay que incorporar al modelo económico, surge la Economía Ecológica, que yendo más allá de la ortodoxia económica, supone una revisión de la teoría económica establecida, a partir de los trabajos pioneros de autores de distintas ciencias sociales y naturales, tales como K. Polanyi, S. Podolinsky, F. Soddy, P. Geddes, K.W. Kapp, H.T. Odum, N. Georgescu-Roegen, etc., cuyas aportaciones se pueden seguir en Martínez Alier & Schlüpmann (1987), Aguilera-Klink (1995), Carpintero (2006) hasta la consolidación de la disciplina en los años 90 con la crítica abierta a los modelos realizados desde la ortodoxia neo-clásica y aplicados por la Economía Ambiental en trabajos como los de Daly, Martínez-Alier, Naredo, etc. (Ropke, 2004; 2005).

Son éstos los precedentes de la consolidación de un modelo heurístico de relaciones ser humano-naturaleza con forma de círculos concéntricos (Figura 1.2c), donde el círculo central correspondería a la economía, que estaría dentro de los límites sociales, que a su vez habitarían dentro de los límites biogeofísicos. Así, la Economía Ecológica no reconoce la idea de externalidad, puesto que parte de que la Economía tiene sus fundamentos en la naturaleza. Son, por tanto, reglas de carácter social (e.g. igualdad, equidad) y biogeofísicas (e.g. termodinámica, reglas de entrada-salida[2]) las que deberían dirigir el mundo de lo económico, de la administración de la casa, y no viceversa.

Y es a partir de las implicaciones de uno de estos condicionantes, en concreto de la segunda ley de la termodinámica, que Georgescu-Roegen (1996) postularía grandes restricciones a la expansión ilimitada de la actividad económica concebida por la ortodoxia económica, y que se pueden resumir en: (1) no existe la posibilidad de realizar un aprovechamiento ilimitado de los aportes de la naturaleza, (2) ni, de modo

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[2] Las denominadas reglas de entrada-salida (Goodland & Daly, 1996) se resumen en, por el lado de las entradas, que no se puede tomar más cantidad de recursos renovables que la capacidad de renovación, ni más recursos no-renovables a una tasa mayor de la que la ciencia es capaz de sustituir por renovables; y por el lado de la salida, que los vertidos y emisiones tienen siempre que estar por debajo de la capacidad de asimilación natural.

práctico, un reciclaje completo de los materiales y la energía, (3) ni será el progreso infinito de la tecnología el que solucione estos problemas, y por tanto (4) el crecimiento no puede ser ilimitado (Carpintero, 1999). H.E. Daly, un economista norteamericano, discípulo de N. Georgescu-Roegen, a partir de la idea de que existían límites biogeofísicos a la expansión del sistema económico, postuló incluso la necesidad de una economía en estado estacionario para hacer operativo el objetivo de la sostenibilidad (Daly, 1977; 2008).

Sobre esta base se acuñaría el concepto de *capital natural* (Pearce & Turner, 1990; Costanza & Daly, 1992). Inicialmente el concepto se definió como “reserva de recursos naturales capaz de proveer un flujo útil de bienes y servicios tanto en el presente como en el futuro”. Dicha definición ha persistido más o menos invariable hasta la actualidad, añadiendo en algunos casos pequeñas modificaciones o matices, cuyo alcance suele depender de la consideración de la sustituibilidad entre capitales que se tenga, es decir, si se piensa que el capital natural se puede sustituir completamente por otros tipos de capitales, o si sólo se puede sustituir una parte más o menos amplia (Daly, 1994; Ayres, 1996; De Groot *et al.* 2003; Brand, 2009).

A su vez, surgió también el concepto de *funciones de los ecosistemas* para la sociedad (King, 1966; Hueting, 1970; Braat *et al.*, 1979), que en un principio se usaba como sinónimo o equivalente al de bienes y servicios de la naturaleza, pero que finalmente fue deslindado de estos, y definido como la capacidad de los elementos y procesos de los ecosistemas para proveer bienes y servicios que satisfagan directa o indirectamente las necesidades humanas (De Groot, 1992; De Groot *et al.* 2002). A aquellos componentes de los ecosistemas que ejercen funciones se les denomina unidades suministradoras de servicios (Vandewalle *et al.* 2008)

Por su parte, el concepto de *servicios de los ecosistemas*[3] (MA, 2005) que, como ya hemos visto, fue acuñado a partir de la idea de bienes y servicios de la economía aplicada a los beneficios obtenidos de la naturaleza, con el objetivo de incorporarlos al

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[3] En la Evaluación de los Ecosistemas del Milenio de Naciones Unidas (2001-2005) se deja de hablar de bienes y servicios de los ecosistemas para utilizar el concepto de servicios de los ecosistemas. La idea era dar a entender que los ecosistemas no podían dividirse, desde este punto de vista, en estructura, que proporcionaba bienes, y funcionamiento, que proporcionaba servicios, sino que había que considerar el todo como proveedor de servicios de los ecosistemas.

marco analítico de la economía, ha sufrido múltiples transformaciones derivadas del enriquecimiento que se ha producido en su debate con otras disciplinas. Una definición internacionalmente aceptada es la que habla de los servicios de los ecosistemas como los beneficios que los seres humanos obtenemos de los ecosistemas, y que hacen que la vida no sólo sea posible sino que además sea digna de ser vivida (MA, 2005; Díaz *et al.* 2006), si bien, hoy día, existe una cierta confusión acerca del uso de este término en la literatura, derivada de las diferentes intenciones con las que se definen y se clasifican los servicios (Boyd & Banzhaf, 2007; Wallace, 2007; Balmford *et al.* 2008; Fisher *et al.* 2009).

Así, en esta tesis doctoral entenderemos que los ecosistemas, a través de su estructura, funcionamiento y dinámica, desarrollan una serie de funciones para los seres humanos, que se traducen, cuando se hacen efectivas a través de un determinado flujo, en servicios de los ecosistemas, convirtiéndose entonces en capital natural para la humanidad (Martín-López *et al.* 2009), siendo el capital natural no tanto una reserva de "recursos", sino más bien una reserva de ecosistemas (Costanza & Daly, 1992).

En consonancia con el nuevo modelo de relaciones en círculos concéntricos, se comienza a hablar no ya de sistema ecológicos o de sistemas socio-económicos, sino de sistemas complejos ser humano-naturaleza o socio-ecosistemas (SES, en adelante) (Berkes & Folke, 1998; Folke, 2006; Liu *et al*. 2007; Ostrom, 2009) con un sub-sistema ecológico y otro sub-sistema socio-económico, tratando no cada elemento por separado, ni uno como complemento del otro, sino uno imbricado dentro del otro, a través de sus relaciones. El sistema se encuentra sometido a las restricciones biogeofísicas que condicionan su dinámica y auto-organización, y a la existencia y persistencia de fuentes de materia y energía que lo alimenten. El sub-sistema ecológico está compuesto por los ecosistemas a distintas escalas (sus componentes y sus relaciones), y el sub-sistema socio-económico está compuesto por sistemas sociales a distintas escalas (componentes, reglas, relaciones, etc.). De este modo, los grandes grupos de relaciones entre ambos subsistemas se pueden resumir en dos (Figura 1.3). De una parte, las funciones que los ecosistemas pueden tener para los seres humanos, que se transforman en servicios de los ecosistemas cuando son utilizadas efectivamente, y que contribuyen a las distintas dimensiones del bienestar humano, lo que convierte a los ecosistemas, desde esta perspectiva, en capital natural sobre el que hay que tomar decisiones a la hora de usarlo, de cara a mantenerlo; de otra parte, la intervención humana, a través de las distintas prácticas e instituciones sobre los procesos impulsores de cambio, que a través de la planificación y gestión humana del territorio condicionan la organización y el funcionamiento de los ecosistemas, o el capital natural.

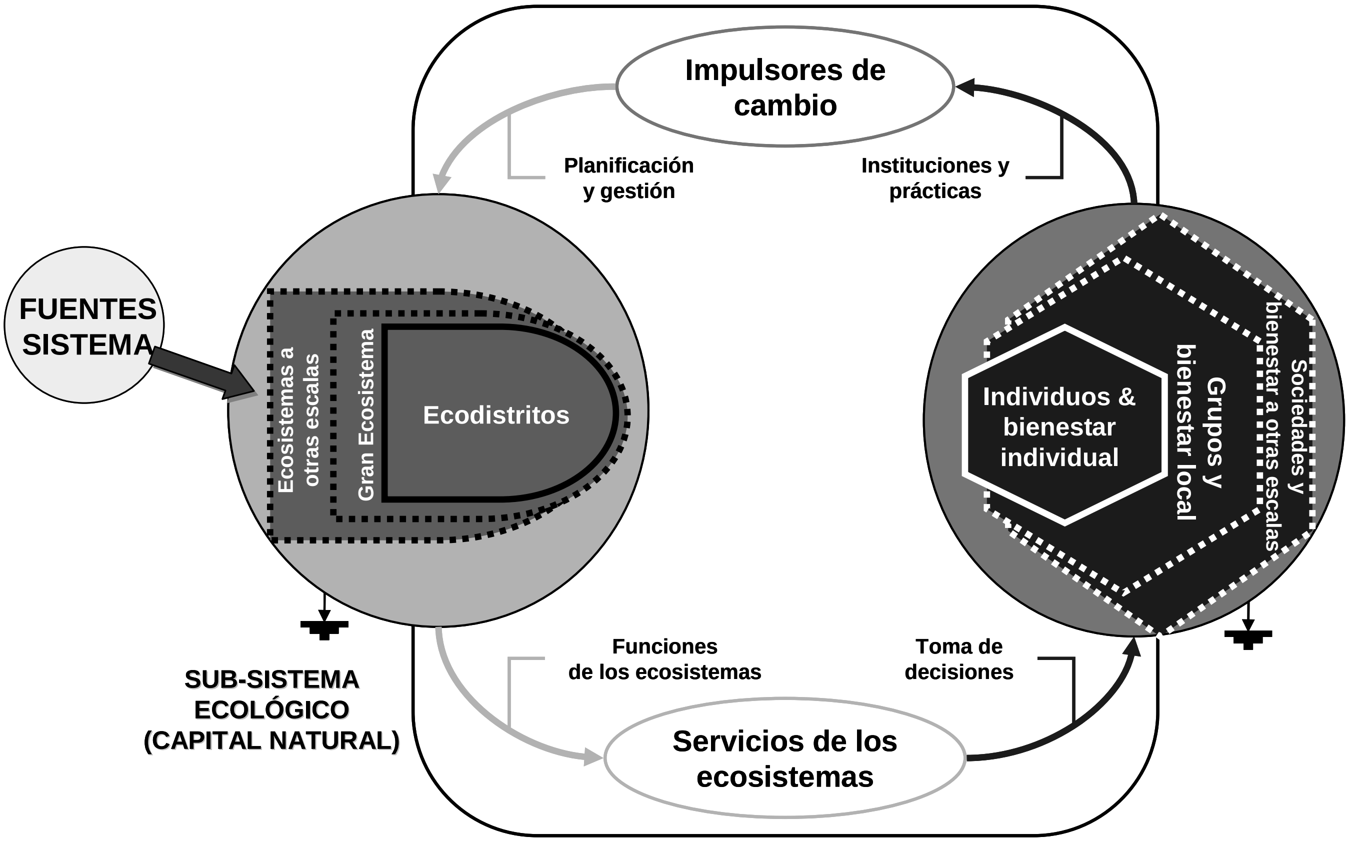

Figura 1.3.- Representación de las relaciones ser humano-naturaleza en los socioecosistemas, bajo el marco del concepto de capital natural.

Bajo esta perspectiva, tanto los servicios de los ecosistemas como la gestión humana son posibles mediante el uso directo de materia, energía, información, etc. que, en forma de flujo, son transferidas desde la base biogeofísica hasta la sociedad y viceversa, y que como consecuencia suponen una degradación de la energía y la materia empleadas en el proceso, de acuerdo con la segunda ley de la termodinámica (Georgescu-Roegen, 1996). Así, en vista de que cualquier proceso en la economía lleva aparejado un coste en términos de materia y energía potencialmente útil, un objetivo clave de la Economía Ecológica sería el de medir este coste adecuadamente para entender la escala de la economía dentro de la ecosfera, es decir, en qué medida nos apropiamos el capital natural (Daly, 1991), y poder dar soporte a un proceso de toma de decisiones para utilizar la materia y la energía adecuadamente con el objetivo de satisfacer las necesidades humanas de manera sostenible.

En el proceso de toma de decisiones correspondiente a esta visión de las relaciones ser humano-naturaleza tienen que estar presentes no sólo la maximización de la rentabilidad monetaria a través de un VET, como se hacía fundamentalmente hasta ahora, sino también los beneficios y costes que a otros niveles (cultural, material, social, etc.) tiene el uso de los servicios de los ecosistemas. Por tanto, desde esta perspectiva, se parte de que no existe un único tipo de valor de las cosas ni una unidad particular de medida que permitan resolver por sí solos, o agregándolos para obtener una cifra, los conflictos de decisión sobre los servicios de los ecosistemas, y por tanto, se aborda la problemática desde el punto de vista de la comparabilidad débil de los valores (O'Neill, 1993; Martínez Alier *et al.* 1998). Se trataría así de un proceso de toma de decisiones basado en una evaluación multi-criterio (Munda, 2004; 2005; 2008).

Bajo este marco, la filosofía adoptada para conocer la escala de la economía en la ecosfera, es decir, para determinar el coste de las actividades económicas a distintas escalas, es la del ciclo de vida (ACV, en adelante) (Ayres, 2004), que nos ofrece un panorama del uso del capital natural por parte de la sociedad desde "*la cuna hasta la tumba*" (costes en materiales, energía y emisiones, vertidos, etc. de la producción, uso y desecho). Se aspira también a conocer el proceso de cierre de ciclos desde los residuos hasta la vuelta de uso de los materiales procesados, lo que se suele medir a través de otros nuevos marcos que han aparecido en los últimos años, y que permitirían conocer el proceso económico desde "*la tumba hasta la cuna*" (Naredo, 2003; Carpintero, 2005), como se puede observar en la Figura 1.4.

Las metodologías usadas dentro del marco del ACV se suelen desarrollar o bien en términos físicos o bien en términos territoriales. Desde el punto de vista de los costes físicos, se usa el concepto de metabolismo socio-económico (Ayres, 1989; Ayres & Simonis, 1994; Adriaanse *et al.* 1997; Daniels & Moore, 2002; Daniels, 2002; Carpintero, 2005), que supone un marco donde se estudia el uso de materia y la energía, así como los residuos, vertidos, emisiones, etc. resultantes de un determinado proceso económico (un país, una fábrica, los hogares, etc.). En este marco, son muchos los métodos concretos empleados, que permiten cuantificar los flujos de materia y energía. En Fischer-Kowalski (1998), Fischer-Kowalski & Hüttler (1998), EUROSTAT (2001) y

Hintenberger *et al.* (2003) se hace una revisión de la historia y metodología de aquéllos que tienen que ver con la contabilidad de los flujos de materiales. En Haberl (1997; 2001a; 2001b) y Haberl *et al.* (2004) los que se refieren a la contabilidad de los flujos de energía, y la apropiación de la producción primaria por parte del ser humano. En Brown & Herendeen (1996) y Herendeen (2004) se realiza una revisión de los métodos que calculan la energía incorporada en los productos usados por la economía. En Ulgiati *et al.* (2006) se da una panorámica breve de los métodos que se suelen usar para capturar la parte referida a las emisiones y residuos, y su impacto, lo que también se aborda desde el punto de vista de la contabilidad por parte de los métodos antes expuestos de contabilidad de flujos materiales y energéticos. En lo que se refiere al punto de vista territorial, ha ganado apoyos a lo largo de las últimas décadas el desarrollo de la Huella Ecológica (Wackernagel & Rees, 1996; Wackernagel *et al.* 2002a; Wackernagel *et al.* 2002b).

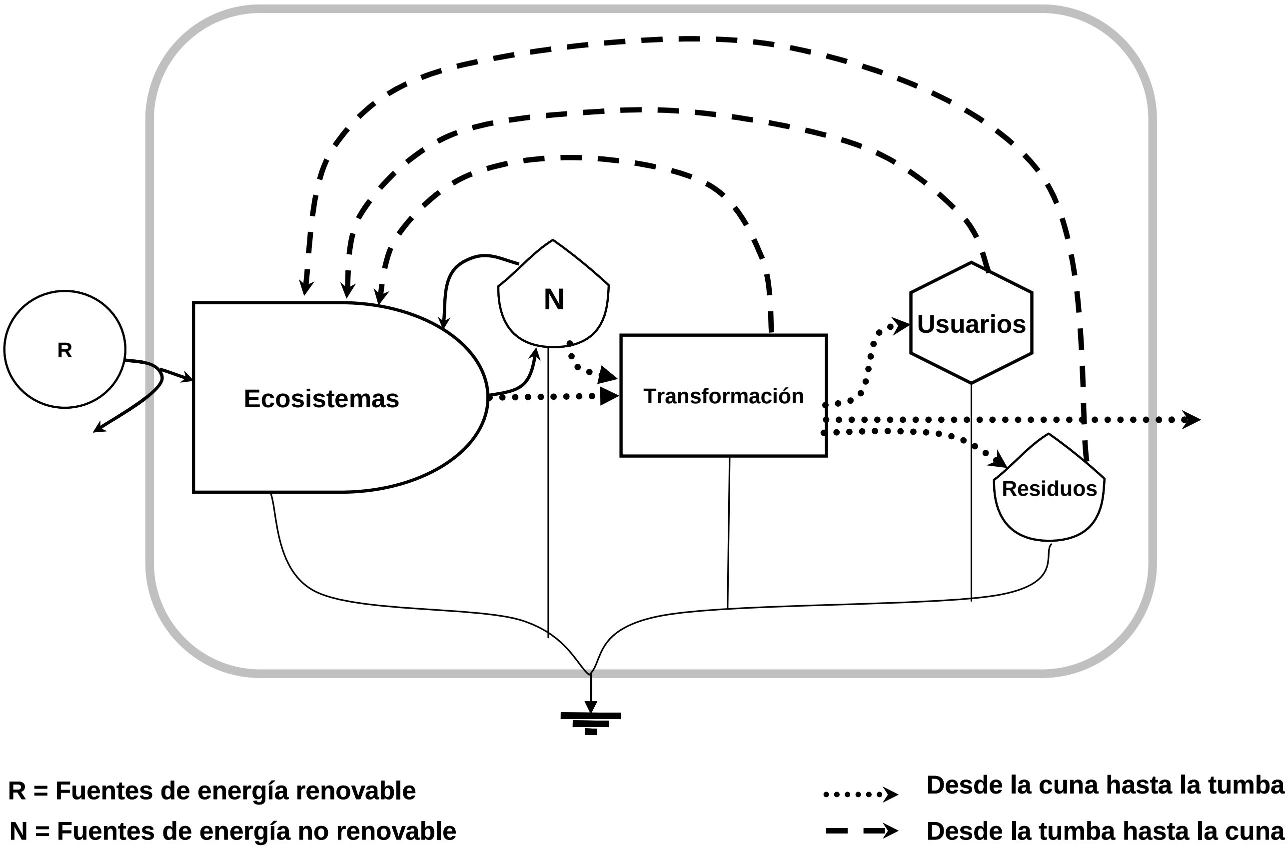

Figura 1.4. Flujo de materia y energía que circula entre los ecosistemas y la sociedad desde "la cuna y la tumba" (servicios de los ecosistemas) y desde "la tumba y la cuna" (cierre de ciclos).

En cuanto a las metodologías usadas para capturar los costes desde "*la tumba hasta la cuna*", es habitual usar el denominado coste exergético, en sus múltiples acepciones (coste exergético, coste exergético extendido, contenido exergético acumulado, etc.). En Naredo & Valero (1999), Sciubba (2001) y Sciubba & Ulgiati (2005) se revisa la exergía en sus diversos significados y aplicaciones.

Sin embargo, al cuantificar sólo la materia y/o energía correspondiente a las materias primas utilizada directamente por la economía o el de los productos consumidos por los usuarios de los servicios de los ecosistemas (lo que entra en el circuito económico y sus flujos ocultos), estamos cuantificando sólo una parte del coste total que esta utilización tiene. Así, la frontera del estudio deja parcialmente inexplorado el campo de la contribución biogeofísica a la generación de estos bienes y servicios económicos usados por la sociedad, es decir, el campo de las funciones y de los servicios de los ecosistemas *sensu stricto*. Por esta razón, los costes físicos así entendidos quedan reducidos al paso de la materia y la energía desde los proveedores económicos de productos hacia la sociedad, o el trabajo, en términos del uso directo de materia y energía por parte de la economía para la generación de estos productos, sin que se tenga en cuenta de manera explícita y directa el trabajo biogeofísico de los ecosistemas para generar los productos que se utilizan en la economía y, por tanto, sin tener en cuenta completamente la contribución ambiental a la generación de esa materia o energía contenida en los productos (Brown & Ulgiati, 1999; Sciubba & Ulgiati, 2005; Franzese *et al.* 2006; Ulgiati *et al.* 2006).

1.3. *Objetivos de la tesis.*

Es esta ventana de oportunidad la que se abre a metodologías capaces de complementar a las otras en lo que se refiere a la captura de los flujos biogeofísicos donde se inscribe el esfuerzo de la presente tesis doctoral, que tiene como ***objetivo general*** el de estudiar algunas de las aportaciones clave de la Síntesis Emergética (Odum, 1996; Brown & Ulgiati, 2004) a la comprensión, cuantificación, valoración y evaluación de los servicios de los ecosistemas a través de diversos casos de estudio que ejemplifiquen dichas aportaciones. Bajo esta perspectiva, los ***objetivos específicos*** que esta investigación se propone son los siguientes:

a) Examinar la viabilidad (validez, posibilidades, etc.) del uso de la Síntesis Emergética y las herramientas de las que está compuesta (ventana ambiental, diagramas de flujos, memoria energética, transformicidad, calidad de la energía, etc.) en el estudio de la interfase ser humano-naturaleza.

b) Experimentar las aptitudes de la Síntesis Emergética para explorar diferentes dimensiones del uso del capital natural (el modo en que se usa, la cantidad que se usa, la evolución del uso, etc.) dentro de SES y entre SES a distintas escalas.

c) Desarrollar las aportaciones de la Síntesis Emergética en la incorporación de los flujos biogeofísicos a una perspectiva de estudio “desde la cuna hasta la tumba y desde la tumba hasta la cuna”, dentro de un marco de evaluación multi-criterio.

En consonancia con estos objetivos específicos, se han elaborado los artículos que constituyen el núcleo de los resultados de esta tesis doctoral, cuyos ***objetivos particulares***, englobados en los ya mencionados objetivos específicos, son los siguientes:

3.1. Analizar qué indican realmente los principales indicadores emergéticos y cuáles son sus fortalezas y debilidades en el estudio de sistemas socio-ecológicos, con respecto a los indicadores habituales, así como la influencia entre unos y otros y su posible articulación desde una perspectiva multi-criterio.

3.2. Recuperar algunas de las principales lecciones que la gestión milenaria de los ecosistemas y el desarrollo de los paisajes culturales del Mediterráneo puede aportar a los modelos de gestión adaptativa en SES y de uso del capital natural.

3.3. Examinar un SES a escala de país, así como sus relaciones con otros países a través de su estudio en términos de uso del capital natural, y sostenibilidad de este uso.

3.4. Estudiar el uso que se hace del trabajo de la naturaleza en un SES a escala de región partiendo de su base biogeofísica, y de sus políticas de gestión del capital natural, examinando el papel que juega el SES en su entorno más cercano, así como la evolución en la relación entre los dos sub-sistemas que lo componen en términos de acoplamiento y desacoplamiento local.

3.5. Determinar el grado de perturbación en el funcionamiento ecológico debido a la influencia humana en un SES a escala local, partiendo de la evolución en el uso que de los flujos de materia y energía ha generado el desarrollo de actividades agrícolas en el territorio.

1.4. Planteamiento de la tesis.

Los resultados de la presente tesis doctoral están contenidos en cinco artículos. Como hemos dicho cada uno de ellos tiene entidad por sí mismo, y a la vez forma parte de un conjunto, que es el que le da hilo conductor al documento. Con el fin de orientar al lector, la Figura 1.5. contiene dicho hilo conductor a partir de la relación establecida entre los distintos artículos.

El argumento de la tesis se articula alrededor de la aplicación de la Síntesis Emergética a los servicios de los ecosistemas dentro de los SES, concepto acuñado por Berkes & Folke (1998) para describir los sistemas complejos adaptativos de ser humano y naturaleza. Como ya se ha dicho, los elementos que forman parte de la estructura de los SES (ecosistemas y sistema socio-económico a distintas escalas), vistos desde una perspectiva antropocéntrica, se interrelacionan entre sí, por la parte de los ecosistemas mediante el aporte de servicios al bienestar humano, convirtiéndose así en capital natural, y por la parte del subsistema humano en forma de gestión y administración de los ecosistemas a distintas escalas.

La Síntesis Emergética se basa en el concepto de memoria energética, sobre cuyas bases se profundiza en el *Capítulo 2*, y que se fundamenta en el estudio de los flujos biogeofísicos y socio-económicos de materia y energía que se intercambian entre los elementos constituyentes de los SES bajo una misma base.

En el *Capítulo 3* de esta tesis se exploran las aptitudes de la síntesis emergética para estudiar distintos aspectos de los servicios de los ecosistemas en varios casos de estudio de SES mediterráneos a distintas escalas.

En el primer artículo, contenido en el *apartado 3.1.*, se cuantifican las contribuciones biogeofísicas y económicas para el funcionamiento de diferentes SES a escala de Estado a través de series históricas de emergía con el objetivo de hacer una exploración previa del significado de los indicadores emergéticos en este contexto.

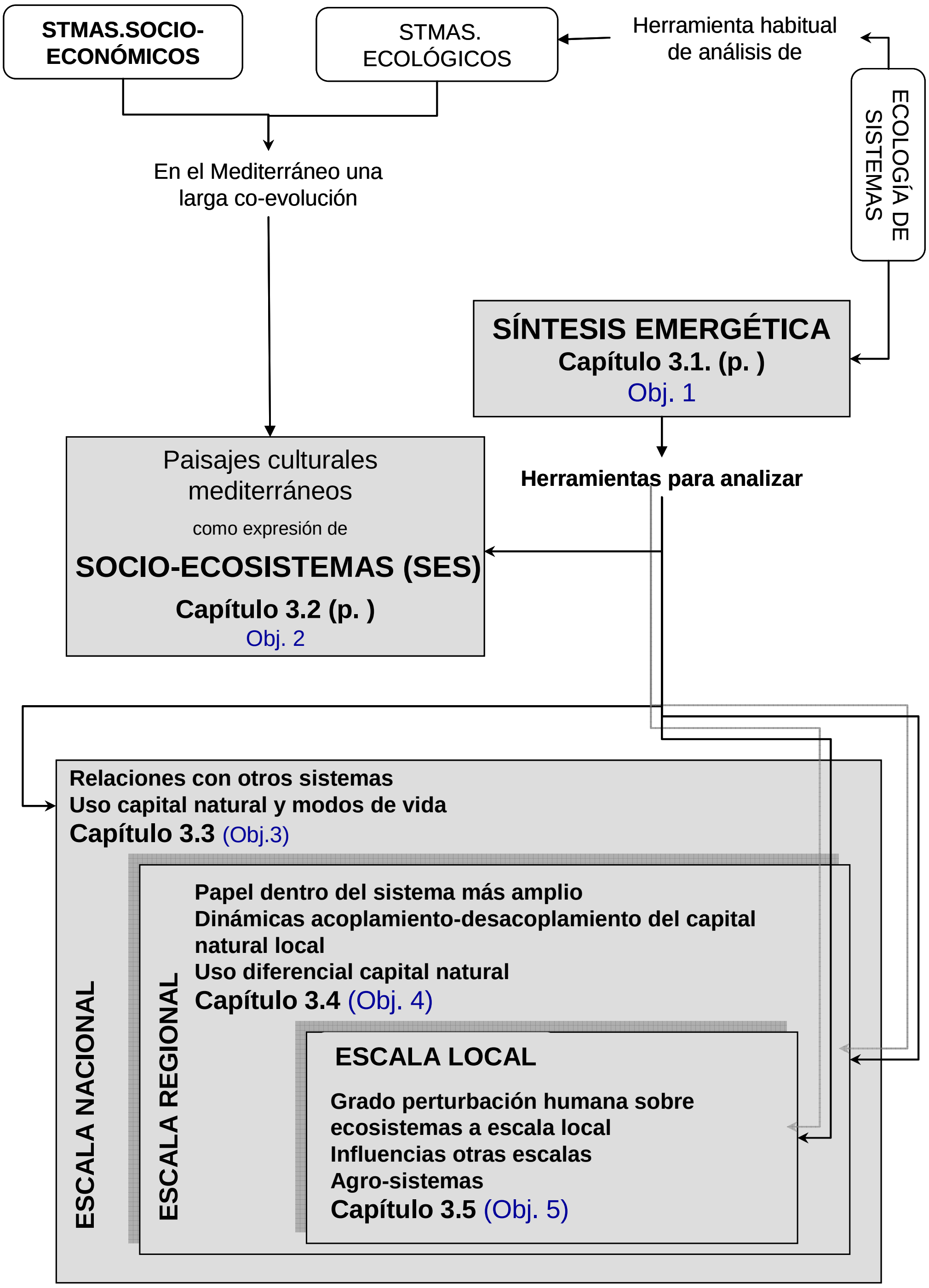

Figura 1.5.- Esquema con el hilo conductor de la tesis, del que se derivan los capítulos y artículos que configuran la misma.

A continuación se presentan los casos de estudio que constituyen la evaluación multiescalar. Todos los casos de estudio tienen como nexo común la identidad mediterránea de los SES estudiados. De hecho, en el *capítulo 3.2.* se aborda la singularidad de los SES mediterráneos en un contexto global a través de sus paisajes culturales, y qué lecciones se pueden extraer de la milenaria experiencia mediterránea de co-evolución ser humano-naturaleza. Cabe destacar que los SES mediterráneos constituyen uno de los espacios transformados más antiguamente por los seres humanos en Europa (Grove & Rackham, 2001), más poblados del planeta y, sin embargo, con mayor biodiversidad (Mittermeier *et al.* 2004). Estas características hacen de la región mediterránea uno de los lugares más adecuados para estudiar las relaciones hombre-naturaleza, en términos de paisajes culturales (e.g. Naveh & Liberman, 1993; Farina, 2000; Pinto-Correia, 2002).

Los casos de estudio se desarrollan en los *apartados 3.3., 3.4., y 3.5.* En primer lugar estudiamos la escala de Estado con el ejemplo de España (*capítulo 3.3.*). El estado español ocupa un lugar privilegiado dentro del Mediterráneo, ya que se trata del país de Europa con mayor superficie absoluta de ecosistemas mediterráneos (más del 75 % de su superficie) dentro de la cuenca mediterránea (Blanco *et al.* 1997). Por tanto, podemos afirmar que, resultado de la milenaria historia de la explotación de estos ecosistemas, el territorio español está compuesto por una de las más diversas representaciones de los paisajes culturales del mediterráneo. Además contiene uno de los puntos calientes de biodiversidad dentro de la propia cuenca mediterránea, que sería la parte bética del complejo bético-rifeño, localizada fundamentalmente en las regiones de Andalucía, Castilla-La Mancha, Valencia y las Islas Baleares (Médail & Quézel, 1999). En este artículo se estudia el coste ambiental del funcionamiento de la economía española a lo largo de los últimos 20 años del pasado siglo.

En segundo lugar, la escala regional-provincial se estudia en el *capítulo 3.4.*, a través de la aplicación de una serie histórica de síntesis emergéticas a distintos años en Andalucía y sus provincias. Andalucía es una de las regiones españolas más representativas de los SES mediterráneos. Se trata de la segunda región en tamaño dentro de España (más de 87000 km^2). Posee la mayor superficie absoluta de ecosistemas mediterráneos (el 100 % de sus más de 87000 km^2 se encuentran incluidos dentro de la región mediterránea) de todo el país, y contiene uno de los mayores puntos de biodiversidad de la cuenca mediterránea, que son las sierras béticas, especialmente Sierra Nevada, con el Mulhacén, la cima de la Península Ibérica con sus 3285 m sobre el nivel del mar (Médail & Quézel, 1999; Lobo *et al.* 2001). En el contexto español, se trata de una región tradicionalmente orientada a la explotación de sus recursos naturales (Delgado Cabeza, 2002; Infante Amate & González de Molina, 2008), y por tanto, que ha estado sujeta a una fuerte co-evolución entre ser humano y naturaleza, resultando en una miríada de paisajes culturales. El intento por preservar estos espacios ha hecho que Andalucía sea la región española con la mayor cantidad de superficie protegida (alrededor del 20 % de la superficie regional). A la vez, la región ha sido objeto de una política de subsidio para adecuar sus índices macroeconómicos a la media de la UE (más de 26000 millones de euros entre 1986 y el 2005), dentro de la política de cohesión europea (Griñán, 2005), lo que ha propiciado enormes cambios de carácter socio-económico. Todo ello proporciona una buena perspectiva de los fuertes cambios ambientales a los que se están sometiendo a los SES mediterráneos bajo el paraguas de la convergencia y cohesión de la UE. Así, en este artículo se ha prestado más atención a las dinámicas de desacoplamiento entre servicios de los ecosistemas locales y el sub-sistema económico, ligadas a fenómenos de globalización económica y a la aceleración de los procesos de antropización que el sistema viene sufriendo. El empleo de la escala provincial sirve para demostrar cómo estos procesos se manifiestan de manera diferencial según la escala y la predisposición a los fenómenos antes comentados.

Por último, la escala local es la que se aborda en el *capítulo 3.5.*, a través del estudio de los cambios en el uso de la memoria energética dentro del SES Doñana (Montes *et al.* 1998; Lomas *et al.* 2007). Doñana es un área emblemática desde el punto de vista conservacionista, dado que es el humedal más extenso de Europa Occidental, importante paso de aves migratorias entre África y el Paleártico (García Novo & Marín Cabrera, 2005), y un lugar único como refugio de especies amenazadas (Fernández-Delgado, 2005). A su vez, es una de las pocas áreas dentro de Andalucía donde actualmente aún se mantiene el carácter mediterráneo derivado del estrecho vínculo entre la población local y los ecosistemas basado en una explotación ligada al conocimiento tradicional (Gómez-Bagghetun et al., *in press*).

En el *Capítulo 4* se aborda la discusión entorno a estos resultados, centrándose principalmente en tres grandes asuntos. En primer lugar, la perspectiva sobre los servicios de los ecosistemas que se puede obtener desde la Síntesis Emergética; en segundo lugar, sobre los aportes de la misma a la comprensión del uso, intercambio, evolución, etc. del capital natural; en tercer lugar, sobre el rol que desempeña la síntesis emergética dentro de un marco multi-criterio de evaluación de los servicios de los ecosistemas y de toma de decisiones.

Por último, en el *Capítulo 5* de la presente tesis doctoral se incluye un resumen de las principales conclusiones de la investigación, y de las aportaciones que se han realizado a lo largo de esta tesis en la resolución de los objetivos de partida, así como algunos de los desafíos que se encuentran interesantes en futuras investigaciones dentro de este campo.

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II. METODOLOGÍA

2.1. La síntesis emergética
2.2. Referencias bibliográficas

2.2. La síntesis emergética

El desarrollo de los aspectos metodológicos de la síntesis emergética que se presenta en este apartado está basado en parte en el material de una publicación y un documento de trabajo en castellano que el autor ha dirigido en los últimos años, resultado del estudio de la metodología empleada en esta tesis doctoral, y que son, respectivamente:

- **Lomas, P.L., Di Donato, M., Ulgiati, S.** 2007. La síntesis emergética: una valoración de los servicios de los ecosistemas con base termodinámica. *Ecosistemas,* **16** (3): 37-45. http://www.revistaecosistemas.net/articulo.asp?Id=497.

- **Álvarez, S., Lomas, P.L., Martín, B., Rodríguez, M., Montes, C.** 2006. *La síntesis emergética ("emergy synthesis"): Integrando Energía, Ecología y Economía.* Publicaciones de la Fundación Interuniversitaria Fernando González Bernáldez para los espacios naturales, nº 2. Documento de Trabajo, Madrid. ISBN 84-96063-72-0.

Como literatura para profundizar más en el significado y las consecuencias de la emergía se recomienda comenzar consultando Odum (1996) y Brown & Ulgiati (2004b), auténticas obras de referencia sobre el tema.

Contrariamente a otros métodos ligados a la filosofía del análisis del ciclo de vida, ampliamente difundidos y conocidos (p.ej. el análisis de los flujos materiales, el análisis de los flujos de energía, el propio análisis del ciclo de vida, etc.), la síntesis emergética y las variantes de carácter más ecológico que aquí se usan, no han sido muy propagadas en España, por lo que en el próximo apartado se hace un breve esbozo de los principios en los que se basa esta metodología para mayor comprensión del lector de esta tesis, y aclaración de algunos aspectos no siempre bien entendidos de la metodología.

Hablar de memoria energética o emergía implica aclarar previamente dos conceptos clave. Por una parte, el concepto de calidad de energía, y por otra, el de transformicidad.

2.1.1. Calidad de la energía

En cuanto al primero, H.T. Odum desarrolla la idea de la calidad de la energía al calor de la crisis energética y ambiental que se produjo en los años setenta, y a partir de las bases teóricas de la Ecología de sistemas, derivada de la Teoría General de Sistemas, y la energética de ecosistemas, aplicación de la termodinámica de los ecosistemas que estaba desarrollando con su hermano Eugene P. Odum (Brown & Ulgiati, 2004a).

H.T. Odum observó que en procesos de auto-organización de sistemas complejos, como los ecosistemas, la segunda ley de la termodinámica implica que la energía que pasa de un nivel a otro de la auto-organización es menor en cada escalón, no existe una eficiencia del cien por cien en el proceso de transformación; pero, por otra parte, la energía necesaria para la construcción de niveles más altos de la auto-organización es cada vez mayor conforme el sistema se hace más complejo, es decir, conforme avanza en la cadena de organización. Así, la energía se concentra conforme avanzamos en niveles de auto-organización y complejidad (Figura 2.1.).

La primera formalización de esta idea se llevó a cabo a partir del trabajo de Odum (1971) y Odum (1973), donde señalaba que “La energía se mide en calorías, BTUs, kilowatios-hora y otras unidades indiscutibles, pero existe una escala de calidad de la energía que no está contenida en estas medias. La capacidad para desarrollar trabajo para el hombre depende tanto de la cantidad como de la calidad de la energía, y se mide mediante la cantidad de energía de un grado de calidad bajo que es necesaria para generar otra de un grado mayor”.

Esta observación implica que 1 joule de energía solar, 1 joule de carbón o 1 joule de electricidad, aunque representan la misma *cantidad* de energía (1 joule), no representan la misma *calidad*, en el sentido del potencial que tienen estos distintos tipos de fuentes energéticas para actuar sobre el conjunto del sistema, es decir, en la necesidad que el sistema tiene de recibir mayores o menores cantidades de energía menos concentrada para generar cada una de ellas. La conclusión obvia es que existe una jerarquía de energías según su calidad o potencial para influir en el sistema (Figura 2.1.), que va desde fuentes de energía poco concentradas (como el sol) hasta aquellas muy concentradas (como el petróleo) (Odum, 1996; Odum, 2003; Brown & Ulgiati, 2004a).

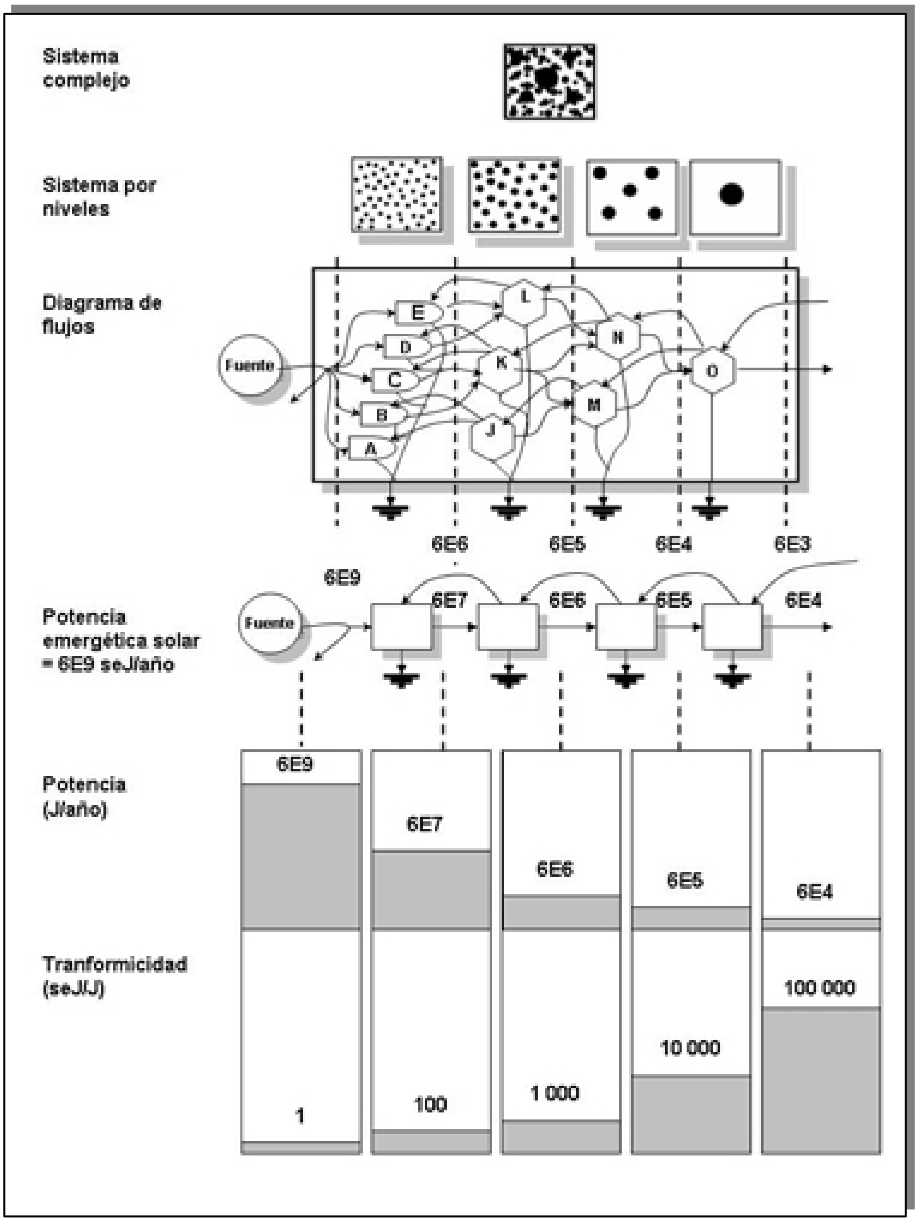


Figura 2.1. Concentración de la energía y formación de una jerarquía de energías a medida que el sistema se hace más complejo.

Así, y con el objetivo de tener en cuenta los distintos tipos de calidad de energía que guían los procesos biogeofísicos, y en último término, la Economía, Odum comienza a usar el término energía incorporada (*embodied energy*) para denominar la cantidad de energía de una calidad poco concentrada (que habitualmente es la energía solar) necesaria para generar otro tipo de energía más concentrada. Posteriormente, y a sugerencia de David Scienceman (1987), la define como **memoria energética o emergía**, es decir, la cantidad de energía útil (exergía) de un determinado tipo necesaria para generar un producto (Odum, 1988; 1996), con el objetivo de distinguirla del concepto de energía incorporada que ya estaba siendo empleado con otro significado, y de diferenciarla de la misma en aspectos de calidad de la energía y memoria energética (Brown & Ulgiati, 2004a).

La elección de la energía solar como referencia se fundamenta en el hecho de que ésta supone la principal entrada de energía a la ecosfera, concibiendo el planeta como un sistema cerrado[1], aunque no deja de ser un convenio (podríamos tomar otras bases de referencia, como por ejemplo el carbón, el petróleo, etc.). Así, la **emergía solar** sería la cantidad de energía de calidad igual a la del sol que necesitaríamos para generar un determinado producto. Y por tanto, las unidades de la emergía serían los joules equivalentes solares (seJ). Nótese, y esto es muy importante a la hora de diferenciar conceptos, que no nos referimos a la cantidad de energía solar contenida en un determinado producto (que sería una aproximación particular de su energía incorporada), sino a la cantidad de energía (no sólo solar, sino cualquiera que sea su origen) con calidad referida a la de la energía solar (es decir, el equivalente de cada una de estas energías en términos de calidad solar) que es necesaria para generarlo. Se trata de calcular el coste en términos de energía (de la misma calidad) movilizada del conjunto de materiales y energía usados en generar un determinado producto. De ahí que hablemos de memoria energética (energy memory o emergy, en el inglés original).

Por otra parte, si tomamos una referencia temporal, se suele emplear el concepto de **potencia emergética**, es decir, el flujo de emergía por unidad de tiempo (seJ/unidad de tiempo), y así tendríamos que:

$$P_x = \frac{d}{dt} Em$$, donde

P_x = potencia emergética (seJ/unidad de tiempo);

E_m= emergía (seJ)

---

[1] En termodinámica los sistemas se pueden clasificar en abiertos (que intercambian materia y energía), cerrados (que sólo intercambian materia) y aislados (que no intercambian ni materia ni energía).

Un asunto relevante, y sin duda fuente de alguna de las críticas más habituales del método es el del papel de la materia en la síntesis emergética. Hasta ahora en las definiciones que hemos dado se presenta simplemente la cara energética del asunto, y parece que se olvida la materia, condenándonos a iniciar un ciclo de reduccionismo energético opuesto a otro de reduccionismo monetario. La segunda ley de la termodinámica que nos permite establecer esa jerarquía de energías, nos permite también, al menos intuitivamente, señalar que no existe el reciclaje perfecto de la materia, al menos a nuestra escala (si bien se podrían señalar los ciclos biogeoquímicos del planeta, a escala global, como ejemplos de reciclaje perfecto, ligados al flujo de energía solar que los activa y mantiene), y establecer los principios para una cuarta ley de la termodinámica (o una aplicación de la segunda al campo de la materia) que señalase la perpetua y paulatina degradación de la materia en su uso, hasta que vuelve a ser reciclada por los ciclos biogeoquímicos a una escala geológica. Más allá de las polémicas surgidas entorno a esta idea planteada por N. Georgescu-Roegen para combatir el creciente reduccionismo energético de su época (Georgescu-Roegen, 1975; 1979), y que están resumidas en Carpintero (2006), hay que decir que la emergía también puede verse desde un punto de vista material, en el sentido de la existencia de una jerarquía de materiales que iría desde aquellos presentes de forma más o menos difusa en la corteza terrestre, y que para ser explotados, normalmente tienen que pasar por un proceso de concentración, refinado, cocinado, etc., hasta aquellos que ya han pasado por distintos procesos y que pueden ser útiles a la sociedad directamente, todo ello a través de un mediador, la energía (Odum, 2001). Así, lo habitual en el procedimiento de la síntesis emergética no es tanto tratar de reducir los distintos componentes materiales, energéticos, monetarios, etc. a energía solar como valor de cambio físico (la emergía no es una teoría del valor económica), sino más bien tratar de introducir tanto elementos materiales como energía en el cálculo del trabajo realizado por la naturaleza para generar un determinado sistema, un determinado componente del sistema, etc., que es medido en equivalentes de energía solar, como corresponde a la propia definición de emergía.

2.1.2. Transformicidad, emergía específica y jerarquía de energías

Por otro lado, la existencia de una jerarquía de energías, y la propia definición de emergía conduce a un problema práctico y a una cuestión teórica, que son, por una parte el problema de transformar las distintas calidades de energía o materia a la calidad de energía de referencia (que, como se ha dicho, suele ser la solar), y por otra la cuestión de qué posición en la jerarquía de las energías ocupa cada elemento, respectivamente.

Para poder transformar las diferentes calidades de energía o materia usadas a una calidad de energía solar (o emergía), usaríamos un factor de equivalencia (UEV, en adelante), la **transformicidad** (*transformity*) o la **emergía específica**, respectivamente, que nos informan de qué cantidad de energía con calidad equivalente a la solar es necesario para generar una unidad de energía o materia de mayor calidad (Odum, 1988; 1996). Por tanto, la transformicidad tendría unidades de seJ/unidad de energía, y la emergía específica de seJ/unidad de masa. Esta cantidad también nos indicaría a qué nivel de la jerarquía de potencial uso se encuentra el componente evaluado, es decir, qué cantidad de energía disipada es necesaria para generar una unidad de un determinado producto con una concentración mayor de energía.

Así, en el álgebra emergético tendríamos que:

$E_i = Tr_i * Ex_i$, donde

- E_i = emergía (seJ) del producto.
- Tr_i = transformicidad (seJ/unidad).
- Ex_i= energía útil o Exergía (unidad de energía).

Y de modo análogo, para el caso de la materia:

$E_i = tr_i * M_i$, donde

- E_i = emergía (seJ) del producto.
- tr_i = emergía específica (seJ/unidad).
- M_i = masa (unidad de masa).

Las transformicidades y emergías específicas son otro de los aspectos teóricos de la síntesis emergética que más suele desconcertar, y que habitualmente tiene más críticos, particularmente su cálculo. Usualmente tres suelen ser las críticas más corrientes:

1. **El uso de transformicidades (o emergías específicas) fuera de contexto.** Durante un tiempo ha estado de moda entre algunos de los investigadores que han usado la emergía el empleo de factores de equivalencia procedentes de otros estudios para completar sus tablas. Este uso, que tiene la ventaja de evitar engorrosos cálculos, tiene a su vez en inconveniente de que puede no tener en cuenta ni el sistema para el que se hizo el cálculo, ni los elementos que entraron en el mismo, ni tampoco el nivel de detalle al que se ha elaborado, llegando a cometer errores significativos en los cálculos. Para evitar este problema hay dos vías. La más obvia, que consiste en recalcular todos los factores de equivalencia en cada estudio, pero que implica un nivel de trabajo y de detalle no siempre posible. La segunda, que consiste en que algunos factores de equivalencia se toman de estudios donde la elaboración concreta de los factores sea conocida, y por tanto se pueda asegurar que coincide significativamente con lo que obtendríamos de calcularlo nosotros, en lo que se refiere al tipo de sistema evaluado como al método de cálculo usado. Si bien la primera opción es la óptima y deseable para el buen desarrollo científico del método, la segunda opción se apoya también en argumentos científicos, y es que empíricamente se ha comprobado que en sistemas parecidos la magnitud de los factores de equivalencia es parecida (tanto más cuanto más parecido sean los sistemas entre sí), por lo que no sería descabellado escoger, por ejemplo, factores de equivalencia de fuentes del sistema (lluvia, mareas, olas, etc.) de un país mediterráneo para usarlos en otro país de similares características. Ésta ha sido la elección del presente trabajo, en el que aún asumiendo que en este caso puede existir un cierto error, se parte de la idea de que dicho error es despreciable en relación con los errores estadísticos contenidos en los propios datos recogidos.

   Esto no es excusa para no reconocer los posibles errores que de ello se puedan derivar, especialmente si uno no examina la fuente de la que proviene el valor usado, y trata de que sea lo más parecida al sistema que está tratando de evaluar.

2. **La circularidad del argumento.** Tal y como se menciona un poco antes, los factores de equivalencia se calculan dividiendo la emergía correspondiente (seJ) entre la exergía (J) o la masa (g), para obtener o bien una transformicidad (seJ/J) o bien una emergía específica (seJ/g). El problema obvio que algunas personas señalan es que para calcular la emergía necesitamos el correspondiente factor de equivalencia (Figura 2.2.). Lo que aparentemente nos conduce a un argumento circular.

$$\begin{array}{ccccc}
\mathrm{Ex1} & \mathrm{x} & \mathrm{Tr1} & = & \mathrm{Em1} \\
\mathrm{Ex2} & \mathrm{x} & \mathrm{Tr2} & = & \mathrm{Em2} \\
\mathrm{Ex3} & \mathrm{x} & \mathrm{Tr3} & = & \mathrm{Em3} \\
\mathrm{Ex4} & \mathrm{x} & \mathrm{Tr4} & = & \mathrm{Em4} \\
\mathrm{Ex5} & \mathrm{x} & \mathrm{Tr5} & = & \mathrm{Em5} \\
\underline{\mathrm{Ex6}} & \mathrm{x} & \mathrm{Tr6} & = & \underline{\mathrm{Em6}} \\
\Sigma \mathrm{Exi} & & & & \Sigma \mathrm{Emi}
\end{array}$$

$$\mathbf{Tr_i = \Sigma Emi/\Sigma Exi}$$

Figura 2.2. Cálculo de la transformicidad para un sistema con 6 entradas. Para ello se emplean la suma de la exergía total resultante del sistema, y la emergía empleada para obtener la misma. Los cálculos son análogos para las emergías específicas.

Y digo aparentemente porque esta paradoja tiene solución. Si tomamos, tal y como ya se ha explicado anteriormente, la calidad de la energía solar como aquella de referencia para nuestros cálculos, y por tanto hablamos de emergía solar, tendríamos que la transformicidad solar es, por definición, 1 seJ/J, puesto que para obtener 1 joule de energía solar necesitaríamos el trabajo equivalente a 1 joule de energía con calidad equivalente a la solar. A partir de esta transformicidad se ha procedido al cálculo de las demás, primeramente mediante varios sistemas de ecuaciones que relacionan la emergía solar con la de las otras fuentes independientes de energía a escala planetaria: la gravitatoria y la procedente del interior del planeta (Odum *et al.* 2000; Odum, 2000). Este sistema permite obtener, por una parte las transformicidades correspondientes a estas tres fuentes independientes de energía en el planeta, y a partir de las mismas se está llegando al cálculo generalizado de los factores de equivalencia para multitud de componentes de distintos sistemas a diferentes escalas.

3. **La variabilidad y debilidad de las cifras.** Otro aspecto que habitualmente se critica en relación con los factores de equivalencia es que para un mismo producto el factor de equivalencia puede variar según los estudios, con lo cual resulta difícil tomar en serio este factor como una cifra objetiva referida al sistema. La razón es obvia, distintas personas toman, al realizar sus cálculos, distintos elementos en consideración. Este problema, que es común a todos los métodos con una filosofía de ciclo de vida, no es grave por varias razones. En primer lugar porque la comunidad de investigadores de emergía tiene la sana costumbre de hacer explícitos sus cálculos, con lo cual cualquiera puede ver qué componentes tiene otro estudio. Además, se comprueba empíricamente que los factores de equivalencia tienen magnitudes muy similares para sistemas muy similares, tal y como se ha mencionado anteriormente. Y finalmente, también hay que señalar que a diferencia de otras medidas, y teniendo en cuenta que la emergía deriva de magnitudes físicas, incluso pequeños cambios en la naturaleza del sistema implican cambios en las magnitudes físicas implicadas, por lo que las cifras variarán. No es lo mismo un tomate cultivado en un invernadero que un tomate cultivado en el campo al aire libre, y la variación en el modo de cultivo tiene su repercusión evidente en el factor de equivalencia correspondiente, por lo que conviene especificar a qué sistema nos referimos cuando hablamos de un determinado factor de equivalencia. Por ejemplo, transformicidad del tomate de invernadero frente a transformicidad del tomate cultivado al modo tradicional, aunque ambas sean transformicidades del tomate.

Para tratar de frenar el mal uso que de estos factores de equivalencia se venía haciendo, desde la Universidad de Florida existe un proyecto que pretende hacer una recopilación de las principales transformicidades y emergías específicas agrupadas por temas, y con los cálculos que derivan en el valor final. Este proyecto se está publicando en forma de manuales, y se puede descargar en la red a través de la siguiente dirección:

http://www.emergysystems.org/folios.php. Además, actualmente se está trabajando en un equipo internacional organizado por el profesor Sergio Ulgiati, de la Universidad de Nápoles (Italia), y el profesor David Tilley, de la Universidad de Maryland (EE.UU.) para desarrollar una base de datos de factores de equivalencia contrastados, aplicando todo el conocimiento y las lecciones aprendidas de estos años de uso de la síntesis emergética, y que tendrá su primer hito el próximo enero de 2010 en el congreso bianual de emergía en la Universidad de Florida.

2.1.3. La metodología: la Síntesis Emergética

Una vez aclarados estos aspectos, podemos decir que la **Síntesis Emergética** (Odum, 1996) es una metodología útil para la evaluación de los ecosistemas, y basada en la comparación de flujos de energía, masa y dinero utilizados por un SES a través de la base común de la emergía ligada a estos flujos. El objetivo de esta metodología es el de estudiar la organización de sistemas termodinámicamente abiertos, es decir, que intercambian materia y energía con el ambiente externo (Franzese *et al.* 2003), a través del uso de una perspectiva sistémica.

Los objetivos generales de su aplicación son:

- La caracterización de las principales fuentes de energía externas al sistema y que dirigen su evolución en el tiempo.

- La estimación de la contribución de los servicios de los ecosistemas al sistema socio-económico, como capital natural.

- La estimación del trabajo de la ecosfera en la dinámica global de los sistemas antrópicos.

- La realización de una contabilidad ambiental económico-ecológica integrada sobre bases termodinámicas, con el objetivo de servir a la toma de decisiones políticas;

- El cálculo de indicadores termodinámicos de rendimiento, impacto, y sostenibilidad.

Su uso ha permitido (Brown y Ulgiati, 2004a), entre otras cosas: (a) investigar sistemas fuera de las actividades humanas, (b) conocer el papel que los sistemas ecológicos tienen para el ser humano, (c) implementar una evaluación ligada a la aportación ambiental en lugar de la clásica evaluación desde el punto de vista del usuario, (d) evaluar procesos donde el soporte directo de materiales es pequeño pero el indirecto es grande, (e) tener en cuenta la escala temporal o memoria de los servicios usados, (f) evaluar la renovabilidad de los servicios, (g) evaluar la calidad de los servicios de un modo cuantitativo, (h) evaluar el impacto de procesos consistentes en unir flujos de baja y alta calidad, (i) incluir en la evaluación el trabajo humano y los servicios en bajo un marco común.

Las principales fases que caracterizan la realización de una síntesis emergética se pueden resumir en las siguientes (a partir de Odum, 1996; Brown & Ulgiati, 2004b):

1. **Descripción del sistema investigado y definición de sus límites espacio-temporales.** Con una base socio-ecológica, y según los objetivos para los que se realice el estudio.

2. **Modelado del sistema socio-ecológico.** Consiste en la representación, a través de diagramas de flujos de materia y energía, utilizando la simbología energética (Figura 2.3.) establecida por Odum (1994), de la interacción entre las fuentes externas e internas del sistema, y los sistemas ecológicos y socio-económicos, así como los flujos de salida del sistema y la retroalimentación del mismo. Se trata de un modo muy instructivo de hacer explícitas las relaciones entre los componentes del sistema (Abel, 2004; Brown, 2004; Odum & Odum, 2000) y, por tanto, de visualizar el criptosistema (González Bernáldez, 1981), que además encierra detrás todo un aparato matemático que permite el modelado del mismo. Un ejemplo se puede observar en la Figura 2.4., donde podemos ver el diagrama de flujos teórico de una explotación maderera de pinos. A efectos de simplificar la contabilidad, los modelos complejos se suelen resumir para capturar las principales entradas y salidas al sistema, así como otros flujos que constituyen los factores clave y/o limitantes, en

gran medida, del funcionamiento interno del mismo (Figura 2.5.). El modelado se compone de los siguientes pasos (a partir de Odum & Odum, 2000):

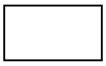
a. A partir de los límites del sistema se definen las principales entradas y salidas de energía del mismo, y se clasifican según su naturaleza (biogeofísca, económica, humana, etc.), de izquierda a derecha en orden de transformicidad creciente alrededor del símbolo de límites del sistema.

b. Se definen los componentes internos del sistema y sus relaciones tanto con las entradas y salidas de materia y energía como entre ellos, teniendo cuidado de implicar todos los elementos del sistema que regulan los procesos que constituyen el funcionamiento del mismo. Se colocan bajo el mismo criterio que en el anterior punto.

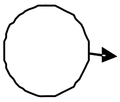
c. Se incluyen los flujos de dinero correspondiente al uso económico que puedan tener algunos flujos del sistema, así como las entradas de dinero que mueven algunos de los componentes socio-económicos del mismo.

d. Se incluye la degradación correspondiente a la segunda ley de la termodinámica.

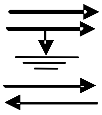
e. Se simplifica el diagrama según los objetivos del estudio mediante una agregación de categorías al nivel de detalle que se quiera llevar a cabo.



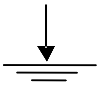
Fronteras del sistema. Representadas por una caja rectangular



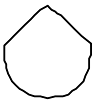
Fuentes del sistema. Se entiende como tales los "focos" ubicados fuera de los límites de sistema, y de los cuales parten flujos de materia y energía al interior del mismo. Se ordenan en el sistema de izquierda a derecha en orden creciente de transformicidad o calidad energética. Las fuentes de tipo ambiental se ubican en la zona izquierda (sol, viento, mareas, olas, etc.) y las socioeconómicas (servicios, información, etc.) en la parte derecha.



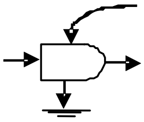
Rutas de flujo. Conecta los diversos componentes del sistema. Refleja las transferencias de energía, materiales o información entre los mismo. Si se trata de una línea discontinua representa flujos de dinero.



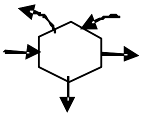
Sumidero de energía. Representa la disipación de energía en calor que acompaña todos los procesos de transformación o acumulación (consecuencia de la segunda ley de la termodinámica). Estas dispersiones están asociadas a depósitos, interacciones, productores, consumidores y símbolos de interruptores.



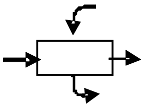
Deposito. Se trata de un almacenamiento de materia, energía, dinero, servicios, información, cuyas tasas de uso son mayores que las de su renovación.



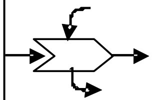
Productor. Componente que, a través de determinados procesos, recoge y transforma energía de baja calidad concentrándola. Hace productos. Pueden representar productores de tipo biótico (plantas) o antrópicos (fábricas). Suelen ubicarse en la parte izquierda de los diagramas.



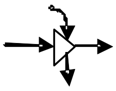
Consumidor. Componentes que consumen más energía de la que producen, aunque contribuyen o aportan servicios con mayor Emergía. Usa los productos de los Productores Pueden representarse así desde poblaciones de animales consumidores hasta núcleos urbanos.



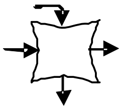
Caja. Símbolo misceláneo. Se suele emplear para delimitar un subsistema de interés dentro de un sistema mayor.



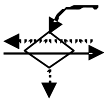
Interacción. Convergencia de flujos de varios tipos que, mediante la actuación de diversos procesos da lugar a flujos de mayor calidad.



Amplificador. Interacción especial, en el que el flujo de salida se controla por otro flujo de menor intensidad



Activación (interruptor o desvío). Indica la puesta en marcha o la finalización de un proceso de un proceso como un incendio o la polinización de las flores.



Transacción. Intercambio de un flujo por otro. Generalmente se refiere a bienes y servicios (línea continua) a cambio de dinero (línea discontinua).

Figura 2.3. Significado de los principales símbolos energéticos de Odum, aplicados en la Síntesis Emergética como forma de modelado de los sistemas socio-ecológicos.

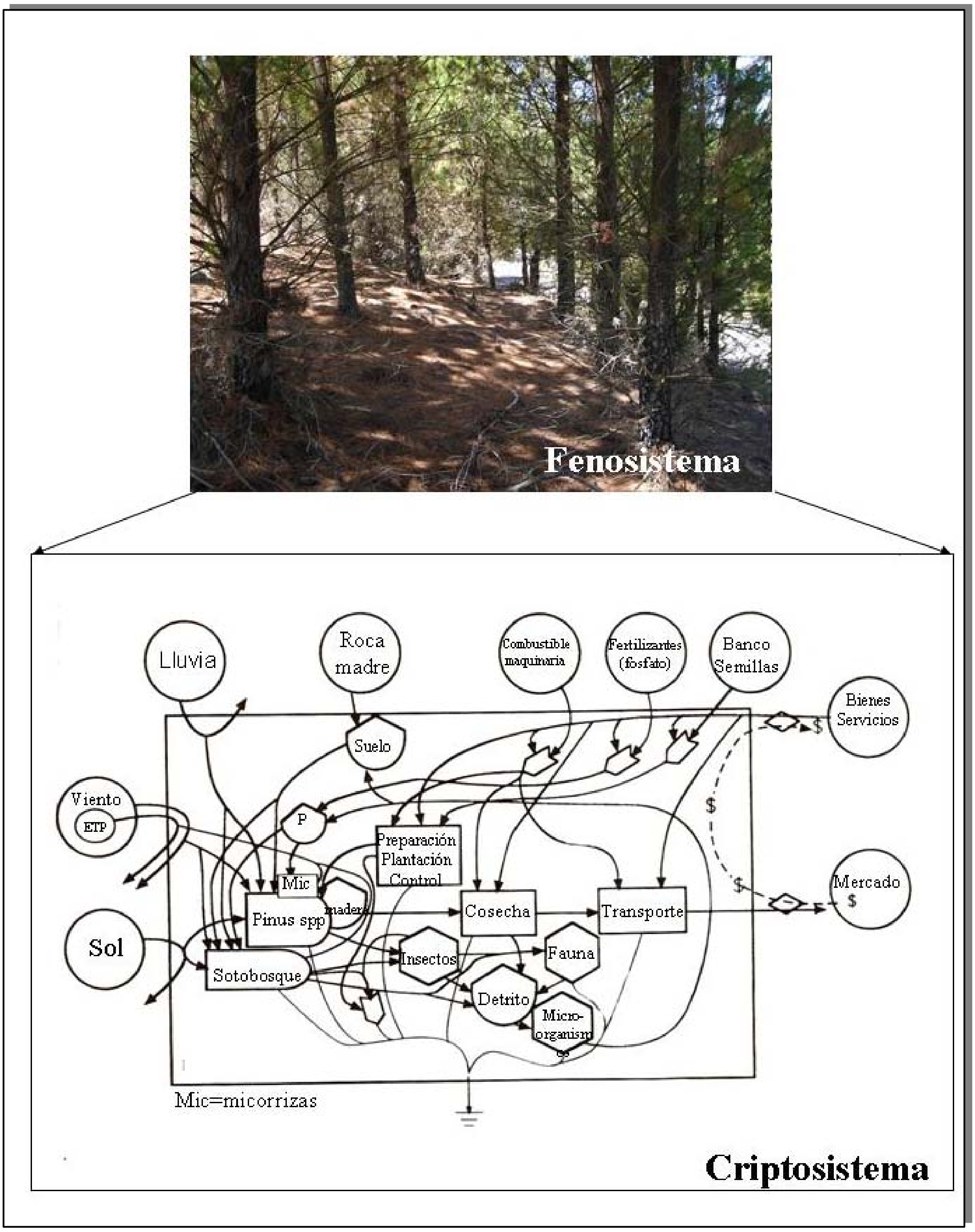


Figura 2.4. Ejemplo de diagrama de flujos para una explotación maderera de pino.

