Journal of Cleaner Production 144 (2017) 171–179

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Does intensification result in higher efficiency and sustainability? An emergy analysis of Mediterranean sheep-crop farming systems

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ARTICLE INFO

Article history:
Received 14 October 2016
Received in revised form
16 December 2016
Accepted 17 December 2016
Available online 27 December 2016

Keywords:
Farm management
Agriculture
Mixed farming systems
Environment
Renewability
Agricultural policy

ABSTRACT

The embodiment of resources in agricultural products depends on the way they are made, i.e., the production system. We applied emergy analysis on three contrasting sheep-crop farming systems according to different degrees of specialization, integration and intensification of production in Mediterranean Spain. We studied emergy flows, transformity values and emergy indices at the system level and per product (lamb meat; permanent crops: rainfed olive and almond; arable crops: rainfed barley, irrigated barley, alfalfa and sunflower). We found that the specialized pasture-based sheep system had the lowest intensity and efficiency and the highest sustainability, as opposite to the partially-integrated mixed system, while the fully-integrated mixed system obtained a balanced position. Lamb meat production was 1.9 and 1.3 times more intensive and efficient, respectively, in the partially-integrated mixed system than in the pasture-based sheep system, but 5.1 times less sustainable. All sheep sub-systems had comparatively lower intensity and higher sustainability than crops due to their higher capacity to use local and renewable natural resources. Our findings suggest that further support of agricultural development based on local and renewable natural resources and best practices is necessary to ensure long-term farming sustainability and social welfare.

1. Introduction

Energy is essential for human development, but the dominant model of economic growth on developed and emerging countries is based on fossil energies, which consumption is the main cause of climate change. Renewable energy and low-carbon emissions technologies contribute to energy security and climate change mitigation but they often have low efficiency as well as material and environmental constraints with yet undetermined consequences (Mathews, 2014). Therefore, beyond technology solutions, the reduction of energy demand and the direct use of renewable energy are essential for a sustainable development.

Agriculture is a primary activity by which human societies channel renewable energy flows into products that support social welfare (Rydberg and Haden, 2006). In particular, pasture-based livestock systems have the ability to convert large areas of free, natural and renewable resources (and therefore capture large quantities of renewable energy) into edible animal food that does not compete with alternative purposes such as human nutrition, which is highly important due to the increasing global demand of food (Wilkinson, 2011). However, the Green Revolution triggered an increasing process of intensification of crop (Pimentel, 2009) and animal productions throughout the world (Bouwman et al., 2005), including Europe and Mediterranean countries, later stimulated by the rapid increase in the opportunity costs of labor and, in Europe, by the Common Agricultural Policy (Strijker, 2005). As consequence, agricultural intensification has resulted in a dramatic increase in commercial non-renewable energy use (Rydberg and Haden, 2006) with inputs such as fertilizers, pesticides, mechanization and irrigation, all fossil energy dependent (Pimentel, 2009). Moreover, intensification together with the abandonment of agricultural and grazing lands are threatening biodiversity and the delivery of important ecosystem services in Mediterranean agro-ecosystems (Henle et al., 2008).

Therefore, agricultural intensification implies, essentially, a shift in the energy resource base of agriculture, from solar energy to

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http://dx.doi.org/10.1016/j.jclepro.2016.12.089
0959-6526/

higher quality energy sources such as fossil energy. But the limited oil reserve or, maybe, the environmental costs of its consumption will force policy making to prioritize alternative sources. So, energy resource allocation may become a central task in agriculture, where multiple sources of materials and energies may be used under different farming production systems. The process of intensification of agriculture has encouraged the specialization of farming systems; and mixed farming systems, that were common in the past, have decreased in Europe since 1970 (Ryschawy et al., 2012). However, a diversity of specialized and mixed farming systems that combine livestock and cash crops productions with different levels of integration (cycling of nutrients) still coexists (Bell and Moore, 2012). They vary according to their degree of intensification in the use of inputs per ha or animal, which is related to land use, yields and labor. They also have different environmental footprints, which have been quantified by accounting methods such as life cycle assessment or energy analysis. However, these approaches usually take for granted the contribution of nature in production processes (Hau and Bakshi, 2004).