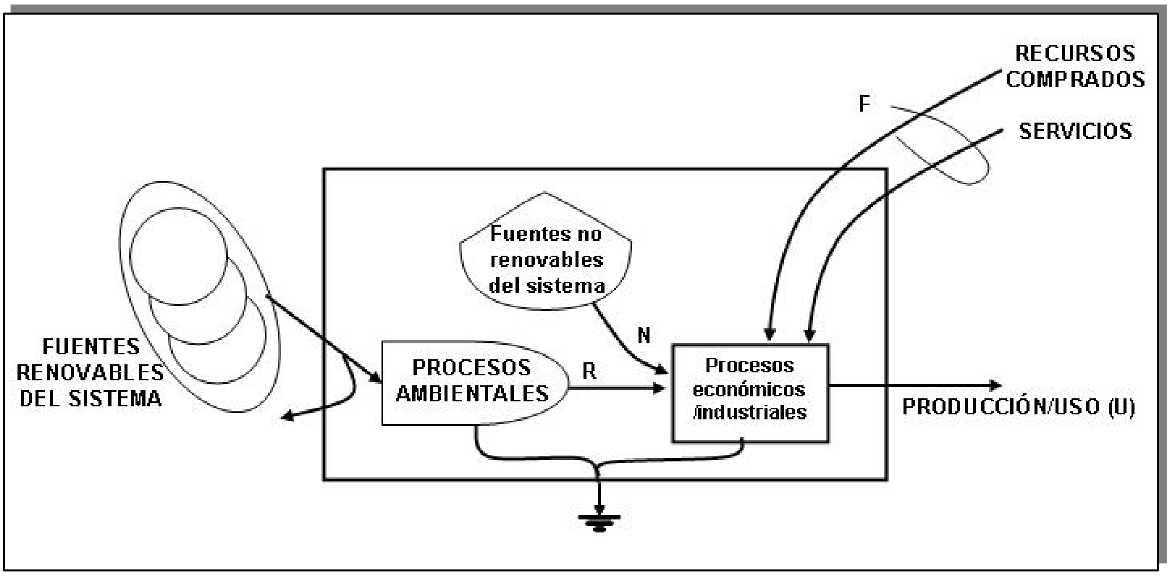


Figura 2.5. Ejemplo de diagrama de tres brazos genérico. Se hacen constar los principales flujos del sistema: R, flujo de emergía renovable; N, flujo de emergía no renovable local; F, importación de bienes y servicios; U= Producción/Uso del sistema.

3. **Obtención de datos y balances del sistema.** Se trata del cálculo efectivo de los flujos de materia y energía que figuran en el diagrama anterior para el período de tiempo investigado, y de la emergía correspondiente a estos flujos, a partir de las transformicidades y energías específicas correspondientes (Brown & Ulgiati, 2004b).

   Implica la construcción de una tabla con los principales flujos de emergía clasificados, y que consta de una serie de campos, tal y como se presenta a continuación en la Tabla 2.1.

Tabla 2.1.- Principales campos de los que consta una tabla de síntesis emergética.

Nota	Item	Dato	Unidad	Transformicidad (seJ/unidad)	Emergía solar (seJ/año)	Valor macroeconómico (em$/año)
1	**Item1**	**xx.x**	**J/año**	**xxx.x**	**Em_1**	**Em_1/EMR**
2	**Item2**	**xx.x**	**g/año**	**xxx.x**	**Em_2**	**Em_2/EMR**
…	**…**	**…**	**…**	**…**	**…**	**…**
…	**…**	**…**	**…**	**…**	**…**	**…**
n.	**Ene-ésimo Item**	**xx.x**	**J/año**	**xxx.x**	**Em_n**	**Em_n/EMR**
Y	**Y-ésimo Producto**	**xx.x**	**J ó g/año**	$\frac{\sum_n^1 Em_i}{xx.x}$	$\sum_n^1 Em_i$	**EMR** $= \frac{\sum_n^1 Em_i}{PIB}$

Fuente: Basado en Brown & Ulgiati (2004b).

La Columna 1 "nota" se refiere al orden en que están colocados cada uno de los flujos, y la nota a pie de tabla en la que se refiere el origen del dato, y los cálculos realizados para la transformación del mismo a las unidades correspondientes.

La Columna 2 es el nombre del "item" o flujo que se evalúa, y que figura, con la simbología correspondiente, en el diagrama de flujos.

La Columna 3 se refiere a la cifra proporcionada por los cálculos elaborados para cada flujo, que figuran numerados en una nota al pie de la tabla, en sus unidades correspondientes, que se encuentran en la Columna 4. El cálculo para alguno de los principales flujos de materia y/o energía que habitualmente se manejan se puede ver en las tablas y los anexos de los artículos del *capítulo 3*.

La Columna 5 se refiere a la emergía por unidad o factor de equivalencia (transformicidad o emergía específica), que transforma las cifras de la columna 3, en las cifras de la Columna 6, que ya son referidas a emergía solar.

La Columna 6, como ya se ha dicho, es la que contiene la emergía, en los equivalentes solares emergéticos (seJ). Como se puede observar en la Tabla 1, la emergía de cualquier producto y/o co-producto del sistema es la emergía total que se introdujo en el sistema, aunque su transformicidad sea distinta (Odum, 1996; Brown & Herendeen, 1996), es decir, que tal y como era de preveer, la emergía no tiene una lógica conservativa, es decir no cumple la ley de la conservación de la masa y energía, puesto que emergía, como ya hemos dicho, no es ni energía ni masa, sino que obedece más bien a una lógica de memorización, es una memoria energética. En este sentido, todos los productos de un determinado sistema (aquellos flujos resultantes del funcionamiento del sistema que atraviesan sus fronteras hacia fuera) tienen la misma memoria energética, aunque la energía o la materia contenida en ellos sea distinta, y por tanto su factor de equivalencia también lo sea.

Por último, la Columna 7 se refiere al denominado valor macroeconómico, o cantidad de actividad económica que se mueve debido a un determinado flujo o reserva de emergía. Se calcula, para cada uno de los flujos, dividiendo su valor en Emergía por la cantidad de actividad económica media movida por el total de Emergía del sistema (Relación dinero-emergía o Emergy to Money ratio, en el inglés original).

Las últimas filas se reservan para los productos del sistema (exportaciones, población, productos monetarios, etc.), y los cálculos relativos a su transformicidad, emergía total, etc.

4. **Cálculo de una serie de indicadores emergéticos.** A partir de los flujos hallados, y sistematizados en la tabla anterior, se pueden calcular toda una serie de relaciones. A continuación se da una lista de algunos de los principales indicadores, tradicionalmente usados, si bien la literatura cada día ofrece nuevas herramientas (Tabla 2.2.).

5. **Evaluación y comparación espacio-temporal de los indicadores emergéticos del sistema con otros sistemas similares y/o el mismo.** Esta comparación se realiza partiendo del criterio ligado al denominado Principio de Máxima Potencia Emergética (Odum & Pinkerton, 1955; Odum, 1983; Odum, 1995; Odum, 1996). H.T. Odum tomó las ideas originales de A.J. Lotka (1922a; 1922b) ligadas a la importancia de la energía en el proceso evolutivo, y las transformó y actualizó para dar lugar al Principio de Máxima Potencia Emergética, que propone que en la competición entre procesos auto-organizativos prevalecen las relaciones y diseños que maximizan la potencia emergética. Hay que recalcar que nos referimos al flujo o tasa de adquisición de emergía o potencia emergética por el sistema (tanto a la entrante como a aquella que retroalimenta el sistema por distintas vías), y no a la energía total o suma de las energía adquirida por los distintos componentes del sistema (Cai *et al.* 2004; Hall, 2004), es decir, no se trata de que cuanto más se consume mejor. Así, se toma en cuenta los procesos de eficiencia en la adquisición, pero también aquellos de retroalimentación dentro del sistema, es decir, que se trata de utilizar del mejor modo la energía que alimenta el sistema, no usar la máxima cantidad.

Tabla 2.2. Algunos de los principales indicadores de la síntesis emergética. Las letras que figuran en la fórmula se refieren a la Figura 2.4.

ÍNDICE	FÓRMULA	UNIDADES	DESCRIPCIÓN
Emergía de fuentes renovables	**R**	seJ/año	Entrada de Emergía de fuentes renovables al sistema
Emergía de fuentes no renovables locales	**N**	seJ/año	Entrada de Emergía no renovable al sistema desde fuentes internas al mismo
Emergía importada	**F**	seJ/año	Entrada de Emergía desde fuentes externas (generalmente con un intercambio monetario)
Emergía usada	**U = R+N+F**	seJ/año	Coste en emergía de la producción del sistema
Fracción renovable de la emergía usada	**R/U**	-	Parte renovable de la Emergía empleada
Índice de apropiación y explotación de Emergía (Emergy yield ratio; EYR)	**U/IMP= 1+1/EIR**	-	Mide la contribución potencial de un proceso al conjunto del sistema debida a la explotación de recursos locales
Índice de inversión en Emergía (Emergy investment ratio; EIR)	**F/(R+N)**	-	Relación fuentes externas al sistema y fuentes internas al mismo. Mide la eficacia en el uso de la emergía invertida en un proceso.
Índice de carga ambiental (Environmental loading ratio; ELR)	**(F+N)/R**	-	Índice de estrés ambiental debido a una producción. Indicador de la presión de un proceso de transformación sobre el medio ambiente
Índice de emergía renovable capturada (Renewable emergy captured)	**R/F**	-	Índice de efectividad del sistema socioeconómico en la captación de los flujos naturales.
Uso de Emergía per capita	**U/población**	seJ/persona/año	Medida del nivel de vida potencial medio de una población
Intensidad territorial de potencia Emergética (Areal empower density)	**U/superficie del país**	seJ/m^2/año	Índice de presión de un proceso sobre el territorio
Capacidad de carga renovable al nivel de vida actual (Renewable carrying capacity in the present lifestyle)	**(R/U)*población**	Población	Estima de la población que podría mantenerse dependiendo sólo de los recursos renovables con el estilo de vida actual.
Índice monetario Emergético (Emergy to money ratio; EMR)	**U/PIB**	seJ/$	Relación Emergía con unidades monetarias. Análisis de relaciones comerciales.
Índice de sostenibilidad (Emergy sustainability index; ESI)	**EYR/ELR**	-	Medida de la contribución del sistema jerárquicamente superior a la producción del sistema por unidad de carga del mismo

Fuente: a partir de Odum (1996); Brown & Ulgiati (1997); Ulgiati & Brown (1998); Brown & Ulgiati (2004b); Raugei *et al.* (2005); Ulgiati *et al.* (2005); Lomas *et al.* (2007).

Aunque el Principio de Máxima Potencia Emergética sean uno de los aspectos más criticados y discutidos del método (Hau & Bakshi, 2004), su significado termodinámico y ecológico en el marco de los sistemas complejos adaptativos es uno de los campos de investigación que actualmente se están desarrollando con más posibilidades e interés dentro de la evolución del método, y sus posibles aportaciones a la Economía Ecológica. Nótese que, frente a las acusaciones de constituir un criterio potencialmente sociobiológico (propicio a justificar injusticias sociales y aspectos de superioridad de raza) que algunas veces ha recibido esta idea, H.T. Odum hace hincapié en la competición entre diseños y relaciones frente a la competición entre individuos dentro de esos diseños o relaciones (Hall, 2004). No debemos olvidar que la emergía es un indicador ligado más a las relaciones que a los componentes de los sistemas. Además, hay que tener en cuenta que la optimización de la potencia emergética tiene su juego de ventajas e inconvenientes con respecto a otros factores del sistema, es decir, que puede que un sistema optimice su potencia emergética, y esto suponga graves desigualdades sociales, políticas o económicas, homogeneidad cultural, u otros aspectos importantes a considerar.

Este principio aporta un criterio, que no pretende ser exclusivo, y que nos permite determinar qué sistemas o diseños, ya sean ecológicos o ecológico-económicos, son más sostenibles en el tiempo desde el punto de vista del uso de la energía frente a otros de similares características, habiéndose convertido así en una de las funciones objetivo de la física (Fath *et al.* 2001).

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III. RESULTADOS

3.1. Emergy analysis of nations: Lessons learned from historical series.
3.2. Investing in eco-cultural capital to deal with a changing world: lessons from the Mediterranean Basin.
3.3. Environmental accounting as a management tool in the Mediterranean context: The Spanish economy during the last 20 years.
3.4. Multi-scalar assessment of the decoupling processes between local economic activities and natural capital by means of emergy synthesis. Andalusia (S Spain) as a case study.
3.5. Agricultural systems and wetlands conservation: The case of rice cultivation in the Guadalquivir marshes (SW Spain).

3.1. Emergy analysis of nations: Lessons learned from historical series.

Pedro L. Lomas, Catia Cialani, Sergio Ulgiati.

Resumen

En este artículo se presentan un conjunto de series históricas de evaluaciones de cinco economías a escala nacional (Italia y España, directamente investigadas por los autores; y Brasil, Suecia y Taiwan, basadas en la literatura científica ya publicada) generadas sobre la base de la metodología de la síntesis emergética. Nuestro objetivo es el de investigar en qué medida los indicadores emergéticos de las naciones reflejan, siguen o anticipan las tendencias a gran escala, a nivel de ecosfera o de economía mundial, así como entender cómo las tendencias globales afectan a las dinámicas regionales y nacionales desde el punto de vista de los indicadores emergéticos.

En este sentido, las evaluaciones a gran escala proporcionan una dirección y una "explicación" de lo que ocurre a la escala local, es decir, actúa como un "macroscopio" como Howard T. Odum solía decir. Por otra parte, cambios en los parámetros a escala local pueden ser explicativos sobre los mecanismos a través de los cuales fenómenos a diferentes niveles jerárquicos afectan unos a otros a través de la interacción de variables intensivas y extensivas.

En el artículo se demuestra que las series temporales de indicadores emergéticos resultan muy útiles a la hora de entender las dinámicas y las perspectivas futuras de las economías nacionales e internacionales a distintas escalas. Este hecho supone un elemento más a favor de la importancia de actualizar las evaluaciones nacionales anualmente, en vista de que los indicadores pueden presentar una cierta variabilidad, incluso en intervalos pequeños de tiempo.

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Emergy Analysis of Nations: Lessons Learned from Historical Series

Pedro L. Lomas[1],*, *Catia Cialani*#, *and Sergio Ulgiati*§.
*Department of Ecology, Autonomous University of Madrid. Madrid, Spain.
Department of Economics and Social Sciences, Dalarna University, Borlänge, Sweden
§Department of Chemistry, University of Siena, Siena, Italy

ABSTRACT

In this paper we present historical series generated on the basis of emergy synthesis evaluations of five national economies (Italy and Spain, directly investigated by the authors, and Brazil, Sweden and Taiwan, based on published literature). Our goal is to investigate to what extent emergy indicators of Nations reflect, follow or anticipate what happens on the larger scales of ecosphere and world economy as well as how global trends affect national and regional dynamics. Larger-scale analyses provide a direction and an "explanation" to what happens on the local scale, i.e. act as a “macroscope” as Howard T. Odum used to say. On the other hand, changes of parameters on the local scales shed light on the mechanisms through which phenomena at different hierarchical levels affect each other by means of the interplay of intensive and extensive variables.

Time series prove to be very useful in capturing the dynamics and future perspectives of national and planetary economies at different scales. This highlights the importance of updating national analyses yearly, since indicators can present variability, even over short intervals.

INTRODUCTION

The dynamics of social-ecological systems (Berkes and Folke, 1998) can be investigated from: (i) the scale of the ecosphere (environmental support, environment as source and sink); (ii) the scales of world and national economies (international trade, inflation, oil price, migration, multinational actors, etc); (iii) the “local” scales of individual and process performance (emergy/hour of labour, emergy *per capita*,

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[1] Corresponding author e-mail: pedro.lomas@uam.es.

emergy/GDP (Gross Domestic Product), emergy based indicators of environmental loading, etc).

Five national social-ecological systems are compared in this paper, with special attention to the evolution of their performance indicators over time: Italy (Cialani *et al.*, 2005), Spain (Lomas *et al.*, 2006), Sweden (Hagström and Nilsson, 2005), Brazil (Coelho *et al.*, 2003), and Taiwan (Huang and Shih, 1992; Huang, 1998).

For comparison purposes, we have used GDP at 1990 constant prices instead of GNP or GDP at current prices, sometimes used by the authors in the original papers. If required, all information has been updated to the present baseline (15.83E+24 sej/yr), recalculated after Odum *et al.* (2000), by multiplying unit emergy values collected by 1.68 (the ratio of 15.83E+24 to 9.44E+24, which was the past baseline).

It is undeniably true that characteristics of studied countries present a great variability, from large countries like Brazil, with an area of more than 8.55E+6 km^2, to a small island, like Taiwan, with an area of 3.6E+4 km^2. We are aware of the fact that all of these countries have very different areas and size, and therefore, comparison may be difficult by a factor of scale. Discussion of results will take factors of scale into account.

Based on the previously described sources of data, our main focus will be to investigate:

(A) The matching of conventional (population, energy, inflation, *per capita* income) to emergy-based indicators (seJ/€, empower density, seJ *per capita*, among others);

(B) The evolution of conventional and emergy based indicators over time; and finally,

(C) The added value of using emergy for economic and trade evaluations.

Figures presented need to be interpreted on the basis of trends and meaning of each indicator. Sometimes, indicators are attributed meanings for which they have not been designed. Sometimes they may point out an unexpected behaviour of systems. Questions about the meaning and the value of indicators are raised, in order to discuss several still unsolved interpretation problems as well as to point out the large usefulness of (a) historical series investigation, (b) comparison among Nations, (c) deep discussion of the meaning and structure of indicators, (d) prudent attitude in drawing conclusions from insufficient time-trend data.

CONVENTIONAL DEMOGRAPHIC AND ECONOMIC INDICATORS

All kind of analyses, either conventional or innovative evaluation methods, need to be referred to a set of demographic and conventional economic data which provide a picture of the system under investigation. Although this picture may be incomplete or may hide several aspects of a system's dynamics, analyses cannot avoid referring to such a preliminary data set, in order to base the investigation on largely available databases provided by national statistical offices within the framework of internationally agreed upon accounting and processing methods. National Governments, International Organizations, economic Organizations and Companies at all levels usually refer to such a stabilized system of information for policy making, business, investments, etc. Within some uncertainty margin and structural problems, these data are reliable since they are checked again and again by several Organizations and individual experts. What remains somehow uncertain is their real meaning, i.e. the amount of reliable information which can be extracted from the available data.

New evaluation and accounting methods, such as Emergy Synthesis dealt with in this paper, aim at providing new understanding of the dynamics of human-dominated systems, by suggesting additional points of view or by highlighting unaccounted for aspects. Additional insights very often complement existing information and reflect trends described by such data, although they may certainly provide a different interpretation of the investigated phenomena.

Population, GDP, Inflation, and GDP *per capita* at constant and current prices are among the most important and most widely used indicators for the investigation of economic systems at any level. From Figures 1 to 4 compare their trends in the studied cases. Such a comparison is of critical importance before getting involved in the construction and interpretation of emergy-based indicators.

Population growth or stability affects *per capita* indices as well as those indices that are indirectly linked to population dynamics (GDP *per capita*, emergy use *per capita*, etc). Italy, Spain and Sweden only show a very small population increase (less than 1% per year) and their population can be considered constant over the years investigated

(Figure 1). Instead, Taiwan almost doubled its population in the 30 years under study, reaching then about 22.1 million people in the year 2000. Brazil shows a large increase of its population in the 15 years investigated (an increase of more than 32%), but its population seems to be slowly levelling off in recent years reaching a total increase of 35% in the year 2000. Converting these data into population density figures (population divided by surface of country) we would get the same trends, with the additional information about population pressure on local environment. As an example, in the year 2000, the highest population densities were shown by Taiwan (610 people/km^2) and Italy (192 people/km^2). Instead, Spain (79 people/km^2), Sweden (20.5 people/km^2) and Brazil (20 people/km^2) showed much lower density values as a consequence of larger amounts of available land.

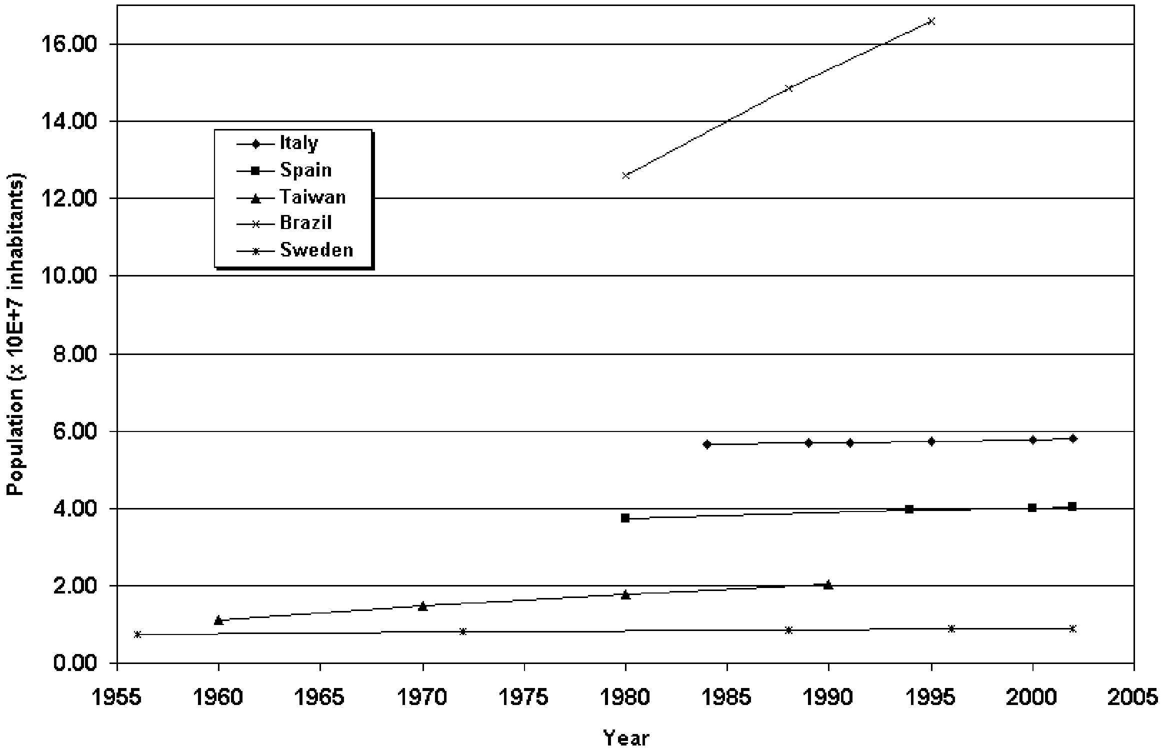

Figure 1. Population trends.

GDP is a measure of the total domestic economic activity. It can be expressed in terms of either constant or current prices. Constant price GDP refers to the average prices of a selected reference year. Constant price series can be used to show how the amount of goods has changed, and are often referred to as “volume measures” or “real value” measures. Real GDP values only change if the amount of goods changes. Current price GDP (also referred to as “nominal value” or “price” measure) refers to the actual price of goods in a given year. Changes in a time series of current price GDPs can be explained by either:

- Changes in the amounts of goods marketed.
- Changes in the price of goods.

The ratio of the current and constant price series provides therefore a measure of price changes. In fact, in such a fraction, the effect of "volume" appears in both numerator and denominator, while the effect of "price" only appears at the numerator, thus generating the so-called "deflator", an index which has a value equal to 1 in the reference year and keeps growing with inflation.

For a comparison among nations other methods to express the GDP were proposed. The level of GDP in different countries may be compared by converting their national currency value according to either:

- Current currency exchange rate: GDP calculated by means of exchange rates prevailing on international currency markets. The method converts the value of goods and services using global currency exchange rates. This method does not offer a meaningful comparison either across time and countries because exchange rate can vary a lot.

- Purchasing power parity exchange rate: GDP calculated by means of the purchasing power parity (PPP) of each currency relative to a selected standard (usually the United States dollar). The PPP method accounts for the relative effective domestic purchasing power of the average producer or consumer within a national economy. This could be a better indicator to compare standards of living, either across time or across countries. An updated database of PPP Gross Domestic Products is available at http://www.imf.org/external/pubs/ft/weo/2006/01/data/index.htm.

Figure 2 shows that global constant price-GDP increase over the considered years for all investigated countries, but for Spain. Before calculating an emergy-based indicator involving GDP's data, the emergy analysts should agree about the choice of the specific GDP measure to be used (constant or current price GDP, PPP GDP, etc). The analyst should also make sure that data used refer to GDPs of countries, not to GNPs, the definition of which would not match the usual scale of National emergy analyses (Cialani *et al.*, 2005). Failing to do this would make results hardly comparable. Despite of lower availability of such data, the use of PPP GDP might be preferable because it seems to provide a better measure of money-based standard of living. If PPP-GDP is used for calculation of emergy-based indicators (see below) results would be more likely to reflect the real resource buying power of a national currency.

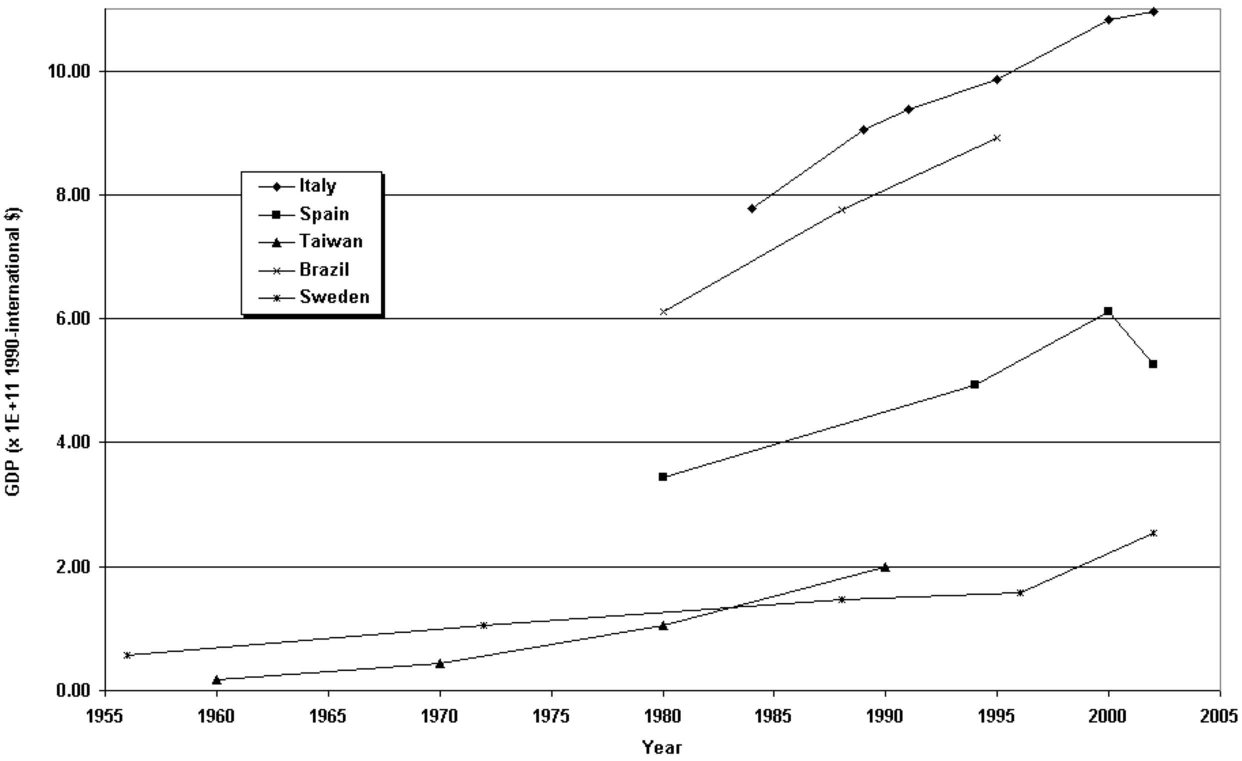

Figure 2. GDP at constant prices

The presence of inflation phenomena in a given country affects GDP, making it to grow even in the absence of a real increase of the global national economic product. The graph in Figure 3 shows a clear increase of inflation for all countries within the period 1974-1985. Inflation then declined, reaching values lower then 3% for all countries but Brazil. The latter shows very wild oscillations, out of the scale of the Figure, in the period 1980-1995, with trend towards stabilization around 6% in the last years investigated.

Again, calculating emergy-based indicators involving GDP without considering how GDP's dynamics is affected by inflation would make indicators not comparable and not even reliable. Inflation affects the real meaning of GDP (Figure 2) and GDP *per capita* (Figures 4.a and 4.b), and as a consequence also affects the values and meaning of

Emergy/GDP ratios (Figure 9) and emergy exchange ratios (Figure 15). The only way for understanding and comparing GDP composite emergy-based indicators is to have clearly in mind the links GDP-inflation over years.

Figure 4a,b shows how composite indices work. GDPs *per capita* are either affected by the numerator (constant or current price GDPs) and the denominator (population dynamics). Population change is no longer significant for Spain, Sweden and Italy, while instead it is still a non-negligible factor in Brazil and Taiwan. Population increase makes the *per capita* GDP to decrease. All investigated countries show an increase of both constant price GDP *per capita* and current price GDP *per capita*, but for Spain (Figure 4.a) and Sweden (Figure 4.b) in recent years. Such results indicate that the increase of population over time is much smaller than the increase of both kinds of GDP. It remains an open question if such higher GDP *per capita* indicates a real progress of buying power, which calls for increased use of PPP-GDP as a more appropriate numerator for composite indicators.

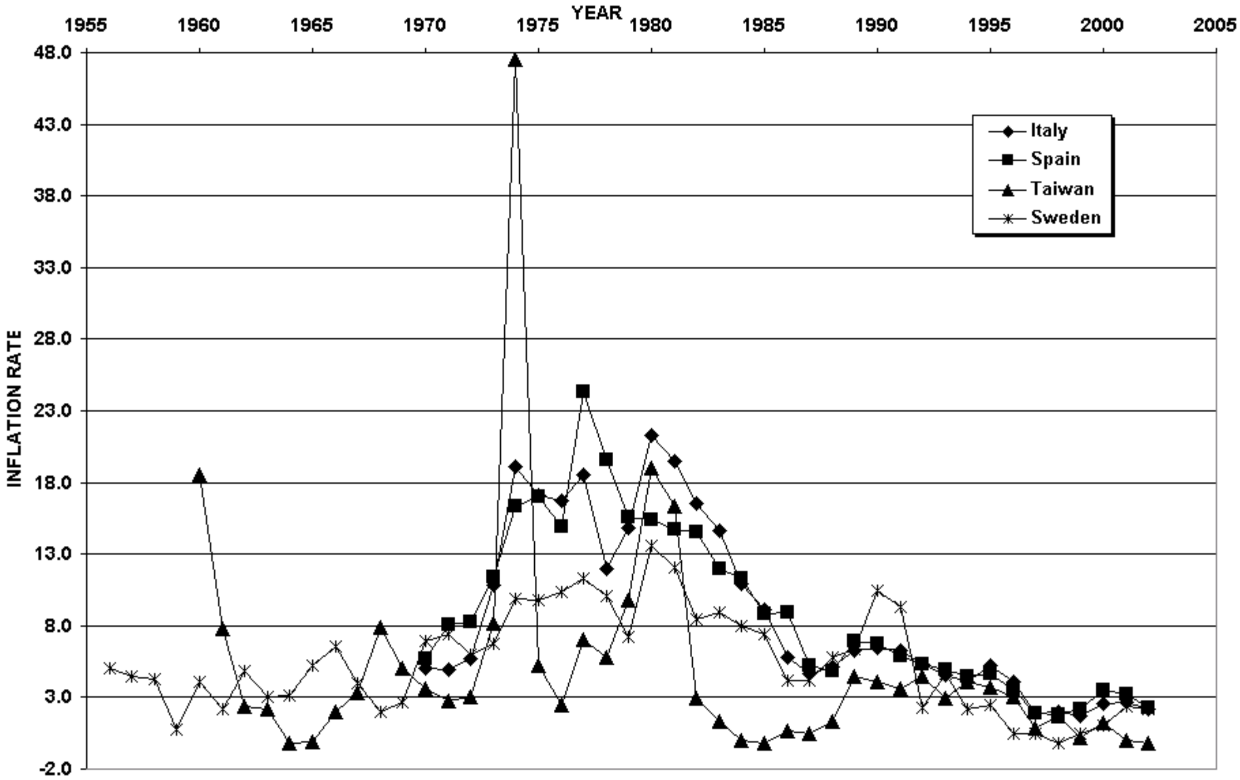

Figure 3. Inflation (Brazil is out of scale in several years and cannot be shown in the diagram).

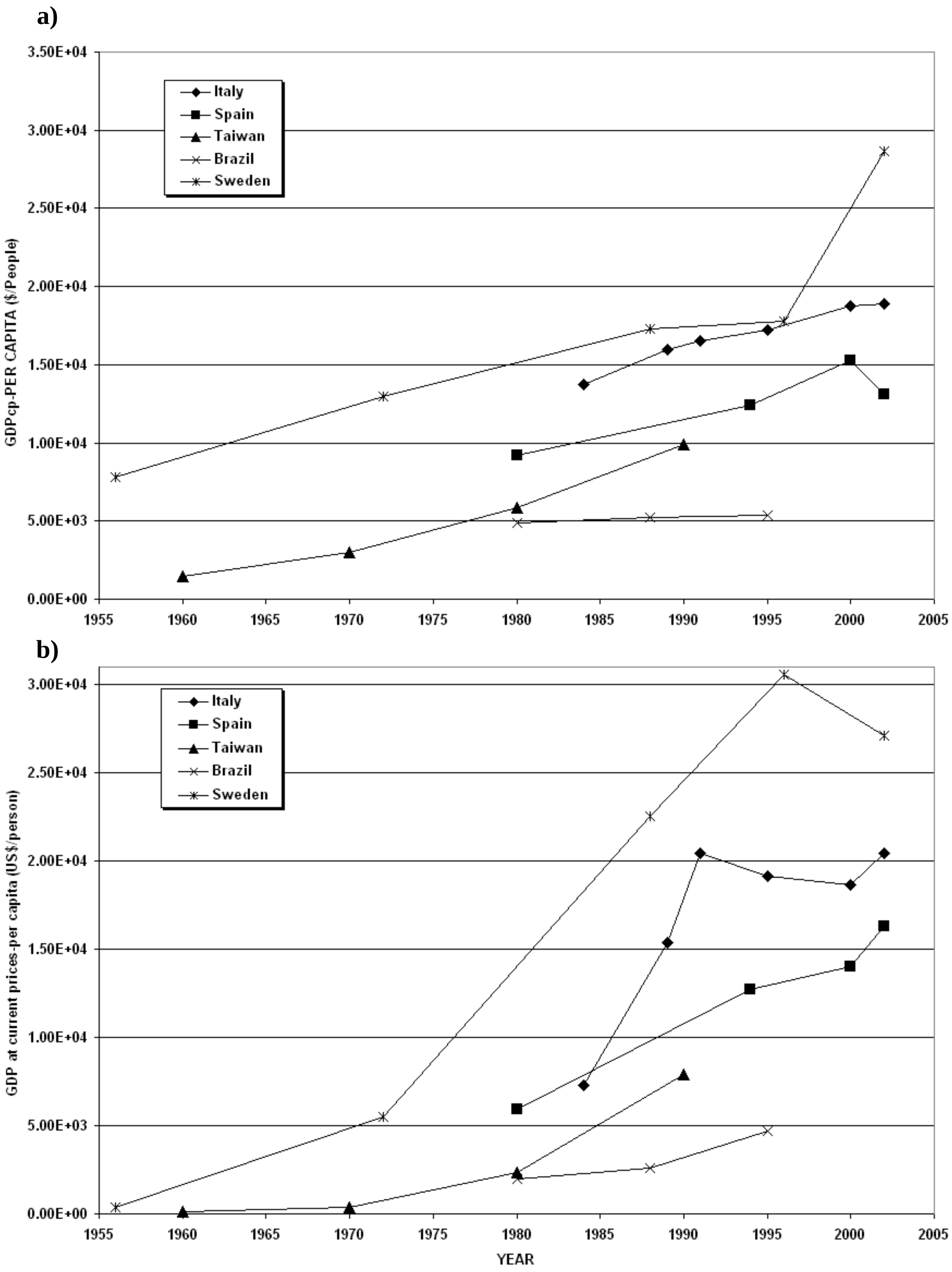

Figure 4. a) Constant price GDP *per capita* and b) Current price GDP *per capita.*

EMERGY USE INDICATORS

Emergy Synthesis (Odum, 1996; Brown and Ulgiati, 2004) looks at systems from the point of view of Ecosphere, i.e. by taking into account the environmental work which generates and provides resources to systems and processes. It also provides a systems view of the cycling and recycling dynamics of matter and energy flows degraded by natural and human-dominated processes.

The total amount of emergy actually used, i.e. the total environmental support directly and indirectly received by a given country provides a measure of the real size of a country's national economy at the eyes of the Ecosphere. Total emergy is a comprehensive measure of ecological footprint, but its definition is to a large extent different than land-based footprint one introduced by Wackernagel and Rees (1995). In fact, by accounting for direct and indirect environmental support, emergy does not only account for "virtual" land needed, but also it accounts for time and evolutionary "trial and error" patterns leading to resource generation and supply.

Figure 5 shows unclear trends for Brazil and Italy, with decreasing emergy use in the last years of the investigated periods. A longer time series would be needed for a clearer picture. Instead, the remaining countries show increasing trends. However, Brazil shows the largest emergy use and Taiwan the lowest. This is due to the very large renewable emergy captured by the huge Brazilian territory. Comparing Figures 2 and 5, available emergy does not seem to be strictly coupled to GDPs and suggests either:

(1) Large emergy available to be a necessary but not sufficient pre-requisite of increased economic performance, or
(2) GDP not to be an appropriate measure of the economic growth, in the sense that does not clearly indicates access to at least part of available resources. It may be assumed that population have access to some resources which are provided freely by nature and remain outside of market economy.

Based on above alternatives, further investigation is still needed about the question if the total available emergy is a measure of actual wealth or just potential wealth. When it is used by non-economic systems (forests, animals) can we claim that human society benefits from this via non-market patterns? Is healthy and shared economic growth

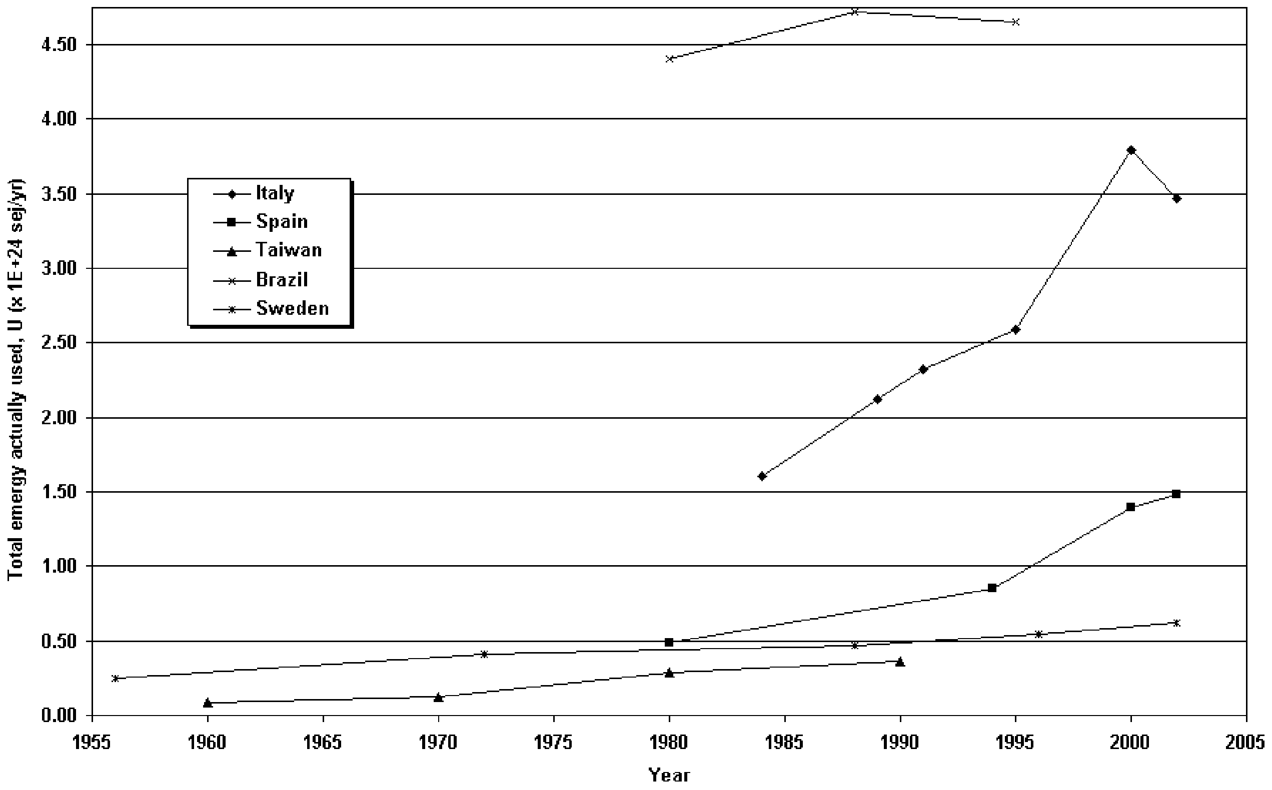

Figure 5 – Total Emergy Actually Used

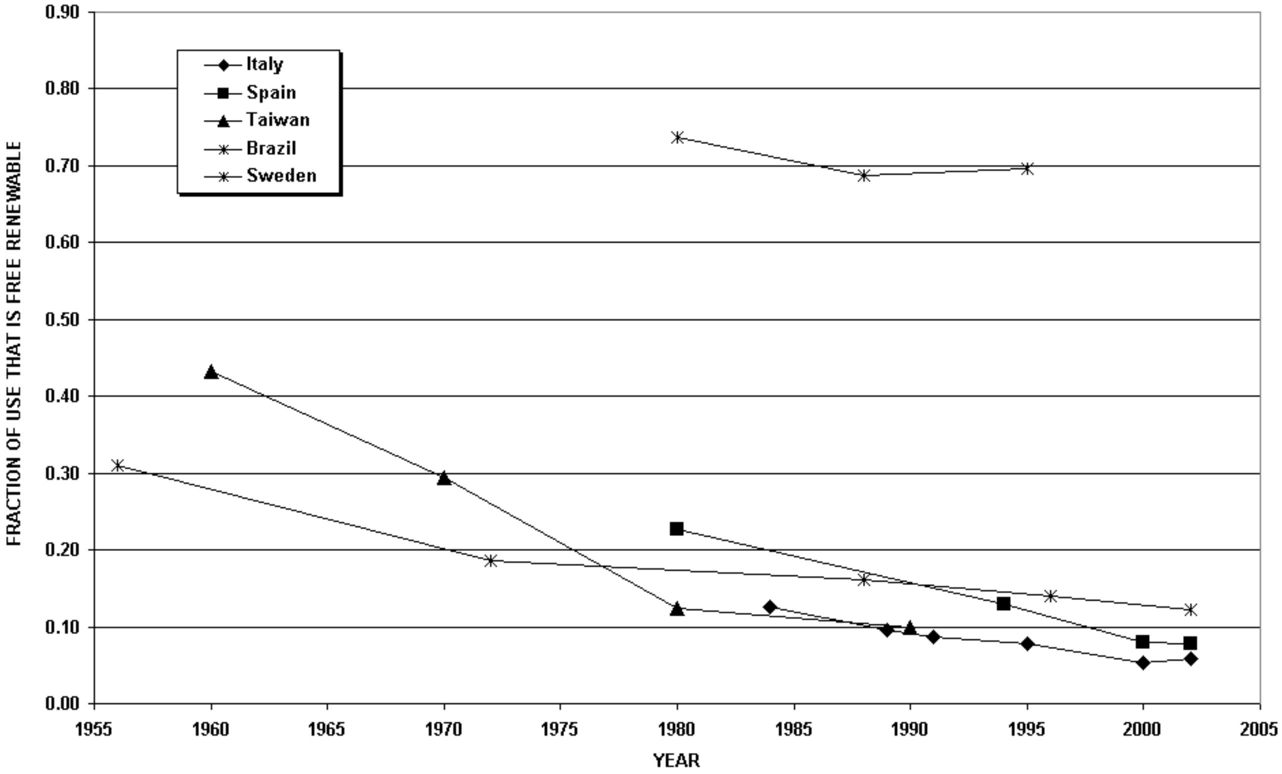

Figure 6. Fraction of Use that is free renewable

A second aspect emerges from calculating the fraction of emergy use that is free renewable (Figure 6), i.e. the emergy provided directly by environmental sources of solar radiation, wind, rain, waves, tides and geothermal heat. These sources are locally available and are never accounted for in any financial accounting, except, perhaps, in some satellite accounting systems. However, they provide significant support to the global social-ecological system of a country, although it is seldom acknowledged. Figure 6 shows a trend towards decreasing fractions of renewable energy in support of national economies, i.e. a lower reliance on the local environment compared with non-renewable imports. Economic performances of Sweden, Taiwan, Spain and Italy are determined by increased use of non-renewable emergy of fossil fuels and minerals. Taiwan and Sweden, for which the time series started in the late 50's show the most evident decrease coupled with industrialization. Instead, the performance of Brazil is still characterized by a large share of renewable emergy. The latter is due to large land availability determining large available solar emergy coupled with small use by a developing economy.

A slightly different aspect is provided by accounting for the use of emergy that is indigenous, no matter it is renewable or not. For example, extraction of wood resources at a rate higher than annual net primary production of forests must be accounted non-renewable resource for us, although it comes from photosynthesis. Figure 7 shows this aspect by diagramming the fraction of use that is imported (i.e. that is not indigenous). The general trend is towards increased reliance on imports for most of the countries investigated, but for Brazil. However, is the portion of indigenous (and renewable) emergy in Brazil still so large because a large fraction of country's population lives in poverty conditions (low *per capita* income)? Would it still be the same if the *per capita* income of Brazilians doubled or reached the *per capita* income of Western Europe, in so allowing a larger access to international market of goods and energy? It is very likely that the growing rate of Brazilian economy will require increased demand of emergy and that this demand cannot be met by renewable sources only, leading first to non-renewable extraction of local resources and then to increased import of non-renewable resources, if still available in the international market characterized by very strong competitive demands.

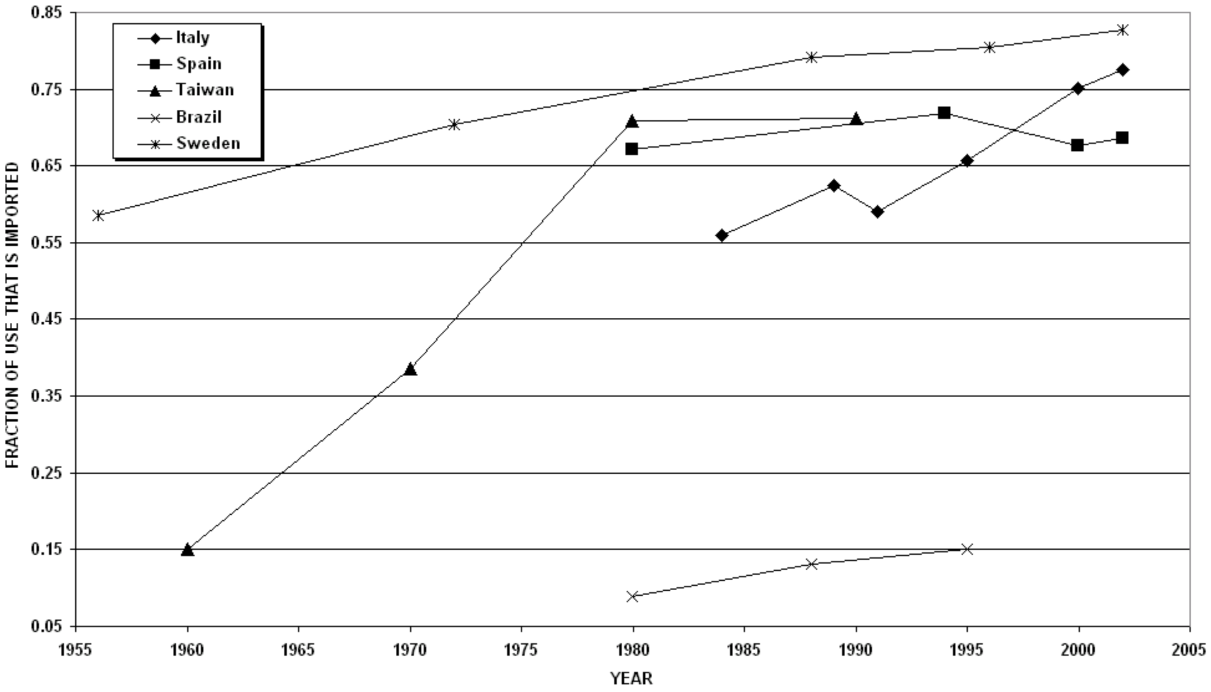

Figure 7. Fraction of Use that is imported

EMERGY INTENSITY INDICATORS

Global economic and emergy use indicators provide interesting information about the size of a social-ecological system, but do not shed any light on the actual relation of supporting flows (emergy) to systems characteristics and products (land available, population supported, GDP). Such performance aspects require a set of “emergy intensity” indicators, analogous to the concepts of temperature and density in Physics. Intensity indicators show how efficiently resources are converted into products or how resources are constrained by system’s size (in terms of population, land or mass).

A very commonly used indicator is the ratio of emergy to GDP (Figure 8), similar to the well-known energy/GDP ratio (energy intensity). The emergy intensity (emergy/GDP) is a composite indicator, affected by the numerator (emergy use) and the denominator (Constant Price GDP, a “measure” of the size of a country’s economy). In general, it indicates the efficiency of the conversion of emergy resources into an economic product. This indicator is affected by the value chosen to measure the GDP (constant or current price, purchasing power, value discounted for inflation) and calls, as previously pointed out, for a different way of calculating economic activity (other than GDP).

As shown in Figure 8, Brazil, Sweden and Taiwan decrease their Emergy/GDP ratio, which may depend on both alternatives: lower emergy demand per unit of GDP generated (higher efficiency) or increased monetary circulation (larger economic product). Increased inflation is excluded by the use of Constant Price GDP. Spain and Italy seem to do the opposite. These trends need to be illuminated by looking at the actual rate of change of each country's GDP evolution (Figure 2) and emergy use (Figure 5), which is however outside of the goals of the present paper.

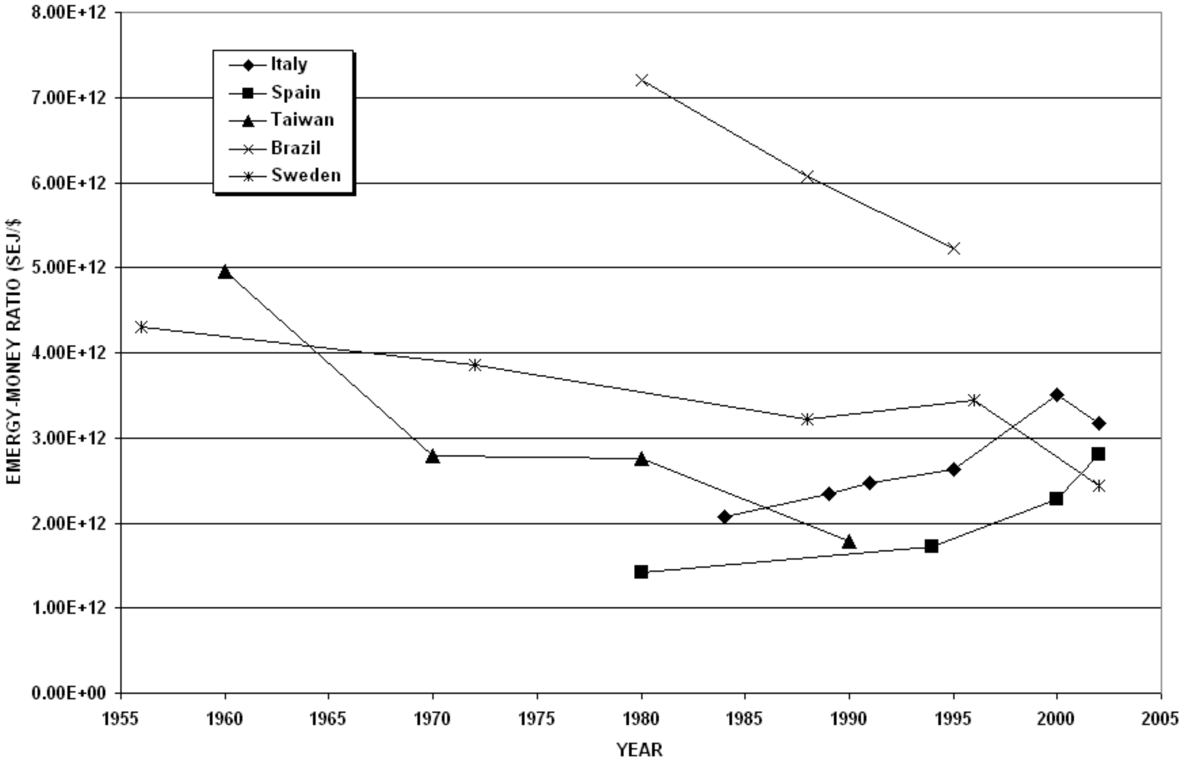

Figure 8. Emergy/GDP ratio (using GDP at constant prices)

The emergy use *per capita*, or better the emergy available *per capita* (Figure 9) is also a composite indicator affected by the choice of values of numerator (emergy use) and denominator (population). Odum very often suggested it should be considered a measure of real wealth, under the assumption that wealth is based on resources, not on money. Emergy "use" *per capita* shows a different ranking than total emergy use (Figure 5), with Sweden in the upper position and Spain and Taiwan in the lowest. In addition, Brazil shows a decreasing trend, due to population increase at a rate higher than available emergy increase, while instead Sweden, Spain, Italy and Taiwan show increasing trends at different rates of change due to the combined effects of increasing emergy use (Figure 5) and decreasing or stable population (Figure 1).

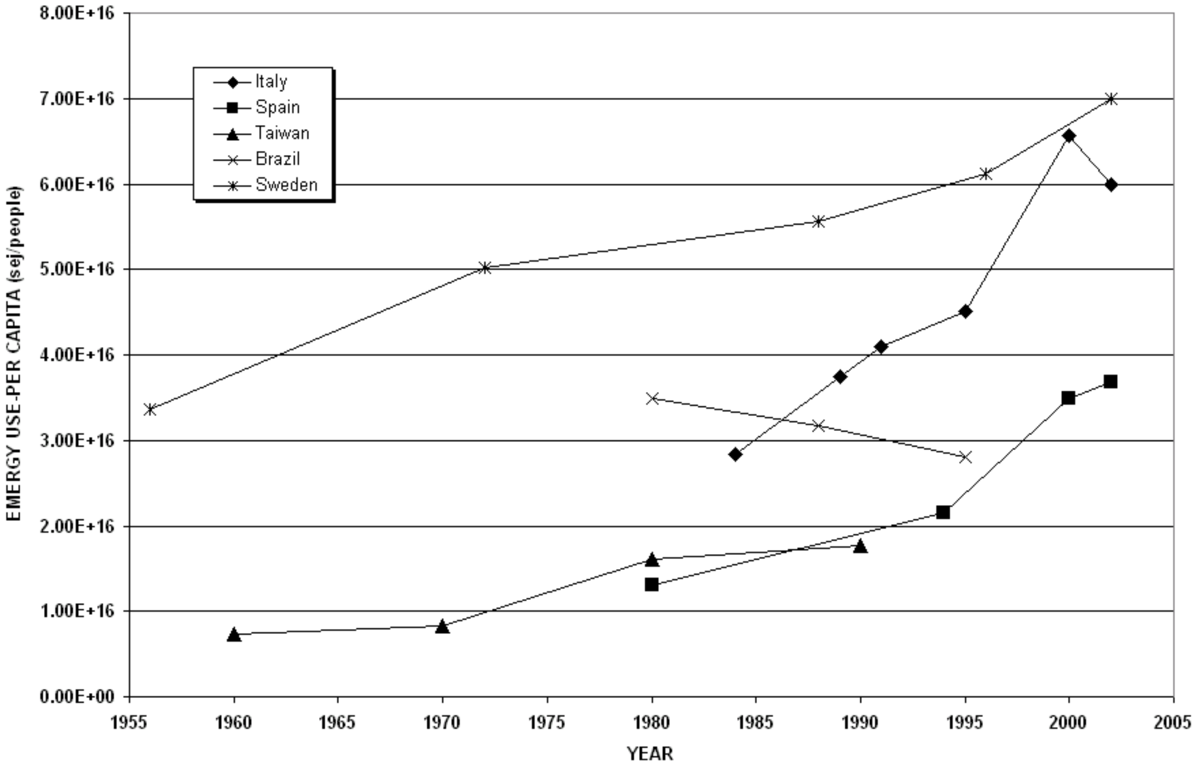

Figure 9. Emergy Use *per capita*

Can emergy use *per capita* be considered a suitable measure of standard of living? Or is it just an indicator of potential, but not actual welfare? What kind of welfare does it indicate? Economic, environmental, social...GDPs *per capita* (Figures 4.a and 4.b) indicate a Brazilian economic standard of life much lower than the other investigated countries, and traditional statistical indicators of life style in Brazil (mortality, access to education, crime, etc) do not show a high-quality standard of living as a consequence of the large emergy available to Brazil as a whole. Available emergy is “used” by non-industrialized countries such as Brazil in the sense that their forests and biodiversity are driven by solar radiation and rain, but population is not yet affected significantly in economic terms. People in the *favelas* do not perceive the healthy environment as a real improvement of their life. Can market access expressed by GDP *per capita* be reconciled to potential environmental support expressed by emergy available *per capita*?

In this regard, an aspect to be further investigated seems to be the fact that a stronger link exists between emergy use and GDP when emergy is mostly concentrated and non-renewable, as for industrialized countries. Instead, when large amounts of renewable emergy are available, the link between economic growth and available emergy is not as strong as it could be expected, due to the large amount of environmental services which remain outside of market economy, so they are not accounted in GDP. Emergy analysts should pay more attention to the difference between available and actually used emergy and call for measures of economic dynamics that include non-market flows and services.

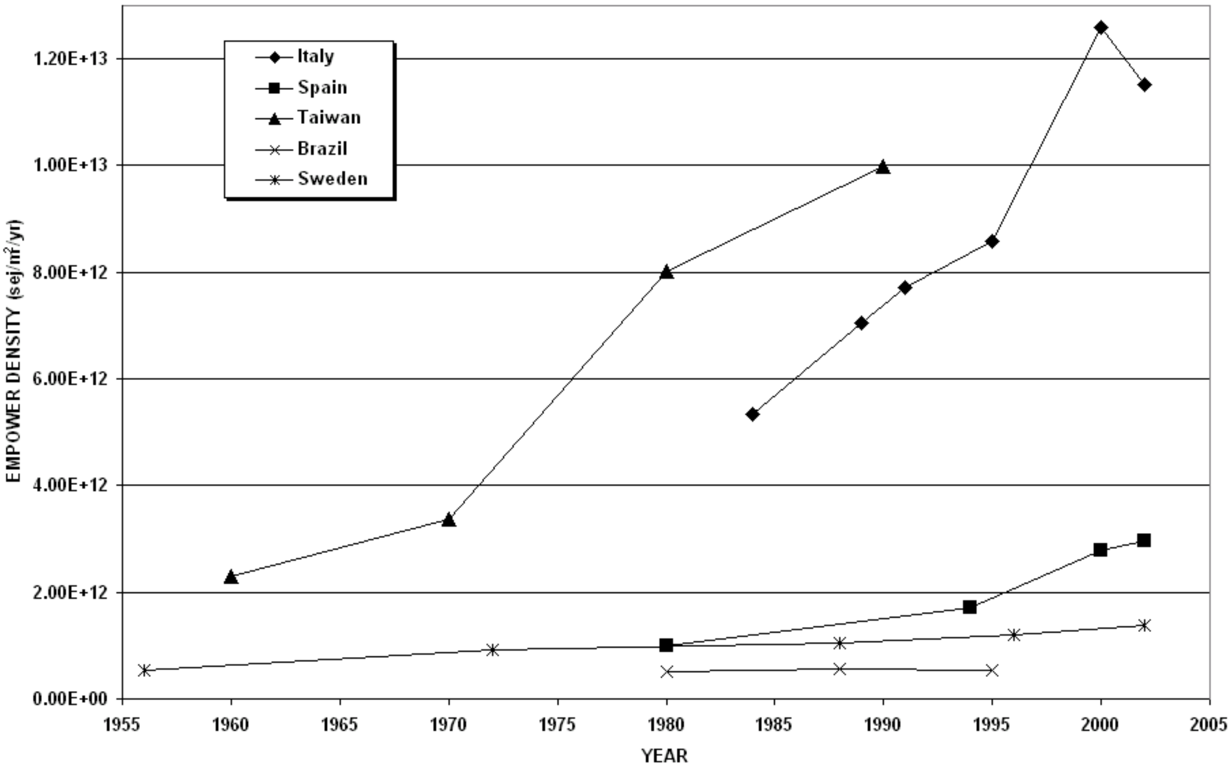

Figure 10. Empower density (emergy per unit time and land area)

Finally, Figure 10 shows how available emergy is related to a country's land area, by means of the so-called empower density (emergy per unit time and land area). Available land may become a buffer in order to dilute the intensity of economic activity. Too intense economic activities (i.e. too much emergy applied over a small portion of land) cannot be supported by local resources without environmental or/and social impacts. If pressure of development is too large, the system performs beyond the local carrying capacity and may not be sustainable. This is especially true if emissions and waste of the process are accounted for: emergy is needed to dilute, to absorb and to process waste towards reuse and recycling. This emergy could be provided by direct solar radiation, rain, wind and other environmental processes able to take care of emissions. Land needed for support, dilution or buffer could be a measure of carrying capacity (Brown and Ulgiati, 2001). In this regard, Brown and Vivas (2005) provided one landscape development intensity (LDI) indicator based on empower density. A look at Figure 10 shows that Spain, Sweden and Brazil have much lower empower densities than Italy and Taiwan. How is this related to excess available land, population density (Figure 1) and emergy use (Figure 5)? Italy and Taiwan show the higher empower densities and increasing trends, thus suggesting large and increasing emergy use. Are they beyond their carrying capacity? How to assess such a limit? Is this limit set by the amount of renewable empower densities? Careful cross-comparison of all extensive (emergy use, population, GDP) and intensive indicators (emergy/GDP, emergy *per capita*, and emergy density) is needed to even try to answer such questions.

OVERALL PERFORMANCE INDICATORS

The class of indicators dealt with in the present Section refers to the performance of a system as a whole based on input flows supporting it. No reference is done to output flows, as in the previous Section, in order to explicitly avoid any "efficiency" aspect (efficiency = relation of output to input). The goal of the indicators discussed in this Section is to highlight quality aspects depending on the characteristics of input flows.

One of the most important indicators of this category is the so-called Emergy Yield Ratio, defined as EYR=(R+N+F)/F, with reference to flows indicated in Figure 11. EYR is a measure of the ability of a process to exploit and make available local resources by investing outside resources. It provides a look at the process from a different perspective than just efficiency, i.e. its "openness", and indicates occurring appropriation of local resources by a process. This exploitation can be read as a potential additional contribution to the economy, gained by investing resources already available (Brown and Ulgiati, 1997; Raugei *et al.*, 2005). The lowest possible value of the EYR is one, which indicates that a process delivers the same amount of emergy that was provided to drive it, and that it is unable to usefully exploit any local resource. Values of 1 or slightly higher indicate conversion processes (e.g.: fossil fuels converted to electricity in a power plant, processing of raw minerals to refined metals, etc) in which the emergy of the material fed to the processing plant (oil, raw ore) is by far the largest input to the process and no local resources are exploited in significant amount. Scale is, of course, an important factor in such a calculation. If the boundary of the calculation is drawn around the plant, EYR is most often equal to 1, due to the assumption that oil and minerals are imported flows (F). If the boundary includes the oil reservoir or the mine, EYR is calculated as much higher, because of the assumption that oil and minerals are local (N). Processes whose EYR is one or only slightly higher do not provide significant additional net emergy to the economy and only transform resources that are already available from previous processes. In so doing they act as consumer processes more than creating new opportunities for system's growth. Processes of actual extraction of primary energy sources (crude oil, coal, natural gas, uranium, minerals) usually show EYRs greater than five, since local resources (N) are exploited by means of a small input from the economy and return much greater emergy flows to the economic system. The emergy return on investment is the emergy generated by previous geologic and ecosystem activities that generated these resources over past millennia.

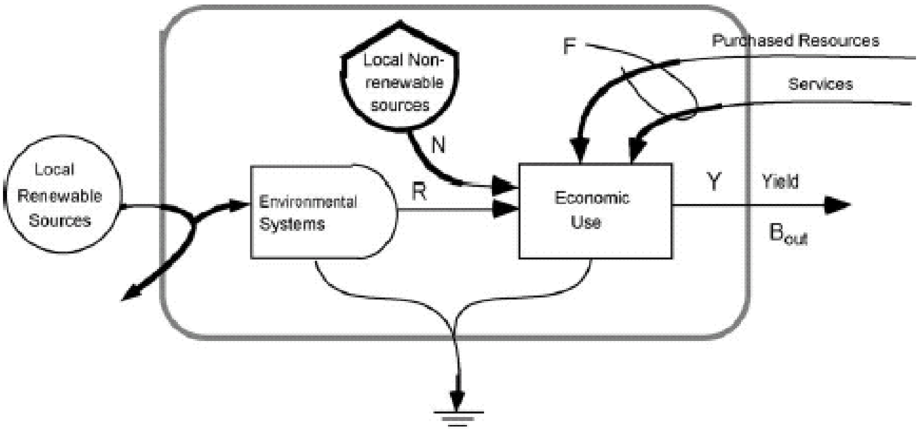

Figure 11. Diagram for calculation of emergy indices and ratios. R, N, and F indicate respectively renewable, non-renewable and imported emergy flows. Y indicates the yield of a process. The total emergy U driving the process (U= R + N + F) is generally named "emergy of the yield".

The EYR is therefore sensitive to the local-imported alternative, but it is not capable to highlight the renewable-non renewable alternative. Some emergy analysts are very concerned when calculated EYR are equal to 1 or very close to such a value, while instead this would be a clear indication of the process being a pure resource conversion process instead of primary resource extraction processes. When applied to economies, EYR equal or close to 1 indicate economies where the investment from outside (international market) does not provide significant emergy return to the investor. Having a high emergy return on investment is a potential measure of contribution to the economic process, but it is not, of course, the only factor affecting the final result. Contribution depends on the way an emergy resource is used (efficiency, proper use of co-products, amplifying feedbacks). For this reason, Raugei *et al.* (2005) suggested a different name (Local Emergy Appropriation Ratio or Local Emergy Exploitation Ratio) in order to highlight the donor-side aspect (local emergy exploitation) instead of the user side (yield and efficiency).

Figure 12 shows Brazil being the only country still providing a high emergy return on investment, while all other investigated countries are lined up at very low values in the vicinity of 1. Furthermore, all countries show declining values of EYR, as an effect of their transition from a state of "primary resource exporting country" to a state of "economically developed country".

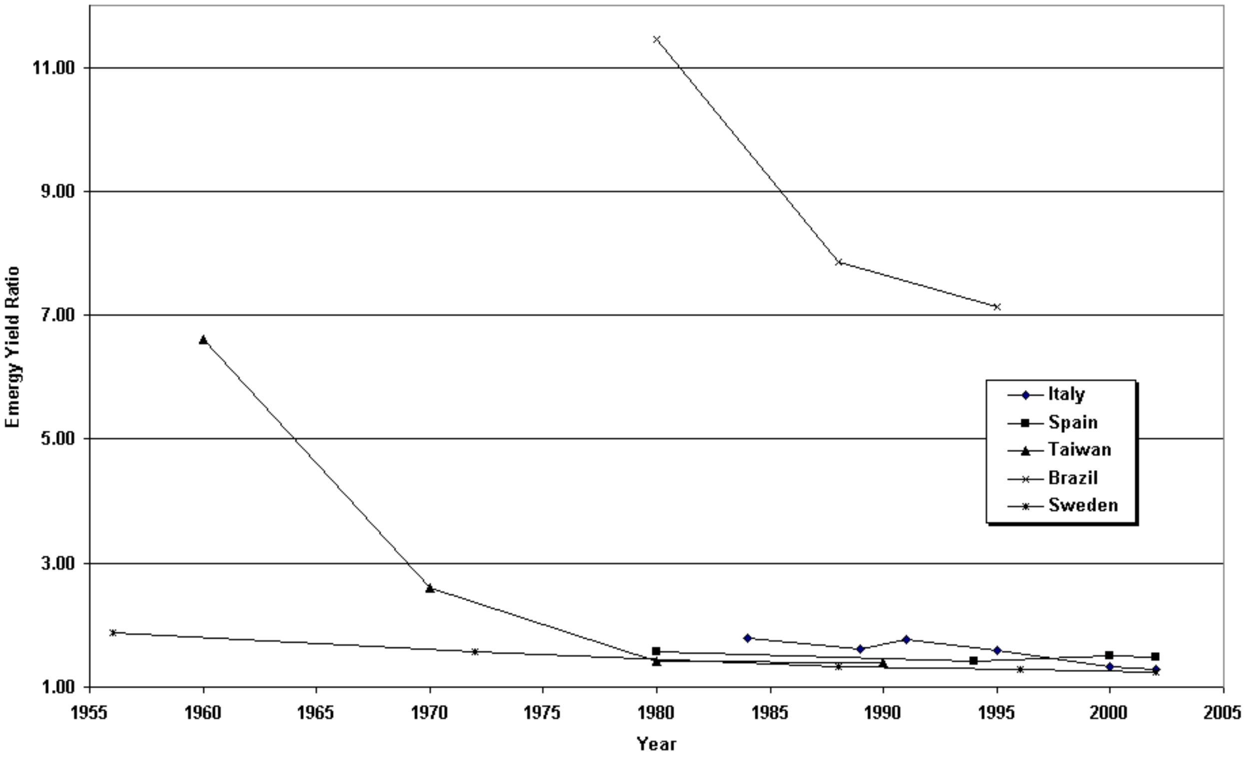

Figure 12. EYR- Emergy Yield Ratio

Another crucial indicator is the Environmental Loading Ratio, defined as ELR= (N+F)/R. It is designed to compare the amount of nonrenewable and purchased emergy (N+F, i.e. the human controlled emergy flows) to the amount of locally renewable emergy (R). In the absence of investments from outside, the renewable emergy that is locally available would have driven the growth of a mature ecosystem consistent with the constraints imposed by the environment and characterized by an ELR=0. Within such a "fully natural" ecosystems, the presence of humans would not be dominant, as for all the other species. Instead, the nonrenewable imported emergy drives a different site development, whose distance from the ideal natural ecosystem can be very clearly measured by the ratio (N+F)/R. The higher this ratio, the bigger the distance of the development from the natural process that could have developed locally. In a way, the ELR is a measure of the disturbance to the local environmental dynamics, generated by a development driven from outside. The ELR is clearly able to distinguish between nonrenewable and renewable resources, thus complementing the information that is provided by the EYR (local versus imported) and by the transformity and all other emergy intensities (efficient versus inefficient).

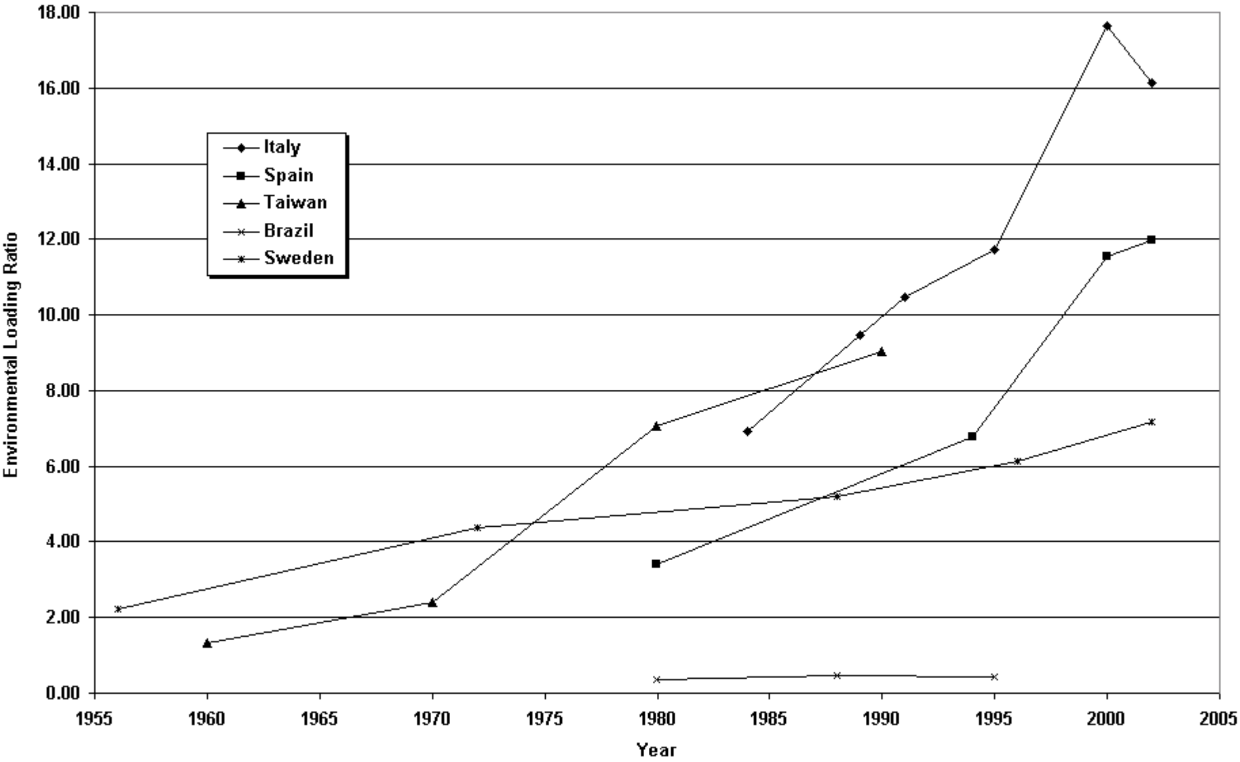

Figure 13. ELR – Environmental Loading Ratio

Figure 13 shows very low ELR for Brazil and higher and still increasing values for the other countries investigated, signaling a huge reliance on nonrenewable and imported emergy resources. Italy shows the worse performance in this regard, followed by Spain and Taiwan, while Sweden's performance seems to be better balanced and be increasing at lower rate. It should be however underlined that a high value of ELR is not a signal of high pollution in the traditional sense. For instance, a protected area is a clean and unpolluted place, but its very healthy state relies on several processes inside and outside which overload the surrounding environment (production of electricity, tools, goods, and services which are used to keep the area in a good environmental state and support tourism, including roads, restaurants and hotels). The huge flow of imported resources and services, measured by F (and maybe N, such as ground water and topsoil) compared to locally available renewable resources, makes the ELR of the natural park very large, although we cannot certainly define it a polluted area. The pressure, the overload, is simply moved to a larger surrounding area. It remains to be understood if it is possible to identify an acceptable value or threshold for ELR (e.g. ELR. = 1, indicating an external load equal to local emergy available).

The Emergy Index of Sustainability helps aggregating results for comparison of different country trends. It is defined as EIS = EYR/ELR (ability of resource exploitation per unit environmental loading generated). Being a mixed index, it is affected by the numerator (EYR, a measure of exploitation of local resources by a system investing emergy from outside) and the denominator (Environmental Loading Ratio – ELR, a measure of the distance of the process from the level it would have reached if only driven by locally renewable emergy). Graphs of Figure 14 show a clear decrease for all countries, converging to values as low as 0.10-0.15. Brazil also decreases but its performance is much better (32.02, 17.25, 16.39 respectively in the three years investigated) and is out of scale in the Figure, so it has not been represented.

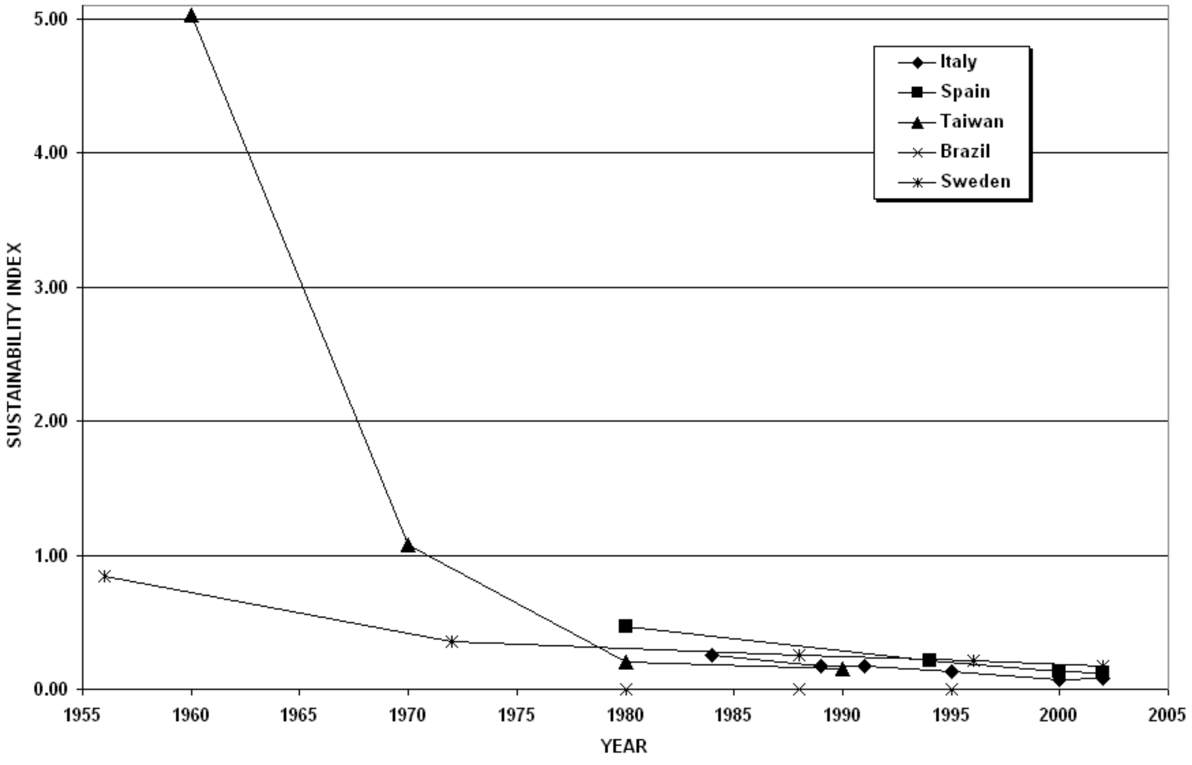

Figure 14. EIS – Emergy Index of Sustainability (resource exploitation per unit environmental loading)

The meaning of this indicator is stressed in Brown and Ulgiati (1997) and Ulgiati and Brown (1998). Economies become more fragile due to their increasing reliance on both non-renewable sources and imports. A deeper discussion about how EYR and ELR oscillate as well as what affects these oscillations is needed.

FAIR AND EQUITABLE TRADE

Economists define the so-called "terms of trade", i.e. the relationship between the price received for exports[2] and the amount of imports[3] a country is able to purchase with that money:

Terms of Trade = Average Price of Exports/Average Price of Imports

The terms of trade tend to be equal to 1 for a country. The terms of trade fluctuate according to changes in export and import prices. Clearly the exchange rate and the rate of inflation can both influence the direction of change in the terms of trade.

Table 1 shows the terms of trade for Italy in selected years. When a complete factor price equalization is not observed because of wide differences in resources, barriers to trade, technology, and purchasing power of a country's currency, the result is almost always an increase of the debt for the developing countries. However, since money only pays for the human labor and services, it is highly unlikely that market price take into account the "hidden imports" embodied in the product.

Table 1. Terms of Trade of Italy in selected years (Cialani *et al.*, 2005).

Term of trade	Selected years				
	1989	**1991**	**1995**	**2000**	**2002**
Exports/Imports	0.97	0.97	1.12	1.01	1.03

Emergy Synthesis provides an alternative definition of "terms of trade", whereby the emergy associated to the traded resource is compared to the emergy associated to the money received (Figure 15). In such a procedure, each traded product is multiplied by a suitable emergy intensity factor (transformity, seJ/J, or specific emergy, seJ/g), so that the emergy supporting its manufacture is calculated. The total emergy (embodied resources) associated to the traded product flow is then compared to the total emergy

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[2] **Exports:** The sale of *goods, services and energy* to buyers from other countries leading to an inflow of currency to a country.

[3] **Imports:** The purchase of *goods, services and energy* from abroad that leads to an outflow of currency from a country

associated to the commodities which can be purchased on the international market thanks to the money received. Diagrams of Figure 16 describe the Emergy Exchange Ratio (Imported emergy/exported emergy) at the level of the whole set of resources traded by a country with the rest of the world. All countries show a ratio higher than one, indicating that more emergy is imported than exported with the money paid for. This is good for individual countries and can be considered the driving force of international trade. Imports and exports involve issues such as dependence on market mechanisms, trade advantage, and fairness of trade, among others. Taiwan shows a sharp increase of imported resources, in support of a significant manufacturing industrial activity, mainly in the hi-tech sector. Sweden constantly increased its imports, which were already very large in the mid 50’s. More than supporting manufacture sectors, imports seem to support high standards of living (large service sector). Brazil recently decreased its ratio below unity, suggesting risk of reversing trend (to be confirmed). In the end, we remain with a large set of questions which can only be answered by long time series of several indicators evaluated together: (1) Is a trend of increasing imports sustainable? (2) Is it better to import primary resources from countries characterized by higher emergy/GDP ratios, or is it better to develop an economy based on local resources? (3) Is there a threshold of renewals below which a country’s economy becomes fragile and not sustainable? (4) How is the emergy exchange ratio linked to fairness of trade? Should it be equal to 1 in all cases or would this “equity” simply prevents world trade and globalized economies? In other words: is there any other pattern possible for world trade different than having few countries exploiting most of the others? (5) How the emergy exchange ratio affects international debt? How much emergy is returned to a rich country in the form of interests received within an international development or cooperation project? (6) Is “Cancel the debt” an appropriate policy? Can it be based on the emergy exchange ratio?

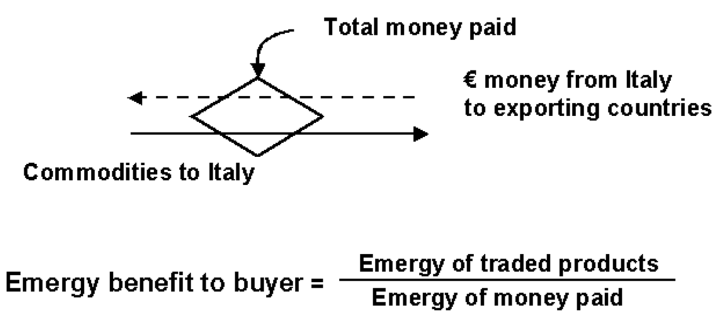

Figure 15. Definition of trade in emergy terms (Odum, 1996).

Finally, another not negligible problem arises from the fact that a large fraction of the money paid for exporting countries goes to international Companies, not to the local producers. This means that the country may not fully benefit from its export, but a significant share of these benefits goes back to importing countries which also own most of the international trading companies. Is it possible to quantify the share going to intermediate traders? Much more research is needed in this regard. As a simple example, Italy imports Fuji apples from the Shandong region of China (La Repubblica, 2005). These apples are mainly produced by small farmers, by means of a very labor-intensive production process. The lack of mechanization decreases the energy costs, but a large use of chemical pesticides is needed in order to maximize the yield by preventing losses of product. Small farmers concentrate their products to Shangai and DongYing at a price of less than 0.15-0.17 €/kg. Then, big export dealers (e.g.: the Brilliant Century Agriculture Developing Company, the largest Chinese apple exporting company) take care of sending these apples to Italy by sea. The transport inside China and the shipping to Italy account for additional 0.12-0.25 €/kg. Apples are delivered to the port of Ravenna, Central Italy, distributed to intermediate dealers at about 0.45-0.85 €/kg and finally to local markets in the price range 1-2 €/kg. This means that less than 10% of the money paid for the apples goes to the primary producer, while most of it benefits national and international dealers. The emergy exchange ratio for apple trade should therefore be calculated over the different steps of the trade chain, taking into account the intermediate price and emergy used in each point. Unfortunately data are hardly available to perform this task in full detail. This is quite a general problem, which points to the complexity of today's international market. It requires a thorough in-depth economic analysis of the whole complex web of direct and indirect money flows that take place between many different countries each time that a commodity or good is exchanged. In fact, a simple emergy exchange analysis as suggested by Figure 15, although already useful to highlight the need for alternative measures of trade equity, is still unable to provide reliable numerical results in lack of such a previous comprehensive economic analysis.

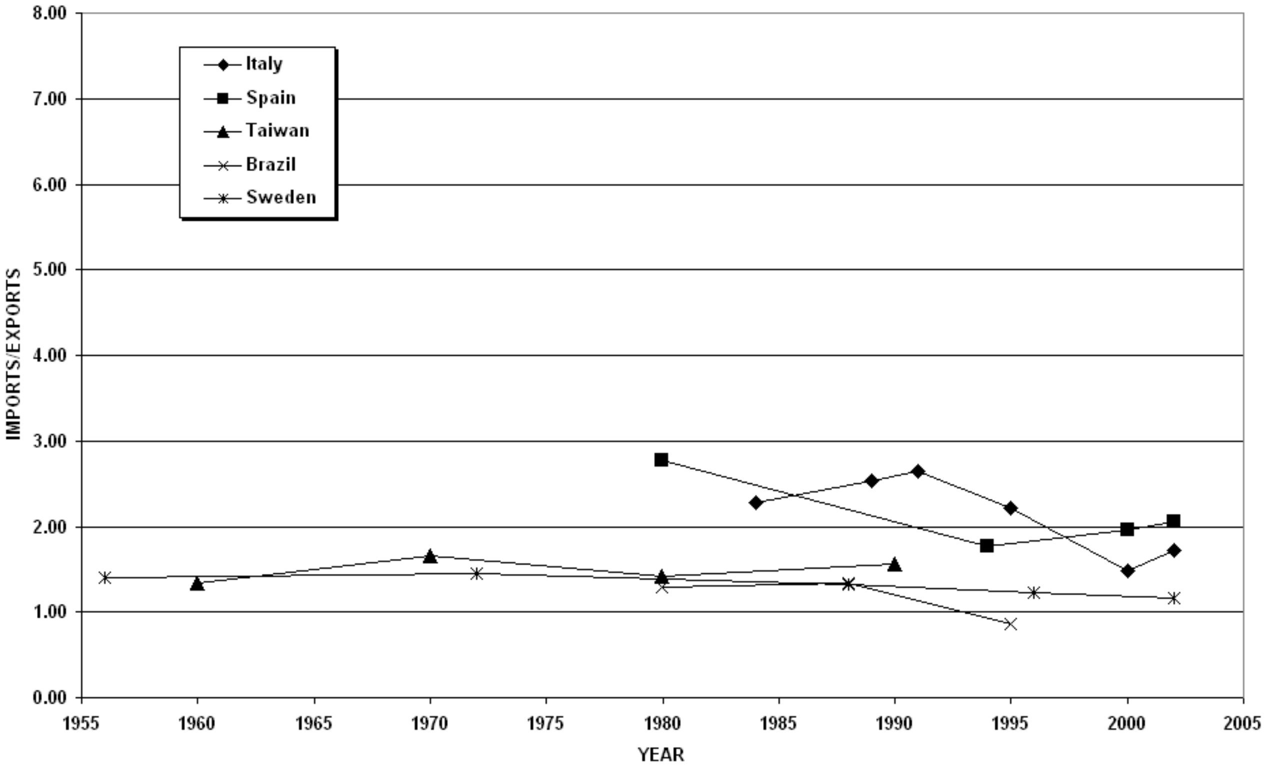

Figure 16. Emergy Exchange Ratio (Imported emergy/exported emergy)

CONCLUSION

Emergy synthesis is a powerful tool to identify aspects of the interaction of economic systems with the larger scale dynamics of ecosphere. However, for this to be possible, a whole set of emergy indicators is needed, with values encompassing a large time scale, so that trends can be clearly understood. In addition to this, emergy based indicators must be compared with conventional economic and demographic indicators for better understanding of systems. Finally, several composite indicators cannot be clearly interpreted if their components (numerator and denominator) are not disaggregated and rates of change compared. This calls for the availability of large databases with updated national analyses over time. Analyses referring to only one year of performance can hardly help to identify reliable policies and simply undervalue the significant contribution which emergy based indices and ratios can provide to the understanding of a country's dynamics.

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3.2. INVESTING IN ECO-CULTURAL CAPITAL TO DEAL WITH A CHANGING WORLD: LESSONS FROM THE MEDITERRANEAN BASIN

Pedro L. Lomas, Erik Gómez-Bagghetun, Carlos Montes, Antonio Gómez-Sal.

Resumen

Los escenarios y los modelos de gestión adaptativos se han propuesto como herramientas para afrontar el cambio global en términos de preservar el flujo de servicios de los ecosistemas que mantienen el bienestar humano. En este sentido, se han usado multitud de ejemplos de casos de adaptación y sus resultados, en términos de resiliencia socio-ecológica, para ilustrar las posibilidades y potencialidades de esta aproximación. Sin embargo, resulta paradójico que gran parte de los ejemplos milenarios de gestión adaptativa en el pasado se han estudiado poco bajo esta perspectiva, y las lecciones aprendidas raramente se han tenido en cuenta.

En este artículo se estudia el ejemplo de los milenarios Paisajes Culturales del Mediterráneo, en los que la naturaleza cambiante del clima ha generado una gran variabilidad de respuestas de gestión, así como una valiosa herencia de conocimiento ecológico tradicional basada en aprendizaje adaptativo. Estas condiciones han permitido la creación de paisajes multifuncionales en el Mediterráneo, en los que, por una parte, la heterogeneidad y complejidad han promovido la biodiversidad, y por la otra, el flujo de servicios de los ecosistemas ha estado garantizado por un nuevo tipo mixto de capital, resultante de la imitación y el aprendizaje humanos de la naturaleza: el denominado Capital Eco-cultural. De este modo, los sistemas mixtos de humanos y naturaleza resultantes han promovido la resiliencia socio-ecológica hasta el presente, si bien hoy día estas características están desapareciendo debido al efecto homogeneizador, tanto en lo económico como en lo cultural, de la globalización.

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INVESTING IN ECO-CULTURAL CAPITAL TO DEAL WITH A CHANGING WORLD: LESSONS FROM THE MEDITERRANEAN BASIN

Pedro L. Lomas, Erik Gómez-Baggethun, Carlos Montes, and Antonio Gómez-Sal[*]
Social-Ecological Systems Laboratory. Department of Ecology. Universidad Autónoma de Madrid. c/ Darwin, 2. 28049 Madrid. Spain.
[*]Department of Ecology. Alcala University. Ctra. Madrid-Barcelona, km 33.6. 28871 Alcalá de Henares, Madrid, Spain.

ABSTRACT

Adaptive scenarios and management have been proposed as tools for dealing with global change in relation to the challenge of preserving the flow of ecosystem services for human well-being. In this sense, many cases of adaptive proposals and their results, in terms of social-ecological resilience, have been used to illustrate the capabilities of the approach. Paradoxically, however, ancient examples of adaptive management have been poorly studied, and the lessons learned rarely taken into account.

This paper studies the example of ancient Mediterranean cultural landscapes, in which the Mediterranean climate's changing nature has given rise to a great variability of management responses, as well as an important heritage of traditional ecological knowledge based upon adaptive learning. These conditions have enabled Mediterranean multifunctional landscapes to be shaped, in which, on one hand, heterogeneity and complexity have promoted biodiversity, and, on the other, the flow of ecosystem services is guaranteed by a new kind of mixed capital, resulting from imitation and learning: Eco-cultural capital. Thus, the resulting mixed human and natural systems have promoted social-ecological resilience up to the present, in which these characteristics are disappearing due to the homogenising effect of economic and cultural globalisation.

Key Words: Traditional Ecological Knowledge; Eco-cultural capital; social-ecological memory; cultural landscapes; Mediterranean Basin.

1. INTRODUCTION

In the context of the Millennium Development Goals, the United Nations (UN) promoted the Millennium Ecosystem Assessment (MA, 2005) in order to assess the consequences of global change for human well-being, and to seek options to respond to these changes.

In order to deal with these topics within the context of environmental global change and the increasing uncertainty involved therein, and in relation to the acceleration, intensification and globalization of human processes, the MA explored some plausible future scenarios for ecosystems and human well-being. MA developed four global scenarios based on workshops with experts and stakeholders, and by means of global models (Alcamo et al. 2005; Butler and Oluoch-Kosura, 2006): “Global Orchestration”, “Order from Strength”, “Adapting Mosaic” and “Techno-Garden”. Although they all have their pros and cons, the last two mainly recognized the role played by ecosystem services in human well-being (Carpenter et al. 2006).

Techno-Garden is an example of a reactive command and control policy mainly based on technological development and complex predictive models, in which the manager attempts to reduce the degree of uncertainty in ecosystems in order to better control environmental variability (Holling and Meffe, 1996). The result might be the weakening of the capacity of the social-ecological system (SES) (Berkes and Folke, 1998) to deal with unpredictability and non-linear changes, characteristic of complex systems. To the contrary, many authors consider that a sustainable future for territorial management should be based upon resilience building, and making SES more adaptable (Carpenter and Gurdenson, 2001; Gunderson and Holling, 2002; Berkes et al. 2003; Olsson, 2003). Thus, environmental sciences recognize not only the importance, but also the limitations of forecast and control, using a “long now” perspective to develop projections, scenarios, etc. to aid decision making (Carpenter, 2002).

Paradoxically, the 18 principal sub-global assessments compiled by the MA, 15 major study cases of the Resilience Alliance and other examples studied by researchers focussing on adaptability, often tend to forget what is considered one of the most ancient examples of what is currently called adaptive by many authors from different natural and social disciplines (e.g. Diamond, 1997; Grove and Rackham, 2001; Fernández-Armesto, 2002; McNeill and McNeill, 2004; Butzer, 2005): the Mediterranean Basin. Furthermore, some characteristics of the Mediterranean way of life are currently particularly appreciated (e.g. cuisine, multifunctional landscapes) as symbols of quality and/or sustainability.

This paper attempts to revisit Mediterranean ecological history, and to recover the main lessons offered by these millennial SES in the development of Mediterranean cultural landscapes.

2. A BIOGEOPHYSICAL VIEW OF THE MEDITERRANEAN'S CHANGING NATURE

2.1. The rhythms of the Mediterranean climate

The Mediterranean climate is situated in a transitional climatic area between the arid zone of the subtropical high, and a more humid northern domain, restricted to a latitude of 30-45 º N and S in the western coastal parts of the continents. It is a relatively young climate (Suc, 1984; Jalut et al. 1997) characterized by high spatial and temporal variability.

In temporal terms, rainfall seasonality is usually bimodal, defined by two peaks of rainfall (spring and autumn), a relatively cold and wet winter, and a hot dry summer. Mediterranean climate therefore presents a changing nature, in which the former periods are favourable for primary production as a result of biological domination of processes, and the latter are unfavourable due to a physical domination (Gómez Sal, 2000).

In terms of spatial variability, the land surrounding the Sea presents a remarkable orographic complexity, and conditions are extremely dependent on altitude, exposure, slope, parent materials, etc. deriving from the typical characteristics of equipotentiality, vectoriality, patchiness, etc., of Mediterranean continental areas (Gómez Sal, 1998). Consequently, there are many local climatic sub-sectors linked by a common dry-summer pattern, but with different degrees of continentality, aridity, duration of frost, temperature range, average annual rainfall, etc. (Le Houerou, 2004).

This inherent spatial-temporal variability creates a complex mosaic of habitats with different associated levels of productivity limited in time, which are concentrated in space and vary according to years (Gómez Sal, 2000). This variability imposes many restrictions upon Mediterranean-type ecosystems (e.g. the existence of two adverse periods for vegetation -dry summer and very cold winter-, concurrence of the highest annual evapotranspiration rate with the temperature peak and the lowest annual rainfall in summer; a surplus of evaporation over precipitation which makes the hydrological cycle predominantly subterraneous; a high rate of mineralisation of organic matter resulting from high temperatures, and the steepness of the slope, which constitute some examples of phenomena that contribute to the soil's fragility and to erosion processes, etc). Mediterranean-type ecosystems have developed many different traits in order to adapt to these rhythms (Ortega et al. 1997; Gasith and Resh, 1999; Joffre et al. 2001: Valladares et al. 2004; Thompson, 2005).

2.2. The Mediterranean disturbances regime as a source of uncertainty

Random or sudden unexpected changes in climatic rhythms (disturbances) are vital in order to understand the functioning and the evolutionary history of Mediterranean-type ecosystems (Valladares et al. 2004; Thompson, 2005) too. Rodó and Comín (2001) or Le Houerou (2004) show the extraordinary inter-annual change in the rainfall coefficient of variation (CV), in contrast with temperature CV, which remains more or less constant. Thus, the natural disturbances regime in the Mediterranean Basin is particularly linked to the unpredictability of rainfall.

In this sense, the unpredictability of average inter-annual variation of rainfall (drought), at a larger temporal and spatial scale, is believed to be greatly influenced by atmospheric circulation at regional and global scales (Dünkeloh and Jacobeit, 2003; Xoplaki, 2004; Lionello et al. 2006). Different authors point out that the annual variability and unpredictability in the recurrence of these phenomena of drought, extreme temperatures and associated dry spells is inversely proportional to mean annual rainfall (e.g. Rodó and Comín, 2001; Grove and Rackham, 2001; Le Houerou, 2004; Kostopoulou and Jones, 2005).

Furthermore, we should highlight the unpredictability of the intensity and the type of precipitation at a smaller scale. On one hand, and in relation to rainfall intensity, the closed-in character of the Mediterranean Sea which can foster an intense warming process after summer, which is related to cold air masses in the higher strata of the atmosphere and which, in addition to the proximity of sea and mountains for most of the main land masses, might be the cause of heavy storm or hail events with high-intensity convective rainfall (e.g. Rodó and Comín, 2001; Bolle, 2003); on the other hand, and regarding the type of precipitation, summers with warm and dry winds coming from the south, along with high temperatures, can prevent high decomposition rates of organic matter due to water scarcity. Thus, there is often a large amount of dead biomass which acts as fuel in the ecosystems, which could be ignited by lightening during dry storms in the autumn-winter period. The fire cycle plays an essential role in the renewal of Mediterranean-type ecosystems, and is not considered negatively but rather as an adaptation, and the ecology of Mediterranean vegetation therefore involves fire, which consumes competitors (Moreno and Oechel, 1994; Grove and Rackham, 2001; Ojeda, 2001; Lloret, 2004).

2.3. Ecological resilience in Mediterranean-type ecosystems

Paradoxically, the result of this great variability and unpredictability is that the Mediterranean climate is the one that contains the highest number of biodiversity hotspots outside the equatorial sector (Mittermeier et al. 2005). In this sense, Thompson (2005) highlights three prevailing factors for diversity in Mediterranean-type ecosystems: geological history, climate and the long anthropic history.

The geological history of the study area, its geographical position, with land masses at the same E-W latitude (Diamond, 1997), and its orographic complexity, with mountains close to the sea, have enabled many species to cross the sea with little effort and to reach the other side of the Mediterranean Basin, and many others to survive and recover from natural disturbances, and to use the southern or mountain areas as refuges.

With regard to climate, we have seen that Mediterranean-type ecosystems are the result of an evolutionary interaction with Mediterranean climatic rhythms, and of adaptive learning, and adjust their organization and functioning to the gradient of annual and inter-annual fluctuations of natural disturbances (González Bernáldez, 1992a; García Mora and Montes, 2003). In this context, the avoidance of catastrophic shifts (Folke et al. 2004), and the subsequent building of ecological resilience (Holling, 1973) has implied the use of different forms of ecological memory (Bengstsson et al. 2003) therein. Some examples in terrestrial ecosystems involve the use of different forms of internal memory, such as seeds or tree stumps, for dealing with drought and recovery from fires (Ortega et al. 1997; Lloret, 2004; Thompson, 2005). In aquatic ecosystems, Gasith and Resh (1999) studied biotic responses to drought and flooding in Mediterranean streams, identifying two typical ones: resistance to elimination by floods, and a rapid re-colonization of the ecosystem, which makes use of the ecological memory residing in the bank of propagules, consisting of eggs, seeds and spores (Brock et al. 2003; Vidal-Abarca et al. 2004).

But we must not forget the long history of human presence. Today, we know that Mediterranean landscapes reflect more than eight millennia (Makhzoumi and Pungetti, 1999; Grove and Rackham, 2001; Naveh, 2003) of agricultural-forestry-pastoral uses, in one of the most densely populated regions of the world.

3. THE ECO-CULTURAL CAPITAL: LINKING HUMANS AND NATURE IN MEDITERRANEAN CULTURAL LANDSCAPES

Mediterranean landscapes and the way of life contained therein result from the clearing of woodlands in an ancient domestication process in Mediterranean-type ecosystems. The particularity of these processes consists of the use, imitation and the adaptation of forestry, agriculture and cattle farming practices to the natural spatial and temporal complexity and variability of climatic rhythms and disturbances regimes.

3.1. The agricultural-pastoral-forestry way of life in the Mediterranean Basin

3.1.1. Domestication of plants: fruit growing forests

Although evidence of domestication of plants is thought to be prehistoric, the Neolithic agricultural revolution is believed to have started in the Levant region of the Near East “Fertile Crescent” 10 millennia ago, parallel to the gradual abandonment of the nomadic hunting-gatherer way of life (Butzer, 2005). This process started with the gradual turning of the original forests into fruit-growing land (González Bernáldez, 1992b) with scattered trees. Initially, there were no big changes in plant types, but the selection and import of certain species, due to their specific features, gave rise to the present variety of Mediterranean crops, and gradually affected their main characteristics. This process was intended to increase the annual productivity period and to make use of tree production as a reserve for more critical years (Gómez Sal, 1998).

Fire was one of the most important methods used for clearing woodlands and extending this process. Stewart (1956) suggested that Palaeolithic people had already intentionally made use of burning to facilitate hunting and gathering, although the first evidence of human-induced changes by fire in the Mediterranean landscape appears during the Neolithic agricultural revolution (Naveh, 1975).

Very diverse practices, however, have been used to deal with the limitations imposed by the Mediterranean climate in this process.

Dealing with drought, flooding and the subterraneous nature of the hydrological cycle in the Mediterranean climate entailed the need to search for water reserves and the use of techniques to extract, transfer and use available local water. In fact, the initial settlements of Mediterranean culture were located close to the main river basins and groundwater reserves (Llamas, 1989). Irrigation techniques were already habitual in 6000 BP in Mesopotamia, and were based upon the exploitation of rivers and annual floods (Bazza, 2007). Ancient Sumerian know-how of irrigation techniques was used and improved by the Romans to supply great Roman *urbs* and *termas*. Subsequently, the Muslim civilization of *Al-Andalus* constructed Mediterranean xero-gardens such as *La Alhambra,* and complex systems of groundwater use based on channels, crop terraces, etc. in areas with arroyos (Ramblas), making use of surface water on floodplains of streams and rivers (Vegas). Decentralized institutions like the medieval Water Court (Valencia, E Spain) were created to avoid social problems in the distribution of water from channels.

In order to cope with the pests and nutrient deficiency of Mediterranean soils, Mediterranean cultures developed practices such as crop rotation, involving different types of crops in the same space in sequential seasons. This practise traditionally consists of seasonal three-year crop rotation, and a period in which the soil is left to lie fallow, during the third year. It is thought to have been a truly "ecological fallow"

(Bengtsson et al. 2003), involving habitual and temporary self-limitation of the use of land, enabling the gradual recovery of the fields.

In relation to the abruptness of Mediterranean territories, another technique used for cropping in marginal or mountainous areas involved stepped terraces, consisting of crops on hillsides or mountains. This system has been used to maximize the area of arable land and to reduce water loss and soil erosion by runoff, enabling the spread of agriculture to new territories. It was often used by Berbers in the south-eastern mountains of Spain (Las Alpujarras, SE Spain), and is widespread all around the Mediterranean Basin under different forms and territories.

3.1.2. Domestication of animals: herbivorism and fire used for clearing woodlands

Fire was also used to create pastures for fodder. Domestication of animals was originally part of nomadic culture, involving seasonal migration, and a consequence of the change in the hunter-gatherer way of life towards sedentary food production, intensification, specialization, and the separation of agriculture from pastoral ways of life (Levy, 1983; Alvard and Kuznar, 2001). Originally, cohabitation with animals was suggested as the origin of many diseases, but it has also led to immunological resistance, and to a comparative advantage (Diamond, 1997).

These relationships were the origin of plant-animal, herbivorism or grazing phenomena, which has been intensely discussed as one of the most important factors of transformation of the original Mediterranean-type ecosystems (Zamora et al. 2001). These phenomena were originally seen as a degradation factor, involving “overgrazing” (Le Houérou, 1993), when herbivore density is high and ecosystem production is mainly controlled by animals rather than geophysical factors; subsequently, it came to be considered as a vegetation management tool for promoting biodiversity in Mediterranean rangelands (Perevolotsky and Seligman, 1998). Thus, many characteristics of vegetation may be interpreted as a response to the action of herbivores, and different types of herbivores were selected according to their adaptation to the environmental complexity, giving rise to the current variety of livestock breeds.

Imitating the movement of wild species, Mediterranean livestock is transported according to changes in primary production, and is based upon seasonal alternation in the case of long distances (transhumance), or in the case of small distances (transterminance), upon geological or topographic gradients (Gómez Sal and Lorente, 2004). Livestock manure was used to fertilize fields along the paths between mountains and lowlands. Institutions such as the *Real Concejo de la Mesta* (Spain) or *Dogana della Mena delle Pecore* (Italy), were created to regulate rights-of-way for shepherds, and to avoid problems with farmers (Pinto-Correia and Vos, 2002).

3.2. Mediterranean cultural landscapes as an Eco-Cultural capital

3.2.1. A Mediterranean social-ecological view

The spatial-temporal scale of these transformations is ancient. Indeed, Naveh and Lieberman (1993) suggested that no strictly “natural” landscapes exist any longer in the Mediterranean Basin. We must therefore talk of cultural landscapes, complex adaptive systems in which the relationships between humans and nature have created socio-cultural and ecological patterns and feedback mechanisms of control (Farina, 2000). In this sense, Mediterranean cultural landscapes are another view of the latest concept of SES (MedSES), in which the ecological systems are linked and affected by one or more social systems (Anderies et al. 2004), and constitute more than just human systems embedded in ecological systems or *viceversa* (Walker et al. 2004).

This co-evolving history of humans and nature, within the framework of traditional resource management in the Mediterranean Basin, has involved the transformation of the original forests into a complex shifting mosaic of patches (Forman, 1995), with ecosystems in different states of maturity between forested areas and intensive croplands. Thus, the aforementioned high diversity values for the Mediterranean Basin are based on both the medium exploitation intensity of the Mediterranean-type ecosystems, and on spatial complexity and heterogeneity in which gives rise to different habitats and ecological niches (Pineda and Montalvo, 1995; De Miguel, 1999; Atauri and De Lucio, 2001; Benton et al., 2003; Bengtsson et al., 2003), in accordance with the intermediate disturbance theory (Conell, 1978; Blondel, 2006).

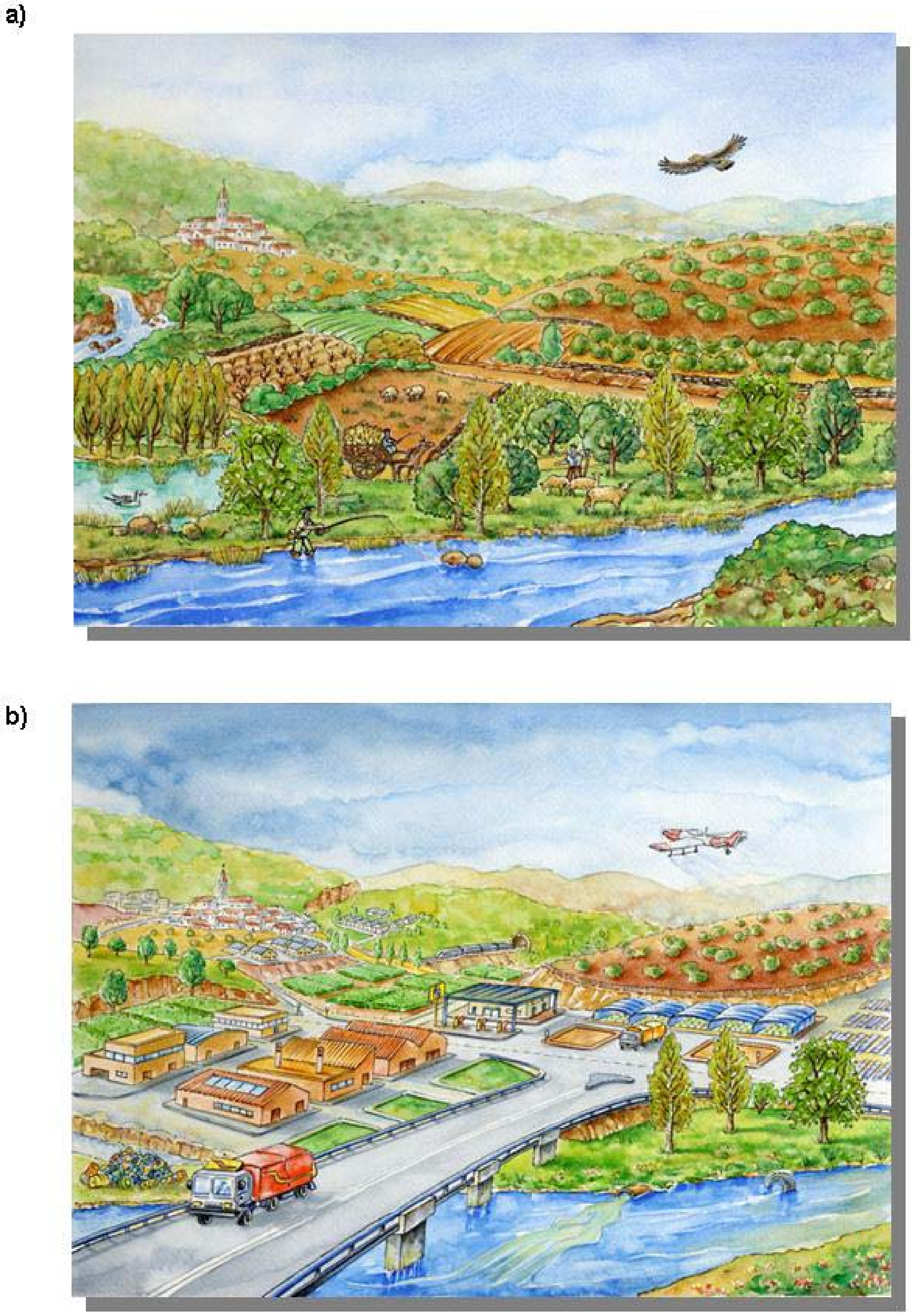

Figure 1. Ideal representation of the changes in the Mediterranean cultural landscapes in the last 50 years a. Multi-functional use with preservation of biodiversity and environmental services. b. Mono-functional landscape with intensification and abandonment, and the simplification of environmental services (Source: reproduced with permission of the Environmental department - Andalusian Regional Government).

Figure 1a is an ideal representation of traditional Mediterranean cultural landscapes and illustrates this concept. As can be seen, the original woodlands only remained in the upper slope zones as a source of forest products (hunting, wood, herbs, etc.), because these areas were not suitable for croplands. In contrast, the lower slope zones were transformed into a mosaic of patches with different uses (agriculture, livestock, fishing, etc.), and many different ecotones between patches were created and biodiversity levels increased (Blondel, 2006). Human elements (constructions, infrastructures, etc.) were integrated into natural ones, and connectivity between patches was therefore well promoted. In structural terms, connectivity was facilitated by the use of grids based on different types of boundaries such as thickets, hedges, groves, fences and others, and by the remaining elements of the original ecosystem structure (Schmitz et al. 2003; Martínez Alandi, 2006); and, in functional terms, by the multifunctional use of ecosystems (Brandt and Vejre, 2004).

One example of this category is the Spanish *dehesa* or the Portuguese *montado* systems in the south-west of the Iberian Peninsula. Forests of *Quercus suber* and *Quercus ilex* have traditionally been exploited in an extensive manner, and rather than removing all vegetation to use pastures for livestock or soil for cropping, some elements of the original forests have been maintained. The exploitation patterns of these systems (Pineda and Montalvo, 1995; De Miguel and Gómez Sal, 2002) tend to situate forested areas in the upper slope zones (*montes*), where agriculture is less advantageous, and a combination of pasture and parts of the original forest (especially trees, walls, hedgerows, etc.) in the lower slope zones. Pastures and trees are used for fodder and to provide fruits and shade for livestock, respectively. The function of livestock in the regulation of this agrosystem is critical, given the role played by the upper slope zones of the system as exporters of nutrients along a gravitational gradient to the lower zones, making use of trees, which pump nutrients from the soil. Consequently, nutrient balance is controlled by the livestock, which extracts more nutrients than gravity deposits or soil formation in the lower slope zones, and supplies more than what is extracted or lost by gravity in the upper zones. In some areas, this exploitation is combined with transhumance, and pastures can therefore be recovered or used for cropping in certain months, or for the extraction of other materials (wood, cork, etc.).

The entry of most northern Mediterranean countries into the EU has entailed an initial phenomenon of subsidized agricultural intensification, and subsequent abandonment, also subsidized. In the Maghreb area, the populations is increasingly reducing forests and shrublands through overgrazing and by increasing the area of arable land, and wildfires are consequently declining (Redjali, 2004).

Figure 1b is an ideal representation of the classical transformation of most northern Mediterranean cultural landscapes over the last 50-60 years. The upper slope zones have been abandoned, becoming marginalized, and are used for mining, etc. The lower slope zones have been urbanized and developed as industrial lands, and the previous extensive croplands have been transformed into intensive ones, with many external inputs of matter and energy. Homogenization and mono-functional use of the territory has led to a loss of heterogeneity and connectivity. Soil erosion, salinisation, and the increasing recurrence of wildfires, etc. are known effects of these processes (González Bernáldez, 1991b; Pinto-Correia, 1993; Puigdefábregas and Mendizábal, 1998; Pausas and Vallejo, 1999; Pineda, 2003).

3.2.2. The MedSES and the Eco-Cultural capital concept

Under this cultural ecosystem perspective, attention must shift from the isolated structure and functioning of the ecosystems or the socio-economic systems to the SES and to the environmental window (Odum, 1996), in which the social-economic and ecological sub-systems of vested interests interact.

Characterizing SES functioning and structure, the cryptosystem (González-Bernáldez, 1981), involves diagramming and modelling links between ecosystems and human activity (Heemskerk et al. 2003; Abel, 2003). In this sense, Figure 2 presents a simplified SES conceptual mode, based on the main links between human activity and nature at different spatial-temporal scales, using the energy language (Odum, 1994), and the elements that build social-ecological resilience promoted by these links. The sub-systems are characterized, on one hand, by resilient ecosystems that are ecologically-sound in terms of structure, functioning and dynamics (the self-organizing natural capital), whose ecological functions have the potential to supply a flow of different ecosystem services to the human sub-system. On the other, they are characterised by the different human capitals (cultural, social, financial, manufactured, etc.) which control mechanisms of feedback (recycling, land use management, etc.) supported by the natural capital.

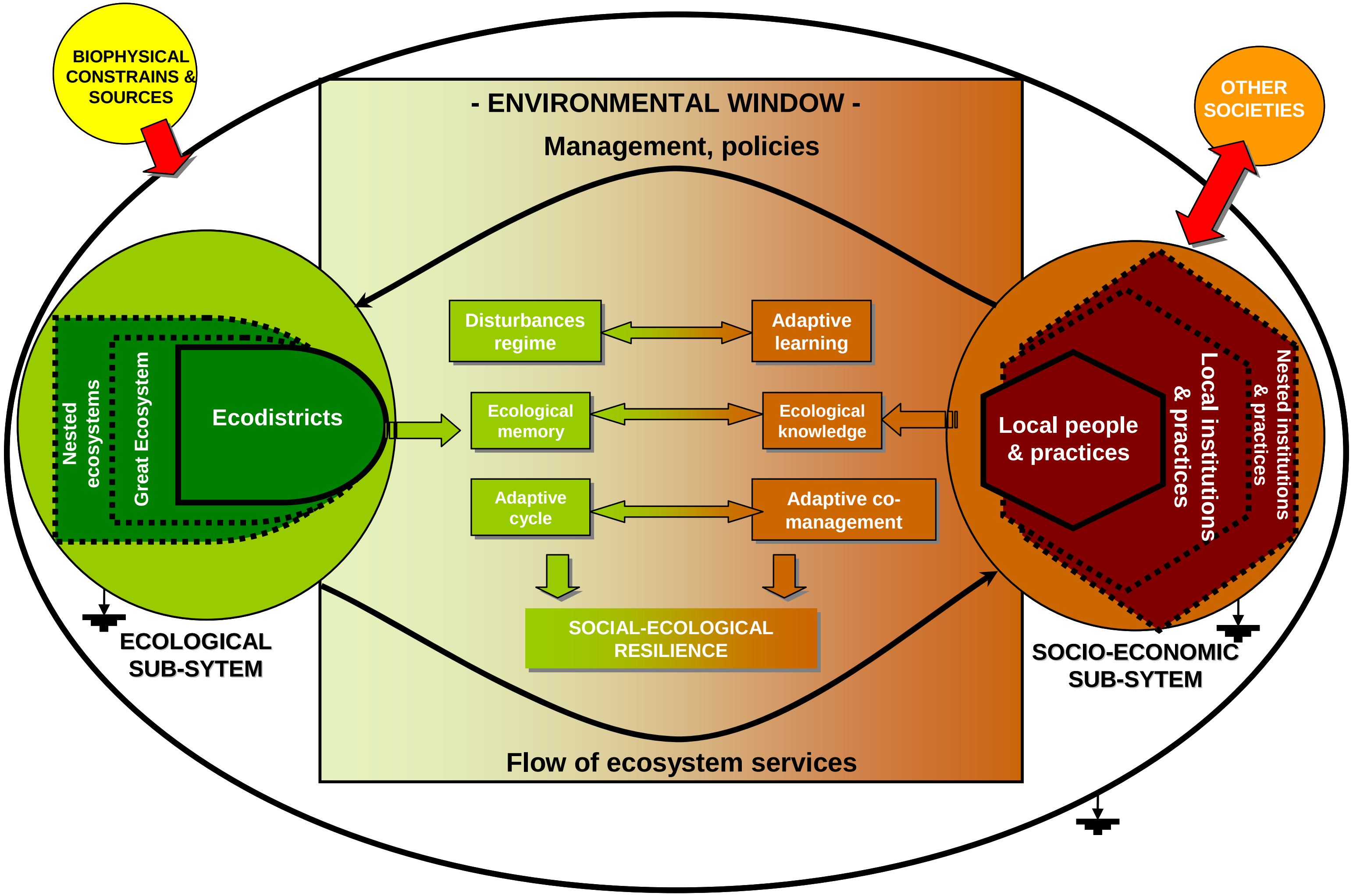

Figure 2. Heuristic model of a MedSES. We use the energetic symbols of H.T. Odum to represent the ecological and socio-economic sub-systems. The ecological sub-systems interact with the socio-economic sub-systems by means of the flow of ecosystem services, and the human feedbacks are mainly contained in management and policies. The disturbance regime is presented as the source of adaptive learning, and the ecological memory as the origin of the ecological knowledge in the MedSES. The result of the practices guided by these principles is the social-ecological resilience.

The development of the SES concept in the Mediterranean context calls for a new vision of the relationships between the sub-systems, as the idea of natural capital as a stock of untouched reservoirs no longer makes any sense, if all the ecosystems are the result of thousands of years of human-nature co-evolution. Thus, Van der Perk et al. (2000) and De Groot et al. (2003) discriminate the cultivated capital, a hybrid form between natural and manufactured capital, but they propose capital only as stocks, and the cultivated capital as a mixture of a great variety of systems with many different characteristics and influences, from multi-functional systems to mono-functional ones, from intensive to extensive in the use of exosomatic energy, etc.

Figure 3, illustrates the main human feedbacks to ecosystems, in terms of capital investments, and presents our concept of mixed capital, in an attempt to describe the above mentioned cultivated capital. Contrary to other theoretical approaches, it should be noted that, in this paper, capitals are not only considered as stocks but also as flows of matter, energy, and information. In his synthesis paper dealing with ecological resilience in the Mediterranean Basin, Blondel (2006) distinguishes different ways of life and their influence on different management models, and possible stability domains. Thus, herein we distinguish, in terms of sustainability criteria, two different forms of mixed capital, located at both ends of a human capital gradient of involvement: the Eco-cultural mixed capital, and the Subsidized/degraded mixed capital.

In the **Eco-cultural mixed capital**, the most important human input is supplied by the social-cultural and the human capitals. The social-cultural capital input is related to the historical co-evolution between human and natural forces throughout many centuries, in the context of management of common property resources, and is related to social cohesion mechanisms. The human capital input is available in the form of traditional ecological knowledge (TEK) (Berkes et al. 2000), social-ecological memory, and intensive human labour. Thus, management appears to be mainly devoted to the maintenance of the flow of ecosystem services to society in the long term. Solar transformity (Odum, 1996) for this kind of capital might be relatively high because of the evolving history of the TEK, but the exosomatic/endosomatic energy ratio would be relatively low due to local control of the energy flows, and the relevance of human labour.

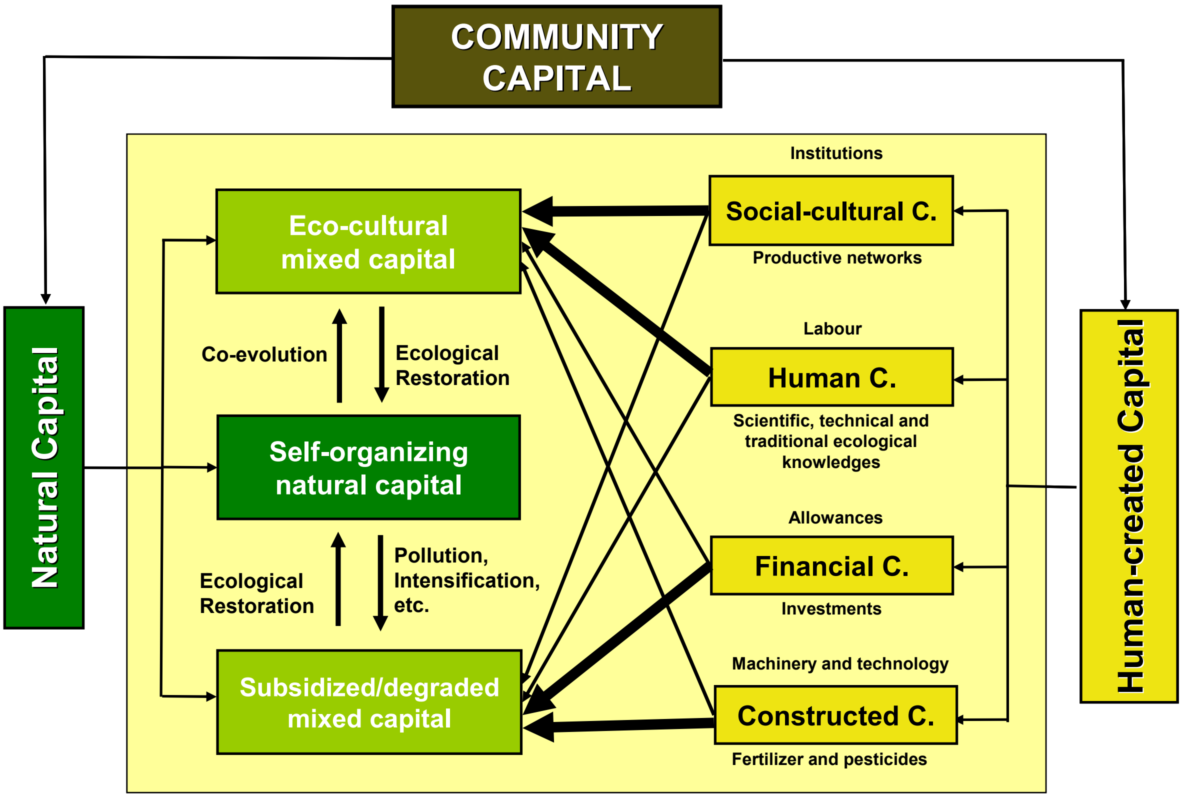

Figure 3. The concept of Eco-cultural capital in the context of the different types of capitals. It shows how eco-cultural capital depends especially on social and human capitals, and how subsidized-degraded capital depends mainly on financial and constructed capital.

In the case of the **Subsidized/Degraded mixed capital,** the most important link with human capitals is supplied by the human-made capital (particularly financial and constructed). Thus, territorial management is mostly devoted to the productive maximization of some specific ecosystem services with direct market value, in the short term. This type of capital would be the result of the different forms of intensification or degradation (pollution, intensification, etc.) of the self-organizing natural capital, under the influence of the acceleration of information, energy and matter flows in a context of economic globalization, and of a decoupling process between nature and humans (increasingly dependent on external flows of ecosystem services). The Eco-cultural capital may be damaged by the abandonment of territory or the management of different forms of subsidized-degraded mixed capital. Solar transformity of this kind of degraded capital might be relatively high, but on this occasion, results from the intense flow of imported exosomatic energy, matter and information controlling the endosomatic energy in the system.

Thus, the development of Mediterranean cultural landscapes can be considered as the process of building the Eco-cultural mixed capital, from which Mediterranean society has historically obtained a great variety of sustainable ecosystem services.

3.3. Avoiding the collapse: the social-ecological resilience of the MedSES

The factors leading to the collapse of some civilizations and why others have survived have constituted a recurrent theme in scientific literature (Abel et al. 2006). In the Mediterranean Basin there are well-known examples of more notable collapses, such as the Roman Empire, the Minoan civilization, the Carthaginian Empire, etc. Notwithstanding, a common pool of Mediterranean cultures survived almost to the present time. Mediterranean mixed culture has been more flexible and resilient than other SES in more homogeneous and invariable environments (Ingold, 2000), or those based upon resistance strategies.

Avoiding the total collapse of MedSES has involved the use of social-ecological memory. Different Mediterranean civilizations have been forced to adapt to the orographic complexity, climatic variability, and to disturbances regimes down through the centuries, and have developed complex systems of imitation and reproduction of natural cycles. This process of empirical learning has given rise to a great number of local mechanisms and practices, which are the origin of the local TEK. In Table 1 we use the classification by Berkes et al. (2000) to concisely provide examples of social mechanisms and management practices which promoted adaptation to the extreme variability of the Mediterranean disturbances regime.

Contrary to more centralized cultures, creativity was developed separately in each part of the Mediterranean Basin by different civilizations at different periods. The buffering nature of the Mediterranean Sea (climatic, cultural, geographical, etc.) had a border effect, which gave it the quality of a cultural edge (Turner et al., 2003). This geographical position has enabled a great variety of civilizations to settle along the Mediterranean coast and to rapidly establish a complex network of different positive (trade, culture, etc.) or negative (wars, invasions, etc.) interchanges (Mc. Neill and Mc. Neill, 2004). As opposed to the slower land-based expansion strategy developed by other civilizations, the Mediterranean Sea facilitated rapid social interaction, crossfertilization, and synergy, as well as active transfer of know-how and technology. This increased the potential for learning from other types of experiences without always having to respond to and learn from crisis (Turner, 2004).

Table 1. Selected examples of mechanisms and practices of the Mediterranean traditional ecological knowledge pool.

MANAGEMENT PRACTICES BASED ON ECOLOGICAL KNOWLEDGE	Direct protection of species, habitats and processes.	Complex protection systems of Roman and Greek forests, hunting prohibition by Islam during the four sacred months in the Middle Ages (*Ashhur Al Hurum*), *Hemas* system of the eastern Mediterranean and western Asia protected areas, sanctioned by the Islamic rule, etc.
	Traditional practices of resource management.	Cork-oak and live-oak traditional management in Spanish *dehesas* and Portuguese *montados*, alternation of fallow lands and rotation of croplands for recovery of nutrients in fields throughout the Mediterranean, crop terraces in many Mediterranean mountains and hills for dealing with drought, erosion, traditional irrigation practices for dealing with drought and floods, etc.
	Practices to cope with in complexity.	Mediterranean (e.g. Italian *coltura* promiscua) mixed cultivation of different crops for promoting heterogeneity, fire used for reproducing natural renewal non-linear dynamics and fighting wildfires, the use of cork oak *dehesas* for feeding pigs throughout the year and for harvesting cork every 9-14 years.
SOCIAL MECHANISMS BEHIND MANAGEMENT PRACTICES	Generation, accumulation, and transmission of local ecological knowledge	Irrigation know-how transmission from Roman to Muslim to Christian Kings to present-day Spain, development of a marine culture using the Mediterranean Sea as a means of communication among people.
	Structure and dynamics of institutions	Medieval Tribunal of Water in Valencia (E Spain), for regulation of irrigation channels, Mesta Royal Council for regulation of pasture use on Spain’s central plains, communal open-field farming practices in many towns of southern Europe up to the 1950-1960s, the institution of Public Dominium, present in many European laws (e.g. water act and coast act in Spanish law). The Roman Senate passes a law to protect water stored during dry periods in order for it to be released for street and sewer cleaning, etc.
	Mechanisms for cultural internalization	Rituals related to certain Goddess (fertility, crop, nature, forests, etc.) in Pre-Christian and Pre-Islamic Mediterranean cultures,
	World view and cultural values	Community open-field farming practices, an organic view of the world in which nature was conceived as mother nature in pre-monotheist Mediterranean religions.

This adaptive learning of local practices, tested by trial-and-error, transmitted by oral and written traditions and shared around the Mediterranean Sea by different civilizations led to the diversification of resources, knowledge and management practices that were used to transform landscapes into the present mosaic of cultural landscapes comprising a multifunctional adaptive mosaic of patches at different stages of maturity, promoting biodiversity, and supporting an increasing level of social and ecological resilience.

4. CONCLUSIONS: LESSONS LEARNED FROM MEDITERRANEAN CULTURAL LANDSCAPES FOR BUILDING SOCIAL-ECOLOGICAL RESILIENCE

Lesson 1. Without change, there is no learning. Without learning, crises tend to lead to collapse

In consonance with the ideas expounded by Carpenter and Gunderson (2001), we argue that the spatial-temporal changing nature of the Mediterranean climate and the disturbances regime which Mediterranean cultures were forced to live with have been the main driver in the development of several different management practices. These practices were transmitted and interchanged around the Mediterranean Sea, thus preventing the need to learn from all crises, and resulting in an authentic legacy of Mediterranean TEK for dealing with uncertainty and change. Thus, living with disturbances, and developing adaptability were habitual practices in the past, when the changing Mediterranean nature was assumed by people.

Today, in the context of economic globalization, stability is essential and change or instability must be avoided (van deer Leeuw, 2000). Furthermore, in policy-making, decisions are taken by distant and centralized institutions, not always well coordinated with the more local ones, and with different interests, values, origins or cultures. Consequently, there is an increasing process of homogenization of management practices and ecological knowledge. This process is in consonance with global economic interests, rather than geared towards improving local management practices and TEK, which would be in accordance with adaptive learning processes of local societies.

Thus, there is a general pattern of disconnection between socio-economic systems and ecosystems, which are increasingly used as a simple physical support for different activities, without taking ecosystem services into account. Local management practices are rapidly changing, to adapt to global interests, and TEK is being lost. This strategy increases social vulnerability to collapse in the context of current global environmental change.