In this context, emergy analysis (Odum, 1996) is a useful tool to evaluate separately "free" renewable and non-renewable inputs from the environment as well as local and external inputs coming from the human economy involved in the production of a certain product or service (Brown et al., 2000). Emergy analysis is assumed as a cradle-to-gate methodology because it considers the direct and indirect energy embodied in products or services. It computes the different qualities of energies involved in the process and expresses all of them in units of one form of energy (usually, equivalent solar energy). It makes possible to define several emergy-based indicators (Odum, 1996) that can provide decision support tools on public policy and environmental management holistically, especially when there are several alternatives (Brown et al., 2000).

There are emergy evaluations of a number of animal products, mainly in specialized systems, such as beef cattle grazing in Argentina's Pampas (Rótolo et al., 2007); milk in dairy systems with low, intermediate and high use of inputs in Mali, France and Reunion Island (Vigne et al., 2013); chicken meat in conventional and organic systems in Italy (Castellini et al., 2006); pork in intensive grow-finisher system in China (Wang et al., 2015); pork, fish and grain in integrated farms of Brazil (Cavalett et al., 2006); as well as many vegetables. Sheep and mixed sheep-crop systems are multifunctional (provide private and public goods), however, their continuity is threaten due to economic, environmental and sociological factors. In recent decades they have experienced a strong reduction in most Euro-Mediterranean regions, both in number of farms and in the number of animals, and making them more viable is a major challenge for agricultural development (Bernués et al., 2011). To our knowledge, the free and renewable contribution of nature to the sustainability of agricultural production processes and products is still unknown in these systems. The quantification is specially challenging, as these systems are complex, and have different degrees of specialization, integration and intensification.

We aimed to evaluate the emergy flowing in representative farming systems and their products in Mediterranean sheep and sheep-crop farming systems with diverse degrees of specialization, integration and intensification of production. This fills a gap of knowledge in Mediterranean farming systems, which allows comparing them with other production systems and provides insight into factors that enhance their environmental sustainability.

2. Materials and methods

2.1. Area of study

We chose the region of Aragon, in north-eastern Spain, due to its heterogeneous environmental characteristics that gives rise to a wide variety of sheep-crop farming systems (Barrantes et al., 2009). Aragon covers 47,720 km^2 and is located within the middle catchment of Ebro River, the largest basin in Mediterranean Spain. The average altitude in the valley is around 200 m and it is bordered on the north by the Pyrenees (altitudes up to 3400 m) and on the south by the Iberian Range (2000 m). Overall, this region has a Mediterranean climate, although there is a strong climatic gradient from the Atlantic Pyrenees (mean annual temperature 8.5 °C, total annual precipitation 1750 mm) and the humid Iberian Range (9.5 °C, 650 mm) to the semiarid middle Ebro basin (15.0 °C, 318 mm) (Cuadrat et al., 2007). The aridity of this valley is increased by the high potential evapotranspiration, that generates a negative water balance in summer, and by the lithology, that makes water retention in the soils difficult (Machín and Navas, 1998). The distribution of vegetative communities is driven by climate, giving rise to a cover mixture of open grasslands, Mediterranean shrubs and pure and mixed deciduous-conifer vegetation in mountains, and gypsophile shrubs and pastures with few areas occupied by pine and degraded juniper forests in the middle Ebro valley (Barrantes et al., 2005).

In this diverse environment, sheep-crop farming systems are managed mainly for commercial production of meat and cereals (mostly winter cereal such as rainfed wheat, barley or rye and irrigated maize), but also forages (commonly irrigated alfalfa) and woody crops (almond, olive and vineyard). Sheep use grazing resources such as stubbles, fallows, crops, grasslands, shrub-lands and forests; as well as both on-farm and off-farm feed supplementation predominantly based on corn and/or barley with alfalfa and straw (Barrantes et al., 2009). Farming systems in Aragon are located in two dominant agro-ecosystems: i) the mountain agroecosystems, with traditional self-sufficient systems characterized by extensive, low-input (stocking densities, agro-chemicals, etc.) and low-output (productivity) farming (Asensio and Casasús, 2004) and with little use of arable land and more dependency on natural pastures; and ii) the semi-arid lowlands in the middle Ebro Valley, with systems that followed Spain's intensification process in the past 50 years, linking sheep to the most developed agriculture with irrigated lands and a higher use of off-farm feed inputs (Olaizola et al., 1995).