Lesson 2. Intermediate disturbance. Heterogeneity and complexity for promoting diversity and avoiding collapses

In the past, local economic processes were coupled with the biogeophysical environment and the disturbances regime by evoking the ecological dynamics of the Mediterranean at small and short term scales. The result was Mediterranean cultural landscapes, a shifting mosaic of patches with different degrees of maturity, preserved by adaptive learning and cultural practices. Thus, heterogeneity and complexity became critical factors to human survival and viability.

Since the 50s, this traditional model of adaptive management has been changing. In their rapprochement to the European Union, northern Mediterranean countries have developed extraction and consumption patterns based upon examples from northern European countries (Lomas et al. *in press*), and southern Mediterranean countries are attempting to establish these patterns within a few decades. The different types of SES become simplified and homogenised as a result of the reduction of the multifunctional uses of territory. The spatial-temporal desynchronized dynamics of different landscape patches are becoming synchronized, so that the difference between patches has been actively reduced. Economic globalization made the scale of this shifting mosaic a larger one, in which patches are economic regions and the shift can be observed from sub-continental to global scale (Farina, 2000).

Depopulation of rural areas, land abandonment, urban expansion, intensification and specialisation of practices and management, are some attributes of these new socio-economic patterns. The consequences of these processes for biodiversity and resilience are noteworthy, from increased soil erosion or fire risk to reduced biodiversity and negative effects on ecological balances (González Bernáldez, 1991a, 1991b; Pinto Correia, 1993; De Miguel and Gómez Sal, 2002; Schmitz et al. 2003).

Thus, cultural and landscape homogenization deriving from economic globalization are causing the previous Eco-cultural capital to become subsidized/degraded capital, the most degraded type of mixed capital, in thermodynamic terms. The Eco-cultural capital, derived from promotion of and adaptation to natural complexity and unpredictability, provided a large variety of ecosystem services, and land uses were not always highly productive but rather resilient and sustainable; to the contrary, the subsidized/degraded land uses now offer an extremely simplified productive use of ecosystems, with systems of land uses much more dependent and fragile, and therefore less sustainable (Gómez Sal and González García, 2007).

Lesson 3. Knowing, valuing and investing in Eco-cultural Capital in order to deal with global change

In the past, Mediterranean rural landscapes were usually inhabited and managed through a millenary adaptive learning process. The resulting TEK was used to design authentic multifunctional landscapes of a clearly local cultural nature, while maintaining ecosystems with a high level of ecological resilience and ecosystem integrity (the Eco-cultural capital). Consequently, the type of ecosystem functioning that was maintained guaranteed a dynamic flow of sustainable ecosystem services to society.

Today, the increasing speed and the distant origin of physical, monetary and information flows promoted by economic globalization are separating socio-economic systems from local ecosystem services. Thus, patterns of local management are increasingly being based on standard recipes resulting from general knowledge, and on progressively more complex technologies, in order to promote more efficient use of ecosystem services, with the fantasy of economic dematerialization in mind. In dealing with this situation, the usual response is based on the use of static and defensive protected areas, in an attempt to protect more or less undisturbed areas from transformation, and conservation efforts usually focus on certain hotspots of biodiversity.

Thus, a dichotomy has been created between protected and unprotected spaces, or rural-urban areas, without taking into account that much of current biodiversity depends upon human management, and that there is an obvious interdependence between people and biodiversity which is as yet unresolved (Araújo, 2007). The ancient experience of the Mediterranean Basin clearly shows that there are no possible undisturbed "islands of sustainability", because of the importance of the Eco-cultural matrix in which protected areas are embedded.

Today, the ancient Mediterranean experience of adaptability and dynamic landscapes illustrates a lesson that was learned in the past and recently rediscovered (Bengtsson et al. 2003). Rather than isolation or dichotomy, promoted by the typical static strategy based on protected areas; or complete social-economic and territorial homogenization, promoted by the present economic and cultural globalization, promoting a future based on the adapting mosaic scenario necessitates the re-harmonisation of man and nature. This process requires investment in Eco-cultural Capital based on rediscovering the role played by people in managing nature, maintaining local TEK in order to adapt it to unpredictability and change, as well as dynamic conservation mechanisms for avoiding territorial dichotomies and enabling management practices to be adapted to biophysical constraints, and ecosystem services to be considered in the decision-making process in order to avoid mismanagement.

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3.3. Environmental accounting as a management tool in the Mediterranean context: The Spanish economy during the last 20 years.

Pedro L. Lomas, Sergio Álvarez, Marta Rodríguez, Carlos Montes.

Resumen

Aunque la presencia humana es una de las principales características de la identidad Mediterránea desde hace milenios, en las últimas décadas viene siendo muy popular una falsa dialéctica entre conservación y desarrollo socio-económico. Por una parte, se toma como paradigma del desarrollo socio-económico una política basada en el crecimiento; por la otra, como principales herramientas en el desafío de la sostenibilidad se toman las áreas protegidas en el marco de una política de conservación a múltiples escalas. La cuenca Mediterránea es el hábitat de muchas especies únicas y unos de los principales puntos calientes de biodiversidad a escala mundial, y como consecuencia, existe una fuerte política de conservación que se ha desarrollado con el objetivo de proteger sus valores ambientales. Al mismo tiempo, los países mediterráneos se han visto envueltos en la promoción de políticas ligadas a un fuerte y rápido crecimiento económico, que no siempre se han coordinado con las políticas ambientales.

En este artículo, se estudia España como un modelo de este tipo de procesos. Debido a razones de carácter político, tanto las políticas de aceleración del crecimiento económico como las de conservación han sido emprendidas durante los últimos 20-30 años. Como resultado España posee una de las más importantes redes de áreas protegidas de Europa Occidental, y al mismo tiempo ha experimentado una de las más fuertes tasad de crecimiento económico en el contexto Europeo y Mediterráneo durante los años 80 y 90.

En el artículo se estudia una serie histórica de uso de los recursos correspondiente a cinco anualidades dentro del período de los últimos veinte años de política de conservación, así como los efectos que ésta ha tenido sobre la preservación del capital natural. Para esta caracterización de los flujos de servicios de los ecosistemas se utiliza la síntesis eMergética (escrito con “m”). El estudio muestra que España se está transformando en menos auto-suficiente, y en más ineficiente en el uso de los servicios, en términos emergéticos. Una gran parte de la economía española se ha hecho dependiente de la importación de bienes y servicios, y gran parte de la actividad económica se basa en los flujos ligados a los servicios turísticos y la construcción, los que promueven una intensificación en el uso urbano del territorio, y en los impactos ambientales locales, así como de aquellos países que proporcionan las materias primas importadas. La consecuencia inmediata es un desacoplamiento de la economía española de los servicios de los ecosistemas locales y un aumento de la huella ecológica, en términos emergéticos. A pesar del incremento de áreas protegidas en número, área y presupuesto, la sostenibilidad, medida en términos emergéticos, está decreciendo.

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Environmental accounting as a management tool in the Mediterranean context: The Spanish economy during the last 20 years

Pedro L. Lomas*, Sergio Álvarez[1], Marta Rodríguez, Carlos Montes

Laboratorio de Socio-ecosistemas, Dpto. Ecología, c/Darwin, 2 Despacho C-201, Edificio Biología,
Facultad de Ciencias, Universidad Autónoma de Madrid, 28049 Madrid, Spain

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Abstract

Although human presence is one of the main characteristics of the Mediterranean identity since ancient times, a false dialectic between conservation and social–economic development has emerged in recent decades. On the one hand, an economic growth policy is taken as the paradigm of social–economic development; on the other hand, there is a multi-scale conservation policy, in which natural protected areas, as patches of preserved nature, are used as one of the main tools to deal with the challenge of sustainability. The Mediterranean Basin is the habitat of many unique species and one of the 25 main biodiversity hotspots in the world, and as a consequence a strong conservation policy has been used to protect environmental values. At the same time, Mediterranean countries are deeply involved in promoting strong economic growth policies, which are not always compatible with environmental ones. In this paper, Spain has been studied as one model of this situation. Due to political reasons, Spanish economic growth and conservationist policies were pursued together during the last 20 years. As a result, Spain owns one of the largest networks of natural protected areas in Western Europe, and at the same time it has experienced one of the strongest periods of economic growths in the European and Mediterranean context during the 1980s and 1990s. An historical series of resource use in five annual periods in the last 20 years of conservation policy, and the effects on the preservation of natural capital have been investigated by means of the eMergy (spelled with an 'm') synthesis approach, which was used to characterize the flow of environmental services supplied by ecosystems, but not in monetary terms. This study shows that Spain is becoming less self-sufficient and more inefficient in resource use, comprehensively measured in eMergy terms. A large part of Spain's economy depends on imported goods and services, and most economic activities are based on tourist services and associated construction, which promotes intensification in the urban use of the territory and more intense environmental impacts and resource use intensification of those countries supplying the raw materials. The consequence is a decoupling of the Spanish economy from local environmental services and the increase of Ecological footprint of Spain, measured by means of eMergy-based indicators. In spite of the increase in number, area and associated budget of the natural protected areas and other conservation measures, the general sustainability of the nation is decreasing.

Keywords: eMergy synthesis; Spain; Sustainability indicators; Conservation policy

1. Introduction

1.1. Background

The recent millennium ecosystem assessment (MEA) Synthesis Report (MA (Milleninum Ecosystem Assessment), 2005) estimates that one third of the planet that has been altered for production purposes. This report shows that 50% of freshwater from rivers and lakes is eventually used by society, and that human activities produce more biologically available nitrogen than all natural cycles combined. Furthermore, this study estimates that 60% of the 24 great global ecosystems are experiencing degradation, and that extinction rates are increasing from 100 to 1000 times over the average estimated for geological time. In addition, they found that up to 20% of known species in many groups are disappearing. These figures are much

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*Corresponding author. Tel.: +34 914978008; fax: +34 914978001.
E-mail address: pedro.lomas@uam.es (P.L. Lomas).

[1] Present address: Subdirección General de Relaciones Internacionales, Secretaría General Técnica, Ministerio de Medio Ambiente, Plaza de San Juan de la Cruz, s/n. 28071 Madrid, Spain.

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worse than those calculated before MEA (Postel et al., 1996; Vitousek et al., 1986, 1997; Rojstaczer et al., 2001), and turn the ideas of "natural environment" or "wild nature" as isolated areas without human participation into a fantasy. In this context, the concepts of Noosphere (Verdnasky, 1945), a biogeochemical cycling entity dominated by human influences, and Anthropocene (Crutzen and Stoermer, 2000), a new geological era in which main biophysical processes that control global dynamics (ecosphere) are driven by humankind, emerge.

From this perspective, one paradigmatic case is the Mediterranean Basin, where relationships between humans and other (living and non-living) components of ecosystems can be traced to before Neolithic times (Grove and Rackham, 2003), and where many of the original forests had already been used 7000 years Before the Common Era (BCE) (Makhzoumi and Pungetti, 1999). Naveh and Liberman (1993) suggest that we should only speak about cultural landscapes in the Mediterranean context.

In the Mediterranean Basin, 52% of plants, 30.5% of vertebrates, 25% of mammals, 13% of birds, 61% of reptiles and 52% of amphibians are endemic species. Consequently, it is considered as one of the 25 most significant hotspots of biodiversity, paradoxically located in one of the most densely populated areas of the world (Myers et al., 2000; Cincotta et al., 2000). It is generally accepted that this ancient relationship between humanity and nature, which is based on combined exploitation systems (mainly agriculture, forestry and livestock) that adapt human cycles to natural ones reinforcing ecological processes, has promoted biodiversity and long-term sustainability (González Bernáldez, 1991; Pineda and Montalvo, 1995; Schmitz et al., 2001; de Miguel and Gómez-Sal, 2002; García and Montes, 2003).

However, since the 1950s, increases in mechanized farming, population growth and economic globalization have radically changed ancient agricultural, forestry and pastoral practices. Many socio-economic constraints, like agricultural subsidies (mainly European Union Common Agriculture Policy, CAP), rural–urban migration and abandonment of traditional practices and land have affected the historic agro-ecosystems (Grove and Rackham, 2003; Mulligan et al., 2004). These changes are being accelerated by the growth of commercial relations among countries and their socio-economic consequences.

1.2. A case study Spain as a social–ecological system

Spain could be considered a typical case presenting the characteristic pattern described in the previous Section. Because of its location and its geological history, Spain is a land of natural contrasts, especially lithologic (lime, siliceous and clayey soils) and climatic ones (Mediterranean and continental in the central-southern area, oceanic in the north, areas of dry subtropical climate in the south-eastern Spain, and specific climatic conditions on mountainous areas all over the country), which create a great variety of ecosystems, from deserts to Atlantic forests. Because of its history and location as a bridge between Europe and Africa, in the Mediterranean framework, Spain is also a land of social contrasts. With four different official languages (Catalonian, Galician, Castilian/Spanish and Basque, the latter being a non-Romance language) and many dialects, Spain is organised into 17 regions and two autonomous cities, each of them with its own government and institutional framework. Although it is the fifth most populous country in the European Union (EU), and its population density has grown considerably in the last century (from 36.79 inhabitants/km^2 in 1900 to 81.26 inhabitants/km^2 in 2000), Spain has the fourth lowest population density in the EU, so it may validly be considered a relatively rural country in the European context.

Similar to other European countries, many changes have affected traditional exploitation systems in the last decades in Spain. If we use the historical series of official statistics, there has been a loss of cultivated areas (percentage of total area has changed from 40.15% in 1980 to 35.43% in 2002), and a relative increase of irrigated lands (from 13.76% of total cultivated areas in 1980 to 19.35% in 2000). In contrast, Spain has suffered an increase of 2.07% in the item "other types", which includes infrastructures and cities (Ministerio de Agricultura, Pesca y Alimentación (MAPA (Ministerio de Agricultura and Pesca y Alimentación), 1991, 1998, On-line). In fact, road density reached 0.32 km/km^2 in 2001 (Ministerio de Fomento (MFOM (Ministerio de Fomento On-line-a), and road surface will be doubled by 2020 according to the new Infrastructures Plan 2005–2020 (MFOM (Ministerio de Fomento On-line-b). There has also been an increase of 1.65% in forest area, probably because of replacement of croplands by forests, which has been favoured under the CAP to reduce the so-called European Community's agricultural surplus. In addition, energy use is growing (Ministerio de Economía (MINECO), On-line; IEA (International Energy Agency), 2003; 1997), and as a result greenhouse gas emissions have grown 45% from 1990 to 2004, and Spain's emissions are 25.6% above the Kyoto Protocol agreements for the country (European Environment Agency (EEA (European Environment Agency), 2005; Observatorio de la Sostenibilidad en España (OSE (Observatorio de la Sostenibilidad en España), 2005). Furthermore, Spain has been transformed into a country devoted to the services sector (Tamames and Rueda, 2000), especially tourism and commerce. This sector was responsible for 61.2% of Spanish employment and 64% of the gross added value in 1999 (INE (Instituto Nacional de Estadística)), On-line; MINECO, On-line), although it only involved 31% of the working population and accounted for 45% of the Gross Domestic Product (GDP) in 1960 (Cuadrado, 1999). In contrast, during this time industry and agriculture have declined in importance for the Spanish economy (Cuadrado, 1999; Tamames and Rueda, 2000).

In addition, the Spanish economy has created an enormous pressure on aquatic ecosystems to satisfy demand for water in a country where water is relatively scarce. This pressure is the result of a policy based on satisfying demand instead of controlling it (Arrojo, 2001). Therefore, with a consumption of 530 m^3 of water/inhabitant/year (Ministerio de Medio Ambiente (MIMAM (Ministerio de Medio Ambiente), 2000), Spain is one of the highest *per capita* water-consuming in 15 countries of the EU (EU-15). It has the greatest number of dams per inhabitant and per unit area in the world, with more than 1150 large dams (World Commission on Dams (WCD (World Commission on Dams), 2000). Water use has become more intensified, with more than 3 400 000 ha of land under irrigation in recent years (Llamas, 2000). Furthermore, it is estimated that there are more than 75 aquifers that are overexploited or have serious salinization problems, 13 of which have been declared ''provisionally overexploited'' and two ''overexploited'' under the Spanish Water Act (MIMAM (Ministerio de Medio Ambiente), 2000). It is estimated that 60% of Spain's wetlands were already lost at the beginning of the 1990s (Casado and Montes, 1991), and 40% of rivers are polluted or seriously polluted (Prats et al., 2000).

Despite the changes and pressures of the last decades, 80–90% of EU-15 vascular plants can be found in Spain, 1500 of which are endemic in a worldwide context, and more than 500 are exclusively shared with Northern Africa. Spain is also the habitat to approximately 50% of the fauna species in EU-15, with more than 7.5% endemic (MIMAM (Ministerio de Medio Ambiente), 1999). Within the EU context, Spain, among other Mediterranean countries, is probably the region with the highest biological diversity.

Due to political and historical reasons, Spain has dealt with most of the processes of intensive industrialization and transformation into a country dedicated to services sector, common to Western European economies, in the last 20 years. In fact, Spain has received considerable EU funding for territorial cohesion, because a great part of its territory has been considered as a priority area to be supported economically within the EU. For these reasons, Spain probably constitutes one of the best laboratories in the Mediterranean world for assessing the effect of the acceleration of societal growth promoted by globalization, its effects on sustainability and the success of different strategies of environmental management adopted by governments.

1.3. Objectives

The main objectives of this paper are (1) to study patterns in the use of environmental goods and services flowing to the Spanish economy, and changes in these patterns over a historical series of 20 years in Spain, (2) to show the changes in patterns of consumption and trade that have promoted economic globalization in Spain in the past two decades, and (3) to study the success of Spanish natural conservation policies and management during the last 20 years, in relation to the preservation of the natural capital that maintains the Spanish economy.

2. Methods

To deal with trends of resource use in the context of these objectives, within the general framework of Ecological Economics (Daly, 1991; Goodland and Daly, 1996; Costanza, 1997; Costanza et al., 1997; Martínez-Alier, 1999), a biophysical valuation of Spain by means of eMergy synthesis (Odum, 1996; Hau and Bakshi, 2004; Brown and Ulgiati, 2004) has been performed for five annual periods (1984, 1989, 1994, 2000 and 2002).

For the purposes of this study, Spain has been considered as a social–ecological system, SES (Berkes and Folke, 1998), comprised of its territories in the Iberian Peninsula and the Balearic Islands, in the Mediterranean Basin (Fig. 1), with a land area of 498 476 km^2 (IGN (Instituto Geográfico Nacional), 1996), which constitutes the second biggest country in terms of area in the EU, after France. Neither the Canary Islands nor the other African territories of Spain have been studied, because of their peculiar characteristics with respect to the rest of the country (distance, singular eMergy flows, different eMergy sources, etc.). To delimit borders, the continental shelf was defined by the area between 300 m of depth, and was estimated by the Spanish Oceanographic Institute (IEO) staff as 74 037 km^2 (Fig. 1).

From the brief description of Spain in the previous section, a flow diagram (Fig. 2) has been drawn to characterize the Spanish SES as a kind of system picture or macroscopic view (Rosnay, 1979; Brown, 2004), allowing us to model interactions between economic and ecological systems in terms of eMergy flows, using energy symbols from Odum (1994). Symbols have been used in accordance with criteria from Odum (1996) to represent the Spanish environmental window or SES. Under these criteria, symbols are placed on the diagram in order of increasing transformity (a measure of quality in eMergy terms, as defined below), and consequently renewable sources and ecological systems are placed on the left and economic flows and components are placed on the right. An aggregated diagram and three-arm diagrams for each year of the study period are respectively presented in Figs. 3 and 4. These diagrams show explicitly the main input-output flows described in the following sections, linking flows from biogeochemical sources (sun, rain, earth cycle, tides, etc.) to those of social–economic processes (industry, commerce, imports, immigration, etc.) in order to provide environmental and social services to Spanish society.

From the flow diagram of Spain presented in Fig. 2 and the summary of this, presented in Fig. 3, most important flows and overview indexes have been calculated for each year studied with the same methodology given by the example shown in Tables 1(a–c), in order to obtain a view of the Spanish social–ecological system dynamics over 20 years (Table 2). According to the usual eMergy evaluation

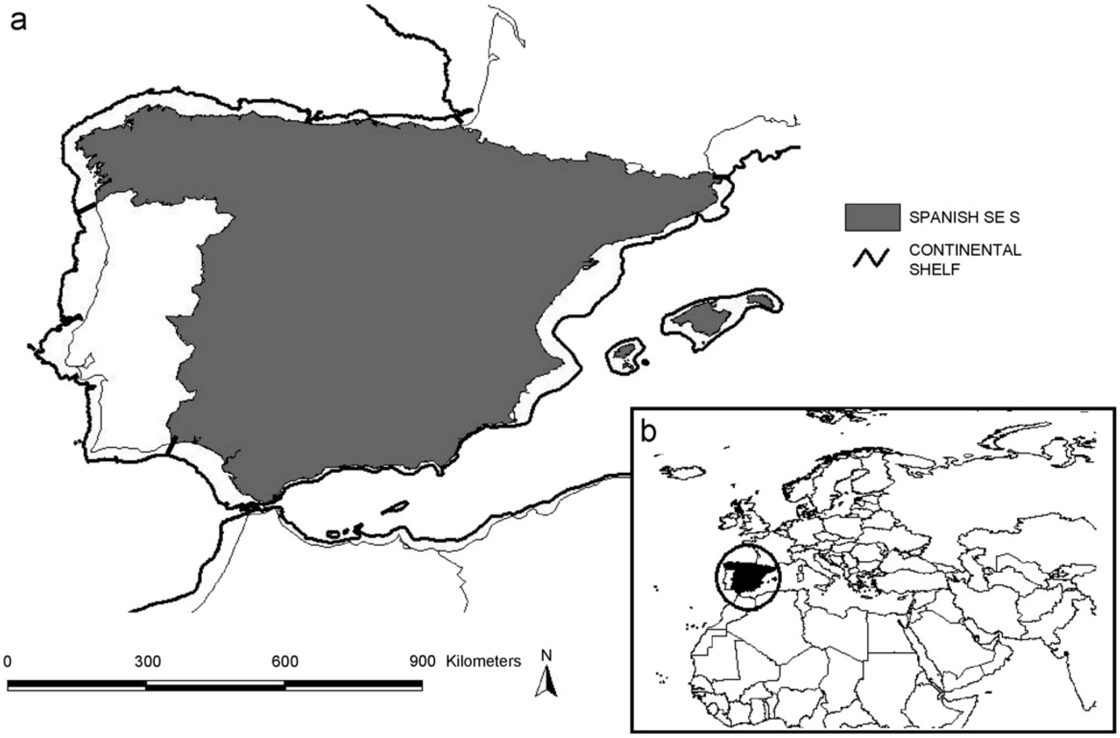

Fig. 1. Spanish social–ecological system in its context: (a) continental Spain and the continental shelf and (b) geographical context within Europe and the Mediterranean Basin.

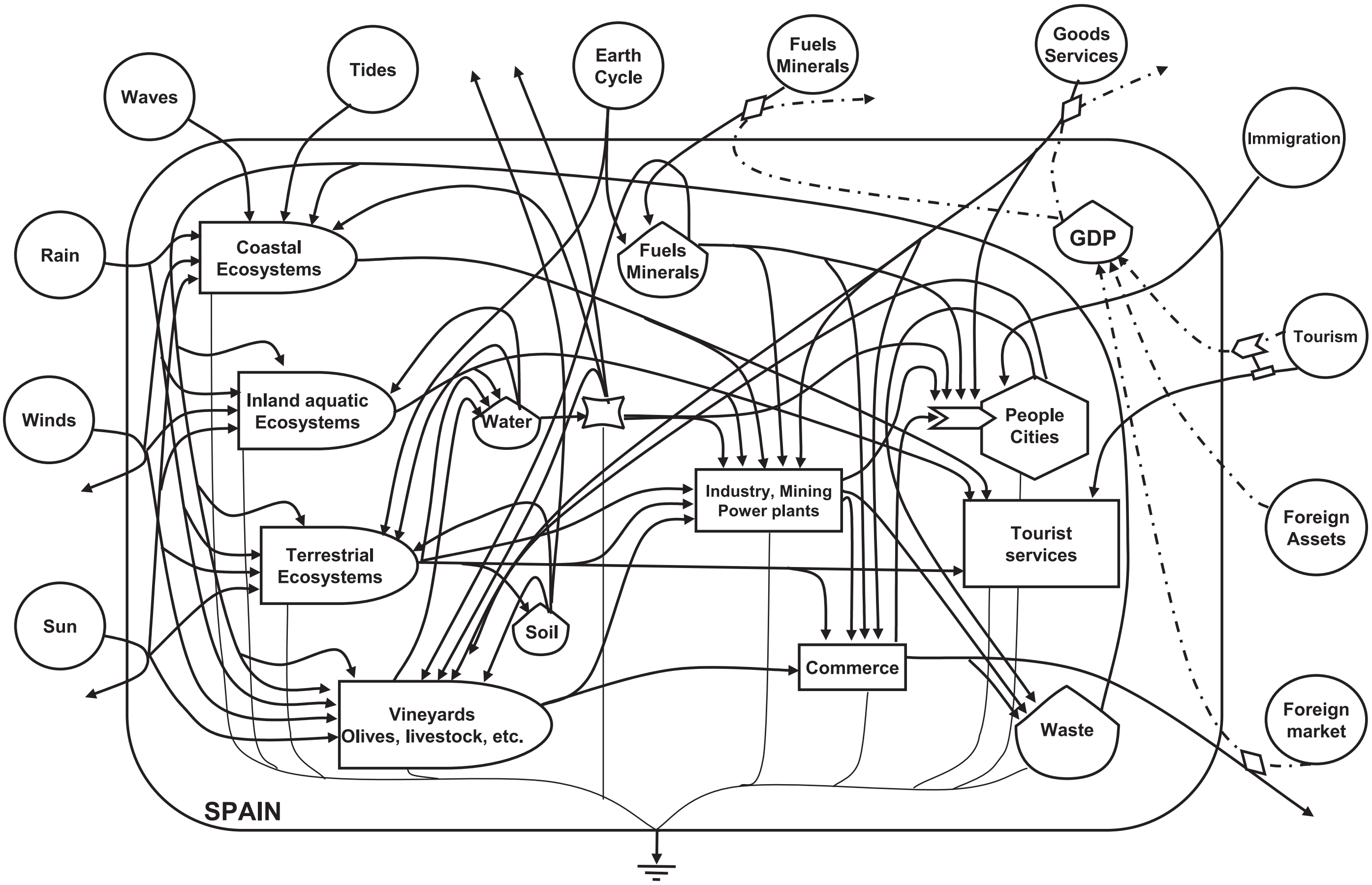

Fig. 2. Emergy flow diagram for Spain.

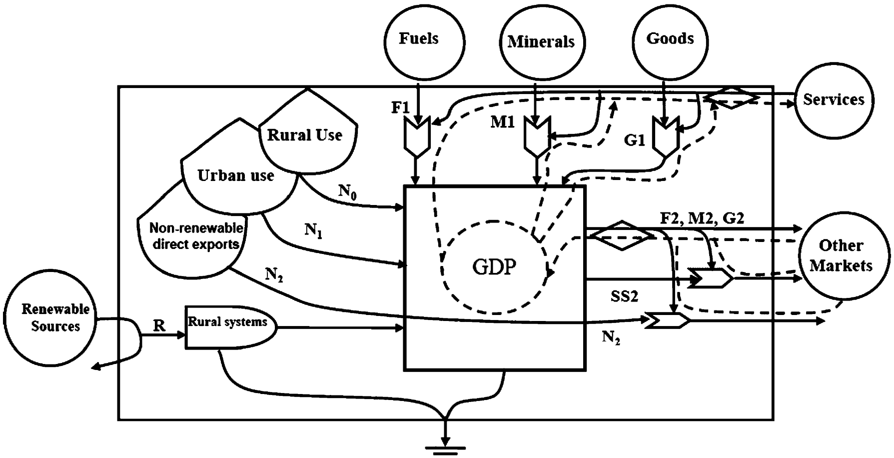

Fig. 3. Summary flow diagram for the main emergy flows in Spain.

procedure (Odum, 1996), the eMergy synthesis of Spain proceeds as follows:

1. Drawing a flow diagram of Spain as a system (following the method established by Odum, 1996; Tilley and Swank, 2003).
2. Preparation of an eMergy evaluation table.
3. Calculation of main flows, storages and unit eMergy values or transformities.
4. Discussion of the performance of main evaluation indicators.

All the transformities used in this work are updated to the new baseline (total contribution of eMergy to global processes = 15.83E + 24 sej/year) recalculated in the year 2000 (Odum et al., 2000) by multiplying unit eMergy values by 1.68 (the ratio of the new baseline between the past one: 15.83/9.44), as it is suggested by Brown and Ulgiati (2004).

In the new baseline framework, under the most accepted criteria in order to avoid double-counting (Odum et al., 2000), the renewable sources flow (*R*) for Spanish social–ecological system has been calculated as the largest inflowing eMergy of renewable ones. To complete our data for average wave height in 1984 and mean tidal range in 1984 and 1989, which were not available, an average among other years has been used. To calculate Real Evapotranspiration (ETa) and runoff rate, an average ETa (67.84% of average annual rainfall) and runoff (32.16% of average annual rainfall) rate calculated for Spain (peninsular and Balearic Islands) for 55 years by MIMAM (Ministerio de Medio Ambiente) (2000) have been used. Taking the Mediterranean nature of Spain into account, mature vegetation forests are assumed to have little net gain or loss of topsoil and it has been considered that harvested lands are net soil-losers. Thus, only the erosion rate in cultivated areas has been used to calculate topsoil energy contributions.

GDP at market prices has been used to calculate the eMergy-money ratios; although the use of Gross National Product (GNP) is very widespread. GDP instead of GNP is used to measure the economic activity within Spain regardless of the producer's nationality, following criteria used by Cialani et al. (2005) in order to avoid problems of measuring economic activity in eMergy terms.

In addition, previous eMergy synthesis data for Italy (Cialani et al., 2005) and a worldwide investigation of national economies (Brown, 2003) are used for comparison with other national economies and, especially, with the Mediterranean and European context of Spain (Appendix A and B).

3. Results

3.1. *Main sources of the Spanish SES*

In accordance with the system picture of Spain (Figs. 2 and 3) and the consequent calculations shown in Tables 1(a–c), main flows introduced to the Spanish social–ecological system (SES) for the studied years are represented by Fig. 5a and summarized in Table 2.

Total eMergy actually used (*U*), as potential investment in eMergy yield of the country, increases with an average of 3.77% annually with a peak in the first period (7.00% annually), except in the period of 1989–1994, in which it decreases 0.65% (Table 2).

Renewable eMergy flow (*R*) introduced to Spain is approximately unchanged at this temporal scale (Fig. 5a), although the Mediterranean nature of Spain is clear in the strong interannual variability of rain, especially in 1994, which was the last drought period of the 20th century in Spain. eMergy from waves, tides and rain (chemical potential) are the largest individual flows among renewable sources for Spain, representing 6.09E + 22, 5.66E + 22, and 4.62E + 22 sej/year, respectively. After these flows, the rank of the natural renewable drivers of the Spanish economy, according to solar emergy flow, was: the earth cycle, solar radiation absorbed, and kinetic energy of wind.

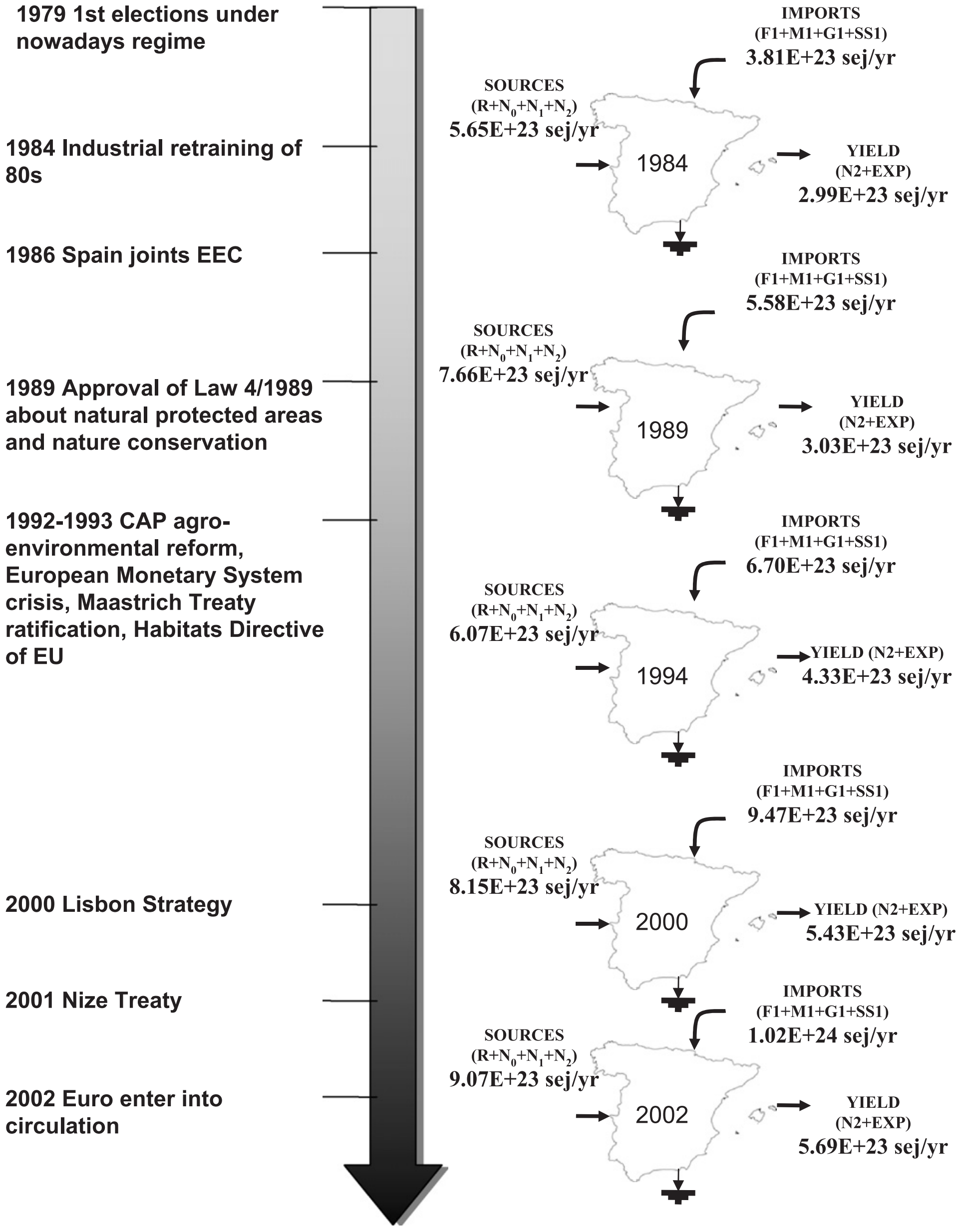

Fig. 4. Summary three arm flow diagram for the main flows in Spain contrasted with some of the main socio-economic events of the decades studied.

Participation of non-renewable eMergy flows from local Spanish sources (*N*) has increased from 5.09E + 23 sej/year in 1984 to 8.47E + 23 sej/year in 2002, although the annual increase rates have been reduced from 7.72% annually in the period 1984–1989 to 6.02% annually in the period 2000–2002 (Fig. 5a). Construction raw materials, like clay, calcium carbonate, sand and gravel are the largest individual *N* flows.

Table 1b lists main imported inputs in terms of eMergy flows (IMP) for 2000 in Spain. IMP eMergy flow has increased from 3.81E + 23 sej/year in 1984 to 1.02E + 24 sej/year in 2002. Oil could be highlighted among the most important imported goods and services eMergy flows, as it involves from 21% to 16% of total eMergy used in 1984 and 2002; worth mentioning are also leather and leather products, textiles, mechanical, transport equipment, and the increasing importance of natural gas and coal. In emergy to money terms, imported goods have become the most important item in this category. Among the export eMergy flows (EXP) could be highlighted petroleum-derived products, minerals and mechanical and transport equipment. In emergy to money terms, eMergy flows related to services exported, in general, and particularly tourism, are increasing as a result of the tourism model introduced in Spain beginning the 1960s. As Table 2 shows, eMergy flow of exports has decreased in relation to IMP in the studied period (IMP/EXP index increases from 1.42 in 1984 to 1.87 in 2002).

The percentage of R involved in U decreases 50% (from 7% to 3%) during the 20 years examined (Fig. 5b), so U is increasingly supported by IMP and N, with a growing role of concentrated eMergy sources (N_1) (concentrated against rural eMergy index grows from 13.64 in 1984 to 29.67 in 2002), and the increase of the relative weight of IMP, exceeding N in 1989–1994 period (Fig. 5a). This increase in IMP results in decreased self-sufficiency (fraction of eMergy actually used derived from home sources decreased from 59% to 46%; Fig. 5b) for Spain, except in the last period, where there is a relative increase of N_1 in U, so self-sufficiency is maintained. In this regard, Spanish dependence on imported energy sources is still increasing strongly, and more than 21% of U is imported oil in 1984 and 16% in 2002, so the purchased (non-free) component of the total economy is becoming more important, supporting the growth of the economy (Fig. 5a).

3.2. *Some factors of scale to understand eMergy indicators*

Taking into account the population factor of scale, the evolution of the potential standard of living in eMergy terms or eMergy use *per capita* shows an increase (Fig. 6a), although the growth rate of this indicator has continuously decreased from 6.69% annually in the 1984–1989 period to 2.68% in the last one, with the exception of the 1994–2000 period, in which it decreases 0.80%.

Taking into account the economic size factor of scale in terms of GDP, the average eMergy which is mobilized per monetary unit or the buying power in the Spanish SES (eMergy to money ratio; EMR) has decreased an average of 2.37% annually throughout the studied period (Fig. 6b), although this indicator experienced an increase of 3.48% annually in the period between 1994 and 2000.

Taking into account the territorial size factor of scale in terms of the Spanish SES area, territorial intensity of the eMergy actually used or Empower Density (flow of eMergy per unit area and time) has increased (except in the recession period in 1989–1994) in absolute terms, at an average annual rate of 3.77% over the whole period, but the annual growth rate within periods has decreased from the 7% annually in 1984–1989 period to 3.23% in 2000–2002 (Fig. 7c). If we consider that the Spanish economy is increasingly dependent on imports and non-renewable sources, territorial intensity of eMergy use depends mainly on the non-renewable fraction of Empower Density (96–97% of total Empower Density is non-renewable; Table 2), especially the imported fraction.

3.3. *Interaction of Spanish SES with other systems*

If the eMergy flow associated with imports and its significance was taken into proper account, the issue of trade would become crucial for Spain from an eMergy point of view. The most important component in the flow of purchased goods and services is the one for fuels and electricity.

An important aspect of trade is highlighted by the EMergy Exchange Ratio (EER, i.e. the ratio of EMR of Spain to EMRs of trade partner countries or the global economy), which shows the relative advantages and disadvantages for Spain in its international trade of products and resources. The EER for Spain with respect to the global economy has increased from 0.33 to 0.64 in the studied period, with a decline between 1994 and 2000 (Appendix B).

Furthermore, we can use macroeconomic value or eMergy price (emprice) to study the amount of eMergy received per monetary unit invested. As we can see in Tables 1(a–c), the highest values in renewable sources are related to waves and tides, with 1.97E+10 em\$/year and 1.83 em\$/year in the 2000, respectively; in non-renewable indigenous sources, those of calcium carbonate and sand and gravel, with 1.06E+11 em\$/year and 4.43E+10 em\$/year in 2000, respectively; oil and petroleum-derived products in imports, with 9.71E+10 em\$/year; and textiles and mechanical and transport equipment in exports, with 2.36E+10 and 2.62E+10 em\$/year, respectively.

3.4. *The appropriation of eMergy by the Spanish SES*

To get information about the appropriation of resources by the Spanish system (Raugei et al., 2004), a comparison of U with emergy purchased by the national economy or eMergy yield ratio (EYR; Fig. 7a) has been used. The EYR decreases an average of 0.90% annually (except in the last period 2000–2002, in which it increases 0.52% annually) because Spain shows a growing pattern of energy and matter consumption, which is imported to produce goods and services, and this increase is higher than the growth experienced in the use of N and R.

Regarding the non-renewable and purchased resources used to produce the yield in relation to these renewable sources, the environmental loading ratio (ELR; Fig. 7a) is used to obtain information about economic pressure on ecosystems and their functions as suppliers of environmental services to society. The ELR increases during the whole period of the study (except in the recession period of 1989–1994), especially in the first part of 1984–1989 (with a growth rate of more than 6% annually) and 1994–2000 (with a growth rate of 5.14% annually).

Both indexes can be combined to evaluate the competence of transformation processes (the ability of foreign and national economic investments to exploit local resources or the return on eMergy investment) in relation to the pressure produced on the environment (relative weight of non-renewable and purchased sources in U), which is called the eMergy sustainability index or ESI (Brown and Ulgiati, 1997; Ulgiati and Brown, 1998). Under a local social–ecological perspective, ESI decreases continuously (Fig. 7b), 5.15% annually in the period 1984–1989 and 3.99% in the 1994–2000 period, because the

Table 1a
Emergy flows supporting Spanish social–ecological system in 2000

		Unit	Amount 2000 (unit/year)	Trans. (sej/unit)	Ref. trans.*	Emergy 2000 (sej/year)	Macroeconomic value 2000 (em$/year)
Renewable inputs							
1	Sunlight[a]	J/year	2.55E+21	1.00E+00	0	2.55E+21	8.24E+08
2	Rain (chemical potential)[b]	J/year	1.11E+18	3.06E+04	A	3.40E+22	1.10E+10
3	Rain (geopotential)[c]	J/year	6.91E+17	1.76E+04	A	1.22E+22	3.93E+09
4	Wind kinetic energy[d]	J/year	3.10E+17	2.52E+03	A	7.80E+20	2.52E+08
5	Waves[e]	J/year	1.18E+18	5.14E+04	A	6.09E+22	1.97E+10
6	Tides[f]	J/year	7.66E+17	7.39E+04	A	5.66E+22	1.83E+10
7	Earth cycle[g]	J/year	4.98E+17	1.20E+04	A	5.98E+21	1.93E+09
Indigenous non-renewable inputs							
8	Oil[h]	J/year	9.63E+15	9.06E+04	A	8.72E+20	2.82E+08
9	Coal[i]	J/year	3.21E+17	6.71E+04	A	2.15E+22	6.95E+09
10	Natural gas[j]	J/year	6.20E+15	8.05E+04	A	4.99E+20	1.61E+08
11	Iron[k]	g/year	7.51E+10	1.68E+09	A	1.26E+20	4.08E+07
12	Gold[k]	g/year	4.32E+06	7.39E+14	D	3.19E+21	1.03E+09
13	Silver[k]	g/year	1.15E+08	5.04E+14	D	5.77E+22	1.87E+10
14	Copper[k]	g/year	2.44E+10	3.36E+09	E	8.18E+19	2.65E+07
15	Feldspar[k]	g/year	4.78E+11	1.68E+09	A	8.03E+20	2.60E+08
16	Zinc[k]	g/year	2.02E+11	1.68E+09	A	3.40E+20	1.10E+08
17	Lead[k]	g/year	5.17E+10	1.68E+09	A	8.68E+19	2.81E+07
18	Salt rock[k]	g/year	3.87E+12	1.68E+09	A	6.50E+21	2.10E+09
19	Sulphur[k]	g/year	7.70E+11	1.68E+09	A	1.29E+21	4.18E+08
20	Glauberite y Thernardite[k]	g/year	8.34E+11	1.68E+09	A	1.40E+21	4.53E+08
21	Fluorite[k]	g/year	1.35E+11	1.68E+09	A	2.27E+20	7.33E+07
22	Magnesite[k]	g/year	2.21E+11	1.68E+09	A	3.71E+20	1.20E+08
23	Pumice[k]	g/year	7.62E+11	7.56E+09	A	5.76E+21	1.86E+09
24	Talc[k]	g/year	1.15E+11	1.68E+09	A	1.93E+20	6.22E+07
25	Quartz and silica sand[k]	g/year	6.59E+12	1.68E+09	A	1.11E+22	3.58E+09
26	Calcium carbonate[k]	g/year	1.95E+14	1.68E+09	A	3.28E+23	1.06E+11
27	Potash[k]	g/year	8.70E+11	1.68E+09	A	1.46E+21	4.72E+08
28	Barite[k]	g/year	3.27E+10	1.68E+09	A	5.49E+19	1.77E+07
29	Sand and gravel[k]	g/year	8.17E+13	1.68E+09	A	1.37E+23	4.43E+10
30	Clay[k]	g/year	4.33E+13	1.68E+09	A	7.27E+22	2.35E+10
31	Gypsum[k]	g/year	9.93E+12	1.68E+09	A	1.67E+22	5.39E+09
32	Quartzite[k]	g/year	2.13E+12	1.68E+09	A	3.58E+21	1.16E+09
33	Dolomite[k]	g/year	8.75E+12	1.68E+09	A	1.47E+22	4.75E+09
34	Ophite and porphyry[k]	g/year	4.74E+12	2.44E+09	A	1.15E+22	3.73E+09
35	Serpentine[k]	g/year	7.39E+11	1.68E+09	A	1.24E+21	4.01E+08
36	Marble[k]	g/year	3.66E+12	2.44E+09	A	8.92E+21	2.88E+09
37	Granite[k]	g/year	1.96E+13	8.40E+08	A	1.65E+22	5.32E+09

Table 1a (*continued*)

		Unit	Amount 2000 (unit/year)	Trans. (sej/unit)	Ref. trans.*	Emergy 2000 (sej/year)	Macroeconomic value 2000 (em$/year)
38	Slate[k]	g/year	2.27E+12	1.68E+09	A	3.82E+21	1.23E+09
39	Net topsoil loss[l]	J/year	1.25E+16	1.05E+05	A	1.31E+21	4.22E+08

*References for transformities (Tables 1(a–c)):

0. Solar transformity is 1 sej J−1 by definition.

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E. Brown, M. T., Ulgiati, S., 2004. EMergy analysis and environmental accounting. Encyclopedia of Energy 2, 329–354.

F. This study.

Calculations:

[a] *Sunlight*: Continental area = 498 476 km^2 (IGN, 1996), continental shelf area = 74 037 km^2 (IEO staff), average insolation = 5 704 091.20 kJ/m^2/año (INM (Instituto Nacional de Meteorología), 2001, 2002, continental albedo = 0.35, shelf continental albedo = 0.2 (Henning, 1989), Energy = (Area)(Average insolation)(1−Albedo) = (498 476 km^2)(10E+6 m^2/km^2)(5 704 091.20 kJ/m^2/year)(10E+3 kJ/J)(1−0.35) + (74 037 km^2)(10E+6 m^2/km^2)(5 704 091.20 kJ/m^2/año)(103 kJ/J)(1−0.2) = 2.55E+21 J/year.

[b] *Rain* (*chemical potential*): Continental area = 498 476 km^2 (IGN, 1996), average rain = 0.67 m (INM, 2001, 2002), ETa (67.84% of rainfall; MIMAM, 2000) = 0.45 m, Gibb's free energy of rainfall (G) = 4.94 J/g (Odum, 1996), rain water density = 1.00E+3 kg/m^3, Energy = (Area)(ETa)(G)(Rain water density) = (498 476 km^2)(10E+6 m^2/km^2)(0.45 m)(4.94 J/g)(1.00E+3 kg/m^3)(1.00E+3 g/kg) = 1.11E+18 J/year.

[c] *Rain* (*geopotential*): Continental area = 498 476 km^2 (IGN, 1996), average rain = 0.67 m (INM, 2001, 2002), runoff (32.16% of rainfall; MIMAM, 2000) = 0.21 m, average elevation = 660 m, rain water density = 1.00E+3 kg/m^3, $g = 9.8$ m/s^2, Energy = (Area)(Runoff)(Rain water density)(Average elevation)(g) = (498 476 km^2)(10E+6 m^2/km^2)(0.21 m)(1.00E+3 kg/m^3) (660 m)(9.8 m/s^2) = 6.91E+17 J/year.

[d] *Wind* (*kinetic energy*): Wind (kinetic energy) estimated from EU/EWEA (European Commission-DG TREN/European Wind Energy Association), 2003 as an annual technical onshore potential of wind energy.

[e] *Waves*: component of length parallel to front wave = 2340 (our estimate from IGN, 1996), sea water density = 1027 kg/m^3, $g = 9.8$ m/s^2, wave height (H_s) = 1.29 m (OAPEstado, On-line), average water depth in the breaker zone (h) = 6 m (Odum and Odum, 1983), Energy = (component parallel to front wave)(1/8)(sea water density)$(H_s)^2(g \times h)$1/2 = (2340 km)(1.00E+3 m/km)(1/8)(1027 kg/m^3)(1.29)2(9.8 m/s^2 × 6 m)1/2(3.15E+7 s/year) = 1.18E+18 J/year.

[f] *Tides*: Continental shelf area = 74 037 km^2 (IEO staff), Tides/year = 730 (2/day), mean tidal range = 167.80 cm (OAPEstado, On-line), sea water density = 1027 kg/m^3, $g = 9.8$ m/s^2, Energy = (Area)(1/2)(Annual tides)(Mean tidal range)2(Sea water density)(g) = (74 037 km^2) (10E+6 m^2/km^2)(1/2)(730)(1.68 m)^2(1027 kg/m^3)(9.8 m/s^2) = 7.66E+17 J/year.

[g] *Earth cycle*: Continental area = 498 476 km^2 (IGN, 1996), heat flow estimated from Odum (1996) = 1.00E+6 J/m^2/year, Energy = (Area)(Heat flow) = (498 476 km^2)(10E+6 m^2/km^2)(1.00E+6 J/m^2/year) = 4.98E+17 J/year.

[h] *Oil*: 2.30E+5 toe (IEA, 2003), Energy = (toe)(1E+7 kcal/toe)(4186 J/kcal) = 9.63E+15 J/year.

[i] *Coal*: 7.66E+6 toe (IEA, 2003), Energy = (toe)(1E+7 kcal/toe)(4186 J/kcal) = 3.21E+17 J/year.

[j] *Natural gas*: 1.48E+5 toe (EUROSTAT, On-line), Energy = (toe)(1E+7 kcal/toe)(4186 J/kcal) = 6.20E+15 J/year.

[k] Iron, gold, silver, copper, feldspar, zinc, lead, salt rock, sulphur, glauberite and thernardite, fluorite, magnesite, pumice, talc, quartz and silica sand, calcium carbonate, potash, barite, sand and gravel, clay, gypsum, quartzite, dolomite, ophite and porphyry, serpentine, marble, granite and slate extraction from IGME (Instituto Geológico y Minero de España).

[l] *Net topsoil loss*: Farmed area = 1.83E+5 km^2 (MAPA, On-line), erosion rate = 150.5 Tm/km^2 (Soto, 1990; Cerdá, 2001), % organic matter in soil = 0.02 (Porta et al., 1994), energy = (Farmed area)(Erosion rate)(% Organic matter in soil)(Energy from organic matter)(4186 J/kcal) = (1.83E+5 km^2)(150.5 Tm/km^2)(1E+6 g/Tm)(0.02)(5 kcal/g)(4186 J/kcal) = 1.25E+16 J/year.

Table 1b
Emergy imports for Spanish social–ecological system in 2000

		Unit	Amount 2000 (unit/year)	Trans. (sej/unit)	Ref. trans*	Emergy 2000 (sej/year)	Macroeconomic value 2000 (em$/year)
40	Oil and petroleum-derived products[a]	J/year	3.32E+18	9.06E+04	A	3.00E+23	9.43E+10
41	Coal[b]	J/year	5.56E+17	6.71E+04	A	3.73E+22	1.17E+10
42	Natural gas[c]	J/year	6.47E+17	8.05E+04	A	5.21E+22	1.64E+10
43	Electricity[d]	J/year	4.44E+16	3.36E+05	A	1.49E+22	4.68E+09
44	Agriculture and forest products[e]	J/year	4.51E+16	1.75E+05	A	7.88E+21	2.48E+09
45	Livestock and products[f]	J/year	4.85E+15	5.33E+06	A	2.58E+22	8.11E+09
46	Food industry products[g]	g/year	7.64E+12	3.36E+05	A	2.57E+18	8.06E+05
47	Fishery products[h]	J/year	5.44E+15	3.36E+06	A	1.83E+22	5.74E+09
48	Metallic minerals[g]	g/year	1.14E+13	1.68E+09	A	1.92E+22	6.01E+09
49	Non-metallic minerals[g]	g/year	1.20E+13	1.68E+09	A	2.02E+22	6.34E+09
50	Steel and pig iron[g]	g/year	1.79E+13	3.69E+09	B	6.61E+22	2.08E+10
51	Metallic minerals (products/alloys)[g]	g/year	1.27E+12	1.68E+09	A	2.13E+21	6.69E+08
52	Mechanical and transport equipment[g]	g/year	7.03E+12	1.13E+10	A	7.91E+22	2.49E+10
53	Industrial minerals[g]	g/year	1.75E+12	1.68E+09	A	2.94E+21	9.23E+08
54	Leather and products[i]	J/year	4.47E+15	1.44E+07	A	6.46E+22	2.03E+10
55	Textiles[j]	J/year	1.91E+16	6.38E+06	A	1.22E+23	3.83E+10
56	Wood and products[k]	J/year	9.19E+16	5.86E+04	A	5.39E+21	1.69E+09
57	Paper[g]	g/year	5.33E+12	6.55E+09	A	3.49E+22	1.10E+10
58	Chemicals[g]	g/year	1.39E+13	6.38E+08	A	8.89E+21	2.79E+09
59	Rubber[g]	g/year	8.85E+11	7.22E+09	A	6.39E+21	2.01E+09
60	Total goods associated to imports[l]	$	1.51E+11	1.85E+12	C	2.80E+23	8.80E+10
61	Total services associated to imports (without tourism)[l]	$	2.60E+10	1.85E+12	C	4.81E+22	1.51E+10
62	Total money associated to tourism services imports[l]	$	5.51E+09	1.85E+12	C	1.02E+22	3.20E+09

*See footnotes in Table 1a.

[a] *Oil and petroleum-derived products*: 7.92E+7 toe (IEA, 2003), energy = (toe)(1.00E+7 kcal/toe)(4186 J/kcal) = (7.92E+7 toe)(1.00E+7 kcal/toe)(4186 J/kcal) = 3.32E+18 J/year.

[b] *Coal*: 1.33E+7 toe (IEA, 2003), Energy = (toe)(1.00E+7 kcal/toe)(4186 J/kcal) = (1.33E+7 toe) (1.00E+7 kcal/toe)(4186 J/kcal) = 5.56E+17 J/year.

[c] *Natural gas*: 1.55E+7 toe (IEA, 2003), energy = (toe)(1.00E+7 kcal/toe)(4186 J/kcal) = (1.55E+7 toe) (1.00E+7 kcal/toe)(4186 J/kcal) = 6.47E+17 J/year.

[d] *Electricity*: 1.06E+6 toe (IEA, 2003), energy = (toe)(1.00E+7 kcal/toe)(4186 J/kcal) = (1.06E+6 toe) (1.00E+7 kcal/toe)(4186 J/kcal) = 4.44E+16 J/year.

[e] *Agriculture and forest products*: 1.54E+13 g (AEAT, On-line), energy = (1.54E+13 g)(0.20)(3.5 kcal/g)(4186 J/kcal) = 4.51E+16 J/year.

[f] *Livestock and products*: 1.05E+12 g (AEAT, On-line), energy = (1.05E+12 g)(0.22)(5.0 kcal/g)(4186 J/kcal) = 4.85E+15 J/year.

[h] *Fishery products*: 1.18E+12 g (AEAT, On-line), energy = (1.18E+12 g)(0.22)(5.0 kcal/g)(0.22)(5.0 kcal/g)(4186 J/kcal) = 5.44E+15 J/year.

[i] *Leather and products*: 2.83E+11 g (AEAT, On-line), energy = (matter)(15 800 J/g) = (2.83E+11 g) (15 800 J/g) = 4.47E+15 J/year.

[j] *Textiles*: 1.21E+12 g (AEAT, On-line), Energy = (matter)(15 800 J/g) = (1.21E+12 g) (15 800 J/g) = 1.91E+16 J/year.

[k] *Woods and products*: 6.10E+12 g (AEAT, On-line), Energy = (matter)(15 800 J/g) = (6.10E+12 g) (15 800 J/g) = 9.19E+16 J/year.

[g] Food industry products, metallic minerals, non-metallic minerals, steel and pig iron, metallic minerals (products and alloys), mechanical and transport equipment, industrial minerals, paper, chemicals and rubber (AEAT, On-line).

[l] Total goods associated to imports, total services associated to imports (without tourism), total money associated to tourism from BDE (On-line-a).

relative importance of the flow of renewable eMergy sources is reduced.

3.5. Carrying capacity of the Spanish SES

In eMergy terms, carrying capacity may have two main approaches (Fig. 8): a people-based one (more similar to the classical concept of carrying capacity), linked to number of people supported by eMergy used (Odum, 1996; Campbell, 1998), and an area-based one (similar to ecological footprint), associated to support area needed to maintain the standard of living of people (in terms of eMergy use *per capita*) (Brown and Ulgiati, 2001). These two approaches could be applied to both "only renewable" and "developed" scenarios. The renewable scenario would be a lower limit, based only on renewable flows, and the

Table 1c
Emergy exports and selected products for Spanish social–ecological system in 2000

		Unit	Amount 2000 (unit/year)	Trans. (sej/unit)	Ref. Trans.*	Emergy 2000 (sej/year)	Macroeconomic value 2000 (em$/year)
Exports							
63	Petroleum-derived products[a]	J/year	3.17E+17	9.06E+04	A	2.87E+22	9.02E+09
64	Coal[b]	J/year	2.26E+16	6.71E+04	A	1.52E+21	4.76E+08
65	Electricity[c]	J/year	2.58E+16	3.36E+05	A	8.68E+21	2.73E+09
66	Agriculture and forest products[d]	J/year	3.42E+16	1.75E+05	A	5.98E+21	1.88E+09
67	Livestock and products[e]	J/year	2.97E+15	5.33E+06	A	1.58E+22	4.97E+09
68	Food industry products[f]	g/year	5.35E+12	3.36E+05	A	1.80E+18	5.65E+05
69	Fishery products[g]	J/year	3.07E+15	3.36E+06	A	1.03E+22	3.24E+09
70	Metallic minerals[f]	g/year	9.93E+11	1.68E+09	A	1.67E+21	5.24E+08
71	Non-metallic minerals[f]	g/year	1.27E+13	1.68E+09	A	2.14E+22	6.71E+09
72	Steel and pig iron[f]	g/year	7.50E+12	3.69E+09	B	2.77E+22	8.69E+09
73	Metallic minerals (products/alloys)[f]	g/year	8.80E+11	1.68E+09	A	1.48E+21	4.64E+08
74	Mechanical and transport equipment[f]	g/year	7.21E+12	1.13E+10	A	8.12E+22	2.55E+10
75	Industrial minerals[f]	g/year	8.00E+12	1.68E+09	A	1.34E+22	4.22E+09
76	Leather and products[h]	J/year	2.12E+15	1.44E+07	A	3.06E+22	9.61E+09
77	Textiles[i]	J/year	1.14E+16	6.38E+06	A	7.30E+22	2.29E+10
78	Wood and products[j]	J/year	1.96E+16	5.86E+04	A	1.15E+21	3.61E+08
79	Paper[f]	g/year	2.79E+12	6.55E+09	A	1.83E+22	5.74E+09
80	Chemicals[f]	g/year	9.11E+12	6.38E+08	A	5.82E+21	1.83E+09
81	Rubber[f]	g/year	6.65E+11	7.22E+09	A	4.80E+21	1.51E+09
82	Total goods associated to exports[k]	$	1.17E+11	3.09E+12	F	3.61E+23	—
83	Total services associated to exports (without tourism)[k]	$	2.28E+10	3.09E+12	F	7.06E+22	—
84	Total money associated to tourism services exports[k]	$	3.12E+10	3.09E+12	F	9.66E+22	—
Selected products							
85	Population 2000[l]	Inhabitants	3.99E+7	4.35E+16	F	1.73E+24	—
86	GDP 2000[m]	$	5.62E+11	3.09E+12	F	1.73E+24	—

*See footnotes in Table 1a.

[a] *Petroleum-derived products*: 7.57E+6 toe (IEA, 2003), Energy = (toe)(1.00E+7 kcal/toe)(4186 J/kcal) = (7.57E+6 toe)(1.00E+7 kcal/toe)(4186 J/kcal) = 3.17E+17 J/year.

[b] *Coal*: 5.40E+5 toe (IEA, 2003), Energy = (toe)(1.00E+7 kcal/toe)(4186 J/kcal) = (5.40E+7 toe) (1.00E+7 kcal/toe)(4186 J/kcal) = 2.26E+16 J/year.

[c] *Electricity*: 6.73E+5 toe (IEA, 2003), Energy = (toe)(1.00E+7 kcal/toe)(4186 J/kcal) = (6.73E+5 toe) (1.00E+7 kcal/toe)(4186 J/kcal) = 2.82E+16 J/year.

[d] *Agriculture and forest products*: 1.17E+13 g (AEAT, On-line), Energy = (1.17E+13 g)(0.20)(3.5 kcal/g)(4186 J/kcal) = 3.42E+16 J/year.

[e] *Livestock and products*: 6.46E+11 g (AEAT, On-line), Energy = (6.46E+11 g)(0.22)(5.0 kcal/g)(4186 J/kcal) = 2.97E+15 J/year.

[g] *Fishery products*: 6.67E+11 g (AEAT, On-line), Energy = (6.67E+11 g)(0.22)(5.0 kcal/g)(0.22)(5.0 kcal/g)(4186 J/kcal) = 3.07E+15 J/year.

[h] *Leather and products*: 1.34E+11 g (AEAT, On-line), Energy = (matter)(15 800 J/g) = (1.34E+11 g)(15 800 J/g) = 2.12E+15 J/year.

[i] *Textiles*: 7.24E+11 g (AEAT, On-line), Energy = (matter)(15 800 J/g) = (7.24E+11 g)(15 800 J/g) = 1.14E+16 J/year.

[j] *Woods and products*: 1.30E+12 g (AEAT, On-line), Energy = (matter)(15 800 J/g) = (1.30E+12 g) (15 800 J/g) = 1.96E+16 J/year.

[f] Food industry products, metallic minerals, non-metallic minerals, steel and pig iron, metallic minerals (products and alloys), mechanical and transport equipment, industrial minerals, paper, chemicals and rubber (AEAT, On-line).

[k] Total goods associated to exports, Total services associated to exports (without tourism), Total money associated to tourism from BDE (Banco de España), 2006.

[l] Population from INE (On-line).

[m] GDP from UNSD (On-line).

developed scenario would be an upper limit, based on actual conditions.

If a people-based approach to renewable carrying capacity for Spain is employed, the population that could be supported only with renewable sources shows a decline of 50%, shifting from values of 6% to 3% of the actual population, caused by the relative decrease in the use of renewable eMergy flows in relation to local non-renewable or imported flows.

When using the people-based approach for developed carrying capacity, Spain is considered embedded in the European or the Mediterranean contexts. The Mediterranean context implies the use of the traditional ecological knowledge accumulated during centuries of adaptive

Table 2
Comparison of main emergy indexes and flows for time series emergy synthesis of Spain

No.	Flow/index	Expression	1984	1989	1994	2000	2002	Units
1	Renewable sources used	R	6.09E+22	6.28E+22	5.90E+22	6.09E+23	6.09E+23	Sej/year
2	Non-renewable indigenous sources	N	5.09E+23	7.05E+23	5.49E+23	7.55E+23	8.47E+23	Sej/year
	Dispersed rural sources	N_0	1.47E+21	1.45E+21	1.31E+21	1.31E+21	1.28E+21	Sej/year
	Concentrated used	N_1	4.76E+23	6.84E+23	5.25E+23	7.30E+23	8.22E+23	Sej/year
	Exported without use	N_2	3.11E+22	2.00E+22	2.26E+22	2.46E+22	2.27E+22	Sej/year
3	Imported emergy	IMP	3.81E+23	5.58E+23	6.70E+23	9.47E+23	1.02E+24	Sej/year
	Fuels and electricity	F1	2.19E+23	2.63E+23	3.00E+23	4.05E+23	4.28E+23	Sej/year
	Minerals	M1	4.21E+22	5.48E+22	6.48E+22	1.08E+23	1.16E+23	Sej/year
	Goods (without fuels and electricity)	G1	9.85E+22	2.00E+23	2.68E+23	3.76E+23	4.10E+23	Sej/year
	Services (without tourism)	SS1	2.03E+22	3.52E+22	2.90E+22	4.81E+22	5.68E+22	Sej/year
	Touristic services	P1E3	1.54E+21	5.70E+21	7.63E+21	1.02E+22	1.23E+22	Sej/year
4	Exported emergy	EXP	2.68E+23	2.83E+23	4.10E+23	5.19E+23	5.46E+23	Sej/year
	Fuels and electricity	F2	5.17E+22	4.79E+22	5.03E+22	3.89E+22	3.34E+22	Sej/year
	Minerals	M2	5.80E+22	3.32E+22	4.85E+22	5.22E+22	5.07E+22	Sej/year
	Goods (without fuels and electricity)	G2	6.40E+22	1.11E+23	1.74E+23	2.60E+23	2.80E+23	Sej/year
	Services (without tourism)	SS2	5.11E+22	3.76E+22	8.45E+22	7.06E+22	8.40E+22	Sej/year
	Touristic services	P1E2	4.34E+22	5.39E+22	5.30E+22	9.66E+22	9.78E+22	Sej/year
5	Total emergy available	$R+N+\text{IMP}$	9.50E+24	1.33E+24	1.28E+24	1.76E+24	1.93E+24	Sej/year
	Total emergy actually used	$U=R+N+\text{IMP}-N_2$	9.19E+23	1.31E+24	1.25E+24	1.74E+24	1.91E+24	Sej/year
6	Economic component of emergy used	$U-R$	8.58E+23	1.24E+24	1.20E+24	1.68E+24	1.85E+24	Sej/year
7	Fraction of use derived from indigenous sources	$(R+N_0+N_1)/U$	0.59	0.57	0.47	0.46	0.46	—
8	Fraction of use that is renewable	R/U	0.07	0.05	0.05	0.04	0.03	—
9	Fraction of use that is free	$(R+N_0)/U$	0.07	0.05	0.05	0.04	0.03	—
10	Fraction of use that is imported	IMP/U	0.41	0.43	0.53	0.54	0.54	—
11	Imports minus exports	IMP−EXP	1.13E+23	2.75E+23	2.59E+23	4.28E+23	4.76E+23	Sej/year
12	Imports/exports	IMP/EXP	1.42	1.97	1.63	1.83	1.87	—
13	Ration of concentrated to rural	$(U-R-N_0)/(R+N_0)$	13.74	19.32	19.79	26.95	29.67	—
14	Emergy use *per capita*	U/population	2.40E+16	3.37E+16	3.20E+16	4.35E+16	4.70E+16	Sej/people/year
15	Fraction of use that is electrical	Electrical emergy/U	0.20	0.22	0.23	0.20	0.18	—
16	Fuels *per capita*	Fuels/population	6.77E+15	7.65E+15	8.12E+15	9.58E+15	1.05E+16	Sej/people/year
17	Population	—	3.83E+07	3.88E+07	3.92E+07	3.99E+07	4.05E+07	people
18a	Empower density	U/Area	1.84E+12	2.62E+12	2.52E+12	3.49E+12	3.83E+12	Sej/m^2/year
18b	Non-renewable empower density	$(\text{IMP}+N)$/Area	1.78E+12	2.53E+12	2.44E+12	3.41E+12	3.75E+12	Sej/m^2/year
19	Emergy investment ratio (EIR)	$\text{IMP}/(R+N_0+N_1)$	0.71	0.75	1.14	1.20	1.16	—
20	Emergy yield ratio (EYR)	1+1/EIR	2.41	2.34	1.87	1.84	1.87	—
21	Environmental loading ratio (ELR)	$(U-R)/R$	14.10	19.79	20.26	27.55	30.32	—
22	Emergy sustainability index (ESI)	EYR/ELR	0.17	0.12	0.09	0.07	0.06	—
23	Emergy exchange ratio (EER)	EMRg/EMR	0.33	0.56	0.74	0.60	0.64	—
24	Gross DOMESTIC product at market prices (GDP)	GDP	1.64E+11	3.94E+11	5.04E+11	5.62E+11	6.55E+11	$
25	Emergy to money ratio (EMR)	$P_1=U/\text{GDP}$	5.62E+12	3.31E+12	2.49E+12	3.09E+12	2.91E+12	Sej/$
26	Global emergy to money ratio	P_2	1.85E+12	1.85E+12	1.85E+12	1.85E+12	1.85E+12	Sej/$
27	Renewable carrying capacity	$(R/U)\times$ population	2.45E+06	1.87E+06	1.84E+06	1.40E+06	1.29E+06	People
28	Developed carrying capacity at European standard of living	ESL $(R/U)\times$ population	6.09E+07	4.48E+07	4.43E+07	3.36E+07	3.11E+07	People
29	Developed carrying capacity at Mediterranean standard of living	MSL $(R/U)\times$ population	3.41E+07	2.51E+07	2.48E+07	1.88E+07	1.74E+07	People
30	Renewable support area ($\text{SA}_{(r)}$)	$(\text{IMP}+N)/\text{REmpD}_{(r)}$	7.28E+12	1.00E+13	1.03E+13	1.39E+13	1.53E+13	m^2
31	Synchronal support area at European standard of living (SSA_E)	$R^*/\text{E\_REmpD}_{(r)}$	1.87E+11	2.66E+11	2.56E+11	3.58E+11	3.93E+11	m^2
32	Synchronal support area at Mediterranean standard of living (SSA_M)	$R^*/\text{M\_REmpD}_{(r)}$	4.42E+11	6.27E+11	6.05E+11	8.45E+11	9.28E+11	m^2

Details about ESL (European Standard of Living) and MSL (Mediterranean Standard of Living) are contained in Appendix C.

R^* is the required amount of renewable emergy necessary to lower the ELR of the country to that of the region. ($R^* = (\text{IMP}+N)/\text{ELR}(r)$, where ELR($r$) is the environmental loading ratio of the region, calculated in Appendix C).

EMRg is the global Emergy to money ratio from Brown (2003) and EMR is the Emergy to money ratio calculated in this paper for Spain.

E_REmpD(r) and M_R EmpD(r) are the renewable empower density for European and Mediterranean context, respectively, and are calculated as renewable emergy used of the region (Europe or Mediterranean Basin)/total area of the region (data in Appendix C).

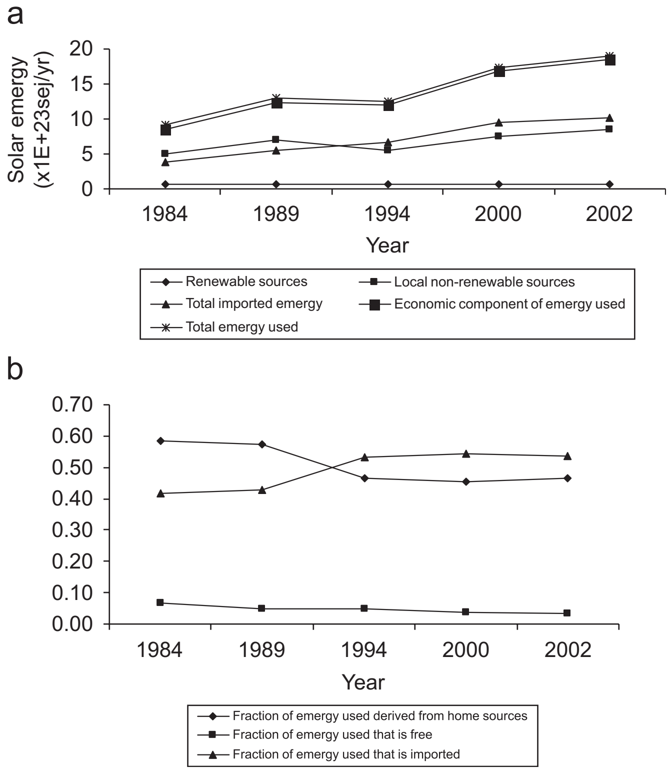

Fig. 5. Main emergy flows in the Spanish social–ecological system: (a) total emergy actually used and its components and (b) main relations among components.

learning to couple the Mediterranean natural perturbation regime with the human activities, although possibilities of economic growth are limited by the connections between the economy and the flow of environmental services that Mediterranean ecosystems supply to Spain. The European context implies the increasing use of international trade to supply goods and services for the national economy, so there is a growing disconnection between local flow of environmental services and the national economy. Potential possibilities for growth are higher for the European context but it means a disconnection between the use of energy and materials and the supply of local environmental services and a loss of resilience as a result. To estimate a benchmark standard of living (ratio of the total eMergy actually used to the renewable one) for those two regions, we have used data contained in Brown (2003) and Cialani et al. (2005) for 14 European and five Mediterranean countries in the 1990s, which are summarized in Appendix C.

If we assume that the Western European standard of living is the correct one, we use the developed carrying capacity with the European Standard of Living (ESL) as the upper limit. The developed carrying capacity at the European standard of living is above present Spanish population in the periods from 1984 to 1994. This means that there was a margin for growth that has been exceeded in the period 1994–2000, in which the

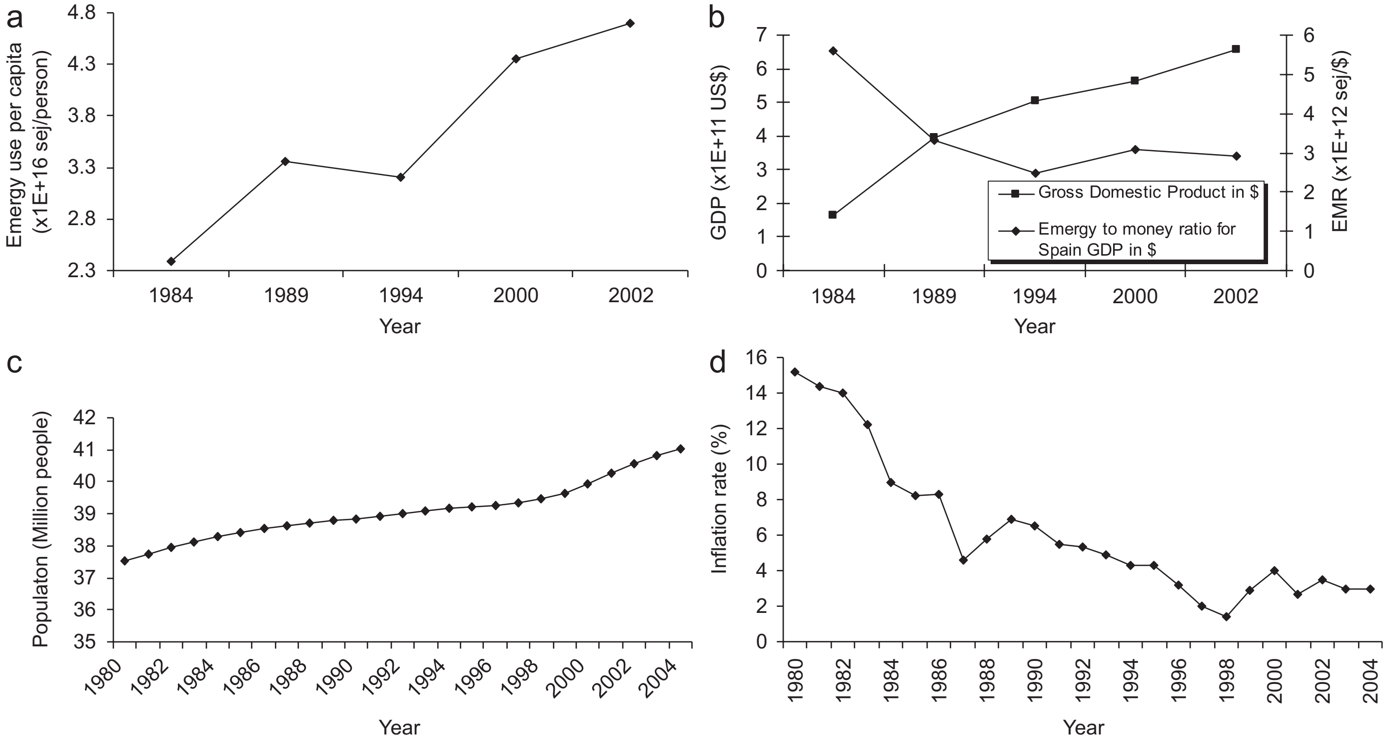

Fig. 6. Some of the standard of living emergy indicators compared with traditional social–economic indicators: (a) emergy use per capita, (b) emergy to money ratio compared with GDP, (c) population patterns in Spain (1980–2004) and (d) inflation rate patterns in Spain (1980–2004).

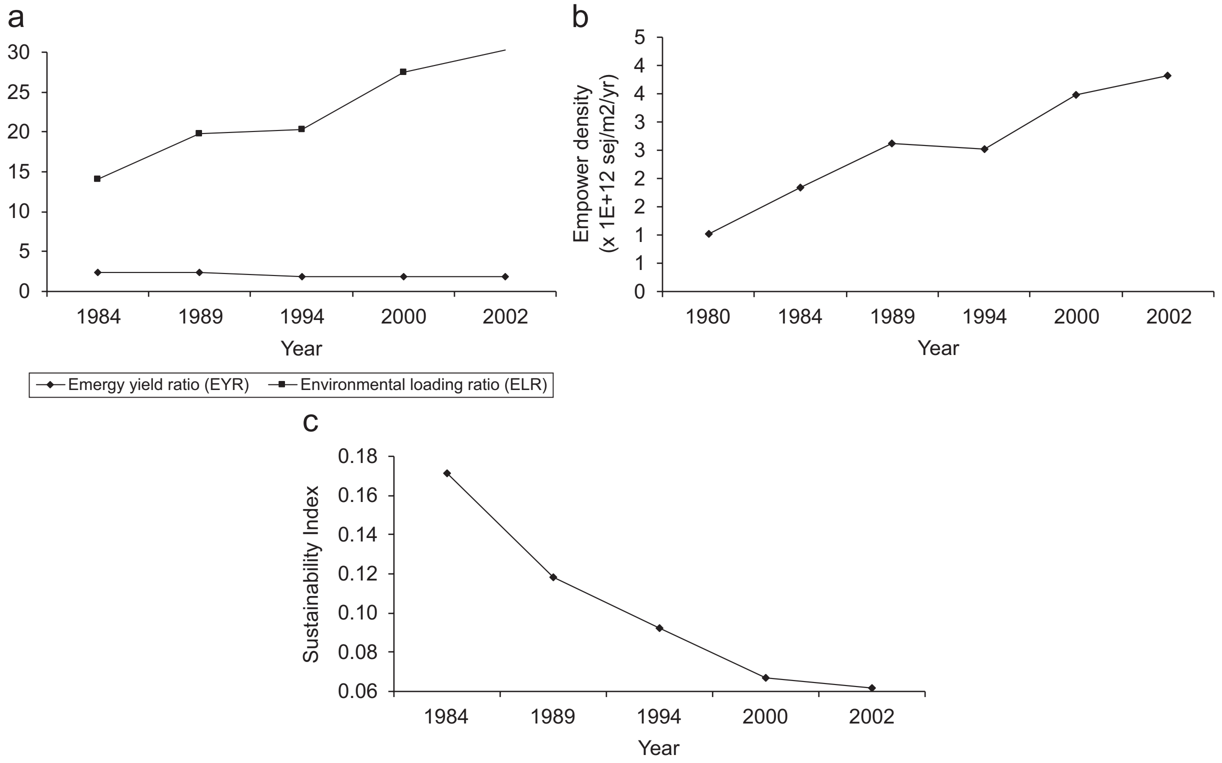

Fig. 7. Emergy indicators for Spain 1984–2002: (a) emergy yield ratio and environmental loading ratio, (b) sustainability index and (c) empower density.

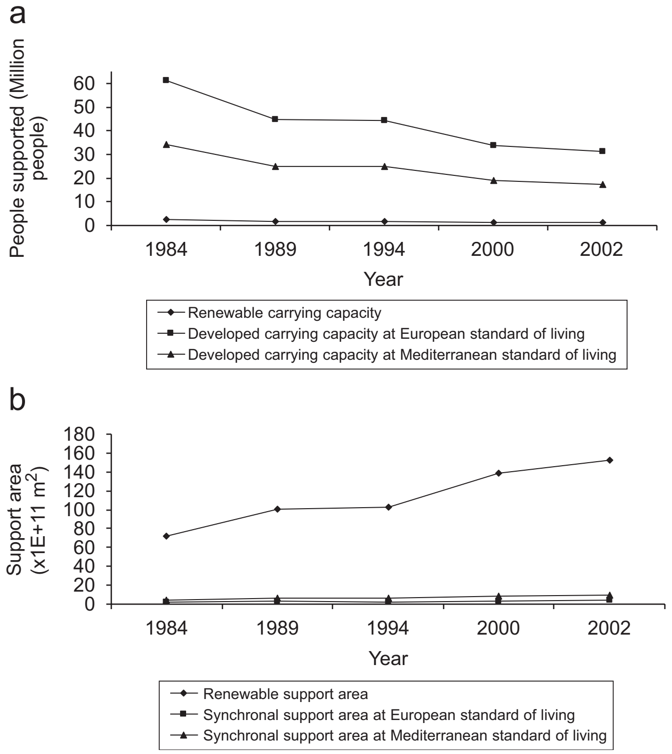

Fig. 8. Evolution of carrying capacity in emergy terms for Spain (1984–2002): (a) people supported and (b) support area.

population supported was 84% of actual population in 2000. In the case of the Mediterranean standard of living, we use the developed carrying capacity at the Mediterranean Standard of Living (MSL) as the upper limit. We have to take into account that it has been calculated with data from only five countries, which was all the available data in the literature for the Mediterranean Basin. The number of people supported decreases from 88% (1984) to 43% (2002) of the respective actual population for these years. It means that the Spanish standard of living had already exceeded the Mediterranean one in the middle 1980s, so if Spain wants to maintain the Mediterranean way of life, which it has experienced so far, Spain has to reduce its eMergy consumption *per capita*.

If the support area-based approach is used for renewable carrying capacity, the area that we would have to use in order to maintain the Spanish standard of living with only renewable sources is 15 (1984) to 30 (2002) times the actual area of the country. This illustrates a doubling of the renewable ecological footprint due to the strong growth experienced in recent decades.

To estimate the support area-based approach for developed carrying capacity (sometimes called synchronal support area), we have to calculate ELR (Appendix C the reference region (Mediterranean or European). We use the same sources that the previous people-based approach to calculate Mediterranean and European regional ELR for 14 European and five Mediterranean countries in the 1990s, summarized in Appendix C. If the standard of living of the European region is employed as a reference, our territorial margin, in terms of the area of Spain that remains after using our territory to reach European ELR, is decreasing, because synchronal support area has increased from 37% of actual area in 1984 to 78% in 2002. In contrast, if the Mediterranean Basin is employed as a reference regional ELR, the increase in support area needed to equal our actual ELR to the Mediterranean regional one was growing from the 88% of the actual area in 1984 to 185% in 2002.

4. Discussion

4.1. Patterns in the supply of environmental goods and services flows to the Spanish economy and its changes

Spanish eMergy use, *U*, has similar values to other western countries (Appendix A). Compared with population size, *U* significantly increased over the investigated two decades. As a result, the Spanish standard of living in terms of resources use has increased (eMergy *per capita*). Spain ranks within the group of highly industrialised countries, although still below the average level of several European countries (Appendix A). The particular decrease in eMergy use *per capita* that took place in the 1989–1994 period may have been affected by the recession of the European Monetary System from 1992 to 1993, which caused the peseta (the Spanish currency at that time) to leave the Exchange Rate Mechanism of the European Monetary System in 1992. Three devaluations of the peseta took place between 1992 and 1993 (Gadea, 2000), causing strong disturbances in the energy and materials required and in economic growth levels within the nation. This indicator coincides with the increase of energy use and total material requirements emphasized in the first sustainability report for Spain (OSE (Observatorio de la Sostenibilidad en España), 2005).

This situation could be considered as a case of inflation in eMergy terms, therefore, more money circulating for the same eMergy. However, we have to take into account that the study has been done during some of the years involved in increasing monetary inflation periods for Spain (1987–1989, 1998–2000 and 2001–2002), despite the decreasing inflation rates during the last two decades (Fig. 6d). It will be necessary to study more years to avoid accounting for only inflation-peak years.

As a consequence, there has been an intensification of transformation activity on the territory (empower density) and an increase of pressure or stress on ecosystems due to production (environmental loading ratio). Spain reaches ELR values close to those of the USA or Switzerland for 1999. This process has been supplied by flows of matter and energy mainly based on imports of external energy memory, thus, Spain has become less autonomous (self-sufficient), especially with regards to fuels. As a consequence, there has been a loss in the potential contribution of local eMergy sources to the main economy (eMergy yield ratio), because growing amounts of resources have to be imported to support the growing Spanish standard of living. In the international context, the Spanish EYR is within the range of EYR for European and other western countries. The result is that the Spanish ESI decreases because of the growing pressure on ecosystems derived from the intensification of the economy related to its high dependency on external eMergy sources, added to the relative low contribution of local eMergy sources to production. The ESI change rate has to be emphasized, especially in the mid-1990s. In the international context, there are many countries which show higher ESI indexes than Spain (Appendix B), but because of different causes. There are countries which have an extremely low value of eMergy use *per capita* with a high use of locally available renewable resources, which sometimes could mean potential wealth not adequately used, and others with a low value of eMergy *use per capita*, but with a high use of non-renewable sources. This could be the case of countries like Bolivia, Kenia, India, etc. Spain shows the patterns of a western country, with a small ESI derived from its high IMP and *N* flows, but still with higher values than most of the European countries, as a result of the relatively late incorporation into the European Union (Fig. 4) economic and consumption patterns.

4.2. Patterns of trade in the context of economic globalization

As we have seen, the IMP has become by far the most significant eMergy flow in the Spanish economy, and so trade is a crucial aspect to the study of Spain as a social–ecological system. In classic and environmental economic assessments of trade employed to support decision-making, the predominant approaches are monetary ones, with a user-side value approach. In these approaches, economic policy is reduced to the balance of payments, and value is measured by what is considered to be the best indicator of utility: price. In this sense, in the official statistics on foreign trade for Spain for every year studied, the countries mainly involved in trade exchanges with Spain in monetary terms are those of the European Union and the Organisation for Economic Co-operation and Development (OECD), whose economies are mainly based on manufacture exports. As a result, Spain could be considered within the group of countries reaching a kind of dematerialization, growing without an increase in matter and energy use, but with some problems in the balance of payments.

On the contrary, in a donor-side value approach, as provided by eMergy Synthesis, the concept of value is related to the work done by nature to produce environmental goods and services that support the economy. In eMergy synthesis, value is related to the energy memory of these environmental goods and services. And, in this case, buying power is not estimated by price but by the EMR or eMergy potentially bought by one monetary unit. Therefore, the origin of the main imported eMergy flows for Spain is the oil and natural gas extracting countries (Nigeria, Algeria and some Middle Eastern countries), whose economies are mainly based on raw materials exports. As a result, Spain could be considered as a net importer of raw materials, with a high increase in the use of energy and matter, promoting a kind of false dematerialization by moving the environmental loading required by its growth to countries that supply raw materials (Muradian et al., 2002; Ramos Martín, 2001, 2003; Cañellas et al., 2004; Carpintero, 2005).

A comparison of EMRs (or buying power in eMergy terms) for different countries to the global EMR (Appendix B) or EER shows that there are differences in the relative buying power of different countries, so in the commerce trade with raw materials exporting countries, Spain commerce with an eMergy advantage in these product exchanges. In these terms, there is a natural decapitalization of supplier countries, promoted by the organization of trade, international division of labour, and economies of scale related to the export of primary sources by developing countries and the import by western countries. In this context, Spain, like other industrialised countries, is promoting natural decapitalization and poverty in the supplier countries with trading disadvantages in eMergy terms (those which have an EER smaller than our EER). This is another example of what Brown (2003) calls resource imperialism. On the other hand, Spanish EER is below the value of most western countries (Appendix B), and therefore many of them have eMergy advantages in trade relations with Spain.

Thus, the greatest part of the pressure, in terms of non-renewable stocks of resource depletion or exploitation, is transferred to the exporting countries (they have to use their own resources and processes to satisfy Spanish demand). These resources are used to exploit and develop the importing country beyond the possibilities that a renewable economy would provide Spain, promoting a decoupling of the Spanish national economy from the flow of local environmental goods and services (natural capital), and the limits that this imposes on the local growth of the importing country.

4.3. Decoupling between national flow of environmental services and the Spanish economy

The Mediterranean standard of living has supported an agricultural way of life for more than eight millennia. This fact might intuitively be interpreted as a measure of the sustainability of this way of life (Butzer, 2005). In the last 40 years, many economies, especially in the northern part of the Mediterranean Basin have become disconnected from this ancient way of life: that is, disconnected from the goods and services that their territories supply. In the present, the standard of living of these countries is mainly supported by imported flows of goods. As we have seen from the eMergy indicators, the strong growth of the Spanish standard of living (eMergy *per capita*) has been mainly supported by imports of primary resources (high content in eMergy and a low monetary value), promoting a disconnection between the original flow of environmental services and the requirements of the Spanish economy. How important is this decoupling? Or to what extent is Spain exploiting its system over its endogenous possibilities?

It seems clear that the Spanish endorsement of the European economic community (EEC) Treaty in 1986 entailed great social–economic changes. It is probable that previous patterns of strong growth in the 1960s were accelerated, and, as is shown by standard of living, carrying capacity and footprint eMergy indicators, Spain left the Mediterranean standard of living to adopt a Western European one. This disconnection becomes evident from the middle 1980s, but its growth rate is especially strong after the middle 1990s. In this sense, both carrying capacity measures show that in the mid-1980s Spain disconnects definitively from its Mediterranean way of life to adopt an European one.

To deal with the challenge of natural capital decapitalization (strong use of N, high dependency on imports, high pressure on environmental systems, low efficiency in the yield, etc.), different Spanish governments invested a great amount of money in conservationist programmes. In fact, Spain ranks as the third country in the EU in terms of the money spent on environmental protection measures, with an average of 0.8% of GDP and 108 € *per capita* (EUROSTAT On-line-a, b). The natural protected areas in Spain will be considered a good measure of conservation policies, in terms of area and money spent during the past 20 years. Creation of a natural protected areas policy has been developed since the 1980s (Morillo and Gómez-Campo, 2000), supported mainly by international and European legislation. The Conservation of Nature-Wild Flora and Fauna Act of 1989 created different types of natural protected areas to preserve some parts of the country outside of the general economic process of growth and land transformation, and it is the real starting point of the natural protected areas declaration in Spain (Fig. 9). In 2003, there were already 950 protected areas in 38 different protection categories embracing more than 9% of the country's surface (EUROPARC-España, 2004).

eMergy indicators illustrate that conservation policies are not successful enough in terms of preservation of natural capital to enhance sustainability. It has been shown that the intensity of use of the territory has grown and that carrying capacity is strongly decreasing, so the Spanish ecological footprint, in eMergy terms, is increasing too. In this Mediterranean context, natural protected areas cannot be managed as islands inside the territory in which they are embedded, since a full set of biophysical, socio-economic and historical–cultural aspects are shared by both sides of the fence (García and Montes, 2003). In fact, other indicators, like the Natural Capital index (NCI) illustrate that Spain has a great quantity of "natural

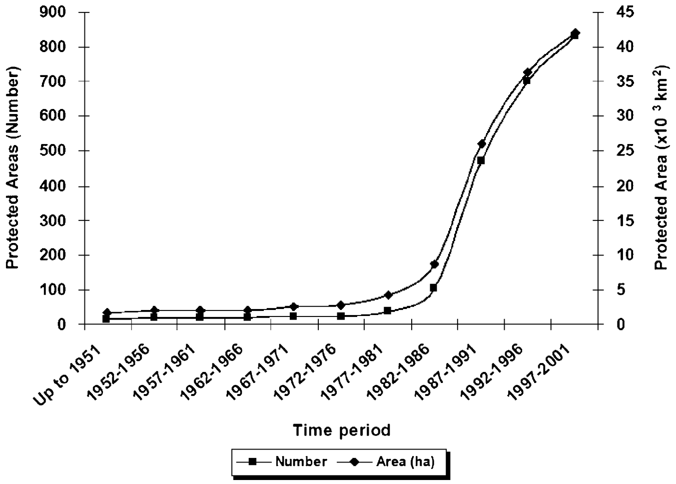

Fig. 9. Evolution of number and area of natural protected areas in Spain during the last 50 years (*Data source*: EUROPARC-España, 2003.)

areas" but that their quality (ratio between current state of the ecosystem and the defined baseline state) is low (Ten Brink, 2000). In fact, there are countries with a low quantity of natural areas but with a high quality, so their NCI is higher than Spain. This is the case with regard to another Mediterranean country, Greece (De Groot et al., 2003).

It would be interesting to have historical series to study previous periods and compare evolution in the last 15 years with the past decades prior to the entry of Spain in the EU. However, these eMergy indicators confirm patterns suggested by other studies of ecological footprint in Spain. Carpintero (2005) has studied the economic metabolism of Spain, and estimates the ecological footprint changes from 2 ha/inhabitant (1955) to 5 ha/inhabitant (2000), which is more than three times the total area of Spain, including the marine portion. The World Wildlife Fund (WWF) (WWF/WCMC-UNEP, 2004) estimates the ecological footprint to be 4.8 ha/inhabitant, so that there would be an ecological deficit of 2.9 ha/inhabitant.

Although Spain has only been studied between 1984 and 2002, it has to be underlined that patterns obtained are confirmed by the partial indicators of the OSE (Observatorio de la Sostenibilidad en España) (2005): so far from recovering a Mediterranean way of life connected to the flow of goods and services of its own territory, sustainability indicators are getting worse and deepening in the "growth without limits" model.

5. Conclusions

Despite ancient transformations of its territory, Spain began the first part of the 1980s with one of the best-preserved natural heritages in the Mediterranean and European area. From a socio-economic point of view, the 1980s starts with a political transition and with the economy in a growth period, without strong pressure on ecosystems and with a productive system that was still extensive in many cases.

In this paper, an historical series of eMergy indicators, instead of traditional monetary ones, has been studied in Spain for five different years to determine the balance and evolution of social–ecological dynamics (trends of resource use) during the last two decades. It can be inferred from the use of these indicators that Spain has suffered a global backward movement in sustainability, with increased intensity in the second part of the 1990s. eMergy indicators stress the magnitude and speed of the changes that the Spanish economy faced in the last two decades, as well as its strong dependence on imported resources. Other eMergy indicators estimate the consequences that those changes have had on the territory, in terms of natural capital decapitalization and the increasing need to spend money to substitute for the free environmental services formerly supplied by the lost of the past Mediterranean way of life to adopt a Western European one.

The sustainable use of resources in the Mediterranean Basin has been accomplished as a consequence of human and ecological resilience (Butzer, 2005). The Mediterranean nature of most of Spain produces highly-resilient ecosystems, because their ecosystems obtain their stability by adjusting their dynamics to couple with climatic local perturbation regime (García and Montes, 2003). Mediterranean way of life has been characterized by the reproduction of these patterns (management of fire, water, etc.) in a smaller scale to avoid great perturbations (wild fires, flooding, etc.). Today, the Mediterranean standard of living is endangered, and there is an effort to preserve some of it characteristics. In this sense, although the Mediterranean nature of the Spanish social–ecological system guarantees a high level of ecological resilience *sensu* Holling (1973), management policies, distant from Mediterranean traditional management that was its identity in the past, are not succeeding in preserving the flow of environmental goods and services that supports our economy. As we have seen in the results of this eMergy synthesis figures, Spain is still in the reversible phase of its economic evolution: in other words, it is more endangered than irreversibly degraded.

A transition to a global and coherent landscape management that overcomes the current dichotomy between territories exclusively managed for conservation and those exclusively dedicated to production is needed. In a Mediterranean context, this goal would be achieved by a landscape management proposal in which natural protected areas contributed to the preservation of a heterogeneous mosaic of traditional uses, in which different ecosystems in many states of maturity that changed with time would be combined and complemented (Burel and Baudry, 1995, 1999; Farina, 1997; González Bernáldez, 1991, 1992). Also, a real integration of conservation practices and the sustainable use of biological diversity with other sectoral or cross sectoral activities, plans and programs that have and impact upon them, is desirable.

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Appendix A

Main emergy flows supporting national economies for Spain and other selected countries, arranged by EMR are given in Table A1.

Table A1
Main emergy flows supporting national economies for Spain and other selected countries, arranged by EMR[a]

Country	U (E+20 sej/year)	Renewable (E+20 sej/year)	Non-renewable (E+20 sej/year)	Population (E+6 inhabitants)	GDP (E+9 US$/year)	Emergy per capita (E+15 sej/inhab)	EMR (E+12 sej/US$)
Nicaragua 1994	816.06	720.00	90.00	4.51	1.40	18.09	58.29
Zambia 1997	1250.00	1030.00	220.00	8.96	2.50	13.94	50.00
Morocco 1994	976.21	380.00	600.00	28.55	8.28	3.42	11.79
Argentina 1994	4520.00	1940.00	2580.00	35.66	54.80	12.67	8.25
Kenia 1999	765.60	370.00	390.00	29.35	10.24	2.61	7.48
India 1999	26 210.60	6750.00	19 440.00	442.00	442.00	2.62	5.93
Spain 1984	**9190.00**	**609.00**	**5090.00**	**38.28**	**164.00**	**24.00**	**5.62**
Syria	790.00	90.00	700.00	15.02	17.00	5.25	4.64
Italy 1984	16 100.00	2030.00	5040.00	56.64	390.00	28.40	4.12
Canada 1999	23 359.05	7800.00	15 550.00	30.49	598.95	76.56	3.90
Spain 1989	**13 100.00**	**628.00**	**7050.00**	**38.79**	**394.00**	**33.70**	**3.31**
Saudi Arabia 1994	7953.00	2580.00	5370.00	22.03	241.00	36.11	3.30
Italy 2000	37 900.00	2030.00	7430.00	57.84	1210.86	65.50	3.13
Spain 2000	**17 400.00**	**609.00**	**7550.00**	**39.93**	**562.00**	**43.50**	**3.09**
Brazil 1995	17 880.00	6870.00	8830.00	167.20	600.00	10.71	2.98
Italy 2002	34 700.00	2030.00	5850.00	57.30	1176.27	60.50	2.95
Spain 2002	**19 100.00**	**609.00**	**8470.00**	**40.55**	**655.00**	**47.00**	**2.91**
Spain 1994	**12 500.00**	**590.00**	**5490.00**	**39.17**	**504.00**	**32.00**	**2.49**
Italy 1989	21 300.00	2030.00	6000.00	56.70	866.00	37.50	2.45
Bolivia 1997	195.20	180.00	10.00	8.04	8.00	2.43	2.44
Italy 1995	25 900.00	2030.00	8020.00	57.33	1070.00	45.10	2.41
South Africa 1999	9270.00	2400.00	6860.00	43.20	412.00	21.44	2.25
Uruguay 1995	308.70	200.00	110.00	3.22	14.70	9.56	2.10
Italy 1991	23 200.00	2030.00	8430.00	56.76	1150.00	40.90	2.02
Global economy 1999	**510 350.00**	**158 600.00**	**343 700.00**	**5900.00**	**27 100.00**	**8.52**	**1.85**
Netherlands 1994	6789.30	250.00	6550.00	15.67	371.00	43.40	1.83
USA 1999	90 100.00	8380.00	81 620.00	266.56	8500.00	33.76	1.75
Denmark 1997	1786.40	20.00	1760.00	5.35	123.20	33.27	1.45
Switzerland 1999	2538.00	280.00	2260.00	7.20	270.00	35.25	0.94
Ireland 1994	469.56	70.00	400.00	3.67	54.60	12.74	0.86
Japan 1999	36 000.00	1330.00	34 600.00	126.97	4500.00	28.30	0.80
Germany 1995	15 257.77	220.00	15 100.00	83.03	2090.10	18.43	0.73

[a] Data source for selected countries, Brown (2003), for Italy Cialani etal., (2005), and this study for Spain.

Appendix B

Some of the main emergy indicators for Spain and other selected countries, arranged by ESI are given in Table B1.

Table B1
Some of the main emergy indicators for Spain and other selected countries, arranged by ESI[a]

Country	U (E+20 sej/year)	EER [EMR_{ge}/EMR_i][b]	ELR [$(U-R)/R$]	EYR [$U/(N_0+N_1+IMP)$]	ESI [EYR/ELR]
Bolivia 1997	195.20	0.76	1.07	15.00	14.00
Nicaragua 1994	816.06	0.03	1.14	8.33	7.33
Zambia 1997	1 250.00	0.04	1.21	5.68	4.68
Uruguay 1995	308.70	0.88	1.57	2.75	1.75
Kenia 1999	765.60	0.25	2.05	1.95	0.95
Brazil 1995	17 880.00	0.62	2.61	2.03	0.78
Argentina 1994	4520.00	0.22	2.33	1.75	0.75
Canada 1999	23 359.05	0.47	1.99	1.50	0.75
Global economy 1999	**510 350.00**	—	**2.17**	**1.46**	**0.70**
Morocco 1994	976.21	0.16	2.56	1.64	0.64
Saudi Arabia 1994	7953.00	0.56	3.08	1.48	0.48
India 1999	26 210.60	0.31	3.88	1.35	0.35
South Africa 1999	9270.00	0.82	3.85	1.35	0.35
Italy 1984	16 100.00	0.45	6.91	1.78	0.26
Spain 1984	**9190.00**	**0.33**	**14.10**	**2.41**	**0.17**
Italy 1991	23 200.00	0.92	10.46	1.76	0.17
Italy 1989	21 300.00	0.76	9.47	1.61	0.17
Ireland 1994	469.56	2.16	6.87	1.17	0.17
Italy 1995	25 900.00	0.77	11.72	1.59	0.14
Spain 1989	**13 100.00**	**0.56**	**19.79**	**2.34**	**0.12**
Syria	790.00	0.40	9.20	1.12	0.12
Switzerland 1999	2538.00	1.97	9.10	1.12	0.12
USA 1999	90 100.00	1.28	10.74	1.01	0.10
Spain 1994	**12 500.00**	**0.74**	**20.26**	**1.87**	**0.09**
Italy 2002	34 700.00	0.63	16.13	1.29	0.08
Italy 2000	37 900.00	0.59	17.65	1.33	0.08
Spain 2000	**17 400.00**	**0.60**	**27.55**	**1.84**	**0.07**
Spain 2002	**19 100.00**	**0.64**	**30.32**	**1.87**	**0.06**
Japan 1999	36 000.00	2.32	27.06	1.04	0.04
Netherlands 1994	6789.30	1.01	27.20	1.04	0.04
Germany 1995	15 257.77	2.53	69.55	1.01	0.01
Denmark 1997	1786.40	1.75	89.00	1.01	0.01

[a] *Data source*: For selected countries Brown (2003), for Italy Cialani et al. (2005), and this study for Spain.
[b] EMRge = EMR of global economy; EMRi = EMR of the country.

Appendix C

Calculations of the average standard of living (ESL and MSL) and regional ELR to be used in carrying capacity and support area for selected European and Mediterranean Basin countries are given in Table C1.

Table C1
Calculations of the average standard of living (ESL and MSL) and regional ELR to be used in carrying capacity and support area for selected European and Mediterranean Basin countries

European Countries	Total emergy actually used (U_E) (sej/year)	Renewable emergy used (R_E) (sej/year)	Area (m^2)	Analysis year	R_E/U_E	ESL = U_E/R_E	ELR
Spain	1.25E+24	5.90E+22	4.98E+11	1994	0.05	20.26	19.67
Italy	2.26E+24	1.21E+23	3.01E+11	1995	0.08	12.73	11.72
Czech Republic	1.55E+23	5.60E+22	7.90E+10	1998	0.36	2.77	2.57
Finland	1.20E+23	2.70E+22	3.38E+11	1994	0.23	4.44	4.44
Ireland	4.70E+22	7.00E+21	8.40E+10	1994	0.15	6.71	6.87
Portugal	1.76E+23	1.70E+22	9.20E+10	1995	0.10	10.35	10.35

Table C1 (*continued*)

European Countries	Total emergy actually used (U_E) (sej/year)	Renewable emergy used (R_E) (sej/year)	Area (m^2)	Analysis year	R_E/U_E	ESL = U_E/R_E	ELR
Slovakia	6.70E+22	6.00E+21	4.90E+10	1994	0.09	11.17	11.75
France	1.32E+24	8.30E+22	5.91E+11	1999	0.06	15.90	15.92
Netherlands	6.80E+23	2.50E+22	4.10E+10	1994	0.04	27.20	27.20
England	2.82E+24	8.30E+22	1.30E+11	1999	0.03	33.95	34.05
Germany	1.53E+24	2.20E+22	3.57E+11	1995	0.01	69.55	69.55
Austria	2.59E+23	1.60E+22	8.39E+10	1997	0.06	16.19	16.19
Switzerland	2.54E+23	2.80E+22	4.13E+10	1999	0.11	9.07	9.10
Denmark	1.78E+23	2.00E+21	4.31E+10	1997	0.01	89.00	89.00
		Total R_E = 5.52E+23	Total area of European countries used = 2.73E+12		Average =	ESL = 24.02	ELR(*r*) = 23.50
					SD =	25.23	25.41

Mediterranean basin countries	Total emergy actually used (U_M) (sej/year)	Renewable emergy used (R_M) (sej/year)	Area (m^2)	Analysis year	R_M/U_M	MSL = U_M/R_M	ELR
Spain	1.25E+24	5.90E+22	4.98E+11	1994	0.05	20.72	19.67
Italy	2.26E+24	1.21E+23	3.01E+11	2000	0.05	18.68	17.65
France	1.32E+24	8.30E+22	5.91E+11	1999	0.06	15.90	15.92
Morocco	9.80E+22	3.80E+22	4.44E+11	1994	0.39	2.58 2	2.56
Syria	7.90E+22	9.00E+21	1.85E+11	1997	0.11	8.78	9.20
		Total R_M = 3.10E+23	Total area of Mediterranean countries used = 2.02E+12		Average =	MSL = 13.44	ELR(*r*) = 13.12
					SD =	7.65	7.18

Data source: Brown (2003) and Cialani et al. (2005).

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3.4. Multi-scalar assessment of the decoupling processes between local economic activities and natural capital by means of emergy synthesis. Andalusia (S Spain) as a case study.

Pedro L. Lomas, Carlos Montes.

Resumen

En las últimas décadas se ha prestado mucha atención a la investigación en sistemas complejos ser humano-naturaleza, o socio-ecosistemas. Los servicios de los ecosistemas han sido considerados como una herramienta muy valiosa para entender, explicar y gestionar la dependencia física que tienen los sistemas socio-económicos de la naturaleza para su bienestar. La creciente alteración humana de los ecosistemas en el contexto del cambio global está modificando rápidamente las relaciones ser humano-naturaleza, de tal modo que la asociación entre los ecosistemas y la economía local está cambiando.

Este artículo explora los procesos de desacoplamiento entre los sistemas económico y ecológico, usando la región española de Andalucía como caso de estudio. Se han empleado indicadores emergéticos para estudiar los cambios en el flujo de los servicios de los ecosistemas que alimentan el sistema económico regional en las últimas dos décadas del s. XX. Los resultados muestran el patrón de uso del capital natural y el incremento en el desacoplamiento de las economías regional y provincial con respecto a los ecosistemas locales. En el artículo se discute cómo este patrón de desacoplamiento se ha acelerado desde mediados de los años 80, después de la integración de España en la Unión Europea, así como la consolidación del papel de Andalucía como proveedor de materias primas al resto del Estado. También se discute el potencial de la síntesis emergética para generar información sobre la interacción ecosistemas-economía en términos de uso del capital natural. Finalmente, se evalúa, en función de los resultados obtenidos, el grado de integración entre la política de conservación y el resto de políticas regionales.

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MULTI-SCALAR ASSESSMENT OF THE DECOUPLING PROCESSES BETWEEN LOCAL ECONOMIC ACTIVITIES AND NATURAL CAPITAL BY MEANS OF EMERGY SYNTHESIS. ANDALUSIA (S SPAIN) AS A CASE STUDY.

Pedro L. Lomas, Carlos Montes

Social-ecological systems laboratory, Department of Ecology, c/ Darwin, 2 Edificio de Biología, Universidad Autónoma de Madrid, 28049 Madrid, Spain

Corresponding author: Pedro L. Lomas; Ph. (+34) 914978008; Fax. (+34) 914978001; e-mail: pedro.lomas@uam.es

Abstract

In the last decade, much attention in research and management practices has been given to coupled systems of human and nature, or social-ecological systems. Ecosystem services have been considered as a valuable tool to understand, explain and manage the physical dependence of social-economic systems on nature's contribution to human well-being. Increasing human-induced alterations in ecosystems in the context of global change are rapidly modifying human-nature relationships, so that the association between local ecosystems and economy is changing.

This paper explores the decoupling processes between economic systems and the local ecosystems in which they are embedded, using the Spanish region of Andalusia as a case study. Emergy indicators are employed to study changes in the flow of ecosystem services to feed the regional economic system in the last two decades of the 20th century. Results show the pattern of natural capital use and the increasing decoupling of the regional and local economy from ecosystems. We discuss how the differential patterns of human-local ecosystems decoupling in Andalusia have been accelerated since the middle 80's, after the integration of Spain into the European Union, and the consolidation of Andalusia's role as a supplier of raw materials in Spain. The potential of the donor-side emergy synthesis to provide information about the ecological-economic interactions in terms of the natural capital use is also discussed.

Keywords: Emergy; Decoupling; Ecosystem services; Andalusia.

1. INTRODUCTION

It is widely accepted that ecosystems can be considered as an authentic natural capital (Costanza and Daly, 1992) supporting human well-being through the deliverance of ecosystem services (MA, 2005). And, humanity is a major force in global change, driving main biogeophysical processes that control global dynamics in a new geological era that has been referred to as Anthropocene (Vernadsky, 1945; Crutzen and Stoermer, 2000).

Much attention has been paid in the last decade to study these relationships between human-nature through the ecosystem services (MA, 2005) and resilience (Folke, 2006) approaches to Social-Ecological Systems or SES (Berkes and Folke, 1998). Liu et al. (2007) and Folke *et al.* (2007) summarize most of the main topics that has been developed in the fields of the complexity of organizational, spatial and temporal couplings of SES and the fit between social and ecological systems.

The aim of this paper is to apply ecological-economic tools in order to analyze SES not from the perspective of the coupling but of the decoupling processes between natural capital at a local scale and the economic systems that are directly linked to it. The notion of decoupling has also been previously used in the literature that discusses the Kuznets curve and dematerialization hypothesis, under the assumption that, as economies develop, they become less dependent (decoupled) (Kuznets, 1955; Dinda, 2004) or more dependent (Cleveland and Ruth, 1999; Stern, 2004) from natural capital inputs. In contrast, decoupling is referred here as the process by which economic activities become increasingly dependent on ecological inputs (e.g. energy and materials) from more distant ecosystems. This does not mean that economic dependence on natural capital decrease, but rather that such dependence expand from local to more distant natural capital.

To this purpose, we study the decoupling processes in the Spanish region of Andalusia, which is suffering large socio-economic changes in the last 20 years, at two different scales (regional and local). Instead of analyzing the issue from the most commonly used user-side perspective (i.e. the perspective of what human are or not able to extract from ecosystems), this research emphasizes the donor-side one (i.e. the perspective of the environmental work required to support the system's dynamics) by using the emergy synthesis (Odum, 1996). Thus, the relative degree of decoupling between the local economy and natural capital is assessed with emergy indicators to know the economic patterns of local and outside natural capital use.

2. METHODS

2.1. Andalusian region as a case study

The Spanish autonomous region of Andalusia lies in the south of the Iberian Peninsula between the Mediterranean Sea (more than 550 km of Mediterranean coast) and the Atlantic Ocean (more than 350 km of Atlantic coast); close 14 km to Africa in the Strait of Gibraltar. Andalusia is the second largest (87 597 km^2) region of Spain, and is divided in 8 historical administrative territories, called provinces: Almería, Cádiz, Córdoba, Granada, Huelva, Jaén, Málaga and Sevilla (Figure 1).

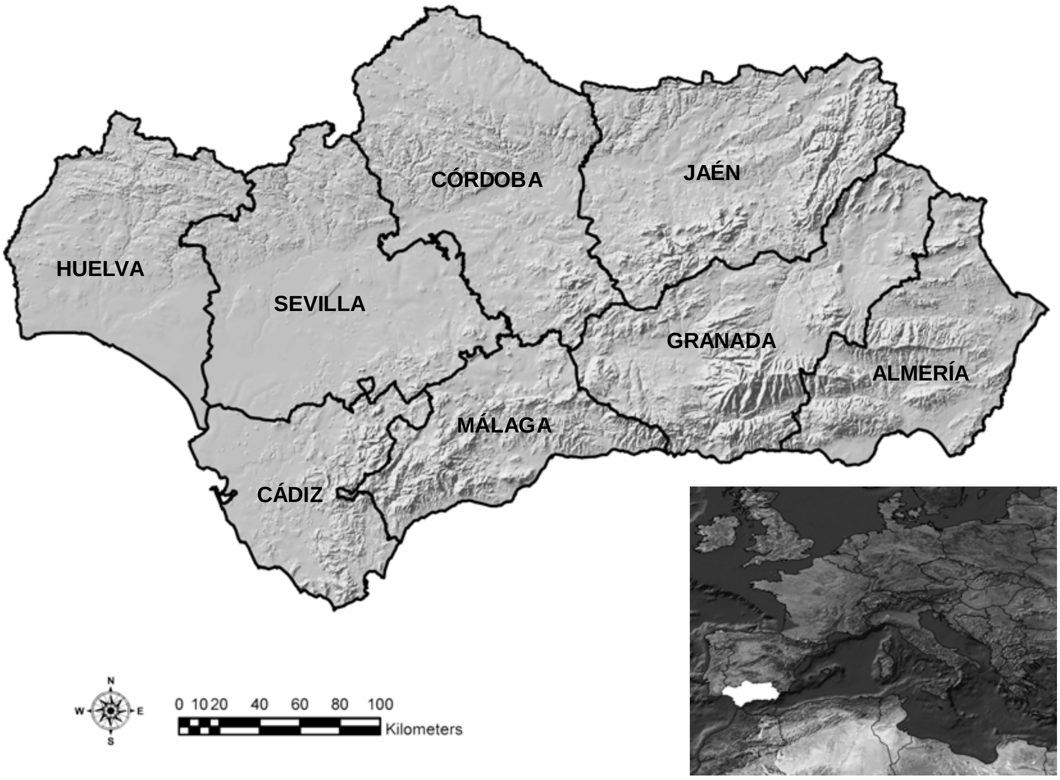

Figure 1.- Location of the Andalusian provinces and region in the Mediterranean, European and Spanish context.

Andalusian region has reached more than 7.45 million of inhabitants (INE, 2004), doubling its population in the last century. The population density in 2002 (more than

85 inhabitants/km^2) was slightly above Spanish average. Málaga, Cádiz and Sevilla are the highest populated, with population densities of 181, 153 and 125 inhabitants/km^2, respectively, and the most populated urban areas. On the other side, Jaén, Huelva and Córdoba are less occupied, with population densities lower than 60 inhabitants/km^2.

In geophysical terms, Andalusia presents a Mediterranean climate with a great diversity, from sub-humid areas of Cádiz or mountains in Sierra Nevada to deserted territories in Almería. It is divided in two great mountain ranges, located in the north (Sierra Morena) and the south-east (Baetic-Rifan complex), and three great watersheds, in the large Guadalquivir depression, the downstream area of the Guadiana basin, and the Mediterranean coastal area and influential zones.

Due to the relative large area of the Guadalquivir watershed, Andalusia has traditionally been an extensive agricultural region. Until the 1960's Andalusian territory presented a predominance of large fields (*latifundios*) of the classical Mediterranean triad: wheat, olive and vine; *vegas*, traditional irrigated fields in the floodplain of rivers or close areas, and large *dehesas* or fields of trees and pastures with forest patches, configuring some of the most particular cultural landscapes of the Mediterranean Spain.

In the last 50 years, Andalusia has suffered strong land use changes, especially intensive in the last twenty years (Figure 2). A key driving force in this process has been the Spanish integration into the European Union (EU) in 1986, and the almost 26 000 million euro of European funds received by Andalusia in different economic subsidies (Griñán, 2005). As a consequence, Andalusian GDP has risen to nearly 75 % of the EU GDP average (Griñán, 2005). Although croplands area has been hardly reduced from 45 % in 1984 to 43 % of land use in 2002 (MAPA 1985, 2003), agriculture has lost part of its monetary weight in the regional economy (in 1998 agriculture was only 10.98 % of total Gross Added Value (GAV), although this is much more than the weight of this sector for the Spanish economy), and service sector is predominant (more than 65 % of Andalusian GAV), especially linked with tourism and construction (Fundación BBV, 1999). As a part of this process, many traditional cultural landscapes have been abandoned or transformed, and intensive cultivation of rice, greenhouses fields and other intensive crops are now widespread. For example, in the area of Campo de las

Dalías, in the province of Almería, the area occupied by greenhouse fields has raised from 75 ha in 1969 to more than 64 000 ha in 2006 (OSE, 2006)).

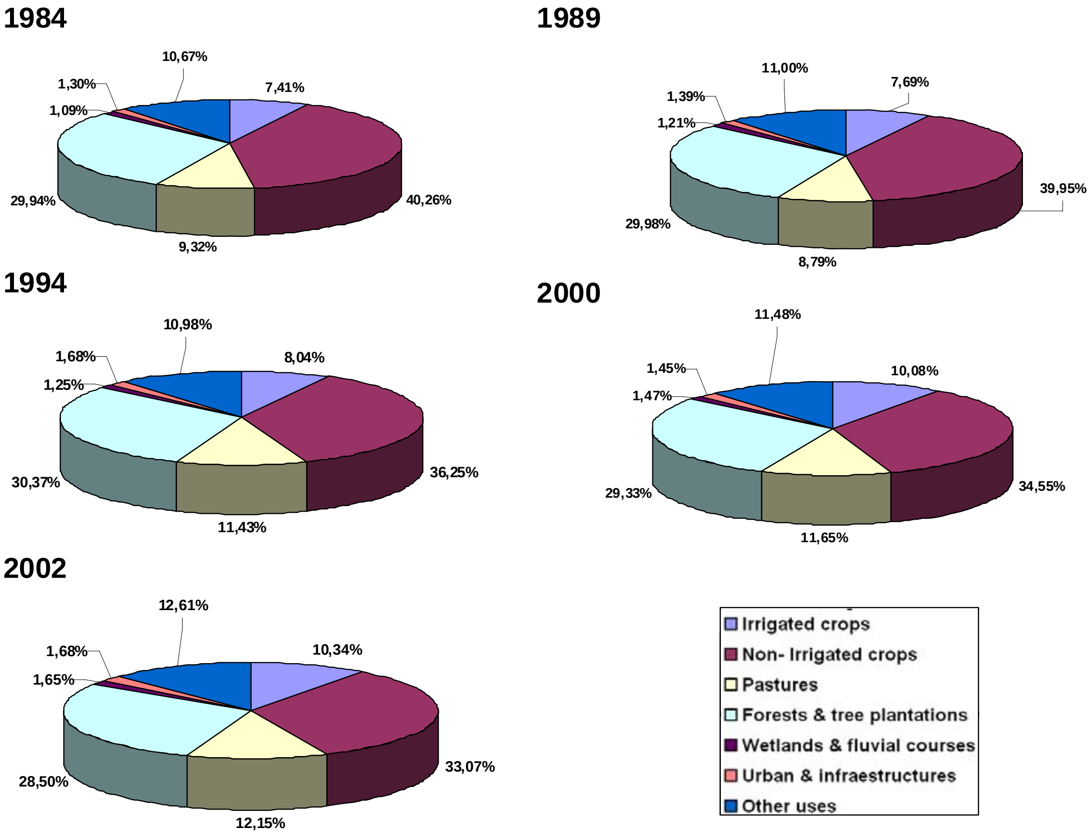

Figure 2.- Main land uses in Andalusia for the studied years

Despite this old and intensive human occupation, by its situation as a bridge between Europe and Africa, and the presence of one the highest Mediterranean mountains of southern Europe (Andalusian Sierra Nevada is the peak of Iberian Peninsula, with 3 478 m), Baetic-Rifan complex is one of the most important hotspots of biodiversity in the Mediterranean Basin (Médail and Quézel, 1999). To manage this natural capital, the Andalusian government has developed the highest network of protected areas in Spain, with more than 29 % of total protected areas of the country, and almost 20 % of the regional surface covered by a legal protection figure. It is particularly significant in the case of Jaén, Huelva and Cádiz, in which 19, 18 and 15 % of provincial area was catalogued as a protected area, respectively (RENPA, 2007).

2.2. Methodology: Emergy synthesis.

Emergy synthesis for this study follows the methodological guidelines developed by Odum (1996), and Brown and Ulgiati (2004) at the scales of nations, regions and land uses. The method was applied following four basic steps:

1. Definition of boundaries. The emergy synthesis of Andalusia was carried out at two scales. On one hand, the regional scale of Andalusia. On the other hand, Andalusian provinces, which constitute main administrative and economic units at the ecological scale used as a bio-geo-physical base for the social-ecological system, therefore, the ecosystems at Eco-area scale (Klinj and Udo de Haes, 1994), in accordance with the hierarchical ecosystems classification of Andalusia established by Borja *et al.* (2004).

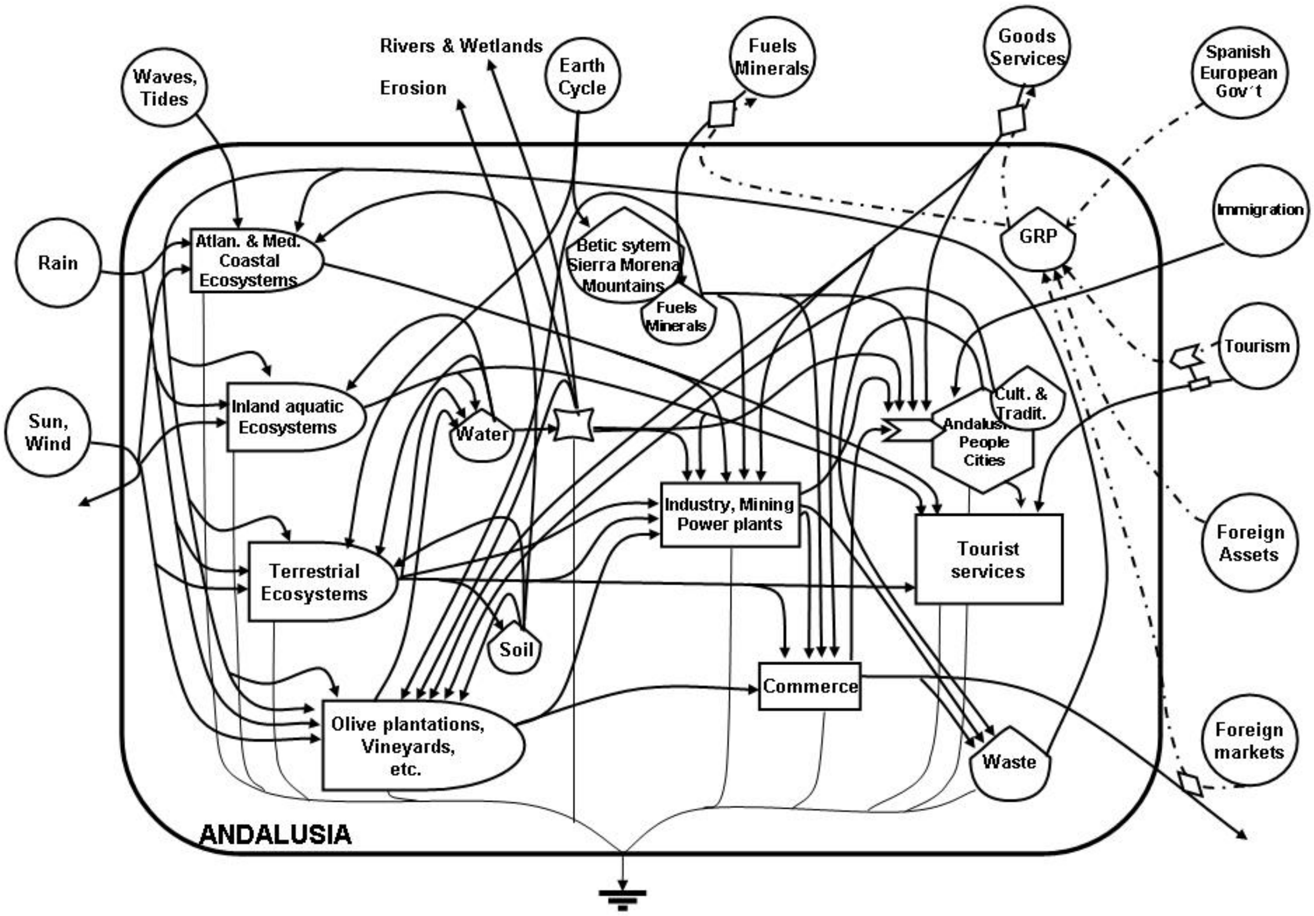

Figure 3.- The emergy system diagram of Andalusia

2. Energy systems diagramming to obtain an overview of the system, its parts and processes, using the energy language (Odum, 1994). The emergy system diagram of Andalusia is shown in Figure 3.

3. Development of an emergy evaluation table. 45 emergy evaluation tables for Andalusia and provinces were developed in Lomas *et al.* (2007), summarizing main flows in renewable sources, local non-renewable sources, imports of goods and services, exports of goods and services, and finally, some selected products for 1984, 1989, 1994, 2000 and 2002.

All the transfomities used in this work were referred to the 15.83E+24 seJ/yr baseline (Odum *et al.* 2000). Under the most accepted criteria to avoid double-counting in this baseline framework, the renewable emergy flow (R) has been calculated by using the largest inflowing emergy of renewable ones.

Complete data series of inter-regional and inter-provincial commercial exchange were not completely available for all years. In these cases, data were estimated using technical coefficients for 1980, 1990, 1995, and 2000 input-output tables at the regional scale (BB, 1985; IEA, 1994, 1999, 2000). These technical coefficients were the result of comparing inter-regional trade to production by sector, and assuming no technological changes. Thus, commercial data of inter-regional trade by sector for 1984, 1989, and 1994 were estimated by using 1980, 1990, and 1995 technical coefficients, respectively. Input-output table provided data to complete items of the 2000, and allowed the estimation of 2002 data, which were compared to the 1995-2005 historical series obtained by the inter-regional trade pilot project C-Interreg (Llano *et al.* 2007). In the case of provinces, we disaggregate Andalusian data for all years by using detailed production and employment data by sector and province for studied years (ESECA, 1987; Fundación BBV, 1992; INE, 1997; INE, 2007). To do this, it was assumed that technical coefficients of trade in the regional input-output tables were valid for provincial production, so that the relation between trade, production and employment was reproducible at the provincial level, taking account provincial production and employment by sector.

Because of its particular nature and importance, trade of energetic mineral and products has not always been calculated by using commercial data provided by input-output tables, but using regional and provincial energetic balances (SODEAN, 1992a, 1992b; Oilgas, 1990, 1995, 2001, 2003; MEH-Delegación en CAMPSA, 1990; AAE, 2004). Energetic mineral or products just passing through Andalusia or any province are not considered as local imports or exports. Emergy exports related to energetic mineral or products are only considered in the case of local extraction. For our case study, when local extraction of energetic minerals = 0, then emergy imports were estimated by using total consumption data. Concerning emergy related to electricity consumption, electrical energy is derived to the national system and it is not easy to attribute a specific production to a particular consumption, so that it has been assumed that emergy imports linked to electricity (+) = consumption – production, and emergy exports (-) = consumption – production.

4. Flow aggregation and development of emergy indicators of performance. Using the summarized version of the emergy diagram (Figure 4), it is possible to aggregate some items and calculate relationships between them in order to evaluate specific aspects of the system.

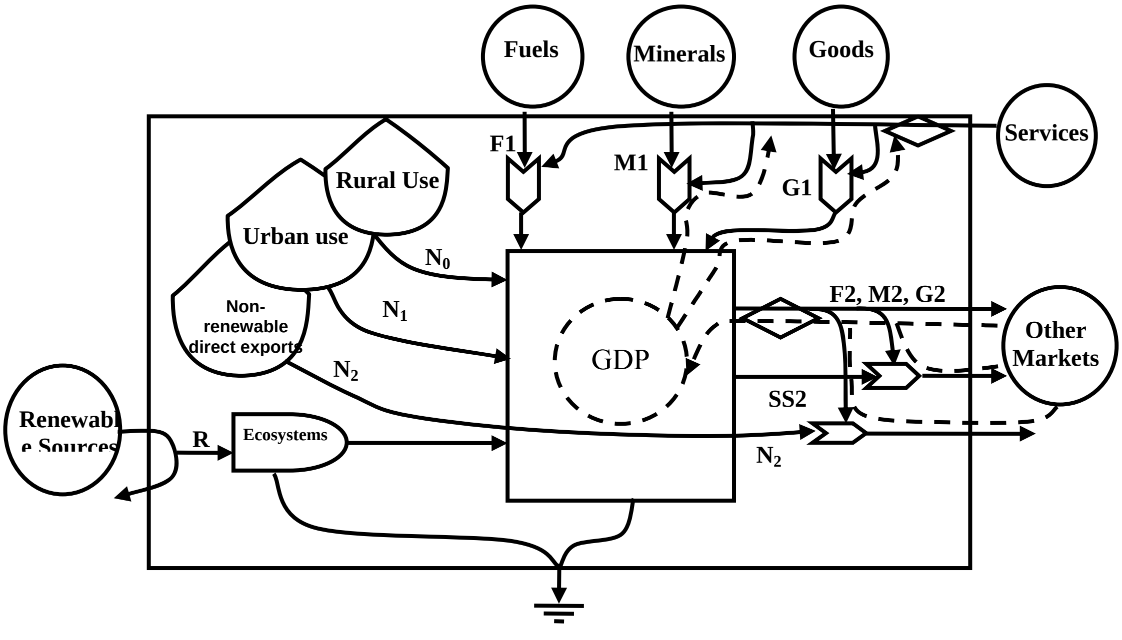

Figure 4.- Summarized version of the emergy diagram for Andalusia.

A summary of main emergy indices for Andalusia and provinces can be found on Table 1 for five years (1984, 1989, 1994, 2000 and 2002).

Table 1. Main emergy flows and indicators of performance for Andalusia and provinces.