2.2. Data collection

2.2.1. Inventory and monitoring of case study farms

We designed a survey in 2014 to collect information in 10 farms (see Appendix A for information on case study selection) about: family structure and labor force (family composition, on- and off-work, hired labor force, etc.); agricultural and pasture area (tenure regime, irrigation vs. rainfed area, land use, species, varieties, productivities, etc.); flock details (species, size, number of batches and management of reproduction, feeding and wastes, etc.); commodities produced and destination of production (self-sufficiency, commercialization); and equipment (machinery and infrastructure).

Subsequently, we monitored the farms along an entire agronomic year (2014–2015). We provided the farmers with forms where they noted the following data: i) management of every crop, inputs used and their doses (seeds, fertilizers, pesticides, water, etc.), time of operation and fuel consumption of machinery used in all practices (tilling, fertilizing, harvesting, etc.), harvests obtained; ii) animal feeding per batch, including a grazing calendar (type and area of pasture, time spent in pasture, shepherding method, etc.) and in-door rations (amounts, origin of feed, etc.); iii) reproduction management, including mating details (number of ewes and males, mating dates, use of artificial methods, etc.); iv) self-consumptions and exchanges of products, work done for third parties and hired labor and machines. We visited the farms regularly (once every 2–3 months) to collect the forms after reviewing with the farmer missing or contradictory data. Additionally, we cross-checked the data with the accounting books of farmers and records from the farmers' cooperatives, extracting also the prices for all inputs and outputs.

2.2.2. Description of contrasting systems for emergy evaluation

For clarity in the presentation of results, we chose three contrasting typical farms (Feuz and Skold, 1992) from typology of Appendix A. We defined them according to their degree of specialization, integration and intensification of production (represented by intensity of sheep reproduction management, feeding strategies of animal batches and land use). These systems were denominated as: "specialized sheep-mountain pastures", "fully-integrated mixed sheep-permanent crops" and "partially-integrated mixed sheep-arable crops". Tables 1 and 2 show the characteristics and environmental conditions and the feed management of the three systems, respectively. All data corresponded to the monitored year that was drier than normal, influencing the inputs and outputs and therefore the results of the emergy evaluation.

The **specialized sheep-mountain pastures (S-MP) system** was located in the Mediterranean high mountain agro-ecosystem. It had large flock size and pastures and low arable land, all rainfed forage. It had low dependency on rented land and hired work. The reproductive management was low-intensive, with one lambing per ewe per year. Animals grazed freely most of the year, mainly in semi-natural vegetation according to seasonal resource availability (upland grasslands in summer, midland shrub and forest pastures in autumn and valley forage crops in winter). During lactation (spring) animals were kept under housing conditions. Forage crops were mainly multi-annual grasses, grazed by ewes in the lambing period or for hay making as occasional supplement in winter. During the monitored year, weather conditions were unusual (very dry spring), which forced the purchase of external feeds (straw and commercial concentrates) during the lactation period.

The **fully-integrated mixed sheep-permanent crops (S-PC) system** was located in the Mediterranean low-altitude mountain agro-ecosystem. It had small flock size and intermediate pastures area and arable land, both rainfed forage and cereal. It had an intermediate dependency on rented land and hired work. The reproductive management was of intermediate intensity, with three lambings per ewe every two years. Animals grazed daily with a shepherd, mainly in forage croplands, and remained many nights at the fields with electric fences; but they were kept indoors during lactation. Therefore, a significant amount of arable land was devoted to forage crops for grazing and hay and silage making. Additional land was cropped with cereals for indoor feeding of ewes, reducing the need of purchased corn for mixed rations. By-products such as straw from winter cereal were also conserved to be used in rations, as well as on- and off-farm summer stubbles that were a common grazing resource. Cash crops were 100% used for animal feeding on farm (fully integrated system). This system also produced almonds and olives for selling. These permanent crops received manure fertilization and the understory was grazed during certain periods of the year.