		U	R	N_0	N_1	IMP	EXP	ED	U per capita	EMR	EYR	ELR
		x1E+22	x1E+21	x1E+19	x1E+22	x1E+22	x1E+21	x1E+12	x1E+16	x1E+12	-	-
		seJ/yr	seJ/yr	seJ/yr	seJ/yr	seJ/yr	seJ/yr	seJ/m^2	seJ/pe.	seJ/$	-	-
Almería	**1984**	1.81	6.72	4.64	0.52	0.62	10.13	1.70	4.26	12.20	2.93	1.70
	1989	2.85	6.72	4.53	1.32	0.85	22.13	2.68	6.38	7.43	3.34	3.25
	1994	2.64	6.58	3.48	1.27	0.70	12.62	2.48	5.53	5.28	3.74	3.01
	2000	5.26	7.28	3.89	1.96	2.56	37.21	4.94	10.12	8.50	2.05	6.22
	2002	7.26	6.31	3.61	2.65	3.97	49.09	6.82	13.28	10.23	1.83	10.51
Cádiz	**1984**	4.93	15.74	5.48	0.27	3.08	33.06	2.74	4.39	14.69	1.60	2.13
	1989	6.19	15.74	5.68	0.41	4.20	43.30	3.44	5.81	7.67	1.47	2.93
	1994	9.00	15.74	4.99	0.48	6.94	54.78	4.99	8.21	9.15	1.30	4.72
	2000	10.56	15.74	5.28	0.99	8.00	85.06	5.86	9.52	9.33	1.32	5.71
	2002	11.71	15.74	5.32	1.06	9.07	93.05	6.50	10.27	8.74	1.29	6.44
Córdoba	**1984**	1.28	0.92	12.27	0.35	0.82	16.06	0.93	1.74	6.14	1.56	12.93
	1989	2.15	0.12	12.18	0.51	1.51	28.40	1.56	2.86	4.42	1.42	17.67
	1994	1.97	0.52	12.45	0.89	1.02	49.81	1.43	2.59	2.95	1.93	36.63
	2000	5.23	0.83	12.45	1.13	4.00	31.66	3.79	6.88	7.10	1.31	61.69
	2002	5.05	1.00	12.32	1.14	3.81	31.88	3.67	6.55	6.01	1.33	49.38
Granada	**1984**	1.65	0.85	10.18	0.99	0.57	8.57	1.25	2.14	7.35	2.91	18.49
	1989	1.82	0.85	10.18	0.77	0.95	14.55	1.37	2.31	3.43	1.92	20.44
	1994	2.14	0.78	9.10	1.17	0.88	3.45	1.62	2.66	3.00	2.43	26.40
	2000	4.31	0.91	9.24	1.35	2.87	24.04	3.25	5.29	5.45	1.51	46.68
	2002	3.52	0.87	8.78	1.83	1.60	9.68	2.66	4.30	3.65	2.21	39.67
Huelva	**1984**	1.24	16.79	3.41	9.32	1.41	17.36	8.27	29.07	76.18	8.79	6.39
	1989	1.29	16.79	3.57	9.07	2.19	25.85	8.63	29.49	32.91	5.91	6.71
	1994	2.64	16.79	2.99	22.04	2.63	23.62	17.56	58.54	59.36	10.02	14.70
	2000	8.97	16.79	2.74	2.88	4.41	39.27	5.98	19.58	17.21	2.03	4.34
	2002	8.69	16.79	2.46	1.29	5.71	48.59	5.79	18.69	14.20	1.52	4.18
Jaén	**1984**	1.03	0.62	12.21	0.40	0.56	12.43	0.76	1.60	5.53	1.85	15.69
	1989	1.65	0.71	12.24	0.62	0.95	23.68	1.22	2.57	3.85	1.74	22.22
	1994	2.37	0.56	11.60	0.63	1.67	6.86	1.75	3.68	4.02	1.42	41.02
	2000	3.36	0.54	11.53	0.92	2.37	45.08	2.49	5.24	5.63	1.42	61.14
	2002	3.69	0.65	11.41	1.22	2.39	44.35	2.73	5.70	5.17	1.54	55.76
Málaga	**1984**	1.78	1.94	6.29	0.69	0.89	16.71	2.01	1.68	5.14	2.00	8.21
	1989	3.19	1.94	6.24	1.14	1.84	34.33	3.59	2.82	3.66	1.73	15.46
	1994	7.04	1.79	5.07	0.91	5.95	29.57	7.94	5.94	6.56	1.18	38.38
	2000	11.86	2.07	5.12	3.09	8.56	37.35	13.37	9.41	8.81	1.39	56.35
	2002	10.45	1.98	5.03	3.63	6.61	50.41	11.78	7.86	6.60	1.58	51.75
Sevilla	**1984**	4.75	0.74	15.75	32.31	1.43	24.70	3.39	3.11	10.60	3.32	62.84
	1989	5.80	1.39	15.56	35.78	2.07	46.69	4.13	3.64	5.05	2.81	40.74
	1994	6.21	0.57	15.61	26.02	3.53	10.76	4.42	3.73	4.03	1.76	107.9
	2000	12.75	0.84	15.68	48.08	7.85	60.46	9.09	7.46	6.93	1.63	150.3
	2002	12.23	0.86	15.12	17.48	10.38	87.16	8.71	6.95	5.52	1.18	142.0
Andalucía	**1984**	3.10	1.77	7.42	1.53	1.39	3.56	2.90	4.69	1.51	2.33	16.54
	1989	3.12	1.77	7.41	1.81	1.12	5.09	2.91	4.55	6.73	2.78	16.63
	1994	3.08	1.77	7.42	1.40	1.49	7.96	2.87	4.34	4.73	2.06	16.39
	2000	3.96	1.77	7.22	1.65	2.12	1.44	3.70	5.44	5.22	1.87	21.38
	2002	4.29	1.77	7.12	1.55	2.56	2.13	4.01	5.74	4.78	1.68	23.26

Source: Lomas *et al.* (2007).

2.3. Emergy indicators to study decoupling processes in SES

In this paper, decoupling of complex human-nature systems at a specific scale is conceptualized as the gradual misfit between local economies and local natural capital, so that people become increasingly dependent on non-locally delivered ecosystem services flows. It has been assumed that a complete decoupling between local natural capital and people at all scales is not physically possible. Even though the flow of some ecosystem services was almost completely disrupted, local ecosystems continued to perform some basic functions such a support for e.g. housing, communication. However, the use of the rest of essential ecosystem services may be moved to other different SES or other territorial scales. On the contrary, a totally coupled SES is considered to be scarcely possible too, as a consequence of the nested organization of SES at different scales, and the global nature of many ecosystem services. This is especially the case of some regulating services, such as carbon sequestration.

We employ the fraction of total emergy actually used (U) that is imported (IMP), therefore the emergy imported from outside per unit of emergy used, as an emergy indicator of ecological-economic decoupling between ecosystem services and people at a local scale (FUIMP=IMP/U). Emergy-based indicators are useful only for those services having a biogeophysical expression, mainly regulation and supply services. Ecosystem services with no physical expression, e.g. many cultural services are likely to be better captured by other valuation languages not necessarily circumscribed only to biophysical parameters (Martínez-Alier, 2004).

If the biogeophysical work employed to maintain or produce a specific system (the emergy) is almost completely based on local emergy sources, like in the traditional agriculture way of life, then it is possible to talk about a highly coupled SES ($FUIMP \approx 0$). In contrast, if the system is largely maintained by the use of imported emergy (IMP) like in a completely urban environment, then it is a highly decoupled system ($FUIMP \approx 1$). As explained before, these decoupling processes do not necessarily denote an economic dematerialization, therefore, a decreasing use of energy and materials related to GDP, but many times they are the sign of delocalization or enlargement of the environmental loading.

In the accepted emergy algebra, U is composed by three main elements:

$U= R+N+IMP-N_2$ where,

- U = Total emergy actually used (seJ/yr).
- R = Renewable emergy flow (seJ/yr).
- N = Non-renewable emergy sources (seJ/yr).
- N_2= Emergy from exported without use local non-renewable sources (seJ/yr).
- IMP = Emergy from imports (seJ/yr).

As a result, there are different potential causes explaining FUIMP to change as a consequence of the differential influence of the U components, and the trade-offs between them. Thus:

- If FUIMP grows, it implies an increase of IMP (decoupling), or a decrease of R (e.g. ecosystem loss) or N (e.g. end of the profitable exploitation of mines, depletion of non-renewable stocks).

- If FUIMP declines, then there is a decrease of IMP (coupling), or an increase of R (e.g. restoration of ecosystems, a rainy year) or N (e.g. exploitation of new mines, overexploitation of aquifers).

3. RESULTS

3.1. The use of natural capital (U) by the Andalusian economy in the context of the Mediterranean Spain.

According to the Andalusian social-ecological model exposed in Figure 3 and main emergy flows summarized in Table 1, potential investment in emergy yield of the region or total emergy actually used (U) by Andalusia increases with an average of 1.72 % annually, 33 % slower than the increase of U for the national scale at the same period (Lomas *et al.* 2008).

Renewable emergy flow (R) used in Andalusia, 1.77E+22 seJ/yr, is approximately constant in the studied period. The largest individual renewable emergy flows are tides, waves and chemical potential of rain, respectively. This may be related to the importance of more than 940 km of coastal length, especially complex at the Atlantic side; and the work made by rainfall, although the Andalusian territory is not very craggy.

Participation of local non-renewable emergy (N) in the regional economic system increases with an average of 1.04 % annually, less than 34 % of Spanish annual increasing for the same period. Some of the traditional mining areas of the northern Andalusian mountains (Sierra Morena) have declined in its exploitation by depletion of coal, gold, iron, or sulphur profitable reserves. As a consequence, their contribution has decreased from more than 60 % of N_1 in 1984 to less than 4 % today. In contrast, some industrial and construction minerals (limestone, sand, gravel, clay, gypsum, dolomite, marble, etc.) have increased their contribution to reach more than 87 % of the concentrated use of local non-renewable emergy (N_1). The small Andalusian natural gas reserves have been almost exhausted and today, national energy authorities are considering using deposits as natural beds for imports.

Concerning outside sources (IMP), Andalusian import of emergy have been increased an average of 3,9 % annually, 1 % less than Spanish emergy increase in emergy imports in the same period. The largest emergy imported (more than 55 % of imports in 1984, and 25 % of imports in 2002) to Andalusian region was related to energy sources (oil and derived products, and electricity), and minerals. In the last years of the studied period there was a diversification and an increase in the relative weight of commodities like textiles or livestock, and their respective products. Andalusian exports (EXP) have been increased an average of 10.30 % annually, more than 7 % of the Spanish emergy average exports increase for this years. In the first part of the studied period, petroleum derived products and minerals constituted almost 45 % of regional emergy exports. However, in the last years there was a diversification and an increase in the weight of agriculture and livestock related commodities, representing almost 25 % of Andalusian emergy exports.

Andalusian empower density (intensity of emergy use on territorial basis) is slightly higher than the Spanish one in the studied period, but it has not experienced significant changes since 1984, increasing at a 0.02 % average annual rate.

Emergy use per capita (intensity of emergy use on population basis) in Andalusia increased 1.08 % annually, a 31 % less than the growing average rate for Spain, although its value is higher than the average Spanish per capita use for all the studied years.

Andalusian emergy to money ratio or EMR (average emergy circulation per monetary unit or emergy buying power) is higher than the Spanish EMR. However, the Andalusian average annual decreasing rate of EMR is more than 1.5 % higher than the Spanish rate, so commercial disadvantages with Spain have decreased.

The emergy yield ratio (EYR) or the relation between emergy appropriated by the system per unit of invested emergy from outside (Raugei *et al.* 2005) is higher than the Spanish EYR for 1984, 1989, and 1994. After that (2000, and 2002), EYR was below average Spanish values, because decreasing annual rate of EYR in Andalusia is 0.40 % higher than the Spanish rate. Regarding the environmental loading ratio (ELR) or the relation between purchased and free renewable emergy used, average increasing rate of the ELR for Andalusia is 46 % of the Spanish value, and absolute values are always under the Spanish rates except in 1984. Thus, the so-called emergy sustainability index (ESI) in Andalusia, a balance between the competences of transformation processes in relation to the environmental loading caused, is slightly higher than the Spanish ESI, always decreasing. However, the average rate at which it is decreasing in Andalusia is more than 1.20 % lower than the Spanish ESI average decreasing rate.

3.2. Andalusian intra-regional variability of natural capital use

The use of natural capital in Andalusian provinces is uneven. Huelva is the province in which U is higher (from 1.24E+23 seJ/yr in 1984 to 2.63E+23 seJ/yr in 1994) from the 1980's to the middle 1990's, followed by Cádiz and Sevilla. In the period between 1994 and 2002, Sevilla, Cádiz and Málaga are the provinces in which the use of natural capital is higher.

However, the natural capital use strategies are based on different sources for each province. Thus, in provinces with long coast-lines and significantly influenced by sea forces (Málaga, Cádiz, Huelva, Almería), R is often higher (x 1E+21-1E+22 seJ/yr) than renewable emergy forces for the inland provinces (x 1E+20-1E+21 seJ/yr), in which the drivers are more related to rainfall.

In terms of the use of local non-renewable provisioning services (N), the first part of the studied period is dominated by the intensive extraction of local minerals in Huelva (reaches 73 % of total concentrated use of natural capital at provincial level) and Sevilla (more than 20 % of concentrated use), linked to the ancient exploitation of the pyrite and related minerals in Sierra Morena. After 1994, Huelva loses its importance in mineral extraction due to the depletion of local non-renewable sources of profitable minerals. As a consequence, there is a diversification in the extraction related to construction sector of the economy (limestone, sand & gravel, marble, etc.), increasing the relevance of industrial minerals, so that Málaga (25 % of N_1) and Almería (more than 18 % of N_1) become the most important sources of minerals together with Sevilla and Huelva, which arrive to Andalusian average levels of concentrated use.

The importation of foreign natural capital (IMP) to feed provincial economy has been the main strategy followed by some Andalusian provinces. Cádiz economy, strongly based on refineries that transform imported oil into petroleum derived products (although decreasing, oil and derived products were more than 83 % of imports for 1984 to 50 % of total imports for 2002), and to a certain extent, Huelva (related to refineries too, and in the last years to minerals and their products) and Sevilla (the Andalusian capital) were good examples for this scheme in the first period of the study until 1989. From 1994, Sevilla, Málaga and Cádiz become the provinces most dependent on imports, with a diversification in the items imported, although energy (with minerals in some cases) is still one of the highest emergy imports for all provinces. Emergy linked to provincial exports (EXP) has traditionally been performed by Cádiz, Sevilla and Málaga, which account for more than 50 % of total provincial exports, although exportation shows enormous differences among provinces. Thus, Almería is the main agricultural exporter, and although this could in principle be a poor emergy activity, it present high emergy values (x1E+22 seJ/yr) as being related to the intensive exploitation of greenhouses in the western part of the province; Cádiz and Huelva are specialized in exporting the emergy rich products of their respective refineries and power plants, which are connected to national imports of oil and derived products, as explained before. Emergy contained in the exports of remainder provinces is primarily based on the extraction of minerals and their products, which is the second activity for the above mentioned provinces too.

In the first part of the studied period, Huelva and Sevilla were the provinces with empower density values over the Andalusian average. Almería, Málaga, and Cádiz have been incorporated into this group since the middle 1990's. In the provices of Córdoba, Granada, and Jaén empower density values showed to be below the Andalusian average.

Concerning the emergy use per capita, Huelva, Almería and Cádiz were the provinces in whit values above the Andalusian average in the 1980's. Finally, all provinces except Granada and Jaén have been incorporated to this group. Huelva presents the highest values of emergy use per capita, 69 % higher than the Andalusian figures, followed by Almería.

The EMR for most of provinces decrease from the 1980's to 1994, and then increase until 2000 to finally decrease in 2002. In terms of buying power, Huelva has the highest EMR, or the lowest emergy buying power for the entire period. This is probably related to its dependence on oil imports. In 2002, the average EMR is already higher than the Andalusian value for all provinces except Granada.

Provincial appropriation of natural capital per unit of emergy invested from outside (EYR) reaches its maximum in Huelva for 1994 as a consequence of the intensive appropriation of emergy from local non-renewable concentrated use. In the second part of the studied period this indicator decreases due to the depletion of resources, as explained before. Sevilla, Almería and Granada have high values of EYR related to local exploitation of non-renewable emergy sources too, but Sevilla is the province in which annual decrease rate of EYR is high (4.76 %), and Granada presents the opposite pattern, with an increasing annual rate of 4.79 %. On the contrary, EYR is low in the case of Córdoba and Cádiz, whose U is essentially based on emergy imports, although Córdoba shows increasing patterns (1.67 % annually), and Cádiz, decreasing rates (0.95 % annually). Concerning the distance of the technological development from the natural process that could have developed locally at a provincial level (ELR), Sevilla shows the highest value of ELR in the whole period and maintain an average increasing rate of more than 6% annually, followed by Granada, Jaén, Málaga and Córdoba at a large distance. And, Almería, Cádiz and Huelva present the lowest ELR values. This last aspect could be considered a paradox if we did not take into account that Almería, Cádiz and Huelva present a high R value, related to their coastal position, and their dependence on local non-renewable emergy use (N). However, Almería shows the highest average rate of annual increasing (13 %). Thus, ESI is inversely related to this last indicator, and presents analogue patterns, so Sevilla is the province presenting the worst balance between EYR and ELR.

4. DISCUSSION

4.1. Multi-scale drivers of change in Andalusia

The strong importance of extractive uses and dedication of the economy to the exportation presents the Andalusian economy as a supplier to Spanish areas with high purchase power. The difference between IMP and EXP has been approximately constant in the period 1989-2000. This is because the high values on imports have been compensated by the high average annual increase in exports. In particular, the value of EXP for all the provinces was higher than IMP for the period 1984-1994, highlighting the importance of inter-regional trade. In the 1994-2002 period, only Almería, Jaén and Cádiz maintain these differences, linked to the agricultural products and electricity for the two first provinces (the first one with an intensive model of greenhouses, and the second one linked to the national and international exportation of olive oil), and the role of transformer of oil and petroleum derived products for the last one. The spectacular growth of emergy imports to drive the economy of Sevilla, Málaga and Córdoba; and the closing of profitable mines, especially in Huelva with the subsequent decreasing of local non-renewable emergy use are the main reasons explaining the changes experienced by other provinces in this period. In contrast to other parts of Spain, agricultural and non-renewable extractive specialization of Andalusia is increasing.

Furthermore, main indicators of the intensity in emergy use suggest that there is an intra-regional differentiation of the emergy use by provinces. Coastal provinces are more intensive in emergy use in both territorial (empower density) and population basis (emergy used per capita) in the whole period because of main provincial capitals are coastal towns, and urbanization and industrialization processes have happened along the coastline (Peña, 2004). This is a common pattern with other parts of Europe, in which coastal areas, more connected to the global trade by the sea, have concentrated the transformation and services activities of the economy. On the contrary, inland provinces present high values of ELR and low values of ESI, both of them related to the high dependence of provincial economy on emergy imports. This is a consequence of the ancient property regime of Andalusia, specially in Córdoba, Jaén and Sevilla (IEA, 2005), in which few owners are in possession of most of land in enormous extensive farms (*latifundios*), mainly dedicated to livestock, hunting, extensive agriculture and private recreational purposes. Not in vain, Andalusia is the Spanish autonomous region with the highest rate of property concentration (Pillet, 2007).

4.2. Differential decoupling dynamics in Andalusia

In the last 20 years, Andalusia has been suffering a progressive phenomenon of economic decoupling from local natural capital, embedded in the general patterns of trade globalization and global change with the subsequent social consequences in terms of environmental justice (Muradian and Martínez-Alier, 2001). Consequently, the growing emergy actually used (U) in the Andalusian economy is not being primarily supported by local emergy sources as in the past, but increasingly supported by emergy imported from other regions or countries. Calculated values of FUIMP in Andalusian, the 8 provinces, and Spain for the period 1984-2002 are presented in Table 2 for comparison purposes.

Table 2. Fraction of emergy actually used that is imported (FUIMP) for Andalusia and provinces in the studied years.

	Andalusia	Almería	Cádiz	Córdoba	Granada	Huelva	Jaén	Málaga	Sevilla
1984	0.45	0.34	0.62	0.64	0.34	0.11	0.54	0.50	0.30
1989	0.36	0.30	0.68	0.70	0.52	0.17	0.78	0.58	0.36
1994	0.49	0.27	0.77	0.52	0.41	0.10	0.71	0.85	0.57
2000	0.54	0.49	0.76	0.76	0.66	0.49	0.71	0.72	0.62
2002	0.60	0.55	0.77	0.75	0.45	0.66	0.65	0.63	0.85

Source: Lomas *et al.* (2007)

Thus, although Andalusian FUIMP is lower than the Spanish one for the 1989-2000 period (6 % higher for 2002), the increase of the average Andalusian FUIMP for the studied period is 1.94 % annually, slightly higher than the Spanish one (1.09 %). The average Andalusian FUIMP for the studied period is 48 %, in contrast to the provincial average, which is 55 %, as a result of the inter-regional trade influence. In the first part of the period (1984-1994), Almería, Huelva and Sevilla present lower FUIMP values, with percentages under 50 % of U. On the contrary, Córdoba and Jaén show values over 60 %. Paradoxically, in the second part of the studied period (1994-2002) Sevilla becomes the province with the highest value (85 %), Córdoba the one with the highest average decreasing rate of FUIMP (more than 1.10 % annually), and Huelva the province with the highest average increase rate of FUIMP (almost 17.2 % annually).

In this case, the differential patterns of FUIMP can be explained by two main factors: an actual growth of IMP in U, or an increase or high dependence on local non-renewable emergy sources. FUIMP low values on the first part of the studied period in Almería, Huelva and Sevilla can be explained by the intensive exploitation of N, therefore, a coupling between systems based on the intensive use of local non-renewable supply services, especially linked to mining. On the contrary, high values of Córdoba and Jaén have different explanations. First of all, the relative low values of N, derived from the extensive agricultural orientation of the respective economies. And second, as a consequence of the circumstantial low values of R, related to the R dependence of these inland provinces on the high variability of rain, in a Mediterranean region like Andalusia. On the contrary, in the second part of the studied period Huelva, Sevilla, Málaga and Cádiz increase their respective FUIMP by an intensification of the economy linked to the increase of emergy import of natural capital in the form of economic goods and services, presenting a high economic decoupling from local ecosystems. Sevilla, the most severe case, reaches the 85 % of dependence on outside emergy. In contrast, Córdoba and Jaén present a more balanced growth in U, although FUIMP values continue to be high (between 65-75 %).

4.3. FUIMP as an indicator of decoupling

FUIMP seems to be a good indicator of the economic decoupling from local ecosystem services in terms of emergy used in a specific territory. However, it has two main inconveniences.

The first lies in the difficulties to capture the proportion of coupled systems due to intensive exploitation of local but non-renewable sources of emergy. In this case, the use of ELR, as an indicator of the site's development distance respect to the expected ecosystem functioning, may be suitable. This problem confirms that the tightest coupling between local natural capital and the socio-economic system is not always the best option to achieve sustainability, especially if this SES coupling is based on the intensive use of local non-renewable emergy sources in a context of stocks depletion, as in the case of some Andalusian provinces. This aspect had already been suggested by Folke *et al.* (2007) in the context of adaptive capacity and institutions, and by Odum and Odum (2001) in the context of the meaning of some emergy indicators (EYR).

The second inconvenience is linked to the nature of IMP, therefore, the fraction of renewable emergy contained on the IMP flow. Although IMP is generally considered as a non-renewable flow due to its origin, it is not always true that the IMP nature is completely non-renewable. This problem is often originated by the poor disaggregation in the original data collected from statistical offices and researchers, especially by the general lack of detailed information related to inter-regional trade of commodities, energy and raw materials. This information does not permit the separation of renewable and non-renewable flows of IMP.

Thus, it seems necessary to include other emergy indicators in order to capture more aspects of the economic decoupling from the local ecosystems. Furthermore, other dimensions of the decoupling patterns (cultural, social, political, etc.) could be capture by different methodologies in a multi-criteria assessment.

5. CONCLUSION

We used emergy synthesis to study main patterns of emergy use for Andalusia and its provinces in the Spanish context. Our results showed that some aspects of decoupling dynamics between social and ecological components in SES seem to be determined by the presence of functional mismatches between local management of emergy sources and national or international economic globalization patterns. Labour division at a national level or the creation of scale economies, consisting on the specialization of some regions or areas in particular functions at national scale appear to be extremely important to determine such decoupling process.

In this sense, Andalusia was increasingly adopting the role of supplier of raw materials at the national scale. Furthermore, our results showed that this process was not homogeneous as a consequence of the privileged location of some provinces to connect to the global trade through the sea, and the ancient property regime institution.

Emergy indicators contributed to understand temporal and spatial patterns in the use of some ecosystem services at the SES level, and the interaction with other scales. The indicator evaluated was sensitive to ecological-economic decoupling. However, it has shortcomings to detect coupled SES mainly depending on flows of local non-renewable sources, or import flows linked to foreign renewable sources. Other indicators seem to be complementary in this sense (e.g. ELR, EYR) in a multicriteria framework.

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3.5. Agricultural systems and wetlands conservation: The case of rice cultivation in the Guadalquivir marshes (SW Spain).

Pedro L. Lomas, Sergio Álvarez, Marta Rodríguez, Carlos Montes.

Resumen

La asociación entre agricultura y humedales ha sido recurrente en el contexto mediterráneo. La industrialización experimentada por muchos cultivos desde los años 50, y el interés actual sobre los humedales como fuente de servicios de los ecosistemas han provocado numerosos problemas, consecuencia de los intereses opuestos entre conservación y agricultura.

Este artículo tiene como objetivo estudiar el papel potencial del cultivo de arroz para la conservación de humedales, usando como caso de estudio el parque nacional de Doñana, en las marismas del Guadalquivir (SO España). Con este propósito, se ha examinado el cambio en la contribución tanto de los ecosistemas como del sistema económico a la producción del arroz en el área a través de la síntesis emergética para el último siglo. Los resultados muestran que la integración de objetivos ambientales en la producción arrocera ha permitido disminuir los costes ambientales de la producción del arroz en las marismas del Guadalquivir. Al mismo tiempo, los resultados de los indicadores emergéticos confirman que el grado de perturbación humana en el cultivo del arroz es más cercano al funcionamiento original de las marismas del Guadalquivir que el de otras formas más intensivas de agricultura presentes en el área. Esto nos permite concluir que los arrozales, gestionados adecuadamente, pueden ser pensados como una buena opción de implementación agrícola en humedales, o como un buen punto de partida para futuras restauraciones en muchas marismas mediterráneas.

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AGRICULTURAL SYSTEMS AND WETLANDS CONSERVATION: THE CASE OF RICE CULTIVATION IN THE GUADALQUIVIR MARSHES (SW SPAIN).

Pedro L. Lomas, Carlos Montes.

Social-Ecological Systems Laboratory, Department of Ecology, c. Darwin, 2, Edificio de Biología, Universidad Autónoma de Madrid, Madrid 28049, Spain.

Abstract

Association between agriculture and wetlands has been traditional in the Mediterranean Basin. Industrialization experienced by many crops from 1950s and the recent interest for wetlands as a source of ecosystem services have caused several problems as a consequence of the opposed interests between conservation and agriculture.

This paper aims to study the potential role of rice cultivation for wetlands conservation by using the Doñana National Park, in the Guadalquivir marshes (SW Spain), as a case study. With this purpose, we have examined changes in the total work contributions by both natural and economic systems to rice production in the area by means of emergy synthesis for the last century. The results show that integrated environmental objectives in agricultural production have allowed diminishing the environmental costs of rice production in the Guadalquivir marshes. At the same time, results on emergy indicators confirm that the degree of human disturbance for rice cultivation is now closest to the original wetlands functioning than other intensive forms of agriculture present in similar areas. We conclude that rice paddies, if properly managed, could be thought as a good option for implementation of agriculture in wetlands, or as a good starting point for future ecological restorations in many Mediterranean marshlands.

Keywords: Emergy synthesis; rice cultivation; wetlands conservation; Guadalquivir marshes; Mediterranean Basin.

1. INTRODUCTION

During the later twentieth century, public attitude towards wetlands has dramatically changed as a result of several studies that revealed the links between human well-being and the ecosystem services of wetlands. Thus, the crucial role of wetlands in providing ecosystem services essential for human social, economic and cultural activities (freshwater, food, plants, animals, raw materials and communication routes) is nowadays widely recognized, together with the fact that productivity in agricultural systems depends on numerous species, and that agricultural systems sometimes are important ecosystems for different species, promoting biodiversity (IUCN/WBCSD, 2008). But this situation has been the result of an historic process in which wetlands were not always conceived as ecosystem services providers but like useless and insalubrious lands to be reclaimed or drained for productive purposes. As a consequence, more than 50 % of wetlands were transformed in Australia, Europe, New Zealand and North America since 1900 (MA, 2005). From 1950s, this transformation process started to be significant in tropical and sub-tropical wetlands too (Finlayson and Davidson, 1999). An important effect of this process has been the loss of biodiversity and the subsequent reduction in ecosystem services for humans due to this loss of area and the deterioration in wetlands conditions.

The Mediterranean Basin has been one of the most affected areas by wetlands transformation processes (Zedler and Kercher, 2005) as a consequence of two main reasons: (1) the relative scarcity of plain lands to cultivate in most of Mediterranean countries, and (2) the high unpredictability of rainfall in the Mediterranean climate, which turned wetlands into reservoirs of freshwater (Cruz, 1994). According to the MedWet initiative within the Ramsar Convention almost 73% of the marshes in northern Greece have been drained since 1930; 86% of the 78 most important wetlands in France were degraded in the thirty years to 1994; Spain has lost an estimated 60% of its original wetland area; and 15% of the area of lakes and marshes in northern and central Tunisia were lost between 1881 and 1987 (MedWet, 1996).

Some of these early transformation experiences initially failed because of the lack of the adequate knowledge and technology or due to their speculative purposes. But after the Second World War this situation changed, and national, regional and local authorities encouraged farmers through subsides to drain wetlands in order to increase agricultural output (Acreman *et al.* 2007), so that the process of wetlands transformation for agricultural reasons was accelerated.

However, an international movement for protection of wetlands encouraged by the Ramsar Convention on Wetlands (1971) was born motivated by the negative effects of these transformations. Thus, as a consequence of the protection of many wetlands (more than 1840 of them are Ramsar Sites today), a competition between wetlands and agriculture for lands (drainage for productive purposes *versus* protection for conservation) started. With the consolidation of conservation policies and protected areas, this threat was being gradually moved to the competition for another ecosystem services, especially for quality and quantity of freshwater (Brinson and Malváez, 2002). This situation has often turned into an open conflict between these two ways of understanding wetlands, sometimes resulting in both frustration of agricultural development policies and environmental problems derived from the intensive exploitation of remaining cultivation lands.

Associated to this crisis, and under the framework of ecosystem services and Ramsar wise-use, the focus on wetlands has been to re-establish their original characteristics and associated functions as a form to guarantee a continuous and a diverse flow of ecosystem services (Ramsar, 2000; MA, 2005; Zedler and Kercher, 2005; Acreman *et al.* 2007). In this sense, MA (2005) highlighted the importance of trade-offs among current uses of wetland resources (e.g. agricultural production, conservation) and between current and future uses (e.g. restoration, future agricultural management).

The aim of this paper is to study the role of agriculture (rice cultivation) for wetlands conservation by using as a case study the Guadalquivir marshes (SW Spain). To this purpose, we have examined historical changes of work contribution on a common basis in both natural and economic systems to generate rice in the area by means of emergy synthesis (Odum, 1996), and compared the potential human disturbance of this production with respect to the original marshes, and to other Mediterranean crops usually cultivated on wetlands.

2. METHODS

2.1. Study area

The Guadalquivir marshes (Figure 1) are the result of a beach-dune-wetland complex formation process at the mouth of the Guadalquivir River (SW Spain), which drains a catchment area of 57000 km^2 being partially blocked by sandy barriers, and resulting in a large estuary of more than 1800 km^2 (Rodríguez Ramírez *et al.* 1996).

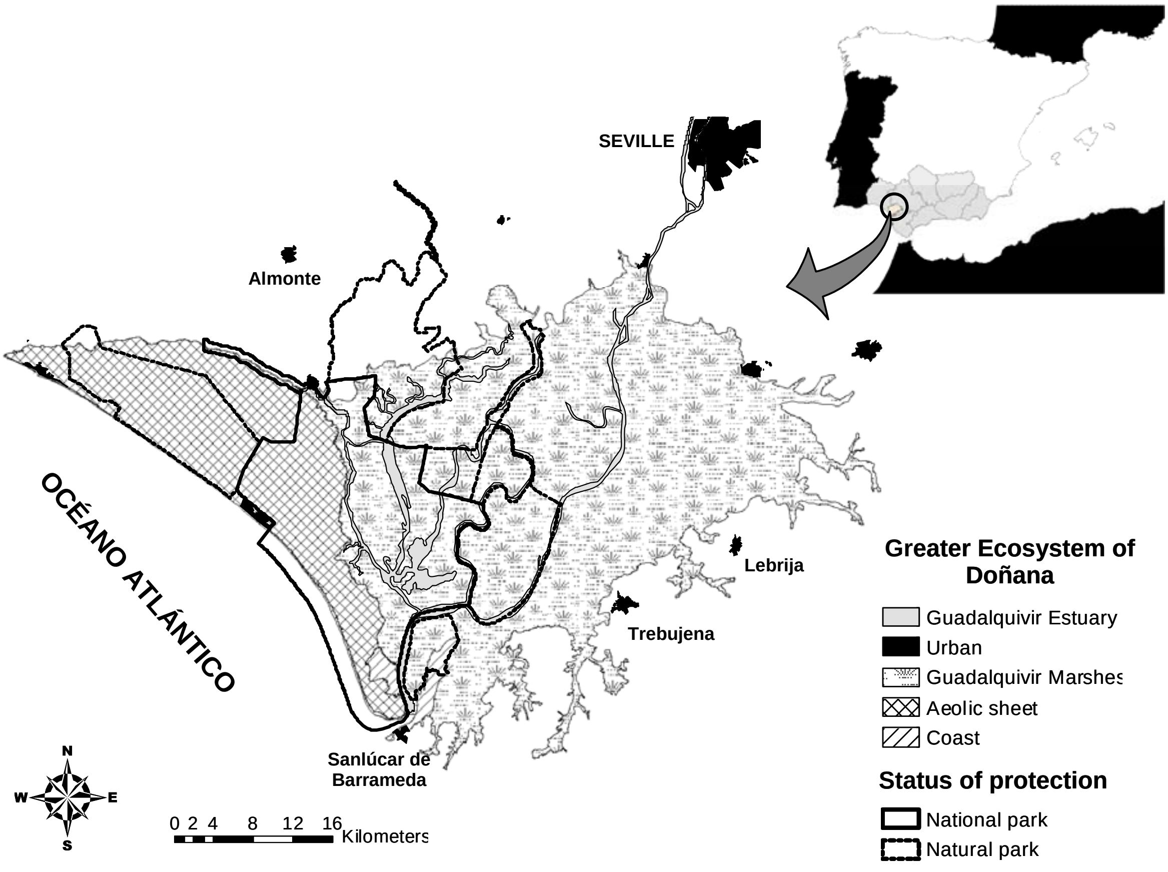

Figure 1.- The Greater Ecosystem of Doñana, with main ecosystems at the Ecodistrict scale.

This estuary forms one of the largest wetlands in Western Europe (García Novo and Marín Cabrera, 2005), internationally known as a migration pathway of birds between Africa and the Palaearctic, and an important over-wintering point for waterfowl. It is partially included, together with part of the dunes and coastal area, in the Doñana National Park (1969), UNESCO Biosphere Reserve (1980), Doñana Ramsar Site (1982), Doñana Natural Park (1989), and UNESCO World Natural Heritage (1994).

Salinity of soils along with the nature of the territory (isolated, marshy, etc.), and the ancient property system, with great portions of the territory (*latifundios*) dedicated to hunting and recreation, traditionally precluded the land reclamation in the Guadalquivir Marshes (Corominas, 1995; González Arteaga, 2005).

Although many works were made on the Guadalquivir River from the 16th century as a consequence of the Seville fluvial port commerce with America, it was not until the late 18th century when the original tidal-fluvial dynamics of the marshes started to be actually altered by river channelization, dikes, etc. (Vanney, 1970; Menanteau, 1984). And then, the increasing marshes isolation from the river tidal-fluvial dynamics due to changes in technology allowed the first agricultural experiences.

2.2. Rice cultivation in the Guadalquivir marshes

It is known that first efforts to cultivate rice in Guadalquivir marshes were made in times of Muslim kingdoms (González Arteaga, 2005), but it was in this context of modernization when cultivation was possible, allowing water withdrawal from river to be distributed by channels to rice paddies and isolating lands from river flooding. Area of rice paddies in the studied years is shown in Figure 2.

Table 1 contains a summary of main phases of rice cultivation in the Guadalquivir marshes in the 20th century. Thus, after some unsuccessful attempts carried out in the 1920s, rice production experienced a first boost during the Spanish civil war (1936-1939) in the so-called “Guadalquivir islands”, at the right margin of the river, but it was not until the 1940s that the rice production system went through a great expansion carried out by private initiative.

Until the 1960s, mechanization of rice farming in the Guadalquivir marshes was poor, and cultivation was supported by a huge quantity of hired labourers, which accounted for 95 % of total production costs per hectare (González Arteaga, 2005). The national trade union of rice farmers facilitated seeds, fertilizers and pesticides to some privileged few farmers. Water for irrigation was raised from the river by pumping stations and distributed by a complex system of channels to the rice paddies.

Table 1. Main phases on rice cultivation techniques in the Guadalquivir marshes.

PERIOD	CHARACTERISTICS
1929-1960	Colonization and first settlements in the area, cultivation of japonica varieties, high dependence on labor hand, cultivation poorly mechanized, governmental guarantee of prices and supply of agro-chemicals (mainly fertilizers). predominance of small properties
1960-1970	Transition period from traditional to industrial agriculture in rice.
1970-1986	Indica varieties start to increase, cultivation, transport and harvesting mechanized, generalized use of agro-chemicals, gradual deregulation of prices, fist problems between conservation and cultivation interests, large properties start to increase.
1986-1998	Growing of indica varieties cultivation. European guarantee of prices, subsidiation, intensive use of agro-chemicals, increasing external imports of rice, strong problems between conservation and cultivation interests (high rate of waterfowl deaths), process of property concentration.
1998-Today	Main cultivation of indica varieties, integrated production based on European agro-environmental mechanisms, know-how and technology to reduce the use of agro-chemicals. strong pressures for concentration of properties.

Source: Sumpsi Viñas (1984); González Arteaga (2005).

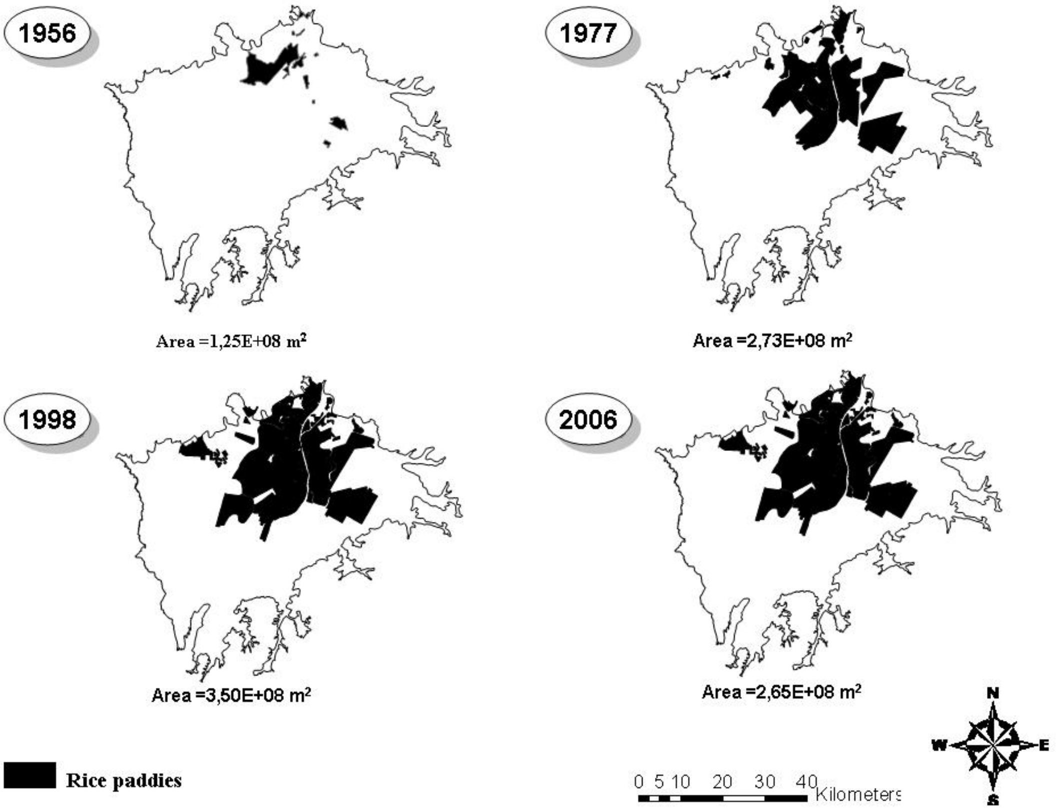

Figure 2.- Area of rice paddies for the studied years in the Guadalquivir marshes context.

Between 1956 and 1977, the governmental National Institute of Colonization (INC) started the transformation of the marshes at the left river margin for agriculture (Grande Covián, 1978). At this time, rice farming techniques suffered a deep transformation, linked to the national economic changes which were taking place in Spain. Cultivation, transport and harvesting were gradually mechanized, so labour-hand lost weight in total costs (less than 45% of total costs in 1973), and the employment of agro-chemicals was generalized. As a result, more than 55 % of the cultivation costs were purchased raw materials (seeds, fertilizers, machinery, pesticides, etc.).

Rice surface area experienced a second boost in the period between 1980 and 1991. There was a land property concentration trend together with an increase in mechanisation, direct seeding, and the use of chemicals. This reorientation of the production system, was forced in the late 1970s by the then decreasing international rice prices, the growing surplus, the fixed guaranteed prices and the increases in labour costs (Iglesias *et al.* 2004).

But this period of huge growth allowed farmers to clearly perceive some of the main limitations of rice farming in the Guadalquivir marshes in environmental and economic terms. In environmental terms, the partial protection of Doñana marshes as a national park in 1969 together with the international recognition of the Doñana natural values put a stop to the land reclamation processes in the area and implied higher controls in quantity and quality of water. Furthermore, the drought experienced for some years (especially 1983, 1989, 1992, 1993, and 1994) prevented cultivation on the whole area of rice paddies.

In economic terms, Spanish entry into the European Economic Community (1986) supposed an initial injection of money by subsidies, but the later acceptance of international trade liberalization of rice established by the GATT/WTO, and the latest EU-CMO reforms in farm subsidies and prices implied a high degree of uncertainty about rice cultivation.

Finally, the European Regulation 2078/92 opened the way to integrate environmental objectives in farming practices. Under this institutional framework, an integrated crop management programme is being implemented in the Guadalquivir marshes from 1998 to nowadays, supported by the EU Common Agricultural Policy. Its implementation has allowed significant improvements in input efficiency while maintaining or even increasing rice yields. According to the FAS (Sevillian Rice Farmers Federation) almost 100 % of the rice paddies participate in this framework.

2.3. Emergy evaluation procedure for rice cultivation

Emergy basis of agricultural systems have been treated with more detail in works such as Odum (1996; 2007), Martin *et al.* (2006), and Rydberg and Haden (2006). What follows is a brief description of the methods used in performing the analyses specific to this paper.

1. Definition of boundaries. The Guadalquivir marshes have been defined at ecodistrict scale (Klinj and Udo de Haes, 1994), in accordance with the hierarchical classification of the Greater Doñana ecosystem established by Montes *et al.* (1998) to the National Park, and extended to the whole area at ecosection scale in Lomas *et al.* (2007) as it is shown in Figure 1.

2. Energy systems diagramming to obtain an overview of the rice cultivation system, its parts and processes, using the energy language (Odum, 1994). The emergy system diagram is shown in Figure 3.

3. Development of an emergy evaluation table with main emergy flows for main periods of rice cultivation in the Guadalquivir marshes.

   All the transformities used in this work were referred to the 15.83E+24 seJ/yr baseline (Odum *et al.* 2000). Under the most accepted criteria to avoid double-counting of solar co-products in this baseline framework, the renewable emergy flow (R) has been calculated by using the largest inflowing emergy of renewable ones. The transformities used in this work include labour and services required to produce economic goods. The transformities for rice production do not include inputs required for transport and, if necessary, drying, and only represent the amount of inputs required to generate a harvested product on the farm.

In the Guadalquivir marshes most of water for irrigation is taken from the river. Just a little part is pumped from the Doñana aquifer, and the rate of extractions is lower than the renewal rate, so water for irrigation is included between the renewable sources.

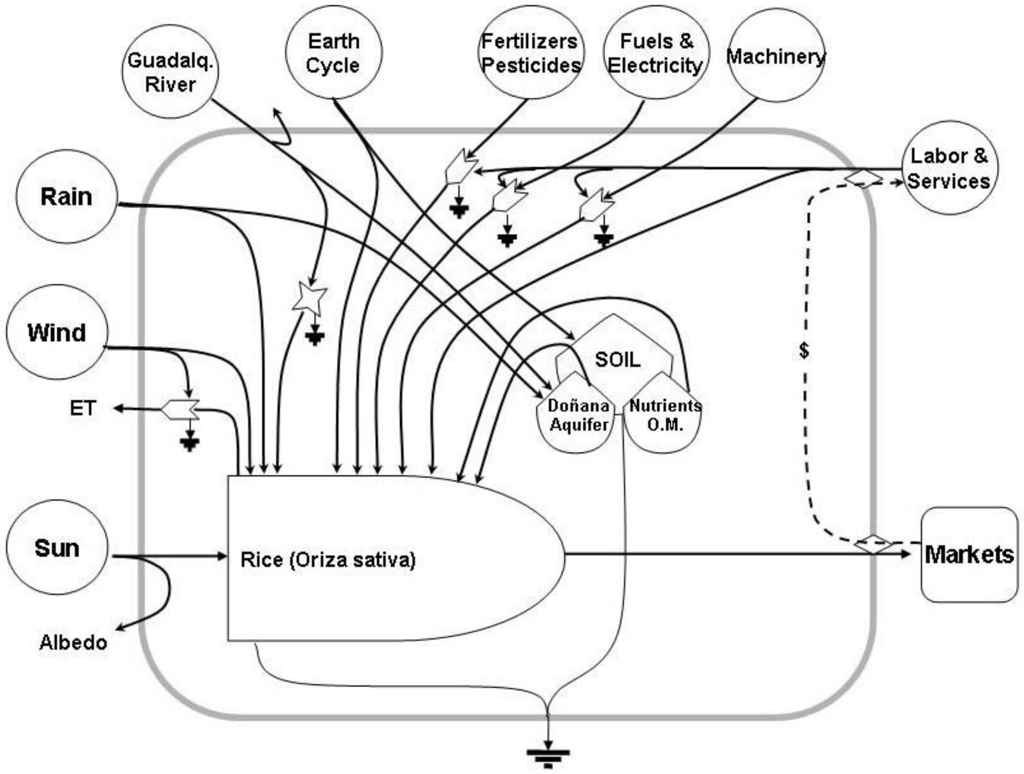

Figure 3.- Energy diagram for rice cultivation in the Guadalquivir marshes.

4. Flow aggregation and development of emergy indicators of performance. Using the summarized version of the emergy diagram, it is possible to aggregate the items and calculate relationships between them in order to evaluate specific aspects of the system.

5. Emergy indicators have been employed to analyze the performance and the potential human disturbance gradient of rice cultivation system in the Guadalquivir marshes. In particular, non-renewable fraction of areal empower intensity (seJ*m^{-2}*yr^{-1}) has been used to calculate a landscape development intensity index (LDI), as defined by Brown and Vivas (2005) for Florida. The

LDI has been calculated as follows:

$$LDI_{total} = \sum \% LU_i * LDI_i$$

Where

LDI_{TOTAL} = LDI ranking for landscape unit.

$\%LU_i$ = percent of the total area of influence in land use i.

LDI_i = landscape development intensity coefficient for land use i. The LDI_i coefficients are calculated as the normalized (on a scale of 1.0 to 10.0) natural logarithm of the empower densities.

3. RESULTS

3.1. Rice cultivation in the Guadalquivir marshes: Contribution of the different emergy flows

Table 2 shows main emergy flows of rice cultivation in the Guadalquivir marshes for the studied period.

The largest inflowing emergy renewable source supporting rice cultivation in the Guadalquivir marshes (R) is the river water used for irrigation (1.21E+16 seJ/ha*yr). As mentioned before, relative high recurrence of drought has prevented all the rice paddies area to be cultivated for some years, but the water for irrigation has not been a problem in the years chosen for the study. The water emergy used for irrigation is related to the increase in the area of rice cultivation. Thus, renewable emergy used increased at a rate of 5.64 % annual in the first period, and more than 1.5 % in the second one, being reduced at a rate of 3 % annually in the last period. The increase of emergy used from local ecosystem non-renewable services (N) in the form of soil erosion and used organic matters has been parallel to the area of marshes involved by the rice cultivation too, and present the same annual change rates than R.

Table 2. Main emergy flows for rice cultivation in the Guadalquivir marshes (1956-2006).

	Flow	**Expression in Figure 4**	**Solar emergy 1956**		**Solar emergy 1977**		**Solar emergy 1998**		**Solar emergy 2006**	
			(seJ/yr)	**(seJ/ha*yr)**	**(seJ/yr)**	**(seJ/ha*yr)**	**(seJ/yr)**	**(seJ/ha*yr)**	**(seJ/yr)**	**(seJ/ha*yr)**
1	Renewable sources	R	1.51E+20	1.21E+16	3.29E+20	1.21E+16	4.22E+20	1.21E+16	3.19E+20	1.21E+16
2	Local non-renewable sources	N	8.88E+17	7.10E+13	1.94E+18	7.10E+13	2.49E+18	7.10E+13	1.88E+18	7.10E+13
3	Purchased goods	G	2.89E+19	2.31E+15	1.69E+20	6.18E+15	1.59E+20	4.53E+15	1.00E+20	3.78E+15
	- Commercial fuels	G1	1.18E+19	9.41E+14	6.96E+19	2.55E+15	7.72E+19	2.21E+15	5.30E+19	2.00E+15
	- Goods for cultivation	G2	1.70E+19	1.36E+15	9.46E+19	3.47E+15	7.70E+19	2.20E+15	4.15E+19	1.57E+15
	- Farm assets	G3	1.02E+17	8.17E+12	4.36E+18	1.60E+14	4.28E+18	1.22E+14	5.71E+18	2.16E+14
4	Purchased labor and services	S	1.10E+20	8.83E+15	3.75E+20	1.37E+16	3.98E+20	1.14E+16	3.26E+20	1.23E+16
	- Labor	S1	3.78E+19	3.03E+15	3.75E+19	1.38E+15	3.98E+19	1.14E+15	1.51E+19	5.71E+14
	- Services	S2	7.25E+19	5.80E+15	3.38E+20	1.24E+16	3.58E+20	1.02E+16	3.11E+20	1.17E+16
5	Emergy used (with services)	Y	2.91E+20	2.33E+16	8.75E+20	3.21E+16	9.81E+20	2.80E+16	7.47E+20	2.82E+16

Sources: see calculations in Appendix 1

Respect to the purchased goods (G) that contribute to the crop production, the first period was characterized by an average annual increase of more than 23 % in the emergy used from this origin. Thus, the emergy linked to machinery (G3) used in 1 ha increased more than 88 % annually. And, as a consequence, the use of emergy attributable to fuels (G1) is intensified, and grew with a rate of 8.15 % annually per hectare. At the same time, the use of the emergy derived from fertilizers, pesticides and seeds (G2) grew at a rate of 7.34 % annually per hectare. In the second period, solar emergy from purchased goods slightly decreased at a rate of 0.28 % annually (1.27 % per hectare), especially pesticides and fertilizers. Finally, the third period implied an annual decreasing rate of 4.60 % in the total solar emergy of purchased goods used, and consequently 2.06 % of solar emergy annual reduction per hectare.

There is a significant reduction in the human labour (L) employed per hectare for all the studied period, -2.60% and -6.2 % of decreasing in the solar emergy attributable to human labour in the rice cultivation for the 1956-1077, and the 1998-2006 periods, respectively. It has been compensated by the growth in the use of emergy from other services (S) for the first period, which presented an increase of 5.40 % in the emergy incorporated to the rice cultivation via services per hectare until the second period. After 1977, there was a slight decreasing period (0.82 % annually), followed by the last period, in which the use of emergy associated to services continues growing at a rate of 1.83 % annually.

3.2. Rice cultivation in the Guadalquivir marshes: Used emergy and unit emergy values

Table 3 shows total emergy used and unit emergy values for rice cultivation in the Guadalquivir marshes.

Table 3. Main emergy indicators for rice cultivation in the Guadalquivir marshes (1956-2006).

	Indicator	Calculation refer to Figure 4	1956	1977	1998	2006	Annual changes 1956-1977 (%)	Annual changes 1977-1998 (%)	Annual changes 1998-2006 (%)
1	Transformity of rice (seJ/J)	-	2.39E+05	3.65E+05	2.30E+05	2.60E+05			
2	Specific emergy of rice (seJ/g)*	-	3.58E+09	5.47E+09	3.45E+09	3.89E+09	2.52	-1.76	0.62
3	Transformity of rice residues (seJ/J)	-	1.47E+05	2.25E+05	1.41E+05	1.60E+05			
4	Specific emergy of rice residues (seJ/g)*	-	2.24E+09	3.42E+09	2.16E+09	2.43E+09			
5	Fraction of emergy used that is free	(R+N)/Y	0.52	0.38	0.43	0.43	-1.31	0.68	-0.03
6	Fraction of emergy used that is purchased	G+S/Y	0.48	0.62	0.57	0.57	1.42	-0.42	0.02
7	Fraction of emergy used that is renewable	R/Y	0.52	0.38	0.43	0.43	-1.31	0.68	-0.03
8	Emergy Yield Ratio (EYR)	Y/(G+S)	2.09	1.61	1.76	1.75	-1.09	0.46	-0.02
9	Environmental Loading Ratio (ELR)	(N+G+S)/R	0.93	1.66	1.32	1.34	3.73	-0.96	0.06
10	Emergy Investment Ratio (EIR)	(G+S)/(R+N)	0.92	1.64	1.31	1.33	3.76	-0.96	0.06
11	Emergy Sustainability Index (ESI)	EYR/ELR	2.25	0.97	1.33	1.31	-2.71	1.77	-0.08

* Specific emergies for products were calculated by dividing their respective transformities by the calorific value. The average calorific values used were: rice (1498 kJ/100g) from USDA (nutrients database: http://www.nal.usda.gov/fnic/foodcomp/search/); rice straw (15.2 MJ/kg) and rice husk (15.5 MJ/kg) from FAO (1994).

Between 1956 and 1977, the total emergy used for rice production (Y) in the Guadalquivir marshes grew with an annual rate of 1.80 % per hectare. On the contrary, in the second period, Y diminished with a rate of 0.60 % annually per hectare. And finally, despite the declining area of cultivation between 1998 and 2006, the emergy used slightly increased with an annual rate of 0.08 %.

Taking account of this emergy use pattern, the emergy contribution per Joule or gram of rice or residues produced (transformity or specific emergy, respectively) increased in the first period at a rate of 2.52 % annually. The 1977-1998 period was characterized by the decreasing in the emergy employed by unit of energy or mass, at a rate of 1.76 % annually. Finally, the unit emergy values grew with a rate of 1.61 % annually in the last phase (1998-2006).

The emergy used per area occupied is the areal empower intensity or AEI (Brown and Vivas, 2008). Part of this intensity use is related to renewable emergy, and the rest of the intensity to non-renewable sources of emergy. In Figure 4, we compare the different components of the total AEI in the rice cultivation for the studied period.

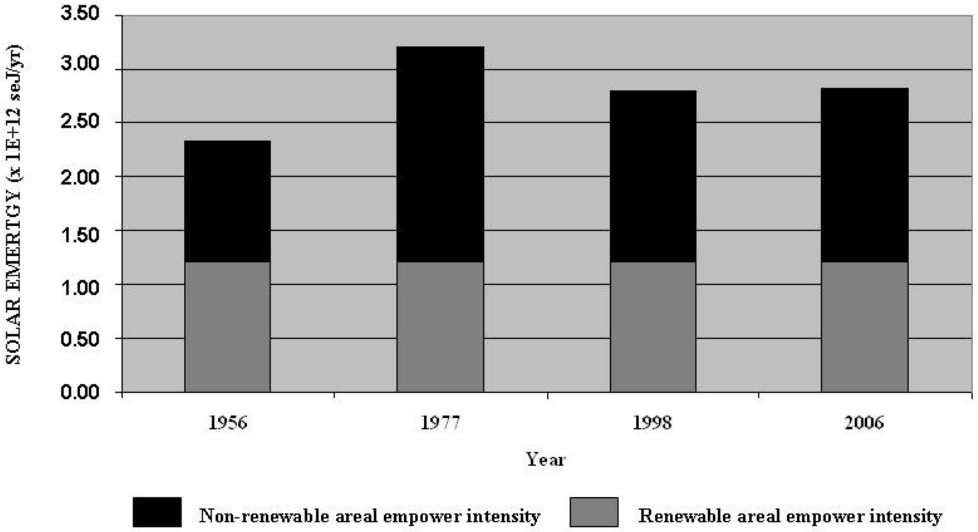

Figure 4.- Areal empower intensity of rice cultivation in the Guadalquivir marshes for the studied years. Part of the column coloured of black represents non-renewable fraction. And the grey part is the renewable part.

Total AEI equals the emergy used per hectare, and present the same pattern of change previously commented. Figure 4 shows that the non-renewable component of the total areal empower intensity has grown to reach more than 62 % in 1977, decreasing to 57 % of total AEI in 2006.

3.3. Rice cultivation in the Guadalquivir marshes: Emergy indicators of performance

Main emergy indicators of performance for rice cultivation in the Guadalquivir marshes are shown in Table 3.

The percentage of emergy contribution to the rice cultivation that comes from local sources (fraction of emergy used that is free) and the fraction of emergy used that is renewable reach a 43 % of total emergy used in 2006, after suffering a clear decreasing pattern before 1977. This decrease was partially neutralized by the subsequent increase with a rate of 0.68 % between 1977 and 1998. Consequently, the fraction of emergy used that is purchased (goods and services) reaches a 57 % in 2006, showing the inverse pattern respect to the local and free emergy used.

The emergy used for rice production per unit of purchased goods invested in the production is computed by the Emergy Yield Ratio (EYR). Between 1956 and 1977 the EYR experienced an annual decrease of 1.09 %. This was partially compensated by the annual increase of 0.46 % showed by the indicator in the period 1977-1998. In the last period (1998-2006), the indicator scarcely decreased 0.06 % annually.

The local non-renewable and purchased emergy used per unit of renewable inflowing emergy to the rice cultivation (Emergy Loading Ratio, ELR) was increased with an annual rate of 3.73 % in the period 1956-1977. There was a reduction of ELR in the second period, at a rate of 0.96 % each year, and a final increase (0.15 % annually) in the third period (1998-2006).

If we compare the ability of the rice production system to exploit and make available local services by investing outside services (EYR) with the distance of the technological development in rice production from the natural processes that could have been developed in the area occupied by the rice paddies (ELR), we obtain the so-called Emergy Sustainability Index (ESI). The ESI decreases at an annual rate of 2.77 % in the first period. In the second period the ESI grows at an annual rate of 1.77 %. The index value is maintained in the third period.

4. DISCUSSION

4.1. Emergy of the rice cultivation in Mediterranean wetlands of Europe

To understand the main characteristics of the rice cultivation model employed to exploit rice paddies in the Guadalquivir marshes within the Mediterranean context, we have compared the patterns of emergy used for rice production in the Guadalquivir marshes with the model employed in other Mediterranean areas in which rice is produced, in particular the Mesta-Nestos Delta in Greece, and the Italian rice production, which is mainly located on the river Po Delta area.

The comparison of main emergy indicators for the three areas of rice cultivation in the Mediterranean Europe is shown in the Table 4.

Table 4. Comparison of main indicators in the rice production for different Mediterranean wetlands of Europe. All transformities have been calculated under the 15.83E+24 seJ/J baseline (Odum *et al.* 2000).

Indicator	Mesta-Nestos Delta (Greece) 2001	Guadalquivir marshes (Spain) 2006	Italy (Po Delta and other Italian wetlands) 1989
Transformity (seJ/J)	1.63E+04	2.60E+05	1.31E+05
R/Y	0.35	0.43	0.26
(G+S)/Y	0.55	0.57	0.72
EYR	3.08	1.75	1.38
ELR	1.16	1.34	2.86
ESI	2.66	1.31	0.48

Sources: Mesta-Nestos Delta (Beerman, 2008); the Guadalquivir marshes (this study), and Italy (Ulgiati *et al.* 1994), assuming that most of rice production in Italy is mainly made on wetlands, especially the river Po Delta.

Regarding to the renewability, the Guadalquivir marshes production present the rice production model with the highest fraction of use that is renewable (43 %), a 17 % higher than the Italian renewability. Italian rice production is the most dependent on purchased goods, and the Guadalquivir marshes present an intermediate position with 57 %, close to the 55 % of purchased goods in the emergy used for rice production in Greece.

The pattern is the same for the rest of the indicators. Thus, the emergy used per unit of emergy invested (EYR) present an intermediate value between the highest of Greece, and the lowest of Italy. At the same time, Italy presents values that exceed the ELR of the Guadalquivir marshes more than two times and the ELR of Mesta-Nestos Delta more than 2.5 times.

If we compare these last figures through the ESI, this indicator suggest that the rice cultivation in the Guadalquivir marshes present intermediate patterns of emergy use between the most rural exploitation of Greece, with a low level of emergy from purchased goods and ELR, and the most industrial production located in Italy, with the highest level of emergy used from purchased goods and ELR.

Following Raugei *et al.* (2005), we can consider transformity as an indicator of a yield ratio, i.e. the total energy requirement per unit of true yield, in emergy terms. The production of rice in the Guadalquivir marshes presents the highest transformity, and doubles the value calculated for the next one, which is the transformity found for rice production in Italian wetlands, and finally, it is the value of the transformity for the Delta located on Greece, with a lower magnitude. It means that the environmental cost for rice in the Guadalquivir marshes is expected to be the highest between the three models of production. In Ulgiati *et al.* (1994), the agricultural system was studied for 1989, so emergy indicators for rice cultivation in Italy were calculated to this year. It could be interesting to have an updated emergy synthesis of rice cultivation in Italy to compare more recent years with the evolution suffered in the Guadalquivir marshes. The magnitude of the transformity calculated in Italy-1989 and Spain-2006 suggest that the transformity of Italy may be higher than the unit emergy value found in the Guadalquivir marshes in a hypothetical comparison made for 2006.

4.2. Evolution of rice cultivation in the Guadalquivir marshes

The patterns of emergy use presented for the 1956-2006 period in the Guadalquivir marshes show that the rice cultivation in the area has suffered an initial period (1956-1977) of transition from the traditional rice farming to the industrial one. In this period, the use of emergy from local renewable and non-renewable sources has been linked to the constant extension in the cultivation area. This was not the case for the emergy from purchased goods and services, which suffered a huge increase derived from the mechanization of farming practices and the increasing use of agro-chemicals. Thus, changes observed in the main emergy indicators calculated for rice cultivation between 1956 and 1977 show a decrease in the ability of the system to exploit local sources by using purchased goods and services, and an increase in the difference between the economic component of the emergy used (Y-R) and the renewable emergy that could have sustained the original functioning of marshes (R).

After this period of fast growth, there was a second period marked by two contradictory phases that seems not to be captured by the extension of the studied interval: 21 years. (1977-1998). The first one was the consolidation phase of the industrial model in rice farming, in which this patterns of growing observed in the preceding period would continue. The second one is the phase that seems to be represented by the 1998 emergy indicators calculated. In this second phase there was a crisis in the industrial model of rice farming, as a consequence of the competition for water between rice and nature protection, and the results of this competition in terms of serious pollution problems at the Doñana national park. Some years of drought and the increasing costs of cultivation provoked the decrease in main indicators of emergy use requirements and environmental loading.

Finally, the third period between 1998 and 2006 was characterized by deep changes on the production model. Most of rice paddies started to be cultivated under the European agro-environmental regulation, with the integration of environmental objectives in the rice production. As it is shown, changes experienced by the integrated production model succeeded in maintaining main emergy indicators of environmental cost in a level close to 1998, without reducing profitability of cultivation for farmers. Transformity value is stabilized around 2.4E+05 seJ/J, the fraction of emergy used from purchased goods in 57 %., and the ESI in 1.31.

There was a reduction on the rice cultivated surface and the partial transformation of these areas on more intensive crops. At the same time, the national park was promoting the restoration of the original hydrological functioning of the Guadalquivir tidal salt-marshes before the huge transformations suffered in the last century for agricultural and navigation purposes. The future of some Mediterranean wetlands in the same situation seems to be linked to this dilemma.

Taking in mind that areas previously compared present different models of production, from more rural to more industrial, we can compare the emergy indicators calculated for rice in the Guadalquivir marshes with those of different crops cultivated on other Mediterranean areas (the Mesta-Nestos Delta and Italy). In particular, we can use the AEI and the derived LDI coefficients of the different crops (Table 5) to understand the intensity of human use of these ecosystems in contrast to their natural functioning.

Table 5. An LDI coefficient for different land uses in the Guadalquivir marshes.

Land use	Non-renewable areal empower intensity (x1E+14 seJ*ha^{-1}*yr^{-1})	Ln (Non-renewable areal empower intensity)	LDI coefficients [range 1-10]	Source
Natural system	0.00	-	1.00	[a]
Natural open water	0.00	-	1.00	[a]
Wheat	47.8	3.87	3.75	[d]
Rice 1956	112	4.72	4.58	[b]
Corn	156	5.05	4.89	[c]
Rice 1998	160	5.08	4.92	[b]
Rice 2006	162	5.09	4.93	[b]
Cotton	172	5.15	4.99	[c]
Beet	176	5.17	5.01	[c]
Rice 1977	200	5.30	5.14	[b]
Sunflower	393	5.97	5.79	[d]

Sources: [a] By definition (explanation in text). [b] This study. [c] Estimated from Beermann (2008). [d] Estimated from Ulgiati *et al.* (1994).

For both agricultural development and future restoration, rice cultivation seems to be one of the best options of agriculture model, because the emergy indicators suggest that rice crop in the Guadalquivir marshes causes intermediate levels of environmental costs, in emergy terms, between the intensive irrigation agriculture, represented by cotton, sunflowers, beet, etc. and cereals (e.g. wheat, corn). In contrast to other opinions (Tilman *et al.* 2001; Wenjun *et al.* 2006), the LDI obtained for rice shows a human disturbance gradient closer to the original marshes than many other crops already cultivated on the area.

5. CONCLUSION

Based on the historical series (1956-2006) of emergy indicators for rice production in the Guadalquivir marshes, we conclude that the integrated production adopted in the last period of exploitation studied has converted industrial farming of rice in a less intensive form of cultivation in the context of an internationally recognized area of natural interest, such as the Guadalquivir marshes.

The comparison of the indicators with those obtained for different areas in the Mediterranean Basin showed that the integrated production in the Guadalquivir marshes present an intermediate level of emergy use between the more industrial Italian model and the more rural Greece one. Furthermore, when comparing rice cultivation in the Guadalquivir marshes with different crops cultivated in the same Mediterranean context, rice was an intermediate option between cereals and other more intensive crops; therefore, more adequate for the relative sustainable exploitation of wetlands in a Mediterranean context.

With regards to the methodology, Emergy synthesis seems to be valid for characterizing changes in the agriculture models beyond purely market interpretations, as a consequence of the integration of environmental and economic information in common basis, a skill that appears to be interesting in a field like agriculture. But, as a consequence of the donor-side nature of the emergy indicators, these conclusions do not took account of the entire life cycle of rice after harvesting, especially relevant aspects related to pollution or emissions. More detailed studies of life cycle assessment with complementary indicators in a multi-criteria framework are recommended to study the problem in depth if we want to solve the dilemma of agriculture in Mediterranean wetlands. In this sense, emergy indicators included in this framework could help to incorporate the ecosystem flows to the crop production in a more integrated approach, as suggested by Ulgiati *et al.* (2006).

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Data and calculations to:

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Content:

Table A. Calculation of emergy flows for rice cultivation in the Guadalquivir marshes 1956.