The **partially-integrated mixed sheep-arable crops (S-AC) system** was located in the semi-arid lowland agro-ecosystem. It had small flock size and pasture area and high arable land, both rainfed and irrigated, with a predominance of cereal rather than forage cropland. It presented a high dependency on rented land and hired work. The reproductive management was intensified in terms of lambings per ewe per year. Animals grazed relatively short periods per day, predominantly in on- and off-farm fallows and stubbles of rainfed winter cereal and forage crops; being kept indoors at night and during lactation. The arable land was used for rainfed and irrigated forages, for both grazing and hay and silage making for indoor feeding of ewes. Indoor feeding included also off-farm feed concentrates and on-farm straw. Part of the alfalfa was irrigated rendering six cuts per year, the production of which was entirely sold to a dehydration plant. This system also commercialized irrigated barley and sunflower, as well as rainfed barley that covered the largest farm area. Therefore, 65% of cash crops were for selling (partially integrated system). An equivalent area to rainfed barley remained fallow, following the typical two-field system of the Mediterranean agriculture.

2.3. Emergy evaluation

Emergy analysis is a quantitative evaluation technique that determines the amount of direct and indirect energy of the same form (*solar emergy*, measured in *solar emjoules* -sej-) that has been used by a certain process to generate products or services (Odum, 1996). We applied the traditional emergy methodology described by Odum (1996) and other authors (Brown and Ulgiati, 2004; Ulgiati and Brown, 1998) to evaluate the three contrasting farming systems previously described and their individual products using the data from the monitored agronomic year. The methodology follows the next three steps.

i) System diagrams

The first step was drawing an **emergy diagram** of each farm, using the energy systems language (Odum, 1983). The diagrams defined the boundaries of the farm and helped to organize the relationships between the main components and processes that drive the emergy flows from the natural resources and purchased inputs to the farm outputs, depicting their connection with the environment and the economy. We evaluated the emergy of farming systems as well as the emergy of sheep and crop products individually as explained in Fig. 1.

Diagrams for the three farms are given in Appendix B. In the S-MP (Figure B.1), we included the family within the system since farmers lived at the farm and there was no off-farm labor; instead, we considered their food as a farm input. In the three farms, lamb meat and wool were considered as *co-products*, i.e., their inputs cannot be separated accounted (Odum, 1996) because they used the same energy sources. We will focus only on lamb meat because nowadays wool has few commercial interest. In S-PC (Figure B.2) and S-AC (Figure B.3), animal products and sold cash crops productions were considered as *splits*, i.e., the emergy required by one product cannot be used by others. In both mixed systems, we calculated first the emergy of sold cash crops and then allocated the rest of the inputs to the sheep co-products. On-farm manure was an input for some crops and stubble was an input for sheep. Commonly, manure and straw are considered as *by-products*, i.e., they carry the emergy assigned to their diagram pathway. We calculated the emergy of manure as the indigestibility proportion of feed intake, simulating an emergy split within the sheep, and we allocated the proportions of renewable, non-renewable and purchased inputs in manure to the crops. The emergy of straw was obtained from bibliography because it is produced in a more standardized way.

ii) Emergy tables

Based on the diagram, the second step was to build the **emergy table** to organize the different inputs (in rows) and convert them to solar emergy (in columns). Emergy tables with detailed

Table 1
Description of the local environment and the characteristics of the three case studies.

	Specialized sheep-mountain pasture	Fully-integrated mixed sheep-permanent crops	Partially-integrated mixed sheep-arable crops
Environmental conditions			
Region	Mediterranean high mountain	Mediterranean low mountain	Semiarid lowland valley
Altitude (m)	800–1050	550–650	≈350
Precipitation (accumulated $mm \cdot yr^{-1}$)[a]	371.5	380.6	285.9
Temperature (average medium °C)	13.6	14.1	15.9
Arable land *(% rented)*	83 *(27%)*	92 *(51%)*	325 *(98%)*
Arable cereal cropland (rainfed/irrigated)	–/–	15/–	220/47
Arable forage cropland (rainfed/irrigated)	83/–	53/–	24/32
Permanent cropland (rainfed/irrigated)	–/–	21/–	2/–
Other (rainfed/irrigated)	–/–	3/-	–/–
Grazing surfaces (ha) *(% rented)*	3835 *(80%)*	1575 *(98%)*	1040 *(100%)*
Flock details			
Breed	Rasa Aragonesa	Rasa Aragonesa	Rasa Aragonesa
Males (average num.)	50	20	19
Ewes (average num.)	1150	550	510
Ewe lambs (average num.)	400	93	90
Reproductive management	1 lambing:1year	3 lambing:2 years	3 lambing:2 years
Lambing per year	1121	561	817
Total n° lambs per year	1540	723	1263
Prolificacy (total n° lambs/n° lambings)	1.37	1.29	1.55
Lamb mortality (%)	4.2	8.4	4.1
Sales			
Lambs sold (num. per year)	1474	640	1181
Shelter wool sold (kg)	1876	800	836
Live weight of lamb sold (average kg)	22	26	24
Labor force (AWU[b]) (% off-farm)	3 (0%)	3 (17%)	2.5 (40%)

Data for the monitored agronomic year 2014/2015.
[a] Climatology comes from weather stations from the Ebro Hydrographical Confederation automatic hydrological information network system (SAIH): http://www.saihebro.com. Average precipitation of the period 2002–2012: 771 (S-MP), 616.3 (S-PC) and 281.1 mm (S-AC).
[b] AWU: Annual work unit.

calculations of all flows are given in Appendix C. The transformation of inputs to emergy was made by multiplying the amount of inputs by their corresponding *unit emergy values* (UEV), defined as the ratio of emergy per energy (*transformity*), emergy per mass (*specific emergy*) or emergy per emergy/euro ratio (*emeuro*). The emergy/euro ratio is an emergy-based indicator to measure the environmental resources used (in sej) per unit of national GDP (in €); therefore. *emeuro* is the term used to describe emergy buying power (Brown et al., 2000). UEVs from bibliography were checked carefully and homogenized on standard global *empower* (emergy flow) of the geobiosphere (15.83E24 sej/yr) calculated by Odum (2000). The last column of each table included the percentage of contribution of every input to the total solar emergy of the output. At the bottom of the tables we calculated the UEV for different functional units of outputs. Transformity and specific emergy are measures of the “quality” of the solar emergy through the production chain, where quality is often the reverse of the efficiency of transformations. Since these measures are usually associated to products, we estimated an equivalent ratio for the farming systems (*efficiency ratio*) that indicated how many solar emjoules were required to make a Joule of commodity (Fig. 1).

We made a table for each farm output, only co-products were presented in the same table. Within each table, input emergy flows were evaluated and allocated following standard emergy methods (Brown and Herendeen, 1996; Odum, 1996). Since renewable resources (sun, wind, rain and evapotranspiration) are co-products of the geobiosphere, we only considered the largest of these inputs to avoid double counting (Odum, 1996); in this case, we considered evapotranspiration as the part of the rain that is actually used for production. Unless otherwise explained, consumable inputs (fuel,

Table 2
Description of grazing and on-farm feeding of the three typical farms.

	Specialized sheep-mountain pasture	Fully-integrated mixed sheep-permanent crops	Partially integrated mixed sheep-arable crops
Total grazing time (annual %)	93	78	25
Semi-natural vegetation (% of total grazing time)	68.5	2.5	1.2
Forages (% of total grazing time)	29.2	86.0	34.0
Stubble (% of total grazing time)	2.3	11.5	64.8
Total on-farm cash crops harvested (kg DM*)	8922	68738	373592
For indoor feeding (% of integration)	100[a]	100[a,b,c,d]	35[a,b]
For selling (%)	0	0	65[c,d,e]

Data from the monitored agronomic year (2014/2015).
*DM (dry matter) calculated following Jarrige (1989) for feeds in Mediterranean area.
[a] Forages (hay).
[b] Forages (silage).
[c] Forages (fresh).
[d] Cereals (grain).
[e] Oleaginous (seed).