		Unit	Data 1956 (unit/yr)	Unit emergy value (seJ/unit)	Ref. Trans.	Solar Emergy 1956 (seJ/yr)
a) Renewable inputs						
1	Solar energy	J	2.02E+15	1.00	0	2.02E+15
2	Rain (Chemical potential energy)	J	2.30E+14	3.06E+04	A	7.03E+18
3	Rain (Geopotential energy)	J	5.19E+11	1.76E+04	A	9.14E+15
4	Wind (Kinetic energy used at the surface)	J	3.27E+14	2.52E+03	A	8.24E+17
5	River water (chemical potential)	J	1.86E+15	8.10E+04	A	1.51E+20
6	Earth cycle (thermal energy)	J	2.40E+14	1.20E+04	A	2.89E+18
b) Local non-renewable sources						
7	Net loss of topsoil	J	8.46E+12	1.05E+05	A	8.88E+17
c) Purchased goods						
8	Fuel (Diesel. gasoline)	J	3.83E+13	1.14E+05	B	4.36E+18
9	Electricity	J	2.54E+13	2.91E+05	A	7.40E+18
10	Nitrogen fertilizer (N content)	g	1.31E+09	6.37E+09	A	8.36E+18
11	Phosphate fertilizer (P_2O_5 content)	g	1.15E+09	6.54E+09	A	7.52E+18
12	Potash fertlizer (K_2O content)	g	6.25E+08	1.84E+09	A	1.15E+18
13	Pesticides	g	0.00E+00	2.48E+10	C	0.00E+00
14	Seeds	g	1.25E+09	6.80E+04	A	8.50E+13
15	Machinery and tools	g	9.03E+06	1.13E+10	A	1.02E+17
d) Purchased labor and services						
16	Labor	US$	1.84E+06	2.06E+13	D	3.78E+19
17	Services	US$	3.52E+06	2.06E+13	D	7.25E+19
e) Outputs						
18	Rice grain (with services)	g	8.13E+10	3.58E+09	D	2.91E+20
19	Rice (residues)	g	1,30E+11	2,24E+09	D	2,91E+20
20	Monetary output	US$	8,76E+06	2,06E+13	D	1,81E+20

Sources: Notes to Table A.

Table B. Calculation of emergy flows for rice cultivation in the Guadalquivir marshes 1977.

		Unit	Data 1977 (unit/yr)	Unit emergy value (seJ/unit)	Ref. Trans.	Solar Emergy 1977 (seJ/yr)
a) Renewable inputs						
1	Solar energy	J	4,41E+15	1,00	0	4,41E+15
2	Rain (Chemical potential energy)	J	5,65E+14	3,06E+04	A	1,73E+19
3	Rain (Geopotential energy)	J	5,83E+11	1,76E+04	A	1,03E+16
4	Wind (Kinetic energy used at the surface)	J	7,14E+14	2,52E+03	A	1,80E+18
5	River water (chemical potential)	J	4,07E+15	8,10E+04	A	3,29E+20
6	Earth cycle (thermal energy)	J	5,25E+14	1,20E+04	A	6,30E+18
b) Local non-renewable sources						
7	Net loss of topsoil	J	1,85E+13	1,05E+05	A	1,94E+18
c) Purchased goods						
8	Fuel (Diesel. gasoline)	J	4,83E+14	1,14E+05	B	5,50E+19
9	Electricity	J	5,04E+13	2,91E+05	A	1,47E+19
10	Nitrogen fertilizer (N content)	g	5,16E+09	6,37E+09	A	3,29E+19
11	Phosphate fertilizer (P_2O_5 content)	g	6,28E+09	6,54E+09	A	4,11E+19
12	Potash fertlizer (K_2O content)	g	1,64E+09	1,84E+09	A	3,02E+18
13	Pesticides	g	7,11E+08	2,48E+10	C	1,76E+19
14	Seeds	g	2,73E+09	6,80E+04	A	1,86E+14
15	Machinery and tools	g	3,86E+08	1,13E+10	A	4,36E+18
d) Purchased labor and services						
16	Labor	US$	2,40E+06	1,56E+13	D	3,75E+19
17	Services	US$	2,16E+07	1,56E+13	D	3,38E+20
e) Outputs						
18	Rice grain (with services)	g	1,60E+11	5,47E+09	D	8,75E+20
19	Rice (residues)	g	1,60E+11	3,13E+09	D	5,00E+20
20	Monetary output	US$	3,20E+07	1,56E+13	D	5,00E+20

Sources: Notes to Table B.

Table C. Calculation of emergy flows for rice cultivation in the Guadalquivir marshes 1998.

		Unit	Data 1998 (unit/yr)	Unit emergy value (seJ/unit)	Ref. Trans.	Solar Emergy 1998 (seJ/yr)
a) Renewable inputs						
1	Solar energy	J	5,65E+15	1,00	0	5,65E+15
2	Rain (Chemical potential energy)	J	5,81E+14	3,06E+04	A	1,78E+19
3	Rain (Geopotential energy)	J	4,68E+11	1,76E+04	A	8,24E+15
4	Wind (Kinetic energy used at the surface)	J	9,15E+14	2,52E+03	A	2,31E+18
5	River water (chemical potential)	J	5,21E+15	8,10E+04	A	4,22E+20
6	Earth cycle (thermal energy)	J	6,73E+14	1,20E+04	A	8,08E+18
b) Local non-renewable sources						
7	Net loss of topsoil	J	2,37E+13	1,05E+05	A	2,49E+18
c) Purchased goods						
8	Fuel (Diesel. gasoline)	J	3,99E+14	1,14E+05	B	4,54E+19
9	Electricity	J	1,09E+14	2,91E+05	A	3,19E+19
10	Nitrogen fertilizer (N content)	g	6,09E+09	6,37E+09	A	3,88E+19
11	Phosphate fertilizer (P_2O_5 content)	g	4,83E+09	6,54E+09	A	3,16E+19
12	Potash fertlizer (K_2O content)	g	0,00E+00	1,84E+09	A	0,00E+00
13	Pesticides	g	2,68E+08	2,48E+10	C	6,64E+18
14	Seeds	g	5,25E+09	6,80E+04	A	3,57E+14
15	Machinery and tools	g	3,78E+08	1,13E+10	A	4,28E+18
d) Purchased labor and services						
16	Labor	US$	6,05E+06	6,57E+12	D	3,98E+19
17	Services	US$	5,45E+07	6,57E+12	D	3,58E+20
e) Outputs						
18	Rice grain (with services)	g	2,85E+11	3,45E+09	D	9,81E+20
19	Rice (residues)	g	2,85E+11	2,05E+09	D	5,83E+20
20	Monetary output	US$	4,55E+11	2,16E+09	D	9,81E+20

Sources: Notes to Table C.

Table D. Calculation of emergy flows for rice cultivation in the Guadalquivir marshes 2006.

		Unit	Data 2006 (unit/yr)	Unit emergy value (seJ/unit)	Ref. Trans.	Solar Emergy 2006 (seJ/yr)
a) Renewable inputs						
1	Solar energy	J	4,28E+15	1,00	0	4,28E+15
2	Rain (Chemical potential energy)	J	7,60E+14	3,06E+04	A	2,32E+19
3	Rain (Geopotential energy)	J	8,09E+11	1,76E+04	A	1,43E+16
4	Wind (Kinetic energy used at the surface)	J	6,92E+14	2,52E+03	A	1,75E+18
5	River water (chemical potential)	J	3,94E+15	8,10E+04	A	3,19E+20
6	Earth cycle (thermal energy)	J	5,09E+14	1,20E+04	A	6,11E+18
b) Local non-renewable sources						
7	Net loss of topsoil	J	1,79E+13	1,05E+05	A	1,88E+18
c) Purchased goods						
8	Fuel (Diesel. gasoline)	J	3,02E+14	1,14E+05	B	3,43E+19
9	Electricity	J	6,40E+13	2,91E+05	A	1,87E+19
10	Nitrogen fertilizer (N content)	g	3,84E+09	6,37E+09	A	2,45E+19
11	Phosphate fertilizer (P_2O_5 content)	g	1,83E+09	6,54E+09	A	1,20E+19
12	Potash fertlizer (K_2O content)	g	0,00E+00	1,84E+09	A	0,00E+00
13	Pesticides	g	2,03E+08	2,48E+10	C	5,04E+18
14	Seeds	g	4,51E+09	6,80E+04	A	3,07E+14
15	Machinery and tools	g	5,06E+08	1,13E+10	A	5,71E+18
d) Purchased labor and services						
16	Labor	US$	2,23E+06	6,78E+12	D	1,51E+19
17	Services	US$	4,58E+07	6,78E+12	D	3,11E+20
e) Outputs						
18	Rice grain (with services)	g	1,92E+11	3,89E+09	D	7,47E+20
19	Rice (residues)	g	1,92E+11	2,20E+09	D	4,21E+20
20	Monetary output	US$	3,07E+11	2,43E+09	D	7,47E+20

Sources: Notes to Table D.

Table A. Emergy evaluation of rice cultivation in the Guadalquivir marshes - 1956.

RENEWABLE SOURCES:

1. SOLAR ENERGY

Farmed area= 1.25E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Insolation = 5.10 kWh/m^2/yr (IGN, 1996).
Albedo of rice fields = 0.12 (Rapport *et al.* 2002).

Solar energy = 5.10 kWh/m^2/yr x 1.25E+8 m^2 x 3.6E+6 J/kWh x (1-0.12) = 2.02E+15 J/yr.
Transformity = 1.00 by definition (Odum, 1996 updated).

2. RAIN (CHEMICAL POTENTIAL)

Farmed area= 1.25E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Precipitation rate = 0.49 m (provided by the Spanish meteorological agency, AEMET).
Actual evapotranspiration rate = 0.37 m. According to ITGME-JA (1998), a 76 % of total rainfall.
Gibbs free energy of water (G) = (RT/w) x Ln (C2/C1) = 4.94 J/g.
R= 8.33 J/mol x ºC; T= 300 ºC; W = 18 g/mol H_2O; C1= 965 ppm on sea water; C2= (1E+6-1E+1) ppm from rainfall.
Water density = 1.00E+6 g/m^3.

Rain (Chemical potential energy) = 1.25E+8 m^2 x 0.37 m/yr x 1.00E+6 g/m^3 x 4.94 J/g = 2.30E+14 J/yr
Transformity = 3.06E+4 seJ/J (Odum, 1996 updated).

3. RAIN (GEOPOTENTIAL)

Farmed area= 1.25E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Precipitation rate = 0.49 m (provided by the Spanish meteorological agency, AEMET).
Runoff rate = 0.12 m. According to ITGME-JA (1998), a 24 % of total rainfall.
Average elevation = 3.6 m (García *et al.* 1993).
Water density = 1.00E+6 g/m^3.
Gravity (g) = 9.8 m/s^2.

Rain (Geopotential energy) = 1.25E+8 m^2 x 0.12 m x 1.00E+6 g/m^3 x 3.6 m x 9.8 m/s^2 = 5.19E+11 J/yr.
Transformity = 1.76E+4 seJ/J (Odum, 1996 updated).

4. WIND (KINETIC ENERGY USED AT SURFACE)

Farmed area= 1.25E+8 m^2 ((Zambrana Pineda and Ríos Jiménez, 2006).
Average wind speed = 2 m/s (CICE, On-line).
Geostrophic wind = (10/6)*wind speed (Reiter, 1969) = 2.83 m/s.
Dragg coefficient = 3.00E-3 (Garratt, 1977).
Air density = 1.225 kg/m^3.

Wind (kinetic energy used at surface) = 2.83 m/s x 1.25E+8 m^2 x 3.00E-3 x 1.225 kg/m^3 x 365 days/yr x 24 hours/day x 60 minutes/hour x 60 seconds/minute = 3.27E+14 J/yr.
Transformity = 2.53E+3 seJ/J (Odum, 1996 updated).

5. RIVER WATER FOR IRRIGATION

Water used = 3.86E+8 m^3/yr. Assuming a water withdrawal of 3.5 l/s/ha; 1/3 of losses by channel system failure, infiltration, etc.; 5 months of irrigation (Del Moral, 1992); 1.25E+8 m^2 of farmed area (Zambrana Pineda and Ríos Jiménez, 2006).
Gibbs free energy of river water (G) = (RT/w) x Ln (C2/C1) = 4.83 J/g.
R= 8.33 J/mol x ºC; T= 300 ºC; W = 18 g/mol H_2O; C1= 965 ppm on sea water; C2= (1E+6-850) ppm from rain water.
Water density = 1.00E+6 g/m^3.

Energy from river water for irrigation = 3.86E+8 m^3/yrx 1.00E+6 g/m^3 x 4.83 J/g = 1.86E+15 J/yr.
Transformity = 8.10E+4 seJ/J (Odum, 1996 updated).

6. EARTH CYCLE (THERMAL ENERGY)

Farmed area= 1.25E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Heat flow = 1.92E+6 J/m^2/yr (Fernández *et al.* 1998).

Earth cycle (thermal energy) = 1.25E+8 m^2 x 1.92E+6 J/m^2/yr = 2.40E+14 J/yr.
Transformity = 1.20E+4 seJ/J (Odum, 1996 updated).

LOCAL NON-RENEWABLE SOURCES:

7. NET LOSS OF TOPSOIL

Farmed area= 1.25E+2 km^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Erosion rate (average for the Guadalquivir Valley) = 119.7 t/ km^2 (Soto, 1990).
Organic matter = 0.025 (percentage of organic matter in soil given as decimal) (Aguilar Portero, 2007).

Energy from organic matter loss = 119.7 t/ km^2/yr x 1.25E+2 km^2 x 1E+6 g/t x 5.4 kcal/g of organic matter x 4186 J/kcal= 8.46E+12 J/yr.
Transformity = 1.05E+5 seJ/J (Odum, 1996 updated).

PURCHASED GOODS:

8. FUELS

Total use = 3.83E+13 J/yr.
Assuming 0.1875 L/CV/hour (Campos and Naredo, 1980); average power = 45 CV (Campos and Naredo, 1980); 9 hours of use/ha (Sumpsi Viñas, 1980); 9655 kcal/L of diesel; 1.25E+8 m^2 of farming area (Zambrana Pineda and Ríos Jiménez, 2006).
Transformity = 1.14E+5 seJ/J (Bastianoni *et al.* 2009).

9. ELECTRICITY

Total use = 2.54E+13 J/yr
Assuming that Electricity investments are around 40 % of exploitation costs in money paid to the Water Authority in the Guadalquivir river Basin (Aguilar Portero, 2007); total costs = 600 ptas/ha/yr (Sumpsi Viñas, 1980); market price of electricity for irrigation = 0.425 ptas/kWh (Carreras and Tafunell, 2005); 1.25E+8 m^2 of farming area (Zambrana Pineda and Ríos Jiménez, 2006); 3.6E+6 J/kWh; Exchange rate = 0.0257 US$/pta (EUROSTAT).
Transformity = 2.91E+5 seJ/J (Odum, 1996 updated).

10. NITROGEN FERTILIZER (N CONTENT)
Total use = 1.31E+9 g/yr (Sumpsi Viñas, 1980).
Specific emergy = 6.37 E+9 seJ/g (Odum, 1996 updated).

11. PHOSPHATE FERTILIZER (P_2O_5 CONTENT)
Total use = 1.15E+9 g/yr (Sumpsi Viñas, 1980).
Specific emergy = 6.54 E+9 seJ/g (Odum, 1996 updated).

12. POTASH FERTLIZER (K_2O CONTENT)
Total use = 6.25E+8 g/yr (Sumpsi Viñas, 1980).
Specific emergy = 1.84 E+9 seJ/g (Odum, 1996 updated).

13. SEEDS
Total use = 1.25E+9 g/yr (Estimated from González Arteaga, 2005).
Specific emergy = 6.80 E+4 seJ/g (Odum, 1996 updated).

14. MACHINERY AND TOOLS
Total use = 9.03E+6 g/yr.
Assuming 2915 tractors in Seville (González Arteaga, 2005); 806669 ha of cultivation in Seville (González Arteaga, 2005); 2 t of average weight (tractor and tools) (Olalquiaga, 1960); 10 yr of average life (Olalquiaga, 1960).
No mechanical harvesters until 1957 (Herruzo, 1986).
Specific emergy = 1.13 E+10 seJ/g (Odum, 1996 updated).

PURCHASED LABOUR AND SERVICES:

15. LABOUR
Labour costs = 5720 ptas/ha/yr (Estimated from González Arteaga, 2005).
Farmed area= 1.25E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Exchange rate = 0.0257 US$/pta (EUROSTAT).

Total labour costs = 5720 ptas/ha/yr x 1.25E+8 m^2 x 1E-4 ha/m2 x 0.0257 US$/pta = 1.84E+6 US$.
Transformity = 2.06E+13 seJ/US$ (this study).

16. SERVICES
Services costs = 10960 ptas/ha/yr (Estimated from González Arteaga, 2005).
Farmed area= 1.25E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Exchange rate = 0.0257 US$/pta (EUROSTAT).

Total services costs = 10960 ptas/ha/yr x 1.25E+8 m^2 x 1E-4 ha/m2 x 0.0257 US$/pta = 3.52E+6 US$.
Transformity = 2.06E+13 seJ/US$ (this study).

OUTPUTS:

17. RICE GRAIN
Total production = 8.13E+10 g/yr (Zambrana Pineda and Ríos Jiménez, 2006).
Specific emergy = 3.58E+9 seJ/g (this study).

18. RICE RESIDUES
Total production = 1.6 tonnes of residues per 1 tonne of rice grain (CIRAT-GRED, 2002) x total production = 1.30E+11 g/yr.
Specific emergy = 2.24E+9 seJ/g (this study).

19. MONETARY OUTPUT
Marked prices paid to the farmer = 0.0042 ptas/g (MAPA, 1977).
Exchange rate = 0.0257 US$/pta (EUROSTAT).
Total production = 8.13E+10 g/yr (Zambrana Pineda and Ríos Jiménez, 2006).

Total monetary output = 0.0042 ptas/g x 8.13E+10 g/yr x 0.0257 US$/pta = 8.76E+6 US$
Transformity = 2.06E+13 seJ/US$ (this study).

Table B. Emergy evaluation of rice cultivation in the Guadalquivir marshes - 1977.

RENEWABLE SOURCES:

1. SOLAR ENERGY
Farmed area= 2.73E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Insolation = 5.10 kWh/m^2/yr (IGN, 1996).
Albedo of rice fields = 0.12 (Rapport *et al.* 2002).

Solar energy = 5.10 kWh/m^2/yr x 2.73E+8 m^2 x 3.6E+6 J/kWh x (1-0.12) = 4.41E+15 J/yr.
Transformity = 1.00 by definition (Odum, 1996 updated).

2. RAIN (CHEMICAL POTENTIAL)
Farmed area= 2.73E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Precipitation rate = 0.55 m (provided by the Spanish meteorological agency, AEMET).
Actual evapotranspiration rate = 0.42 m. According to ITGME-JA (1998), a 76 % of total rainfall.
Gibbs free energy of water (G) = (RT/w) x Ln (C2/C1) = 4.94 J/g.
R= 8.33 J/mol x ºC; T= 300 ºC; W = 18 g/mol H_2O; C1= 965 ppm on sea water; C2= (1E+6-1E+1) ppm from rainfall.
Water density = 1.00E+6 g/m^3.

Rain (Chemical potential energy) = 2.73E+8 m^2 x 0.42 m/yr x 1.00E+6 g/m^3 x 4.94 J/g = 5.56E+14 J/yr
Transformity = 3.06E+4 seJ/J (Odum, 1996 updated).

3. RAIN (GEOPOTENTIAL)
Farmed area= 2.73E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Precipitation rate = 0.55 m (provided by the Spanish meteorological agency, AEMET).
Runoff rate = 0.13 m. According to ITGME-JA (1998), a 24 % of total rainfall.
Average elevation = 3.6 m (García *et al.* 1993).
Water density = 1.00E+6 g/m^3.
Gravity (g) = 9.8 m/s^2.

Rain (Geopotential energy) = 2.73E+8 m^2 x 0.13 m x 1.00E+6 g/m^3 x 3.6 m x 9.8 m/s^2 = 5.83E+11 J/yr.
Transformity = 1.76E+4 seJ/J (Odum, 1996 updated).

4. WIND (KINETIC ENERGY USED AT SURFACE)
Farmed area= 2.73E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Average wind speed = 2 m/s (CICE, On-line).
Geostrophic wind = (10/6)*wind speed (Reiter, 1969) = 2.83 m/s.
Dragg coefficient = 3.00E-3 (Garratt, 1977).
Air density = 1.225 kg/m^3.

Wind (kinetic energy used at surface) = 2.83 m/s x 2.73E+8 m^2 x 3.00E-3 x 1.225 kg/m^3 x 365 days/yr x 24 hours/day x 60 minutes/hour x 60 seconds/minute = 7.14E+14 J/yr.
Transformity = 2.53E+3 seJ/J (Odum, 1996 updated).

5. RIVER WATER FOR IRRIGATION
Water used = 8.42E+8 m^3/yr. Assuming a water withdrawal of 3.5 l/s/ha; 1/3 of losses by channel system failure, infiltration, etc.; 5 months of irrigation (Del Moral, 1992); 2.73E+8 m^2 of farmed area (Zambrana Pineda and Ríos Jiménez, 2006).
Gibbs free energy of river water (G) = (RT/w) x Ln (C2/C1) = 4.83 J/g.
R= 8.33 J/mol x ºC; T= 300 ºC; W = 18 g/mol H_2O; C1= 965 ppm on sea water; C2= (1E+6-850) ppm from rain water.
Water density = 1.00E+6 g/m^3.

Energy from river water for irrigation = 8.42E+8 m^3/yr x 1.00E+6 g/m^3 x 4.83 J/g = 4.07E+15 J/yr.
Transformity = 8.10E+4 seJ/J (Odum, 1996 updated).

6. EARTH CYCLE (THERMAL ENERGY)
Farmed area= 2.73E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Heat flow = 1.92E+6 J/m^2/yr (Fernández *et al.* 1998).

Earth cycle (thermal energy) = 2.73E+8 m^2 x 1.92E+6 J/m^2/yr = 5.25E+14 J/yr.
Transformity = 1.20E+4 seJ/J (Odum, 1996 updated).

LOCAL NON-RENEWABLE SOURCES:

7. NET LOSS OF TOPSOIL
Farmed area= 2.73E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Erosion rate (average for the Guadalquivir Valley) = 119.7 t/ km^2 (Soto, 1990).
Organic matter = 0.025 (percentage of organic matter in soil given as decimal) (Aguilar Portero, 2007).

Energy from organic matter loss = 119.7 t/ km^2/yr x 2.73E+2 km^2 x 1E+6 g/t x 5.4 kcal/g of organic matter x 4186 J/kcal= 1.85E+13 J/yr.
Transformity = 1.05E+5 seJ/J (Odum, 1996 updated).

PURCHASED GOODS:

8. FUELS

Total use = 4.83E+14 J/yr.

-For tractors: assuming 0.1875 L/CV/hour (Campos and Naredo, 1980); average power = 53 CV (Campos and Naredo, 1980); 35.5 hours of use/ha (Sumpsi Viñas, 1980); 9655 kcal/L of diesel; 2.73E+8 m^2 of farming area (Zambrana Pineda and Ríos Jiménez, 2006).

-For harvesters: assuming 206327 kcal/hour (Campos and Naredo, 1980); 4 hours of use/ha (Sumpsi Viñas, 1980); 2.73E+8 m^2 of farming area (Zambrana Pineda and Ríos Jiménez, 2006).

Transformity = 1.14E+5 seJ/J (Bastianoni *et al.* 2009).

9. ELECTRICITY

Total use = 5.04E+13 J/yr

Assuming that Electricity investments are around 40 % of exploitation costs in money paid to the Water Authority in the Guadalquivir river Basin (Aguilar Portero, 2007); total costs = 4500 ptas/ha/yr (Sumpsi Viñas, 1980); market price of electricity for irrigation = 3.51 ptas/kWh (MIE, 1977); 2.73E+8 m^2 of farming area (Zambrana Pineda and Ríos Jiménez, 2006); 3.6E+6 J/kWh; Exchange rate = 0.0131 US$/pta (EUROSTAT).

Transformity = 2.91E+5 seJ/J (Odum, 1996 updated).

10. NITROGEN FERTILIZER (N CONTENT)

Total use = 5.16E+9 g/yr (Sumpsi Viñas, 1980).

Specific emergy = 6.37 E+9 seJ/g (Odum, 1996 updated).

11. PHOSPHATE FERTILIZER (P2O5 CONTENT)

Total use = 6.28E+9 g/yr (Sumpsi Viñas, 1980).

Specific emergy = 6.54 E+9 seJ/g (Odum, 1996 updated).

12. POTASH FERTLIZER (K_2O CONTENT)

Total use = 1.64E+9 g/yr (Sumpsi Viñas, 1980).

Specific emergy = 1.84 E+9 seJ/g (Odum, 1996 updated).

13. PESTICIDES

Total use = 7.11E+8 g/yr (Estimated from CHG, 1983).

Specific emergy = 2.48 E+10 seJ/g (Brown and Arding, 1991 updated).

14. SEEDS

Total use = 2.73E+9 g/yr (Estimated from González Arteaga, 2005).

Specific emergy = 6.80 E+4 seJ/g (Odum, 1996 updated).

15. MACHINERY AND TOOLS

Total use = 3.86E+8 g/yr.

-For tractors: assuming 410 tractors in the municipalities with rice paddies in Seville (González Arteaga, 2005); 22000 ha of cultivation in municipalities with rice paddies in Seville (González Arteaga, 2005); 2 t of average weight (tractor and tools) (Olalquiaga, 1960); 10 yr of average life (Olalquiaga, 1960).

-For harvesters: assuming 250 harvesters in the municipalities with rice paddies in Seville (González Arteaga, 2005); 22000 ha of cultivation in municipalities with rice paddies in Seville (González Arteaga, 2005); 5.5 t of average weight

(harvester and tools) (Valero and Ortiz Cañavate, 2000); 6 yr of average life (Olalquiaga, 1960).
Specific emergy = 1.13 E+10 seJ/g (Odum, 1996 updated).

PURCHASED LABOUR AND SERVICES:

16. LABOUR
Labour costs = 6702 ptas/ha/yr (Estimated from González Arteaga, 2005).
Farmed area= 2.73E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Exchange rate = 0.0131 US$/pta (EUROSTAT).

Total labour costs = 6702 ptas/ha/yr x 2.73E+8 m^2 x 1E-4 ha/m2 x 0.0131 US$/pta = 2.40E+6 US$.
Transformity = 1.56E+13 seJ/US$ (this study).

17. SERVICES
Services costs = 60311 ptas/ha/yr (Estimated from González Arteaga, 2005).
Farmed area= 2.73E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Exchange rate = 0.0131 US$/pta (EUROSTAT).

Total services costs = 60311 ptas/ha/yr x 2.73E+8 m^2 x 1E-4 ha/m2 x 0.0131 US$/pta = 2.16E+7 US$.
Transformity = 1.56E+13 seJ/US$ (this study).

OUTPUTS:

18. RICE GRAIN
Total production = 1.60E+11 g/yr (Zambrana Pineda and Ríos Jiménez, 2006).
Specific emergy = 5.47E+9 seJ/g (this study).

19. RICE RESIDUES
Total production = 1.6 tonnes of residues per 1 tonne of rice grain (CIRAT-GRED, 2002) x total production = 2.56E+11 g/yr.
Specific emergy = 5.47E+9 seJ/g (this study).

20. MONETARY OUTPUT
Marked prices paid to the farmer = 0.01524 ptas/g (MAPA, 1977).
Exchange rate = 0.0131 US$/pta (EUROSTAT).
Total production = 1.60E+11 g/yr (Zambrana Pineda and Ríos Jiménez, 2006).

Total monetary output = 0.01524 ptas/g x 8.13E+10 g/yr x 0.0131 US$/pta = 3.20E+7 US$
Transformity = 1.56E+13 seJ/US$ (this study).

Table C. Emergy evaluation of rice cultivation in the Guadalquivir marshes - 1998.

RENEWABLE SOURCES:

1. SOLAR ENERGY
Farmed area= 3.50E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).

Insolation = 5.10 kWh/m^2/yr (IGN, 1996).
Albedo of rice fields = 0.12 (Rapport *et al.* 2002).

Solar energy = 5.10 kWh/m^2/yr x 3.50E+8 m^2 x 3.6E+6 J/kWh x (1-0.12) = 5.65E+15 J/yr.
Transformity = 1.00 by definition (Odum, 1996 updated).

2. RAIN (CHEMICAL POTENTIAL)

Farmed area= 3.50E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Precipitation rate = 0.44 m (provided by the Spanish meteorological agency, AEMET).
Actual evapotranspiration rate = 0.34 m. According to ITGME-JA (1998), a 76 % of total rainfall.
Gibbs free energy of water (G) = (RT/w) x Ln (C2/C1) = 4.94 J/g.
R= 8.33 J/mol x ºC; T= 300 ºC; W = 18 g/mol H_2O; C1= 965 ppm on sea water; C2= (1E+6-1E+1) ppm from rainfall.
Water density = 1.00E+6 g/m^3.

Rain (Chemical potential energy) = 3.50E+8 m^2 x 0.34 m/yr x 1.00E+6 g/m^3 x 4.94 J/g = 5.81E+14 J/yr
Transformity = 3.06E+4 seJ/J (Odum, 1996 updated).

3. RAIN (GEOPOTENTIAL)

Farmed area= 3.50E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Precipitation rate = 0.44 m (provided by the Spanish meteorological agency, AEMET).
Runoff rate = 0.11 m. According to ITGME-JA (1998), a 24 % of total rainfall.
Average elevation = 3.6 m (García *et al.* 1993).
Water density = 1.00E+6 g/m^3.
Gravity (g) = 9.8 m/s^2.

Rain (Geopotential energy) = 3.50E+8 m^2 x 0.11 m x 1.00E+6 g/m^3 x 3.6 m x 9.8 m/s^2 = 4.68E+11 J/yr.
Transformity = 1.76E+4 seJ/J (Odum, 1996 updated).

4. WIND (KINETIC ENERGY USED AT SURFACE)

Farmed area= 3.50E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Average wind speed = 2 m/s (CICE, On-line).
Geostrophic wind = (10/6)*wind speed (Reiter, 1969) = 2.83 m/s.
Dragg coefficient = 3.00E-3 (Garratt, 1977).
Air density = 1.225 kg/m^3.

Wind (kinetic energy used at surface) = 2.83 m/s x 3.50E+8 m^2 x 3.00E-3 x 1.225 kg/m^3 x 365 days/yr x 24 hours/day x 60 minutes/hour x 60 seconds/minute = 9.15E+14 J/yr.
Transformity = 2.53E+3 seJ/J (Odum, 1996 updated).

5. RIVER WATER FOR IRRIGATION

Water used = 1.08E+9 m^3/yr. Assuming a water withdrawal of 3.5 l/s/ha; 1/3 of losses by channel system failure, infiltration, etc.; 5 months of irrigation (Del Moral, 1992); 3.50E+8 m^2 of farmed area (Zambrana Pineda and Ríos Jiménez, 2006).
Gibbs free energy of river water (G) = (RT/w) x Ln (C2/C1) = 4.83 J/g.

R= 8.33 J/mol x ºC; T= 300 ºC; W = 18 g/mol H_2O; C1= 965 ppm on sea water; C2= (1E+6-850) ppm from rain water.
Water density = 1.00E+6 g/m^3.

Energy from river water for irrigation = 1.08E+9 m^3/yr x 1.00E+6 g/m^3 x 4.83 J/g = 5.21E+15 J/yr.
Transformity = 8.10E+4 seJ/J (Odum, 1996 updated).

6. EARTH CYCLE (THERMAL ENERGY)
Farmed area= 3.50E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Heat flow = 1.92E+6 J/m^2/yr (Fernández *et al.* 1998).

Earth cycle (thermal energy) = 3.50E+8 m^2 x 1.92E+6 J/m^2/yr = 6.73E+14 J/yr.
Transformity = 1.20E+4 seJ/J (Odum, 1996 updated).

LOCAL NON-RENEWABLE SOURCES:

7. NET LOSS OF TOPSOIL
Farmed area= 3.50E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Erosion rate (average for the Guadalquivir Valley) = 119.7 t/ km^2 (Soto, 1990).
Organic matter = 0.025 (percentage of organic matter in soil given as decimal) (Aguilar Portero, 2007).

Energy from organic matter loss = 119.7 t/ km^2/yr x 3.50E+2 km^2 x 1E+6 g/t x 5.4 kcal/g of organic matter x 4186 J/kcal= 2.37E+13 J/yr.
Transformity = 1.05E+5 seJ/J (Odum, 1996 updated).

PURCHASED GOODS:

8. FUELS
Total use = 3.99E+14 J/yr.

-For tractors: assuming 8 L/hour (Márquez, 2007); 23.1 hour/ha (Estimated from González Arteaga, 2005); 3.50E+8 m^2 of farming area (Zambrana Pineda and Ríos Jiménez, 2006); 9655 kcal/L of diesel.

-For harvesters: assuming 19.5 L/hour (Pérez, 1992); 5 hour/ha (Estimated from González Arteaga, 2005); 3.50E+8 m^2 of farming area (Zambrana Pineda and Ríos Jiménez, 2006); 9655 kcal/L of diesel.

Transformity = 1.14E+5 seJ/J (Bastianoni *et al.* 2009).

9. ELECTRICITY
Total use = 1.09E+14 J/yr
Assuming that Electricity investments are around 40 % of exploitation costs in money paid to the Water Authority in the Guadalquivir river Basin (Aguilar Portero, 2007); total costs = 57558000 ptas per 5000 ha/yr (Campos and López, 1998); market price of electricity for irrigation = 13.26 ptas/kWh (CNE, 2000); 3.50E+8 m^2 of farming area (Zambrana Pineda and Ríos Jiménez, 2006); 3.6E+6 J/kWh; Exchange rate = 0.0067 US$/pta (EUROSTAT).
Transformity = 2.91E+5 seJ/J (Odum, 1996 updated).

10. NITROGEN FERTILIZER (N CONTENT)

Total use = 6.09E+9 g/yr (Estimated from González Arteaga, 2005).
Specific emergy = 6.37 E+9 seJ/g (Odum, 1996 updated).

11. PHOSPHATE FERTILIZER (P_2O_5 CONTENT)
Total use = 4.83E+9 g/yr (Estimated from González Arteaga, 2005).
Specific emergy = 6.54 E+9 seJ/g (Odum, 1996 updated).

12. PESTICIDES
Total use = 2.68E+8 g/yr (Estimated from Aguilar Portero, 2007).
Specific emergy = 2.48 E+10 seJ/g (Brown and Arding, 1991 updated).

13. SEEDS
Total use = 5.25E+9 g/yr (Estimated from González Arteaga, 2005).
Specific emergy = 6.80 E+4 seJ/g (Odum, 1996 updated).

14. MACHINERY AND TOOLS
Total use = 3.78E+8 g/yr.

-For tractors: assuming 19653 tractors in Seville (CAP, 1998); 853435 ha of cultivation in Seville (CAP, 1998); 4.32 t of average weight (tractor and tools) (Márquez, 2006); 10 yr of average life (Campos and Naredo, 1980).

-For harvesters: assuming 588 harvesters in Seville (CAP, 1998); 853435 ha of cultivation in Seville (CAP, 1998); 7.5 t of average weight (harvester and tools) (MAPA, 2006); 6 yr of average life (Campos and Naredo, 1980).

Specific emergy = 1.13 E+10 seJ/g (Odum, 1996 updated).

PURCHASED LABOUR AND SERVICES:

15. LABOUR
Labour costs = 154.3 €/ha/yr (Estimated from González Arteaga, 2005).
Farmed area= 3.50E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Exchange rate = 1.121 US$/€ (EUROSTAT).

Total labour costs = 154.3€/ha/yr x 3.50E+8 m^2 x 1E-4 ha/m2 x 0.0067 US$/pta = 6.05E+6 US$.
Transformity = 6.57E+12 seJ/US$ (this study).

16. SERVICES
Services costs = 1388.99 €/ha/yr (Estimated from González Arteaga, 2005).
Farmed area= 3.50E+8 m^2 (Zambrana Pineda and Ríos Jiménez, 2006).
Exchange rate = 1.121 US$/€ (EUROSTAT).

Total services costs = 1388.99 €/ha/yr x 3.50E+8 m^2 x 1E-4 ha/m2 x 1.121 US$/€ = 5.45E+7 US$.
Transformity = 6.57E+12 seJ/US$ (this study).

OUTPUTS:

17. RICE GRAIN
Total production = 2.85E+11 g/yr (Zambrana Pineda and Ríos Jiménez, 2006).
Specific emergy = 3.45E+9 seJ/g (this study).

18. RICE RESIDUES
Total production = 1.6 tonnes of residues per 1 tonne of rice grain (CIRAT-GRED, 2002) x total production = 4.55E+11 g/yr.
Specific emergy = 3.45E+9 seJ/g (this study).

19. MONETARY OUTPUT
Marked prices paid to the farmer = 0.0465 ptas/g (CAP, 1998).
Exchange rate = 0.0067 US$/pta (EUROSTAT).
Total production = 2.85E+11 g/yr (Zambrana Pineda and Ríos Jiménez, 2006).

Total monetary output = 0.0465 ptas/g x 2.85E+11 g/yr x 0.0067 US$/pta = 8.87E+7 US$
Transformity = 6.57E+12 seJ/US$ (this study).

Table D. Emergy evaluation of rice cultivation in the Guadalquivir marshes - 2006.

RENEWABLE SOURCES:

1. SOLAR ENERGY
Farmed area= 2.65E+8 m^2 (IEA, 2008).
Insolation = 5.10 $kWh/m^2/yr$ (IGN, 1996).
Albedo of rice fields = 0.12 (Rapport *et al.* 2002).

Solar energy = 5.10 $kWh/m^2/yr$ x 2.65E+8 m^2 x 3.6E+6 J/kWh x (1-0.12) = 4.28E+15 J/yr.
Transformity = 1.00 by definition (Odum, 1996 updated).

2. RAIN (CHEMICAL POTENTIAL)
Farmed area= 2.65E+8 m^2 (IEA, 2008).
Precipitation rate = 0.76 m (provided by the Spanish meteorological agency, AEMET).
Actual evapotranspiration rate = 0.58 m. According to ITGME-JA (1998), a 76 % of total rainfall.
Gibbs free energy of water (G) = (RT/w) x Ln (C2/C1) = 4.94 J/g.
R= 8.33 J/mol x ºC; T= 300 ºC; W = 18 g/mol H_2O; C1= 965 ppm on sea water; C2= (1E+6-1E+1) ppm from rainfall.
Water density = 1.00E+6 g/m^3.

Rain (Chemical potential energy) = 2.65E+8 m^2 x 0.58 m/yr x 1.00E+6 g/m^3 x 4.94 J/g = 7.60E+14 J/yr
Transformity = 3.06E+4 seJ/J (Odum, 1996 updated).

3. RAIN (GEOPOTENTIAL)
Farmed area= 2.65E+8 m^2 (IEA, 2008).
Precipitation rate = 0.76 m (provided by the Spanish meteorological agency, AEMET).
Runoff rate = 0.18 m. According to ITGME-JA (1998), a 24 % of total rainfall.
Average elevation = 3.6 m (García *et al.* 1993).
Water density = 1.00E+6 g/m^3.
Gravity (g) = 9.8 m/s^2.

Rain (Geopotential energy) = 2.65E+8 m^2 x 0.18 m x 1.00E+6 g/m^3 x 3.6 m x 9.8 m/s^2 = 8.09E+11 J/yr.
Transformity = 1.76E+4 seJ/J (Odum, 1996 updated).

4. WIND (KINETIC ENERGY USED AT SURFACE)

Farmed area= 2.65E+8 m^2 (IEA, 2008).
Average wind speed = 2 m/s (CICE, On-line).
Geostrophic wind = (10/6)*wind speed (Reiter, 1969) = 2.83 m/s.
Dragg coefficient = 3.00E-3 (Garratt, 1977).
Air density = 1.225 kg/m^3.

Wind (kinetic energy used at surface) = 2.83 m/s x 2.65E+8 m^2 x 3.00E-3 x 1.225 kg/m^3 x 365 days/yr x 24 hours/day x 60 minutes/hour x 60 seconds/minute = 6.92E+14 J/yr.
Transformity = 2.53E+3 seJ/J (Odum, 1996 updated).

5. RIVER WATER FOR IRRIGATION

Water used = 8.17E+8 m^3/yr. Assuming a water withdrawal of 3.5 l/s/ha; 1/3 of losses by channel system failure, infiltration, etc.; 5 months of irrigation (Del Moral, 1992); 2.65E+8 m^2 of farmed area (IEA, 2008).
Gibbs free energy of river water (G) = (RT/w) x Ln (C2/C1) = 4.83 J/g.
R= 8.33 J/mol x ºC; T= 300 ºC; W = 18 g/mol H_2O; C1= 965 ppm on sea water; C2= (1E+6-850) ppm from rain water.
Water density = 1.00E+6 g/m^3.

Energy from river water for irrigation = 8.17E+8 m^3/yr x 1.00E+6 g/m^3 x 4.83 J/g = 3.94E+15 J/yr.
Transformity = 8.10E+4 seJ/J (Odum, 1996 updated).

6. EARTH CYCLE (THERMAL ENERGY)

Farmed area= 2.65E+8 m^2 (IEA, 2008).
Heat flow = 1.92E+6 J/m^2/yr (Fernández *et al.* 1998).

Earth cycle (thermal energy) = 2.65E+8 m^2 x 1.92E+6 J/m^2/yr = 5.09E+14 J/yr.
Transformity = 1.20E+4 seJ/J (Odum, 1996 updated).

LOCAL NON-RENEWABLE SOURCES:

7. NET LOSS OF TOPSOIL

Farmed area= 2.65E+8 m^2 (IEA, 2008).
Erosion rate (average for the Guadalquivir Valley) = 119.7 t/ km^2 (Soto, 1990).
Organic matter = 0.025 (percentage of organic matter in soil given as decimal) (Aguilar Portero, 2007).

Energy from organic matter loss = 119.7 t/ km^2/yr x 2.65E+2 km^2 x 1E+6 g/t x 5.4 kcal/g of organic matter x 4186 J/kcal= 1.79E+13 J/yr.
Transformity = 1.05E+5 seJ/J (Odum, 1996 updated).

PURCHASED GOODS:

8. FUELS

Total use = 3.02E+14 J/yr.

-For tractors: assuming 8 L/hour (Márquez, 2007); 23.1 hour/ha (Estimated from González Arteaga, 2005); 2.65E+8 m^2 of farming area (IEA, 2008); 9655 kcal/L of diesel.

-For harvesters: assuming 19.5 L/hour (Pérez, 1992); 5 hour/ha (Estimated from González Arteaga, 2005); 2.65E+8 m^2 of farming area (IEA, 2008); 9655 kcal/L of diesel.

Transformity = 1.14E+5 seJ/J (Bastianoni *et al.* 2009).

9. ELECTRICITY

Total use = 6.40E+13 J/yr

Assuming that Electricity investments are around 40 % of exploitation costs in money paid to the Water Authority in the Guadalquivir river Basin (Aguilar Portero, 2007); total costs = 60 €/ha (Aguilar Portero, 2007); market price of electricity for irrigation = 0.0893 €/kWh (CNE, 2007); 2.65E+8 m^2 of farming area (IEA, 2008); 3.6E+6 J/kWh; Exchange rate = 1,2556 US$/€ (EUROSTAT).

Transformity = 2.91E+5 seJ/J (Odum, 1996 updated).

10. NITROGEN FERTILIZER (N CONTENT)

Total use = 3.84E+9 g/yr (Aguilar Portero, 2007).

Specific emergy = 6.37 E+9 seJ/g (Odum, 1996 updated).

11. PHOSPHATE FERTILIZER (P_2O_5 CONTENT)

Total use = 1.83E+9 g/yr (Aguilar Portero, 2007).

Specific emergy = 6.54 E+9 seJ/g (Odum, 1996 updated).

12. PESTICIDES

Total use = 2.03E+8 g/yr (Aguilar Portero, 2007).

Specific emergy = 2.48 E+10 seJ/g (Brown and Arding, 1991 updated).

13. SEEDS

Total use = 4.51E+9 g/yr (Aguilar Portero, 2007).

Specific emergy = 6.80 E+4 seJ/g (Odum, 1996 updated).

14. MACHINERY AND TOOLS

Total use = 5.06E+8 g/yr.

-For tractors: assuming 32556 tractors in Seville (CAP, 2006); 861236 ha of cultivation in Seville (CAP, 2006); 4.32 t of average weight (tractor and tools) (Márquez, 2006); 10 yr of average life (Campos and Naredo, 1980).

-For harvesters: assuming 1906 harvesters in Seville (CAP, 2006); 861236 ha of cultivation in Seville (CAP, 2006); 7.5 t of average weight (harvester and tools) (MAPA, 2006); 6 yr of average life (Campos and Naredo, 1980).

Specific emergy = 1.13 E+10 seJ/g (Odum, 1996 updated).

PURCHASED LABOUR AND SERVICES:

15. LABOUR

Labour costs = 67.12 €/ha/yr (Aguilar Portero, 2007).

Farmed area= 2.65E+8 m^2 (IEA, 2008).

Exchange rate = 1.256 US$/€ (EUROSTAT).

Total labour costs = 67.12 €/ha/yr x 2.65E+8 m^2 x 1E-4 ha/m2 x 1.256 US$/€ = 2.23E+6 US$.
Transformity = 6.78E+12 seJ/US$ (this study).

16. SERVICES
Services costs = 1379.08 €/ha/yr (Aguilar Portero, 2007).
Farmed area= 2.65E+8 m^2 (IEA, 2008).
Exchange rate = 1.256 US$/€ (EUROSTAT).

Total services costs = 1379.08 €/ha/yr x 2.65E+8 m^2 x 1E-4 ha/m2 x 1.256 US$/€ = 4.58E+7 US$.
Transformity = 6.78E+12 seJ/US$ (this study).

OUTPUTS:

20. RICE GRAIN
Total production = 1.92E+11 g/yr (Aguilar Portero, 2007).
Specific emergy = 3.89E+9 seJ/g (this study).

21. RICE RESIDUES
Total production = 1.6 tonnes of residues per 1 tonne of rice grain (CIRAT-GRED, 2002) x total production = 3.07E+11 g/yr.
Specific emergy = 3.89E+9 seJ/g (this study).

22. MONETARY OUTPUT
Marked prices paid to the farmer = 258 €/t (Aguilar Portero, 2007).
Exchange rate = 1.256 US$/€ (EUROSTAT).
Total production = 1.92E+11 g/yr (Aguilar Portero, 2007).

Total monetary output = 258 €/t x (1/1E+6) t/g x 1.92E+11 g/yr x 1.256 US$/€ = 6.22E+7 US$
Transformity = 6.78E+12 seJ/US$ (this study).

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IV. DISCUSIÓN GENERAL

4.1. Estudio de los servicios de los ecosistemas mediante las herramientas de la síntesis emergética.

4.1.1. Una imagen vale más que mil palabras: la ventana ambiental y los diagramas de flujo como herramientas para la representación de los SES

Originalmente, la simbología energética (p. 46, *capítulo 2*) fue concebida con el objetivo de representar los elementos de la estructura de los ecosistemas y sus relaciones en términos de flujos de materia y energía, con una base de carácter termodinámico y sistémico (Odum, 1994; Brown, 2004). Frente a las descripciones habituales de los sistemas ecológicos donde la estructura se estudiaba a través de listados de especies y el funcionamiento a través de modelos matemáticos (Franzese *et al.* 2005), estos esquemas permitían integrar ambos aspectos en una imagen gráfica con una potente base modelística que pretendía ser fiel reflejo del criptosistema (González Bernáldez, 1981), puesto que estas representaciones no son sólo dibujos sino que detrás de cada símbolo existe una formulación matemática precisa (Odum, 1994; Odum & Odum, 2000).

Es en su libro *Environment, Power and Society* (Odum, 1971), H.T. Odum comenzó a aplicar este lenguaje a sistemas resultantes de la interacción entre ser humano y naturaleza, tales como sistemas agrícolas, industriales, etc. (Brown, 2004). Cada diagrama obligaba al investigador a conocer la estructura, el funcionamiento y la dinámica del sistema, y a hacer explícito el modelo de relaciones dentro del SES en el que se basa para el desarrollo de sus cálculos. Estos diagramas permiten representar gráfica y cuantitativamente los flujos de materia y energía que fluyen desde los ecosistemas hacia los sistemas socio-económicos, y se alimentan de información relativa tanto a fuentes de materia y energía de origen biogeofísico como a importaciones de materia, energía e información provenientes de otros sistemas socio-económicos.

La escala espacio-temporal donde interaccionan directamente los seres humanos con los ecosistemas es la que H.T. Odum (1996) denominó *Ventana Ambiental*, y viene representada a través de diagramas de flujo, donde los procesos ecológicos alimentan los procesos socio-económicos para generar un determinado producto o sistema, y éstos a su vez actúan sobre los anteriores, cerrando ciclos y reforzando la auto-organización del sistema. Así, los diagramas de flujo se pueden entender como una potente representación gráfica de la estructura y el funcionamiento de los ecosistemas, así como de los flujos de materia y energía que van desde estos hacia la sociedad y viceversa (Odum, 1996; Abel, 2003; 2004). Por tanto, podemos decir que los diagramas de flujo son una representación gráfica de la dimensión física de los componentes y el funcionamiento de los SES, así como de las funciones y los servicios de los ecosistemas que tengan carácter físico, es decir, que se puedan estudiar desde el punto de vista de la materia y la energía.

En la Figura 4.1. se puede observar una ventana ambiental genérica de relación entre los seres humanos y los ecosistemas representada mediante un diagrama de flujos, donde las necesidades humanas que potencialmente se pueden satisfacer a través del uso de los ecosistemas se abastecen de servicios de los ecosistemas por dos vías, una que está determinada por el uso económico de los flujos de materia y energía, y otra que no lo está.

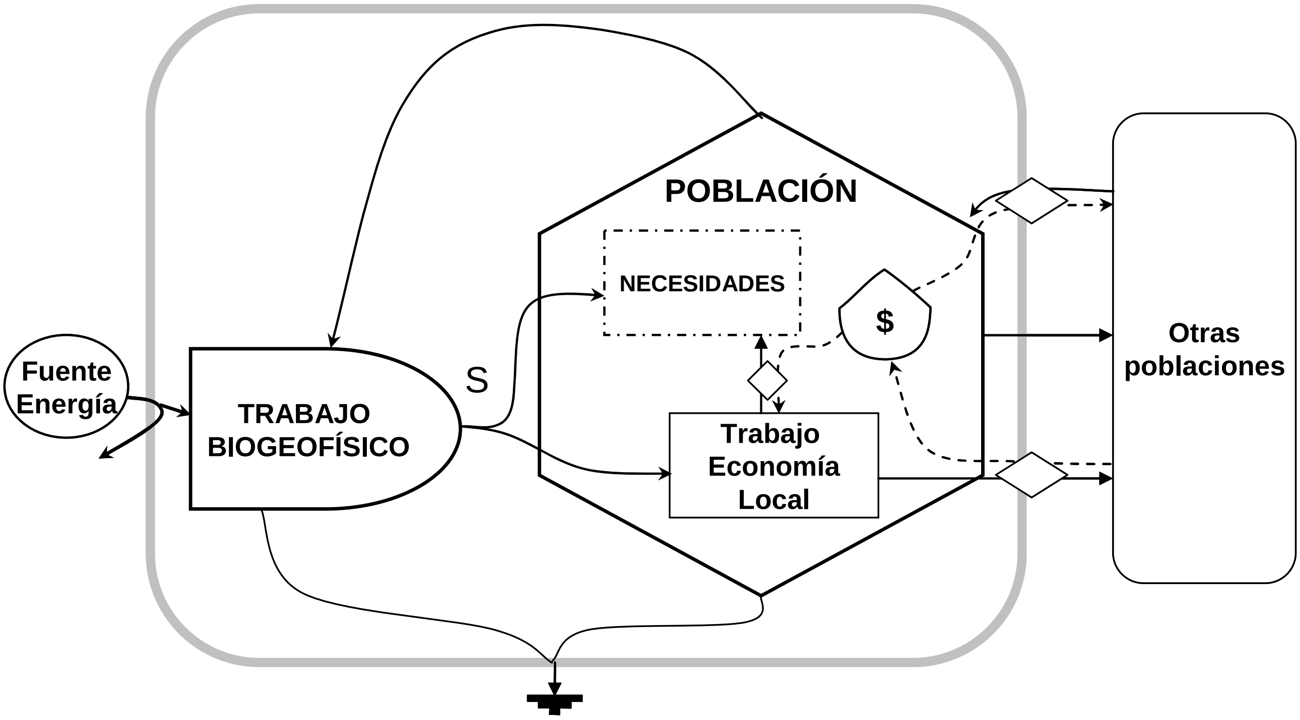

Figura 4.1. Diagrama de flujos simplificado de una ventana ambiental, donde se observa, dentro de la línea gris, el foco de atención de la síntesis emergética. La S representa el flujo de servicios de los ecosistemas

Como todo modelo, los diagramas de flujo pretenden ser representaciones simplificadas de la realidad, nunca contener toda su complejidad, entre otras cosas porque la emergía es una medida que no se calcula a partir de dimensiones de naturaleza no física. Mientras que en la representación de la realidad que supone el modelo circular de Economía que vimos en el *capítulo 1* (p. 5, capítulo 1), los servicios de los ecosistemas son economías externas al sistema, y la solución es la de trasladar estas economías externas al lenguaje del sistema (el monetario) para internalizarlas, es decir, encajar la realidad compleja en el modelo simple; en el caso de los diagramas de flujo utilizados para el desarrollo de la síntesis emergética la idea es la contraria, es decir, tratar de representar del mejor modo posible un aspecto de la realidad: los flujos de materia y energía entre los ecosistemas y la sociedad, aproximando al máximo posible la simplificación que supone el modelo a este aspecto concreto de la realidad compleja. En un razonamiento análogo a la idea que defiende Naredo (2003) para el desarrollo de un enfoque ecointegrador de la Economía, en la síntesis emergética es el objeto de estudio (la memoria energética de los flujos de materia y energía entre el sub-sistema biogeofísico y el sub-sistema socio-económico) el que determina el modelo empleado para su estudio, un modelo de ACV o de metabolismo.

Por otra parte, los diagramas de flujo son objetivo-dependientes, es decir, no existe un modelo único para un sistema específico, sino que en función del objetivo de nuestro estudio, los diagramas de flujo diseñados pueden resaltar unos determinados componentes u otros del sistema que hay que estudiar. Odum (1994; 1996) sugería, además, que con el objetivo de aportar claridad no se incluyesen más de 25 componentes del sistema en los diagramas finales (aquellos que representasen al menos un 1% del total de la emergía usada en el sistema). En los *capítulos 3.3. y 3.4.* los diagramas de flujo desarrollados (pp. 119-120 en el *capítulo 3.3.* y pp. 144-146 en el *capítulo 3.4.*) caracterizan socio-ecosistemas a una escala de poco detalle, el funcionamiento macro-económico de los territorios España, Andalucía y las provincias andaluzas, mientras que en el *capítulo 3.5.* (p. 172 en *capítulo 3.5.)* se caracteriza un aspecto concreto de las relaciones productivas entre el ser humano y la naturaleza en las marismas del Guadalquivir, a un detalle mayor. En los primeros se estudia el funcionamiento general del sistema, mientras que en el último se analiza una producción concreta, el arroz. La propiedad de que los diagramas de flujo no sean fijos para cada sistema, permite además simplificarlos de tal modo que se resalten propiedades concretas de los flujos de materia y energía que nos interesan estudiar (renovabilidad, flujo interno o externo, etc.), y se puedan obtener indicadores emergéticos según estos objetivos.

4.1.2. Coste ambiental y satisfacción de las necesidades: el punto de vista del proveedor vs. el punto de vista del usuario

El intento por frenar la tendencia al aumento de las tasas de pérdida de biodiversidad se venía apoyando habitualmente en un modelo de conservación basado en los valores intrínsecos de las especies, es decir, en su belleza, en su derecho a vivir, su carácter único, etc. Se trataba de mantener los espacios y las especies en peligro, vulnerables, singulares, etc. alejados de la explotación humana para su conservación. La reciente Evaluación de los Ecosistemas del Milenio ha puesto de manifiesto (MA, 2005a) que este modelo no ha conseguido reducir completamente la pérdida de biodiversidad a unos niveles naturales, y que en los escenarios proyectados se espera que la situación actual o bien se mantenga o bien se acelere incluso más. En la actualidad, se está extendiendo la aproximación a la conservación ligada a los servicios de los ecosistemas, considerando los denominados valores instrumentales de la biodiversidad, es decir, los beneficios que los seres humanos obtenemos de la biodiversidad, haciendo la vida físicamente posible y digna de ser vivida (MA, 2005a; Díaz *et al.* 2006).

Bajo esta aproximación es habitual querer utilizar el dinero como modo de cuantificar estos costes y beneficios que aportan los ecosistemas a la sociedad (Naredo, 2003; Spash, 2008; Gómez-Bagghetun *et al.* 2009; Kosoy & Corbera, 2009). El razonamiento que se utiliza en estos casos es el de que capturando la cantidad de dinero que o bien ya se paga (mercados existentes) o bien se pagaría, es decir, la disposición a pagar o a ser compensado, por el servicio o por su carencia (mercados relacionados, mercados hipotéticos), se podría alcanzar un precio ajustado. Dicho precio permitiría internalizar las externalidades que suponen los servicios de los ecosistemas dentro de los mecanismos de mercado. De este modo, los precios estarían ajustados ambientalmente, y los mecanismos de mercado que, bajo esta aproximación, se asume, más o menos implícitamente, que son los que gestionan de la mejor manera los servicios, los gestionarían de manera más eficiente (en un sentido paretiano) para el bienestar social (Boyd, 2007; Barbier, 2007; Boyd & Banzhaf, 2007; Balmford *et al.* 2008; Fisher *et al.* 2008; Fisher *et al.* 2009). Dicha aproximación a los problemas, en este caso a los servicios de los ecosistemas como beneficios (normalmente monetarios), se conoce con el nombre de aproximación desde "el punto de vista del usuario (*user-side approach*)" (Figura 4.2a). Se trata de una visión que se caracteriza por tomar como criterio para la evaluación, valoración, etc. de un sistema lo que se obtiene del mismo, el beneficio, de acuerdo con la definición de servicios de los ecosistemas aceptada.

Cuando tratamos los servicios de los ecosistemas a través de cantidades físicas, como lo hace la síntesis emergética, buscamos, sin embargo, conocer las cantidades reales de materia y energía empleadas, así como la disipación de energía asociada (residuos, emisiones, vertidos, etc.) para satisfacer las necesidades de los usuarios, que en este caso sería el beneficio obtenido del uso de la naturaleza. Tal y como se menciona en el *capítulo 3.1.*, el razonamiento empleado aquí es, por tanto, el que podríamos denominar desde el punto de vista del proveedor (*donor-side approach*) de la materia y la energía (Figura 4.2b), desde el punto de vista de los ecosistemas. Se trata de una visión del proceso que se caracteriza por tomar como argumento para la evaluación, valoración, etc. de una determinada cantidad de producto o nivel de auto-organización de un sistema lo que se ha invertido en su generación, sin excluir otros argumentos pertinentes.

Esta naturaleza de la memoria energética como una medida desde el punto de vista del proveedor tiene implicaciones en lo que se refiere a la visión que ésta ofrece acerca de los servicios de los ecosistemas. La definición habitualmente aceptada de servicios de los ecosistemas, que ya hemos visto, se refiere a los mismos como "beneficio", es decir, desde el punto de vista del usuario. Ello implica habitualmente el uso de métodos monetarios de caracterización de estos beneficios, ligados a un sistema de toma de decisiones de coste-beneficio crematístico. El beneficio de mercado se complementa con beneficios de mercados relacionados o mercados hipotéticos, y así se argumenta que los beneficios de la conservación serán mayores que los de la destrucción, en términos del dinero que se obtiene de la primera frente a la segunda.

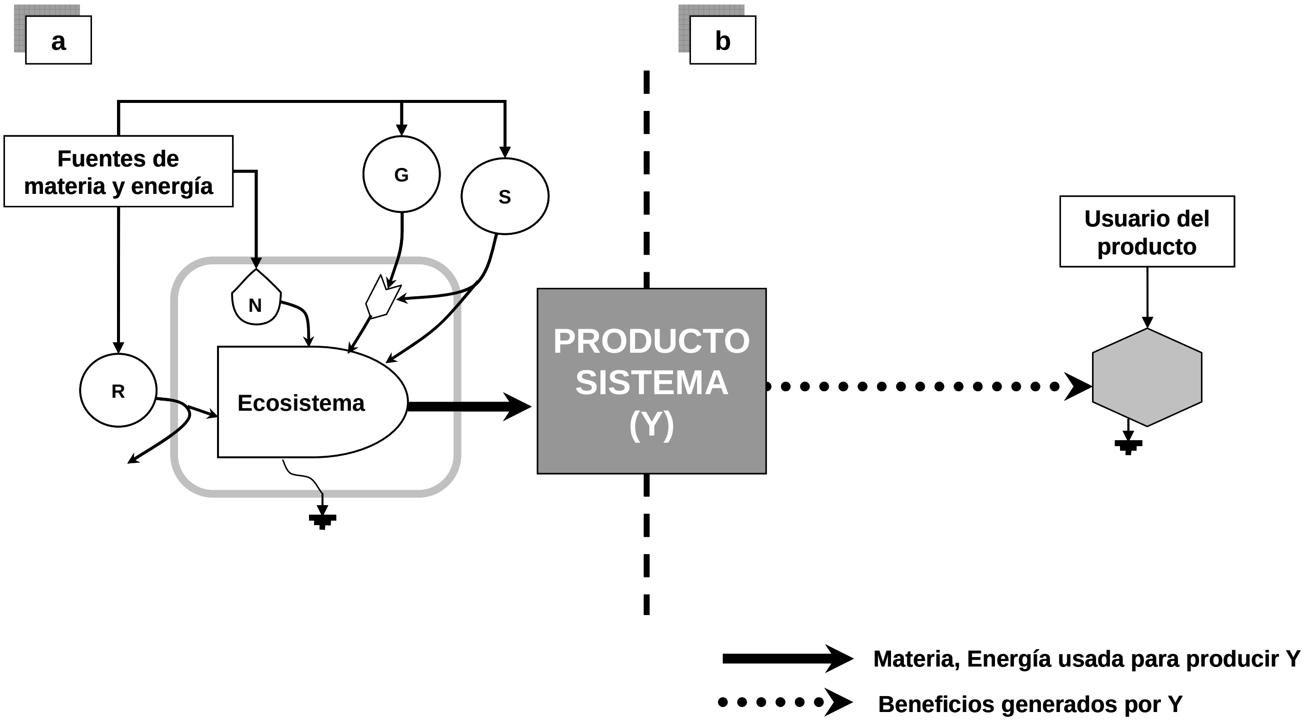

Figura 4.2. (a) *Punto de vista del proveedor*, donde el producto es el resultado del uso de una determinada cantidad de materia y energía dentro de un sistema; (b) *Punto de vista del usuario*, donde el producto aporta un beneficio (monetario, estético, etc.) a un consumidor.

La Síntesis Emergética aporta, sin embargo, una conceptuación diferente de las funciones y los servicios de los ecosistemas, en términos de costes ecológicos, que se define estructuralmente a partir de su punto de vista, el del proveedor, el de los ecosistemas. Las cantidades estudiadas pretenden responder, a una determinada escala espacio-temporal, a la pregunta de ¿qué cantidad de energía de la misma calidad ha sido necesaria para movilizar la materia y energía contenida en un determinado compartimento del socio-ecosistema, o en sus productos finales?[1], es decir, ¿cuál es su memoria energética?, ¿cuál es su emergía? No se parte, por tanto, de la cantidad de dinero obtenido del intercambio (venta) más o menos hipotético de un determinado servicio, ni tampoco de la cantidad de materia o energía obtenidas a cambio de dinero, sino más bien del coste que tiene el compartimento en términos de trabajo socio-ecológico. En los *capítulos 3.3. y 3.4.* estudiaríamos el cambio del coste ambiental de mantener una determinada población, o generar una determinada producción monetaria a lo largo del tiempo, es decir, de mantener un determinado sistema. En el *capítulo 3.5.*,

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[1] Nótese que no se trata de la pregunta ¿qué cantidad de energía está contenida dentro de un determinado compartimento? A dicha pregunta respondería mejor un análisis de la energía incorporada o una contabilidad de flujos de energía.

sin embargo, abordamos la variación del coste ambiental de un producto concreto en el tiempo.

Si utilizamos la teoría de las necesidades (Max-Neef *et al.* 1993; Doyal & Gough, 1994; Sempere, 2009) para explicarlo, el "beneficio", en estos términos, sería la satisfacción de la necesidad en sí misma (como ya adelantaba N. Georgescu-Roegen), para ello se habría usado una determinada cantidad de materia y energía (en términos de metabolismo socio-económico), que supondría, si lo expresamos en términos emergéticos, un determinado coste ambiental. Aquello con lo que satisfacemos la necesidad, el intermediario, sería el satisfactor, que sería un producto físico, pero que también podría ser el cariño, un cuadro, un paisaje, etc. El dinero, en este sentido, sería simplemente el vehículo de intercambio para obtener el satisfactor, en el caso de satisfactores que se encuentran en el mercado, no una medida del beneficio, puesto que el beneficio es la satisfacción de la necesidad. Se devolvería así al dinero su papel inicial de vehículo de intercambio, deshaciendo el error habitual que confunde el vehículo del intercambio con el objeto intercambiado y su valor.

4.1.3. Los flujos de servicios de los ecosistemas en la síntesis emergética

Como ya se ha explicado en el anterior punto, el estudio del capital natural a través de la síntesis emergética se hace desde el punto de vista del proveedor, es decir, desde el punto de vista de los flujos de entrada al sistema y el coste ambiental de los productos del mismo. En la síntesis emergética realizada en los *capítulos 3.3., 3.4., y 3.5.*, se estudian los flujos de materiales y energía que constituyen los servicios de los ecosistemas a una determinada escala espacio-temporal en términos de emergía. En los dos primeros (pp.115-162) se estudian los flujos de materia y energía, tanto desde los ecosistemas como desde otros sistemas socio-económicos, para mantener a dos sistemas socio-económicos a distintas escalas. En el último (pp. 163-208) se estudian la participación diferencial de la naturaleza y los insumos humanos en la producción agrícola. Así, bajo esta perspectiva, la definición del objeto de estudio (el capital natural, los servicios de los ecosistemas), se hace explícita y directamente en términos reales, físicos. Sin embargo, desde la aproximación del usuario se suele definir el objeto de estudio de manera indirecta e implícita a través de una propiedad que contiene dicho objeto, que lo convierte en valioso, con mucha frecuencia su valor de cambio en términos monetarios. Este tipo de estudio excluiría a todos aquellos objetos que poseyendo la misma naturaleza física, no poseen valor de cambio, y obliga a que si se desea estudiar este objeto bajo el mismo marco se deba codificar en términos de valor de cambio.