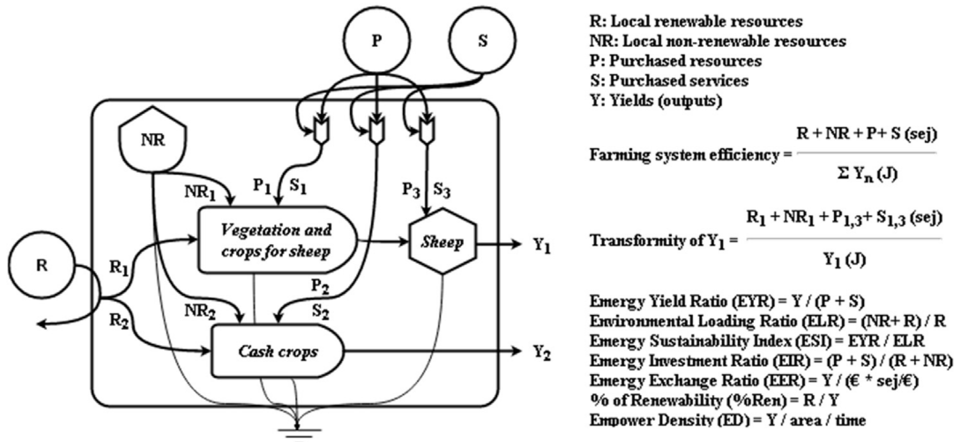

Fig. 1. Generic emergy diagram of sheep-crop farming systems. Modified from Brown and Ulgiati (1997).

fertilizers, etc.) were allocated in mixed farms according to their consumption per output; while non-consumable goods, such as machinery, were allocated according to the usage time per output. The input of *services*, which represents off-farm emergy consumption, was evaluated by multiplying the money paid for them by the emergy/euro ratio for Spain. However, hired work services (harvesting, packing) complemented farmer's labor within farms; so we considered them as a different input (harvest service), adding the fuel price to general services and the fuel amount to the fuel input.

iii) Emergy indices

The final step in each evaluation was to calculate several **emergy indices** that relate emergy flows of the economy with those of the environment. They predict, ultimately, the environmental and economic sustainability of the different farming systems; allowing comparisons among investment alternatives (Brown et al., 2000). Emergy indices represented *self-sufficiency* (emergy yield ratio, EYR), *environmental stress* (environmental loading ratio, ELR), *sustainability* (emergy sustainability index, ESI), *dependency* (emergy investment ratio, EIR), *delivered emergy* (emergy exchange ratio, EER), *renewability* (percentage of renewability, %Ren), and *intensity* (empower density, ED). Their calculations are explained in Fig. 1 and they are described in greater detail in Appendix D.

3. Results

Fig. 2 summarizes the main environmental and economic emergy flows that drive the three farming systems and their individual products. Table 3 summarizes their corresponding emergy indicators. Original emergy tables and their calculations can be found in Appendix C.

3.1. Emergy evaluation of the global farming systems

Total emergy flow required per year (Fig. 2) was similar in the S-MP and S-AC systems (2.99E18 and 2.63E18 sej/yr, respectively), while the S-PC system had lower requirements (1.69E18 sej/yr), which provided an idea of the systems dimensions. According to the origin and renewability of the emergy, the **S-MP** obtained 61.6% of its total emergy from the local natural resources (58.4% renewable, R, from the rain evapotranspired; and 3.2% non-renewable, NR, from the topsoil of arable lands), 27.8% from purchased inputs and 10.7% from services. In the **S-PC**, local natural resources represented 53.8% of the total emergy flow (45.2% R, 8.6% NR), 34.5% from purchased inputs and 11.8% from labor and services. The **S-AC** got 40.9% of its emergy from local natural resources, equally split between renewable and nonrenewable flows (19.3% R, 21.7% NR), 40.3% from purchased inputs and 18.8% from labor and services.

The ***efficiency ratio*** (Table 3) indicated that the S-MP had the lowest efficiency (1.7E07 sej/J), the S-PC intermediate (8.54E06 sej/J) and the S-AC the highest one (4.79E05 sej/J). The ***self-sufficiency-EYR*** indicated that the total emergy released in outputs was more than double the emergy invested in the S-MP (2.60) and S-PC (2.16), indicating their high ability to use free local emergy to satisfy their total emergy requirements; while the S-AC had a lower self-sufficiency (1.69). The ***environmental stress-ELR*** indicated that S-MP and S-PC systems resulted in lower environmental stress (0.53 and 0.95, respectively), mainly due to their lower demand of non-renewable resources, than the S-AC system (3.22). Consequently, the S-MP, with the highest *self-sufficiency* at the lowest *environmental stress*, obtained the highest ***sustainability-ESI*** (4.92), followed by the S-PC (2.27), while the S-AC (0.53) had an even lower economic and environmental compatibility. The ***dependency-EIR*** showed that the S-MP (0.62) and S-PC (0.86) had low dependency on emergy investments from the economy compared to the high free local emergy contribution from the environment, which also indicated their higher competitive capacities, self-sufficiency and long term sustainability as compared to the S-AC (1.44). The ***delivered emergy-EER*** indicated that S-MP (11.78) and S-PC (10.67) provided considerable benefit to the regional/national economies, while the purchaser of the products from S-AC (5.65) received a lower emergy benefit in the exchange. The ***renewability-%Ren*** of the total emergy was higher in the S-MP (58.4%) and S-PC (45.2%) than in the S-AC (19.3%). The ***intensity-ED*** for the S-MP, S-PC and S-AC was 7.64E14, 1.01E15 and 1.90E15 sej/ha/yr, respectively, reflecting in that order the increasing intensity of emergy use across the different systems.

3.2. Emergy evaluation of the individual agricultural products

3.2.1. Lamb meat

Total emergy flow driving sheep sub-systems per year was 2.99E18, 1.64E18 and 1.97E18 sej/yr in S-MP, S-PC and S-AC, respectively (Fig. 2). All systems obtained more than a half of their emergy from the local environmental resources, although S-AC used few renewable resources. The main non-renewable components in the **S-MP** were the feed (14.5%, commercial concentrates