En la síntesis emergética, la naturaleza física de la medida conlleva aparejada la necesaria distinción entre la materia y la energía que utiliza el SES a una determinada escala espacio-temporal (que se ve reflejada en los balances de materia y energía que constituyen la tabla de emergía, ver ejemplos en pp. 123-126; pp. 188-191), y el trabajo que ha costado esta utilización, en términos energéticos, lo que se ve reflejado en las mismas tablas cuando, utilizando la transformicidad, se calcula la emergía de cada flujo. La primera categoría es la que estudia el metabolismo socio-económico, en sus versiones de contabilidad de materiales y de energía, y la segunda, es de la que se encarga la síntesis emergética, utilizando la información anterior. En este sentido, también cabe distinguir entre los elementos productores del flujo de emergía, y el flujo en sí mismo, es decir, utilizando la terminología ligada a los servicios de los ecosistemas que se explica en el *capítulo 1*, entre las unidades suministradoras de servicios y los servicios en sí mismos. La síntesis emergética concentra sus esfuerzos en estudiar los servicios desde el punto de vista del esfuerzo que tienen que hacer las unidades suministradoras de servicios en el marco del capital natural para generar físicamente la cantidad de servicios utilizada por los usuarios.

Otra consecuencia de la naturaleza física de la medida es la limitación a la hora de abordar determinados tipos de servicios de los ecosistemas. Si tomamos la clasificación de servicios de los ecosistemas derivada de la Evaluación de los Ecosistemas del Milenio (MA, 2003), y que los divide en: servicios de soporte[2], de regulación, de aprovisionamiento y culturales, la síntesis emergética, por su naturaleza, sería más apta para la cuantificación del coste ecológico de prestar una determinada cantidad de servicios de regulación y de aprovisionamiento, cuya naturaleza física permite una clara distinción y cuantificación. La síntesis emergética podría señalar qué cantidad de emergía, con calidad solar, fue necesaria para generar la cantidad de servicio utilizada.

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[2] Se eliminan los servicios de soporte al ser considerados no tanto servicios como el propio funcionamiento del sistema, que permite la generación de servicios. El funcionamiento del sistema, es decir, las relaciones entre los componentes del mismo, es también objeto de estudio a través de los diagramas de flujo y la Ecología de Sistemas.

Por otra parte, la naturaleza a veces inmaterial de los servicios culturales, haría que la representación de muchos servicios culturales no sea el objeto de la síntesis emergética. Por ello podemos decir que a través de la emergía se puede capturar el coste ecológico de obtener una pintura, pero no el servicio cultural, en términos estéticos, por ejemplo, que presta a los posibles visitantes del museo donde se encuentra. Así, por poner algunos ejemplos concretos, la síntesis emergética de España y de Andalucía (*capítulos 3.3.y 3.4.*) no captura las transformaciones culturales que van asociadas a los cambios promovidos desde el contexto europeo en el modo de uso del capital natural mediterráneo mas que por los cambios en el propio uso. En el *capítulo 3.5.* tampoco se abordan las problemáticas sociales surgidas a raíz de las transformaciones que ha tenido el cultivo del arroz a lo largo de su tecnificación mas que en forma de reducción en el uso de materia, energía y dinero asociado a la mano de obra.

4.1.3. Indicadores emergéticos: Integrando estadísticas bajo una misma base

Los indicadores y flujos de emergía tienen una naturaleza económico-ecológica, es decir, son el resultado de integrar tanto datos de carácter biogeofísico como información macroeconómica, comercial, etc. bajo una base común. Esta base común es el trabajo realizado por el SES para generar la cantidad de materia, energía, dinero, etc. que expresa el dato, codificando la energía en calidad igual a la solar. La integración de bases de datos e información de fuentes distintas, que habitualmente se maneja de manera separada, es otra de las características de la síntesis emergética, en la medida en la que esta metodología no sólo utiliza baterías de datos que luego se relacionan entre ellos, como ocurre normalmente en los sistemas habituales de indicadores presión-estado-respuesta (o en su versión impulsor-presión-estado-respuesta-impacto), sino que integra toda la información de los datos bajo un marco común (el de la síntesis emergética) con el objetivo de obtener indicadores *sensu stricto* de las distintas dimensiones del coste ambiental de un determinado producto o sistema (Figura 4.3.).

Por tanto, la síntesis emergética necesita de la participación de gran cantidad de bases de datos de diversa naturaleza (al respecto se pueden ver los cálculos asociados a la tabla de emergía del *capítulo 3.3.*, en las páginas 123-126 o el apéndice del *capítulo 3.5.*, en las páginas 187-208). La gran exhaustividad de la metodología en la cantidad y variabilidad de la información necesaria implica, por tanto, una problemática añadida, dado que los datos necesarios para la realización de una síntesis emergética son tantos y tan diversos que, en la situación actual, es difícil que todos se encuentren disponibles, o que puedan ser fácilmente calculados o estimados.

De hecho, la orientación monetaria de la mayoría de las estadísticas correspondientes a las cuentas nacionales y los sistemas estadísticos en países de la Unión Europea, ha supuesto un serio problema a la hora de abordar los *capítulos 3.3., 3.4., y 3.5.* de la presente tesis, especialmente los dos últimos. La mayoría de las estadísticas de variables no monetarias forman parte, cuando existen, de cuentas satélite (agua, residuos, emisiones, flujos de materiales, etc.), que no siempre se desarrollan a escalas de mayor detalle que la estatal. Son especialmente serias las deficiencias del sistema en lo que se refiere a datos comerciales o de entrada y salida de mercancías, que son la base del cálculo de las importaciones y las exportaciones de emergía entre sistemas, y cuyo cálculo material se aborda fundamentalmente a nivel estatal. Por debajo de esta escala, la información disponible depende mucho de las comunidades autónomas, y de las provincias, no encontrándose información a nivel local, siendo rara la información disponible para el comercio entre regiones y provincias, que constituye el grueso del mismo a esas escalas[3], y que tiene una gran importancia para el desarrollo de la síntesis emergética.

Es imperiosa, por tanto, la necesidad de disponer de estadísticas de base en formato no monetario, que alimenten un sistema estadístico con mayor base biogeofísica, y que presenten una extensión temporal adecuada, que permita hacer estudios de largo plazo, no ya sólo con el objetivo de conocer los costes ambientales en el marco de la síntesis emergética, sino también de alimentar otros métodos dentro de estos enfoques de metabolismo socio-económico y ACV que constituyen la Economía Ecológica.

Naredo (2003) señala algunas de las cuentas esenciales sobre el patrimonio natural y la economía de las que debería disponer un sistema estadístico como éste cuando habla de su enfoque ecointegrador. Especialmente importantes, a la hora de proveer de la

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[3] De hecho, en España gran parte de la base en peso de las estadísticas comerciales entre regiones a nivel autonómico o provincial con cierto nivel de desagregación se están desarrollando a partir de un proyecto europeo INTERREG, denominado C-INTERREG (http://www.c-intereg.es/), llevado a cabo por el CEPREDE de la Universidad Autónoma de Madrid, y que pretende ser el inicio de una base de datos de referencia para estudiar el comercio interregional en el marco de los sistemas estadísticos regionales.

información comercial adecuada a los distintos métodos basados en los enfoques de ACV o del metabolismo soci-económico, serían las tablas input-output de carácter físico (TIOF), que contabilizarían las cantidades de materiales y energía de un determinado tipo necesarias para alimentar cada una de las actividades productivas a una determinada escala, ya sean locales o importadas; así como las cantidades de materiales y energía de cada tipo exportadas a otros sistemas.

Además, la necesidad de grandes bases de datos procedentes de diferentes fuentes, y la mezcla de esos datos implica la integración bajo las cantidades emergéticas de medidas con errores de medición y/o cálculo de distinta magnitud, no siempre explícitos en las fuentes de datos a las que se recurre para su obtención. Ésta es, entre otras, la razón por la que se entiende que las UEVs no son cantidades fijas, sino que se encuentran dentro de un rango que se define, por una parte, a partir de la variabilidad de tecnologías y ambientes en que un mismo producto (como es el caso de la producción de arroz en diferentes áreas del mediterráneo, estudiada en el *capítulo 3.5*) o sistema (como es el caso de los SES analizados en los *capítulos 3.3. y 3.4.*) puede generarse o surgir, así como el margen de error con el que se cuenta a la hora de obtener la información que alimenta el modelo. Este problema es común a la mayoría de las metodologías que adoptan un enfoque ACV.

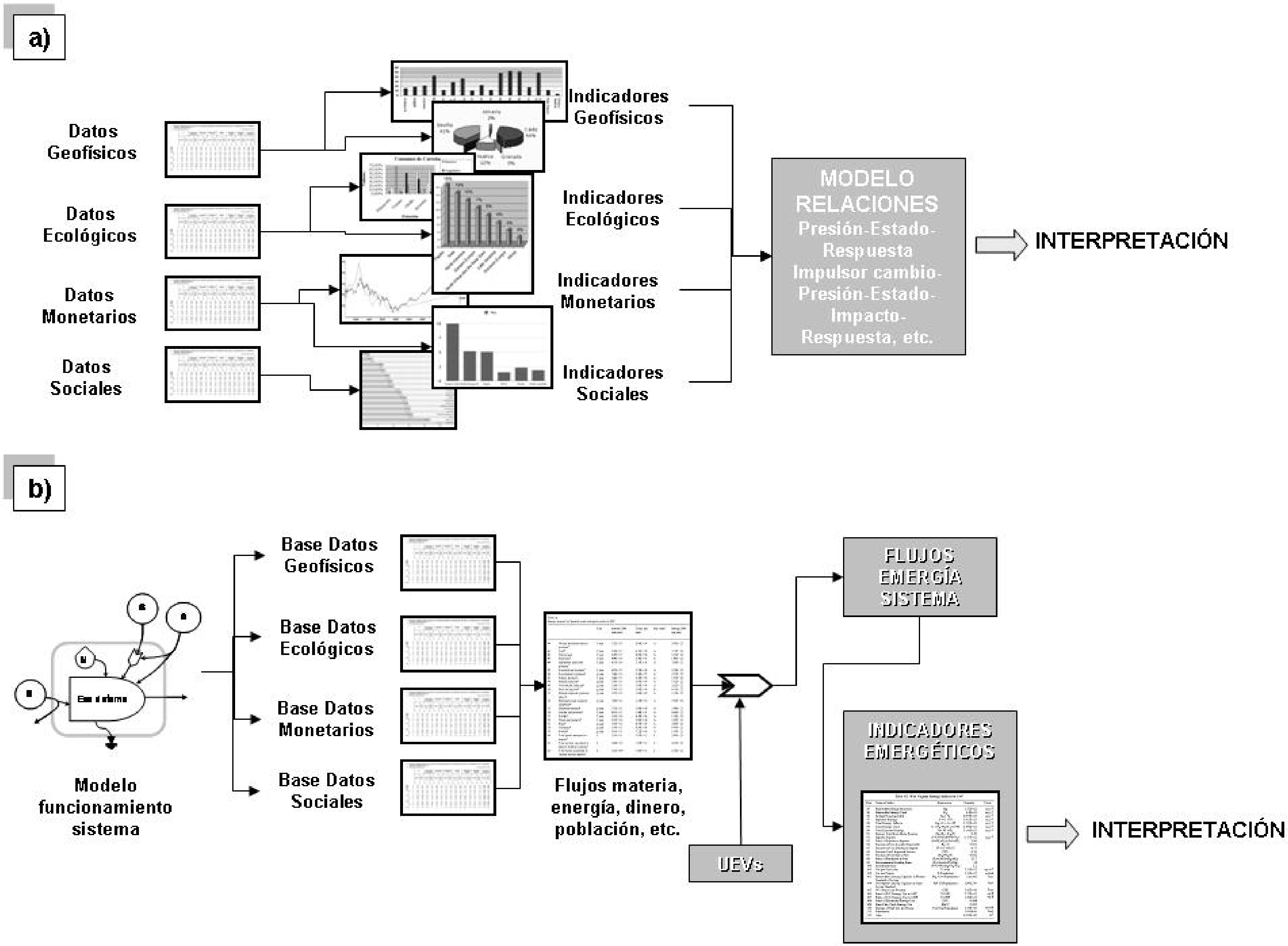

Figura 4.3. Desarrollo de (a) sistemas de indicadores convencionales, que se relacionan a través de un modelo "*a posteriori*" y (b) indicadores emergéticos, que surgen de la integración efectiva de bases de datos, trabajo de campo o análisis a partir de sistemas de información geográfica.

4.2. Evaluación multi-escalar del uso del capital natural: aportaciones de la síntesis emergética

En el *capítulo 4.1.* se ha discutido el aporte de la síntesis emergética al estudio de los servicios de los ecosistemas a través de algunas de sus herramientas, y el alcance del concepto de emergía dentro de este marco. En este capítulo estudiaremos la aptitud de estas herramientas para comprender causas, consecuencias y evolución del uso del capital natural a varias escalas.

4.2.1. La evolución en el uso del capital natural y los indicadores emergéticos

A diferencia de otras medidas, la dimensión temporal del uso del capital natural viene ya incorporada en cada cifra cuando hablamos de emergía, es decir, cada punto de un gráfico de emergía incorpora una evolución temporal, resultante de un proceso de ensayo-error en que el sistema ha ido adoptando diversos grados de auto-organización hasta llegar al grado de complejidad actual, a ocupar un determinado nivel dentro de la escala de jerarquía energética. Por tanto, dicha evolución temporal se tiene en cuenta a través de los UEVs. Tal y como se definen los UEVs ya en el *capítulo 2* (p. 39), la transformicidad o la emergía específica son los factores de transformación que explican la cantidad de seJ (joules equivalentes solares) por joule o gramo de elemento del sistema (ya sea componente, producto, fuente, etc.), respectivamente. Es decir, en cada cifra de este indicador se contiene el total del trabajo biogeofísico y/o económico que la naturaleza y/o sociedad han llevado a cabo a lo largo del tiempo para generar una unidad de ese elemento o producto, dándonos así un verdadero indicador de la eficiencia[4] del sistema. Así, los *capítulos 3.3. y 3.4.* nos proporcionan cifras de la cantidad de energía equivalente solar que es necesaria para mantener la población de cada SES o para generar el dinero producido por la economía del sistema en ese tiempo (PIB). En el *capítulo 3.5.* se proporcionan cifras de emergía específica y transformicidad para la producción anual del arroz y los distintos residuos obtenidos en la producción del mismo en el contexto de las marismas del Guadalquivir, y en comparación con los mismos indicadores para otras áreas mediterráneas y otros cultivos localizados en áreas parecidas.

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[4] Eficiencia = cantidad de entradas de materia y/o energía necesarias para obtener una unidad de producto, o relación input/output.

La evolución de las UEVs dentro de la serie histórica de indicadores emergéticos para una misma escala espacio-temporal nos da una idea de los cambios en la eficiencia del funcionamiento del sistema económico de aprovechamiento del capital natural en este marco temporal. Así, podemos ver cómo en los SES estudiados (*capítulos 3.3., 3.4., y 3.5.*) se va perdiendo eficiencia (la transformicidad se eleva, y por tanto se requiere más trabajo por parte de la naturaleza para generar la misma cantidad de producto u organizar el sistema al mismo nivel) a lo largo de la serie histórica. El aumento o disminución del UEV implica un aumento o disminución del trabajo realizado por la naturaleza, del tiempo y esfuerzo (materia y energía) invertidos. Por tanto, los cambios en los UEV nos dan una idea de la responsabilidad que adquiere el usuario en el uso de los productos del sistema, es decir, a una mayor transformicidad (menor eficiencia, mayor trabajo) la responsabilidad del usuario a la hora de usar indiscriminadamente el producto del sistema es mayor, especialmente cuando estamos hablando de modelos de uso cada vez más ligados a fuentes no renovables y a importaciones de memoria energética de otros SES.

La dimensión temporal también se captura en la síntesis emergética a través de series históricas de los flujos e indicadores emergéticos, es decir, cómo varía el uso de la memoria energética contenida en los elementos que sustentan el sistema a lo largo del tiempo. En el *capítulo 3.1.* las figuras (p. 68-82) nos muestran series históricas de la evolución de los principales flujos e indicadores emergéticos para distintos SES a escala de país, destacando la necesidad de obtener series históricas largas con el objetivo de comprender los patrones de uso del capital natural y la dinámica del mismo. Por su parte, en el *capítulo 3.3.* se aborda, a través de una serie histórica de indicadores emergéticos, el estudio de un SES a escala nacional. La posibilidad de comparar la evolución histórica de la parte del uso de emergía correspondiente a fuentes renovables (el flujo de los sistemas ecológicos), con la ligada a fuentes no renovables (el flujo de los componentes de estos sistemas usados de modo no renovable y/o la importación de emergía de otros sistemas), permite identificar cuánto es mayor el uso de emergía del sistema del que se correspondería a un uso conectado a fuentes completamente renovables en el tiempo, e identificar así el grado de aprovechamiento por encima de lo renovable que éste tendría. Partiendo de esta base se han estudiado estos indicadores en España, y se han comparado con los existentes en la literatura para un entorno mediterráneo y para un entorno europeo en la misma época. Así se ha observado cómo el socio-ecosistema España ha adoptado, a lo largo del período estudiado, unos usos más propios de socio-ecosistemas de Europa occidental que de su origen europeo mediterráneo. Esta conclusión complemente la obtenida por Carpintero (2005) cuando, a partir del estudio del metabolismo socio-económico, afirma que se ha producido un cambio en España desde una economía productiva, más cercana a la explotación de los ecosistemas propios y las potencialidades que ofrecían los ecosistemas locales, hasta una economía de la adquisición, ligada a la generación de dinero a través de los servicios y la compra de las materias primas a otros países. Este patrón se repite a medida que vamos descendiendo a escalas de mayor detalle, si bien los tiempos se retardan, y en el caso de las provincias el hecho es diferencial, según la conexión de las provincias a los impulsores de cambio económicos a escala internacional.

4.2.2. Dinámica de cambio en los SES e indicadores emergéticos

Con respecto a la dinámica de uso del capital natural en los SES, hay que señalar que durante mucho tiempo el paradigma imperante sobre la dinámica en el funcionamiento de los ecosistemas en Ecología ha sido el del equilibrio de las comunidades y los ecosistemas, en el que éstos tendían hacia una sucesión espacio-temporal de creciente organización o complejidad, alcanzando un estadio final de equilibrio estático denominado clímax (Clemens, 1916; 1936). Dicho estado de equilibrio se veía perturbado por distintas fuerzas impulsoras de cambio, que eran vistas, en términos negativos, como desplazamientos fuera del equilibrio (Pimm, 1984; De Angelis & White, 1994; Molles, 2005). Esta idea del equilibrio estático ha estado presente en la mayoría de los modelos de relaciones ser humano-naturaleza a lo largo del tiempo, otorgando un papel negativo al ser humano como una perturbación sobre el equilibrio de los ecosistemas. En el *capítulo 3.2.* se rebate la idea del ser humano como elemento externo y negativo para el contexto de los SES Mediterráneos, concluyendo que los actuales sistemas ecológicos son el fruto de la co-evolución milenaria entre ser humano y naturaleza para formar paisajes culturales, y que no es posible estudiar la estructura, funcionamiento y dinámica de estos ecosistemas sin tener en cuenta al ser humano, o simplemente concibiéndolo como una perturbación frente a una situación de equilibrio, supuestamente natural.

Esta concepción negativa de las perturbaciones y lineal del cambio ha sido rebatida con la experiencia ganada durante décadas, en los años 70 y 80, en estudios que demostraban que los ecosistemas se comportaban de modo más bien cíclico, con fases de fuerte aumento de productividad, seguidas de repentinos colapsos, y posteriores reorganizaciones. Holling (1986) desarrollaría entonces el ciclo adaptativo (Figura 4.4a), un modelo heurístico que pretendía incorporar a estas fases de aumento de productividad (r) y estabilidad (k), también aquellas de colapso (Ω) y recuperación del sistema (α). Este modelo sería generalizado posteriormente a los socio-ecosistemas en Gunderson & Holling (2001).

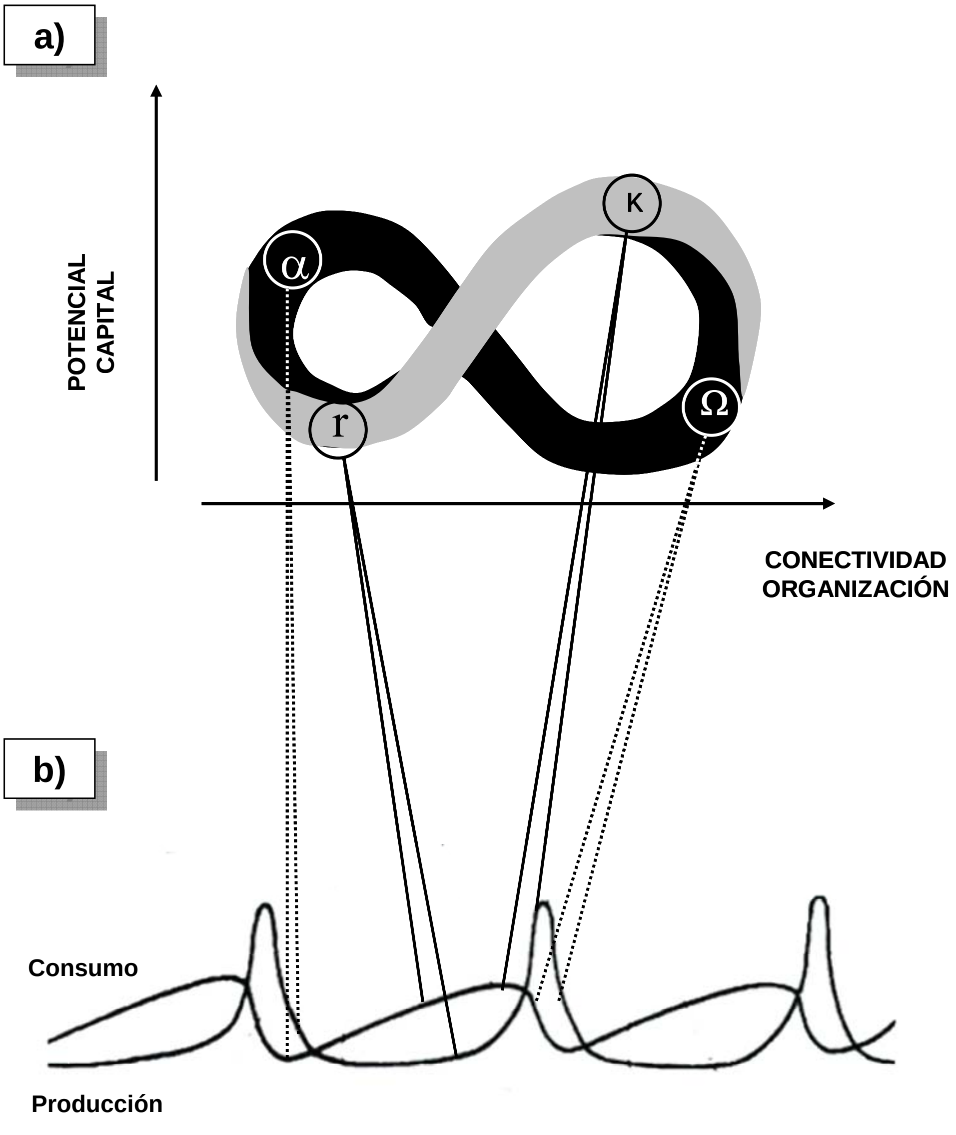

Figura 4.4. Representación de los modelos heurísticos de: (a) Ciclo adaptativo (Holling, 1986), con sus cuatro fases, y del (b) sistema ecológico pulsante (Odum, 1995) con sus respectivas equivalencias.

A la vez, y convergiendo con la idea anterior, Odum desarrollaría el paradigma de la naturaleza pulsante de los ecosistemas (Odum, 1995), donde las fases del ciclo tendrían el nombre de crecimiento, clímax y transición, descenso y restauración de baja energía (Figura 4.4b), fases que posteriormente generalizaría a los sistemas ecológico-económicos en Odum (1996).

Odum & Odum (2001), en su libro *Prosperous Way Down*, señalan que a cada fase del ciclo le corresponden unos rasgos característicos de acuerdo con las restricciones biogeofísicas que determinan cada fase (Tabla 4.1.).

Tabla 4.1. Rasgos característicos correspondientes a cada fase del pulso de los SES a partir de Odum & Odum (2001).

FASE DEL CICLO	RASGOS CARACTERÍSTICOS
r (crecimiento)	Crecimiento sobre la base de capital natural abundante, con baja eficiencia en la explotación y fuerte competencia.
k (clímax y transición)	El sistema alcanza su escala máxima en base al capital natural existente, aumenta la eficiencia y se desarrollan patrones de colaboración, a la vez que se acumula información y conocimiento para la futura transición.
Ω (descenso)	Adaptación a menor disponibilidad de servicios de los ecosistemas con el correspondiente descenso en el uso total del capital natural con una mayor preocupación en el cierre de ciclos
α (renovación)	Renovación de baja energía, con un estado donde predomina la acumulación para el inicio de un nuevo ciclo de auto-organización.

Y es bajo esta perspectiva que, tal y como se menciona en el *capítulo 3.1.*, se puede afirmar que el significado de los indicadores emergéticos es contexto-dependiente, es decir, el significado de valores altos o bajos de cada uno de los indicadores es más o menos positivo según la fase del ciclo adaptativo en la que se encuentre el sistema. Así, en las fases de crecimiento (r) experimentadas por los SES en los *capítulos 3.3., 3.4. y 3.5.* un alto EYR tiene inicialmente un significado positivo, puesto que conlleva un mayor aprovechamiento de los flujos de emergía con origen en fuentes locales (capital natural local) por unidad de emergía incorporada a partir del trabajo realizado por otros SES, pero el mantenimiento de esta dinámica a medio-largo plazo tiene un efecto negativo cuando implica un aumento excesivo del ELR en el tiempo, derivado de una intensificación del uso de las fuentes de emergía no-renovables de carácter local en lugar de un mejor aprovechamiento de las fuentes de emergía renovables, lo que sucede en los casos de estudio aportados para algunas provincias andaluzas (*capítulo 3.4.*), donde además el flujo de importaciones procedentes de otros SES es también alto. Esta situación puede forzar, como así ocurre en el caso de los arrozales de las Marismas del Guadalquivir (*capítulo 3.5.*), el paso hacia una fase de crisis del sistema productivo (r a

Ω), con contracciones de mayor o menor intensidad en el uso total de emergía *per capita* o en la intensidad emergética territorial (emergía usada por unidad de superficie), y la necesidad de que instituciones procedentes de otra escala del SES aporten reglas para entrar en una fase de renovación.

4.2.3. Desacoplamiento de los ecosistemas locales y acoplamiento a otros SES

Desde la Economía convencional (Ambiental) se defiende que si bien en fases iniciales de crecimiento (monetario), existe una fuerte correlación entre el uso de los servicios de los ecosistemas y este crecimiento, a partir de cierto punto, las economías tenderían a una terciarización, con un cambio en el consumo final de bienes y servicios, un aumento en la eficiencia en el uso de los recursos y una sustitución de ciertas materias primas tradicionales por otras más eficientes. El resultado sería que desde ese momento, el crecimiento comenzaría a desacoplarse del uso de los ecosistemas, y por tanto, alcanzado ese nivel podríamos seguir creciendo de manera más o menos ilimitada, con un consumo menor de servicios de los ecosistemas. El gráfico resultante es lo que se denomina una Curva de Kuznets Ambiental (Figura 4.5.), que tendría forma de U invertida (Malembaum, 1978; Dinda, 2004; Stern, 2004). Esta idea ha recibido muchas críticas (e.g. Ekins, 1997; Cleveland & Ruth, 1999; Heisaken & Jalas, 2000; Ropke, 2001; Carpintero, 2002), pero sigue siendo fuente de multitud de debates.

En España, son numerosos los estudios que cuestionan empíricamente esta hipótesis (e.g. Ramos-Martín, 2001; Roca *et al.*, 2001; Carpintero, 2005), basándose en indicadores como la intensidad energética, la contaminación atmosférica, o los requerimientos de materiales, etc. En lo que se refiere a las aportaciones de la síntesis emergética a este debate, desde el punto de vista de la desmaterialización absoluta (disminución del uso de servicios de los ecosistemas a la vez que aumenta la producción medida por el PIB), en los *capítulos 3.3. y 3.4.* se puede observar cómo, en general, el uso de emergía total se incrementaba a lo largo de prácticamente todo el período abarcado para todos los sistemas estudiados, paralelamente al aumento del PIB o del producto regional/provincial correspondiente. Desde el punto de vista de la desmaterialización relativa (disminución de la relación entre el uso del capital natural y el PIB) podemos decir que los sistemas experimentan fases de desmaterialización relativa, donde el EMR decrecía, seguidas de otras fases de fuerte rematerialización, donde el EMR crecía fuertemente, lo que en el caso de nuestros sistemas se da fundamentalmente a partir de los años 90, lo que por otra parte coincide con la hipótesis cíclica de los SES mencionada anteriormente.

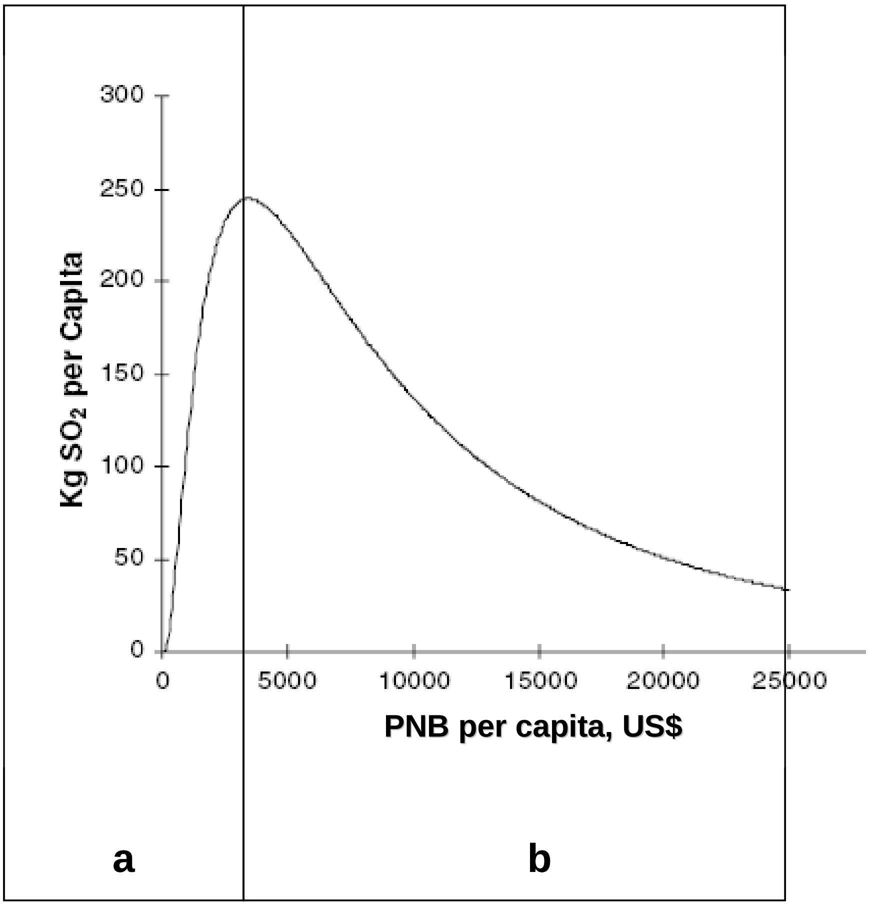

Figura 4.5. Curva de Kuznets Ambiental para las emisiones de azufre (A partir de Stern, 2004), donde (a) implica un mayor crecimiento y una mayor contaminación y (b) es la fase donde se produce un mayor crecimiento con una menor contaminación.

Por su parte, en el *capítulo 3.4.*, el estudio del uso del capital natural está enfocado a entender las dinámicas de acoplamiento-desacoplamiento de la economía con respecto a los servicios de los ecosistemas locales, mediante el empleo del indicador fracción del uso de emergía realmente usada que es importada (FUIMP). El uso de este índice, complementado con el resto de indicadores, pone de manifiesto que aun en el caso de una disminución en el uso de servicios de los ecosistemas locales por parte de Andalucía y sus provincias, el crecimiento económico (en términos de PIB regional y/o provincial) se ve soportado por la importación masiva de emergía procedente de SES externos. Así, la carga ambiental sobre los ecosistemas locales no desaparece, de hecho, el ELR tiende a aumentar considerablemente en la mayoría de las provincias y en

Andalucía en su conjunto, sino que parte de la carga ligada al nuevo crecimiento experimentado se vería desplazada hacia otros SES, que serían concretamente los que exportan su emergía hacia Andalucía y sus provincias, que obtendrían dinero a cambio de la explotación de su memoria energética. Muradian & Martínez-Alier (2001) alertan sobre el efecto que esta situación tendría desde el punto de vista de las emisiones y los vertidos en los países hacia donde se exportan estas cargas.

4.2.4. El comercio de memoria energética: el estudio de las relaciones con otros SES

Las relaciones de un determinado SES con otros sistemas planteadas anteriormente nos llevan a discutir también acerca de otro aspecto sobre el que los indicadores emergéticos permiten dar luz y complementar otras perspectivas, que es el del intercambio de materia y energía entre SES, no ya sólo bajo una perspectiva monetaria (comercio), sino también de memoria energética, dado que la ventana ambiental supone una visión explícita de la relación espacial entre los SES, dado que enlaza el funcionamiento interno del sistema, con los flujos de materia y energía que lo alimentan desde otros SES a distintas escalas.

Desde el punto de vista monetario, el comercio entre dos naciones, por poner un ejemplo, se evalúa en términos de balanza de pagos, es decir, el saldo del dinero ingresado por las exportaciones frente al dinero gastado en las importaciones (un análisis del tipo coste-beneficio), asumiendo que la única diferencia entre las mercancías intercambiadas es el precio, y primando aquellas situaciones en las que la balanza de pagos es positiva. Se trataría así de explotar las ventajas comparativas de las economías locales para generar economías de escala que permitan exportar estos productos, y abastecerse a través de la importación de otros países de aquellos cuyos costes de producción sean altos en lo local.

Si adoptamos el punto de vista del proveedor, en la síntesis emergética, la relación Emergía-Dinero (Emergy to Money ratio, EMR) compara la cantidad de emergía usada por un sistema, con la cantidad de dinero derivada de la producción del mismo sistema (el PIB, por ejemplo), es decir, la cantidad de emergía movilizada por unidad monetaria producida en un determinado periodo de tiempo. Si examinamos cualesquiera sistemas que intercambian materia y energía entre sí (no sólo países) es obvio que la EMR será diferente en cada uno de ellos, y por tanto, en el intercambio entre sistemas habrá algunos de ellos que obtengan más emergía por unidad monetaria que otros, saliendo así favorecidos en el intercambio (Figura 4.6.). Siguiendo este razonamiento, Brown (2003) propuso otro indicador emergético, la Tasa de Cambio Emergética, que permitía poner de manifiesto las ventajas o desventajas comparativas en los intercambios entre socio-ecosistemas.

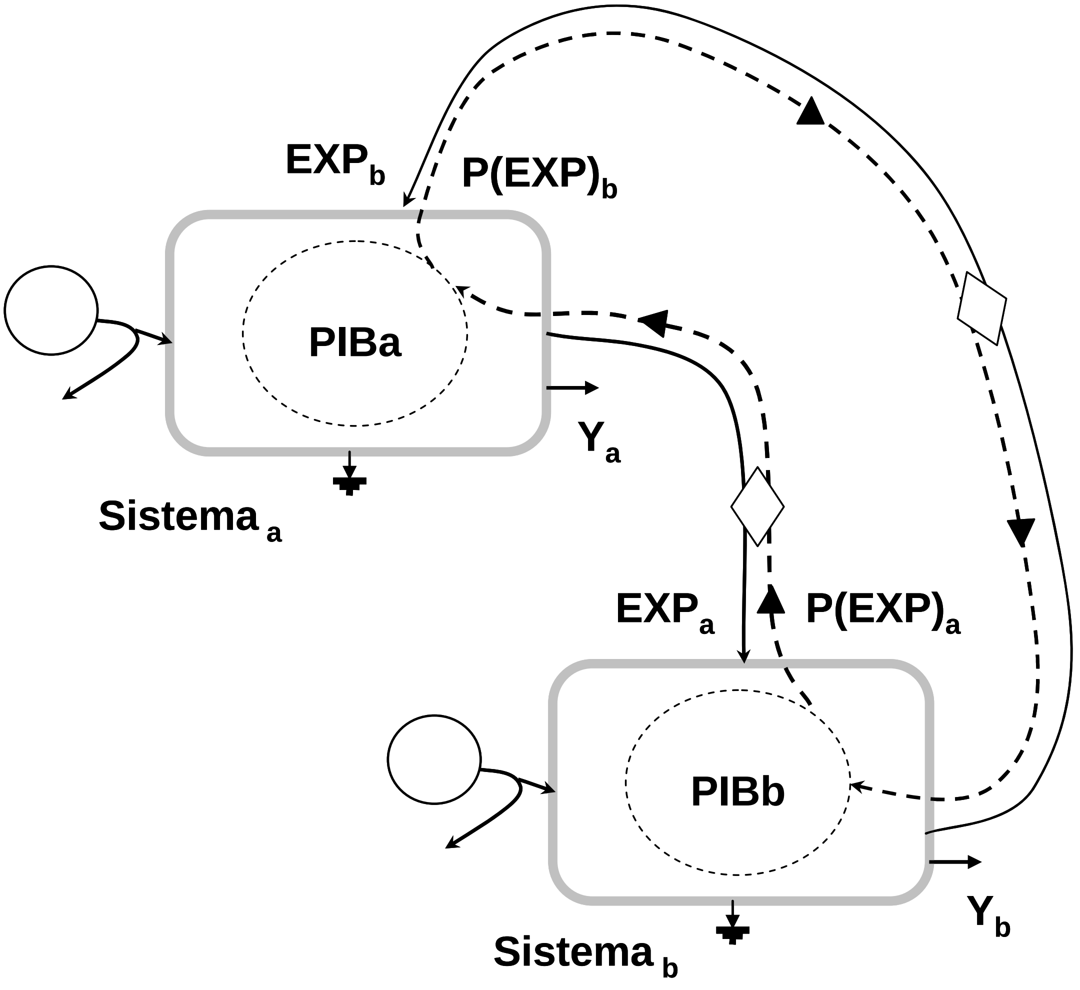

Figura 4.6. Esquema de intercambios de emergía. Las exportaciones del i-ésimo sistema (EXP_i) obtienen a cambio una cantidad $P(EXP)_i$. Si la EMR del sistema i es igual a Yi/GDPi, entonces la tasa de de intercambio emergético (EER) entre los sistemas a y b será igual a EMRa/EMRb. Una EMR mayor de un sistema frente a otro, es decir, la necesidad de más emergía por unidad monetaria producida implicará una desventaja en el intercambio entre sistemas.

En el *capítulo 3.3.* se puede observar la tasa de cambio emergética para España y las relativas ventajas comparativas con otros países del mundo, en particular con algunos que le suministran algunas materias primas de importancia. Este indicador nos permite estudiar una suerte de división del trabajo a varias escalas, donde los sistemas con ventajas comparativas en el uso del dinero y la obtención de emergía especializan a otros países en el suministro de sus necesidades, externalizando de su territorio así las cargas ambientales (el uso masivo de la memoria energética almacenada a nivel local) que ello reporta, y las consecuencias que esto tiene (degradación ambiental, empeoramiento de calidad de la vida, etc.). Se puede así observar cómo aquellos países, que se transforman en adquisidores, utilizando la terminología de Naredo (2003; 2006) y Carpintero (2005), y por tanto importadores netos de emergía, como es el caso de España, suelen tener una ventaja comparativa respecto a aquellos otros que son productores, y normalmente grandes exportadores de emergía, dado que es frecuente que el EMR sea menor que estos últimos.

En el caso de las regiones, como es el abordado en el *capítulo 3.4.*, nos permite ver qué papel juegan dentro de un marco estatal mayor. Como podemos observar, Andalucía se ha transformado en una región claramente extractiva y exportadora, manteniendo gran parte de su exportación un destino nacional, con lo que, a través del estudio de estos indicadores hemos podido llegar a afirmar que Andalucía juega (viene jugando, aunque ahora esté cambiando esta situación, tal y como se observa en el *capítulo 3.4.*) un papel de abastecedor de materias primas dentro del contexto Español, sufriendo así una desventaja comparativa, en términos emergéticos, con otras regiones orientadas fundamentalmente al sector servicios, como podrían ser algunas de la costa mediterránea o la región madrileña. Esto apoya las conclusiones del estudio de Delgado Cabeza (2002), basado exclusivamente en indicadores monetarios. Esta dinámica se reproduce también a la siguiente escala estudiada, que sería la provincial. En esta escala podríamos observar, a través del uso de los indicadores emergéticos, cómo son las provincias situadas en la costa las que se organizan más alrededor de esta dinámica comercial y transforman sus relaciones con el capital natural de acuerdo con esta lógica, teniendo un fuerte ritmo de explotación del capital natural local, lo que trata de compensar monetariamente con un fuerte ritmo de exportación. Son las provincias interiores las que tienen otra dinámica de aprovechamiento menos intensiva del capital natural local, pero a su vez también impactante, ligada a un bajo uso del capital natural local y a una fuerte dependencia de importación de servicios de los ecosistemas externos.

Esta localización geográfica específica de las provincias más ligadas a las dinámicas de acoplamiento a los servicios prestados por SES externos observada en las provincias costeras dentro de la región andaluza, apoya la idea de que la tendencia al desacoplamiento entre el modelo económico y los ecosistemas locales está relacionada con dinámicas de globalización económica y la extensión de un modelo de comercio desigual a nivel internacional, en las que son parámetros externos y de organización de mercado (en este caso de mercado común) los que determinan el modelo de relaciones entre el ser humano y la naturaleza, a todas las escalas, incluida la local, es decir, que son impulsores de cambio indirectos los que condicionan, cada vez con más fuerza, la relación ser humano-naturaleza, incluso a esta escala local.

Por otra parte, en el *capítulo 3.5.* se observa cómo la tendencia a la externalización de la carga ambiental se puede, al menos, frenar. La implantación de una institución, como es la producción integrada, dentro de un sistema de explotación agrícola, ha permitido mantener unos niveles de producción altos más ligados a los ecosistemas locales, en este caso al funcionamiento original de las marismas del Guadalquivir, con una cierta tendencia al decreciente uso de emergía externa. La crisis vivida por el sector en los años 80-90 ha forzado a cambiar el sistema de aprovechamientos y a apostar por la calidad y el rendimiento frente a la cantidad. Esto ha implicado un descenso en el uso de productos químicos dentro de la explotación, lo que ha redundado en un mantenimiento mucho más local, y un empleo de químicos más controlado. La transformicidad y la emergía específica correspondientes han disminuido, y se ha aumentado la memoria energética de carácter renovable y local, aumentando así el nivel de acoplamiento entre los dos sistemas, el productivo y el ecológico, a escala local.

4.3. La síntesis emergética en un contexto multi-criterio

Los artículos que constituyen los resultados que se presentan en el *capítulo 3* de esta memoria tienen, aparte de la metodología y el tratamiento del uso del capital natural desde la síntesis emergética, algo más en común. Se trata del llamamiento a la adopción de una perspectiva multi-criterio a la hora de abordar la evaluación de los servicios de los ecosistemas. Este llamamiento parte del uso y la aplicación de una metodología (la síntesis emergética) que paradójicamente ha sido asociada con frecuencia a un reduccionismo energético en el plano de la valoración de los servicios de los ecosistemas (Farber *et al.* 2002; Patterson, 1998; 2002; Álvarez *et al.* 2005).

Este apartado trata de discutir acerca de la síntesis energética como método de evaluación/valoración/contabilidad de los servicios de los ecosistemas a la luz del empleo de la metodología, así como del significado preciso de los indicadores del método que se han aplicado.

En primer lugar conviene hacer una aclaración de lo que entendemos por estos conceptos. Si se consulta el diccionario de la Real Academia de la Lengua Española (RAE, en adelante) se puede ver que las acepciones de evaluación y valoración son muy parecidas, aunque en ocasiones tienen aplicaciones ligeramente distintas, y la confusión acerca de estos términos es muy fuerte.

De acuerdo con la RAE, en castellano comúnmente se entiende por *Evaluación* (*assessment*) el acto de señalar el valor de algo. En el contexto ambiental, con frecuencia se suele hablar de una evaluación como el conjunto de procesos destinados a comparar el valor en distintas alternativas con el objetivo de llevar a cabo aquella que se considere mejor. Así, hablamos de evaluación de impacto ambiental cuando nos referimos al proceso de comparar el valor del impacto de distintas alternativas sobre el medio ambiente y se trata de elegir aquella que presente menor impacto, dependiendo del objetivo, o de evaluación de riesgos cuando comparamos el valor de las pérdidas esperadas en función de la probabilidad de que se produzca un determinado evento, y de evaluación de ecosistemas cuando nos referimos al proceso por el que se compara, por ejemplo, la integridad de un ecosistema en función del grado de alteración que haya sufrido.

Por su parte, la Valoración (*valuation*) tiene que ver con el proceso de valorar, de dar valor. Sin embargo, como ya hemos visto, el concepto de valor es un concepto que tiene, como mínimo, dos caras. Por una parte, tendríamos la aptitud que poseen las cosas para satisfacer una necesidad o proporcionar bienestar; por otra, hablaríamos de la cualidad de las cosas en virtud de la que se da por poseerlas una cierta suma de dinero o algo equivalente. El primero de ellos es lo que comúnmente se conoce en Economía como el valor de uso; el segundo es el que se conoce como valor de cambio. Partiendo de estas dos definiciones de valor, tenemos dos modos de entender lo que significa valorar, y por tanto, de entender la valoración. Respectivamente tendríamos el proceso de reconocer y/o apreciar el valor o mérito de una persona o cosa, y el proceso de señalar a una cosa el valor correspondiente a su estimación, es decir, ponerle precio. A su vez, estas ideas de la valoración se corresponden con los dos modos clásicos de entender lo económico desde Aristóteles, el que se corresponde con la Economía aristotélica, y que sería el arte de vivir bien procurándose los valores de uso para una buena vida; y el que se corresponde con la Crematística aristotélica, es decir, el arte de adquirir bienes y servicios mediante el comercio, y venderlos obteniendo un beneficio pecuniario, cuanto mayor mejor.

Cuando hablamos de Contabilidad (*accounting*) normalmente la relacionamos con la acción o efecto de cuantificar. Así pues, la contabilidad sería el proceso de asignación de un número cardinal como representativo de un conjunto de elementos que se pueden expresar en las mismas unidades (es lo que en algunos ámbitos se denomina conmensurabilidad fuerte, o que una determinada variable se puede expresar en unas únicas unidades de medida). Por ejemplo, podemos contabilizar la masa de un cuerpo porque podemos expresarla en una misma unidad del Sistema Internacional, el kilogramo. O contabilizar el valor de cambio de un objeto porque podemos expresarlo en euros. La contabilidad es una herramienta útil dentro de los procesos de evaluación, puesto que permite comparar alternativas para un determinado criterio en las mismas unidades.

Así pues, el concepto de evaluación es un concepto general que engloba al resto. En la mayoría de las evaluaciones existe alguna forma de valoración, puesto que ése es su objetivo, que se implementa mediante algún método de contabilidad, ya sea monetaria o mediante otras formas de contabilidad. La evaluación está más ligada, por tanto, a la toma de decisiones, mientras que la valoración y la contabilidad estarían más ligadas a las herramientas con las que se realiza de manera práctica la evaluación. Perspectivas distintas a la hora de abordar la evaluación implican modelos distintos de valoración y herramientas de contabilidad distintas, no siempre compatibles entre sí.

Desde la perspectiva de la Economía Ambiental, el único método de evaluación sería el análisis coste-beneficio monetario, la valoración sería monetaria, y los métodos de contabilidad monetaria irían desde los ligados a contabilidad de mercados reales, pasando por los mercados relacionados hasta los mercados hipotéticos, con sus distintas variantes más o menos participativas, a distintas escalas, con distintos actores, etc. Sin embargo, desde la Economía Ecológica esto no es posible, ya que, al no ser sujetos de intercambio monetario, no se puede trasladar al mercado la mayoría de los servicios que presta la ecosfera, y son múltiples las perspectivas desde las que se puede mirar el problema (equidad, justicia, escasez absoluta, renovabilidad, etc.), no ya sólo desde la eficiencia paretiana y el balance de coste-beneficio monetario, que son los criterios de las metodologías de valoración monetaria. En este sentido, el método de evaluación está necesariamente avocado a ser la Evaluación multi-criterio, donde la valoración es múltiple (se abordan múltiples tipos de valores, no sólo el monetario en sus diferentes acepciones: valor de uso, de no uso, de opción, etc.) y los métodos de contabilidad son diversos, de acuerdo con los aspectos a valorar, existiendo aspectos difícilmente cuantificables, especialmente en lo cultural, lo espiritual, etc., que tendrán que ser abordados de otro modo (narrativo, participativo, deliberativo, etc.) cuando así sea necesario.

La síntesis emergética es un método de contabilidad de la memoria energética de un producto o sistema dentro de una valoración de los costes ecológicos del uso humano del capital natural, que puede ser usado dentro de una evaluación multi-criterio para apoyar la toma de decisiones en colaboración con otros métodos que permitan obtener visiones complementarias a la del coste ecológico de cara a incorporar otros criterios, de carácter ecológico, social, monetario, cultural, etc. Frente a las ideas de la síntesis emergética como el método único de toma de decisiones o como el método de valoración económica de carácter energético que, incluso el propio autor de esta tesis ha defendido anteriormente de manera equivocada (Álvarez *et al.* 2005), la emergía se convierte así en un método más dentro de una serie de metodologías encaminadas a apoyar la toma de decisiones. Además, por su naturaleza, la síntesis emergética queda encuadrada dentro de los métodos que se encargan de estudiar aspectos de carácter económico-ecológico, es decir, flujos que relacionan los sistemas económico y ecológico. Como es lógico, fuera de su ámbito quedan aspectos de carácter no físico, y cuestiones que escapan al coste ecológico que se abordan a través de otras metodologías o aproximaciones.

Como ya se ha adelantado, los métodos que abordan los flujos que relacionan algún componente o el conjunto del sistema económico con algún componente o el conjunto de los sistemas ecológicos tienen, por lo general, el marco del ACV. Como ya hemos visto, bajo este marco se suelen utilizar métodos desde el punto de vista de los costes físicos (Metabolismo económico) o los costes territoriales (Huella Ecológica) para capturar el proceso económico desde *la cuna hasta la tumba*; mientras que se usan los costes exergéticos para entender el proceso económico desde *la tumba hasta la cuna*. En general, el modelo sirve para cuantificar flujos de materia y energía que se utilizan para la generación de un determinado producto o sistema, así como sus residuos, emisiones y vertidos, y el coste energético de cerrar los ciclos para éstos. Como podemos ver, bajo estos enfoques los resultados del proceso económico son el producto y la degradación del sistema asociada a la segunda ley de la termodinámica en forma de residuos, emisiones, vertidos, etc. (y, cabría añadir, la felicidad obtenida por la satisfacción de la necesidad, siguiendo a Georgescu-Roegen). Los costes ambientales vienen medidos en términos de materia y energía usada.

Son muchas las comparaciones que se han elaborado entre la síntesis emergética y los distintos métodos que se podrían encuadrar dentro de esta perspectiva, tanto desde el punto de vista del marco conceptual como del marco metodológico. Una comparación de la síntesis emergética con los análisis de energía y el análisis de energía incorporada se puede encontrar en Brown & Herendeen (1994), Ulgiati (2001), Franzese *et al.* (2003; 2009), y Herendeen (2004). Una comparación con la Contabilidad exergética se puede encontrar en Ulgiati & Sciubba (2005). Una comparación con la contabilidad de flujos materiales se puede encontrar en Lee & Huang (2005) o Huang *et al.* (2006). La comparación con la huella ecológica se puede encontrar en Niccolucci *et al.* (2007).

El papel concreto que juega la síntesis emergética dentro de este conjunto de metodologías, en un marco multi-criterio de evaluación, no es el de reducir estos costes físicos a cantidades de energía, bajo un marco reduccionista energético análogo al monetario, pero bajo una perspectiva física, sino más bien el de ampliar la escala de estudio de estas metodologías, incluyendo no sólo la materia y energía extraídas o producidas por la economía (o de origen comercial), sino introduciendo también la que proviene de los ecosistemas y su base biogeofísica (de origen mayoritariamente no comercial) a lo largo de todo el proceso de ensayo-error que ha derivado en la generación de las mismas y su uso por parte del ser humano. Como hemos visto a lo largo del *capítulo 3*, la síntesis emergética hace visibles de manera explícita los flujos biogeofísicos desde las unidades suministradoras de servicios hacia la economía, es decir, los servicios de los ecosistemas de carácter físico, y además éstos se mezclan, a la hora de generar las cantidades de emergía y los indicadores emergéticos, teniendo en cuenta la calidad de los mismos.

Así, las posibles aportaciones prácticas de la síntesis emergética a la gestión de los socio-ecosistemas y a la comprensión, cuantificación, valoración y evaluación de la contribución del capital natural a la sociedad, más allá de las elaboraciones llevadas a cabo hacia el mundo académico, dependerán de que sea finalmente posible dejar de lado el marco utilitarista de toma de decisiones en la economía (monocriterio monetario, lineal, aislado, circular, etc.), y apoyarse en el desarrollo de marcos integrados con multiplicidad de criterios, en los que la posición real del sistema económico dentro de las restricciones biogeofísicas y socio-culturales sea tenida en cuenta verdaderamente. La apuesta de la Economía Ecológica por la Evaluación multi-criterio y sus distintas variantes (Munda, 2004; 2005; 2008), proporciona esperanzas en este sentido. La necesidad de la síntesis emergética de apostar por integrarse en estos marcos como un método complementario con los aportes mencionados en esta tesis, en lugar de afanarse en buscar el modo de generar una teoría energética del valor análoga a aquella monetaria, comienza a ser percibida, tomada en cuenta y reivindicada (Hau & Bakshi, 2004; Ulgiati *et al.* 2005; Ulgiati *et al.* 2006; Raugei *et al.* 2007).

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V. CONCLUSIONES GENERALES

1. Existe un creciente interés en reincorporar el papel de los ecosistemas a la toma de decisiones económicas, puesto que se considera que el divorcio entre el crecimiento, que ha sido el foco de debate dentro de la ciencia económica, y los ecosistemas, que son el objeto de la mayoría de los esfuerzos de conservación, es una de las causas primordiales de la pérdida de biodiversidad que vivimos actualmente en el marco del cambio global. La síntesis emergética es una metodología que se inscribe en este intento, partiendo des una base ecológica y termodinámica.

2. La síntesis emergética consta de una potente base modelística, que se apoya en el uso del lenguaje energético y en los diagramas de flujo. Dichos diagramas de flujo, en tanto que simbolizan la ventana ambiental, constituyen una representación de los sistemas socio-ecológicos, y por tanto, del capital natural, las funciones y los servicios de los ecosistemas, haciendo explícitos estos enlaces entre ecosistemas y sociedad. Los casos de estudio permiten ilustrar esta idea y, además, muestran que los diagramas de flujo son objetivo-dependientes, así que no es un modelo *a priori* el que define el objeto de estudio, sino más bien el objeto de estudio el que define el modelo, y los diagramas correspondientes.

3. La síntesis emergética como método, y los indicadores derivados de los flujos de emergía adoptan el denominado “punto de vista del proveedor” a la hora de estudiar un producto o sistema. El “punto de vista del proveedor” significa que la síntesis emergética cuantifica el coste socio-ecológico de un producto o sistema, es decir, la materia y la energía de índole tanto biogeofísica como socio-económica que se ha invertido en su generación a lo largo del tiempo, y no los beneficios que aporta este producto o sistema a un determinado usuario (que sería lo que habitualmente se denomina desde el “punto de vista del usuario”).

4. La síntesis emergética, en general, y la emergía, en particular, cuantifican los servicios de los ecosistemas directa y explícitamente. Esto quiere decir que en la cuantificación y caracterización de los servicios no se utilizan categorías intermedias, como el valor de cambio, sino que se captura directamente la cantidad de materia y energía que constituye el servicio. La síntesis emergética concentra sus esfuerzos en estudiar los servicios desde el punto de vista del trabajo que tienen que

hacer las unidades suministradoras de servicios en el marco del capital natural para generar físicamente la cantidad de servicios utilizada por los usuarios.

5. La naturaleza física del indicador implica algunas restricciones en cuanto a las posibles aplicaciones del mismo a los servicios de los ecosistemas, tal y como hoy día son definidos. En este sentido, los denominados servicios culturales son, en muchas ocasiones, de carácter inmaterial, lo que hace que su cuantificación no se aborde preferentemente mediante la síntesis emergética. Por ello, en los casos de estudio de la presente tesis no se abordan estos servicios culturales, que requieren de metodologías y /o aproximaciones complementarias.

6. La síntesis emergética genera indicadores *sensu stricto*, en el sentido de que a partir de un marco conceptual y metodológico concreto que implica la mezcla de multitud de bases de datos de distinta naturaleza (geofísica, ecológica, monetaria, etc.) se calculan las respectivas emergías y se construyen relaciones entre ellas. Los casos de estudio realizados nos han permitido construir indicadores con los que estudiar diversos aspectos del uso del capital natural y los costes ecológicos de los servicios de los ecosistemas. La necesidad y el uso de grandes bases de datos de distinta naturaleza es otro de los limitantes de la metodología, en términos de la fuerte necesidad de información y de la mezcla que se realiza de diversos órdenes de magnitud de los errores en las medidas de los datos que se utilizan.

7. Los indicadores emergéticos incorporan estructuralmente la dimensión temporal a través de la transformicidad y la emergía específica que calculan el trabajo socio-ecológico total que ha costado a lo largo del tiempo generar una unidad de un determinado producto o sistema, constituyéndose en un verdadero indicador de eficiencia del sistema en el uso de la materia y la energía. Los casos de estudio analizados nos han permitido estudiar el cambio en la eficiencia en el uso del capital natural por parte de varios sistemas a distintas escalas.

8. Otro modo de estudiar la variable temporal dentro de los servicios de los ecosistemas a través de la emergía son las series históricas de indicadores emergéticos. Los casos de estudio donde se ha aplicado la síntesis emergética demuestran que las series históricas son útiles para entender el uso del capital

natural a lo largo del tiempo, así como para comprender las dinámicas y las perspectivas futuras de las economías a distintas escalas en su empleo del trabajo de la naturaleza, apoyando así la necesidad de mantener una actualización constante de las bases de datos de síntesis emergética a lo largo del tiempo.

9. Los indicadores emergéticos son contexto-dependientes, es decir, que un valor alto o bajo del indicador tiene distintos significados de acuerdo con la fase del ciclo adaptativo en la que el sistema socio-ecológico se encuentre o su contexto. Los casos de estudio ilustran que si la fase en la que se encuentra el sistema socio-ecológico es de crecimiento, unos valores altos de los indicadores que señalen un aumento y/o diversificación del uso de las funciones de los ecosistemas, y por tanto del aporte de servicios que realice el capital natural, serán positivos; al contrario, si se trata de fases de transición o crisis, un aumento en el uso del capital natural puede forzar la crisis o profundizarla. Esto implica también un cierto grado de dificultad a la hora de leer los indicadores, y la posibilidad de caer en errores al descontextualizar las cifras.

10. La perspectiva amplia que aportan los indicadores emergéticos, que cubre toda la ventana ambiental de un producto o sistema, así como lo directo y explícito en las relaciones entre sub-sistemas dentro del sistema socio-ecológico hacen que sea imposible mantener la hipótesis de perfecta sustituibilidad entre capitales. Los casos estudiados nos han permitido codificar el supuesto desacoplamiento de economías terciarizadas con respecto a los servicios de los ecosistemas (la desmaterialización que sustituye el capital natural por capital de origen humano), en términos de traslado del coste ecológico del uso del capital natural a otros socio-ecosistemas mediante importaciones masivas de materia y energía de los mismos.

11. La implementación de la síntesis emergética supone trabajar a varias escalas a la vez, en la medida en que, al menos, es la escala inmediatamente superior la que proporciona las entradas de materia y energía al sistema. Desde el punto de vista emergético, las relaciones entre socio-ecosistemas dentro de la misma escala o a distintas escalas se codifican en términos de intercambio de materia y energía. Los casos de estudio de esta tesis han demostrado, a través de indicadores emergéticos, que los intercambios de materia y energía entre varios socio-ecosistemas implican

ventajas o desventajas de uno o varios de los sistemas con respecto a los otros, en términos de la emergía contenida en los productos por unidad monetaria recibida o pagada, siendo fuente de desigualdades, y de especialización de la parte productiva de los socio-ecosistemas, generando así economías de escala desde un punto de vista socio-ecológico.

12. La síntesis emergética es una metodología con base ecológica y termodinámica, que permite incluir los flujos de materia y energía procedentes de la base biogeofísica de los socio-ecosistemas dentro de la valoración de los costes ecológicos de la economía, complementando la escala de acción de otras metodologías tradicionalmente usadas con este objetivo, en un contexto multi-criterio de evaluación del uso del capital natural. Para que la síntesis emergética llegue a tener un papel dentro en la resolución de los problemas ligados a las relaciones ser humano-naturaleza, debe explotar estas propiedades dentro de este contexto multi-criterio.

GENERAL CONCLUSIONS

1. There is an increasing interest in reintegrating ecosystem services into the economic decision-making, assuming that the divorce between economic growth, leading focus of the economic dedication, and ecosystems, subject of major conservation efforts, is one of the main reasons for biodiversity loss. Emergy synthesis is a methodology oriented to this purpose on ecological and thermodynamic basis.

2. Emergy synthesis uses powerful modelling basis supported by the energy diagrams and language. The illustration of the environmental window by means of energy diagrams constitute an actual representation of social-ecological systems, and then, natural capital, and ecosystem functions and services, making links between ecosystems and society explicit. Study cases of this PhD thesis confirm this idea, showing that energy diagrams are goal-dependent, so that it is not an a priori model to define the study objective but the objective to define the model, and associated diagrams.

3. Emergy synthesis and derived indicators adopt the “donor-side approach” to study products or systems. It means that emergy quantifies social-ecological costs of system or products, therefore, both biogeophysical and socio-economic energy and matter invested on making them along time, and not benefits derived from the product or system (often called “user-side approach”).

4. Ecosystem services are directly and explicitly quantified by emergy synthesis. So, quantifying and characterizing ecosystem services by emergy synthesis does not employ intermediate categories such as e.g. exchange value, but treats with energy and matter directly. Emergy synthesis is focused on studying ecosystem services from the point of view of the ecological work made by natural capital (the services providing functions) to generate services used.

5. Physical nature of emergy indicators raises some restrictions about the use of emergy to study ecosystem services as defined currently. Cultural services often are not material elements, so quantification is not tackled by means of emergy

synthesis. Because of it, in the case studies of this PhD thesis, cultural services are not studied, assuming the need for other approaches or methodologies.

6. Emergy synthesis produces indicators *sensu stricto*, therefore, it integrates many different data bases (geophysical, ecological, monetary, etc.) starting from a particular conceptual and methodological framework in order to establish ratios between them. The study cases analyzed present different emergy indicators employed to study some aspects of natural capital use and ecological costs associated to ecosystem services. This use and the need for large data bases of different nature is one of the method's bottlenecks in terms of scarcity of information sources for many data, and mixture of used data with different magnitude errors.

7. Emergy indicators structurally incorporate the temporal dimension to the study through the use of transformities and specific emergies, which calculate total social-ecological work employed to generate a product or system along time. Thus, these unit emergy values constitute genuine efficiency indicators of the system's energy and matter use. Main changes in systems' efficiency to use the natural capital at different scales have been analyzed in the study cases of this document.

8. To study temporal dimension, it is possible to employ historical series of emergy indicators too. Study cases show that time series prove to be very useful in order to understand the natural capital use along time, and capturing the dynamics and future perspectives of economies at different scales. This highlights the importance of updating emergy synthesis data bases with a regular recurrence.

9. Emergy indicators are context-dependent. Thus, a low or high indicator value has different meanings according to the adaptive cycle phase in which the social-ecological system is embedded, therefore, the social-ecological system context. The study cases illustrate that in growth phases, the increasing and/or diversification of ecosystem function and services use from natural capital, showed by the high values of emergy indicators, are positive; on the contrary, in transition or crisis phases, a high use of natural capital could force a crisis. This changing nature is a source of

complexity to interpret indicators and making errors linked to the consideration of figures out of context.

10. Both the broad perspective of emergy indicators and the direct and explicit view of relationships between sub-systems under the social-ecological system framework makes difficult to maintain the perfect substituibility among capitals hypothesis. Study cases allow codifying the alleged decoupling between developed economies respect to the ecosystem services (dematerialization or substitution of natural capital by human capital) in terms of transference of the ecological costs associated to natural capital use to other social-ecological systems by means of massive imports of energy and matter.

11. Emergy synthesis works at different scales, at least two: the working scale and the immediately higher scale that supply energy and matter to the social-ecological system. From the emergy point of view, relationships between sub-systems in social-ecological systems are explained in terms of energy and matter terms. Through emergy indicators, study cases have shown that energy and matter interchanges between social-ecological systems are linked to advantages and disadvantages in trade terms. One of the social-ecological systems involved receives more emergy by monetary unit than the other one, creating an unequal exchange. Thus, the exploitation of these characteristics involves the creation of scale economics from a social-ecological point of view.

12. Emergy synthesis is a methodology with ecological and thermodynamic basis, used to include energy and material flows from social-ecological systems’ biogeophysical basis in the economic valuation of ecological costs. Thus, it is a complementary methodology to others traditionally used with this goal, in a multi-criteria framework of natural capital assessment. For emergy to have a significant role on decision making associated to human-nature relationships, it is necessary to exploit the emergy properties mentioned before under a multi-criteria framework.