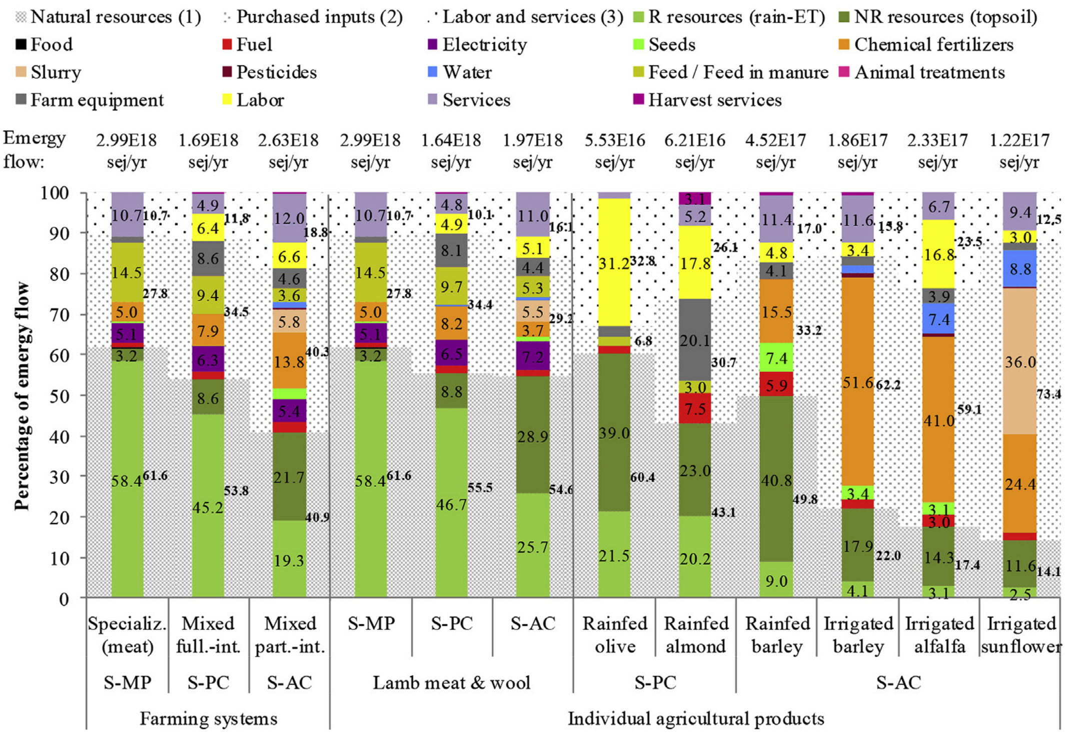

Fig. 2. Emergy signature of farming systems and their individual agricultural products.
Emergy sources contributing to the total emergy flow of specialized sheep-mountain pastures (S-MP), fully-integrated mixed sheep-permanent crops (S-PC) and partially-integrated mixed sheep-arable crops (S-AC) farming systems and their individual products.
Emergy sources include: 1) natural resources (renewable and non-renewable resources); 2) purchased inputs (food, fuel, electricity, seeds, chemical fertilizers, slurry, pesticides, water, feed/feed in manure, animal treatments and farm equipment); 3) labor and services (labor, services and harvest services).

and straw) and the services (10.7%); in the **S-PC** the feed (9.7%, mainly corn) and the inputs related to forage and cereal production for animals (8.8% non-renewable arable soils, 8.2% fertilizers and 8.1% farm equipment); while in the **S-AC** the most important were the arable soils (28.9%) for forage production and stubble grazing, followed by the services (11.0%).

The ***specific emergy*** (Table 3) indicated that the efficiency for lamb meat production increased from S-PC and S-MP to S-AC (9.23E10, 9.83E10, 6.95E10 sej/g, respectively); i.e., S-AC was 1.3 times more efficient than S-MP. The ***sustainability-ESI*** suggested that S-MP (4.92) obtained the highest *self-sufficiency-EYR* at the lowest *environmental stress-ELR*, followed by the S-PC (2.43); while

Table 3
Summary table of comparative emergy indicators among farming systems and their individual agricultural products.

Farming systems	Efficiency ratio[a] (sej/J)	EYR[b]	ELR[b]	ESI[b]	EIR[b]	EER[b]	%Ren[b]	ED[b] (sej/ha/yr)
Specialized S-MP*	1.70E+07	2.60	0.53	4.92	0.62	11.78	58.4	7.64E+14
Fully-integrated mixedS-PC*	8.54E+06	2.16	0.95	2.27	0.86	10.67	45.2	1.01E+15
Partially-integrated mixed S-AC*	4.79E+05	1.69	3.22	0.53	1.44	5.65	19.3	1.90E+15

Individual products	Specific emergy[c] (sej/g)	Transformity[d] (sej/J)	EYR[b]	ELR[b]	ESI[b]	EIR[b]	EER[b]	%Ren[b]	ED[b] (sej/ha/yr)
S-MP lamb meat	9.23E+10	1.70E+07	2.60	0.53	4.92	0.62	11.78	58.4	7.64E+14
S-MP wool	1.60E+12								
S-PC lamb meat	9.83E+10	1.81E+07	2.25	0.93	2.43	0.80	12.71	46.7	9.81E+14
S-PC wool	2.04E+12								
S-AC lamb meat	6.95E+10	1.28E+07	2.20	2.27	0.97	0.83	10.13	25.7	1.42E+15
S-AC wool	2.35E+12								
S-PC rainfed olive	6.02E+09	6.83E+05	2.53	2.13	1.19	0.65	5.14	21.5	4.26E+15
S-PC rainfed almond	1.19E+10	2.35E+06	1.76	2.66	0.66	1.32	3.47	20.2	7.77E+15
S-AC rainfed barley	2.15E+09	1.45E+05	1.99	8.24	0.24	1.01	5.10	9.0	4.08E+15
S-AC irrigated barley	1.89E+09	1.27E+05	1.28	19.36	0.07	3.54	4.48	4.1	8.84E+15
S-AC irrigated alfalfa	8.26E+08	8.58E+05	1.21	23.35	0.05	4.74	2.04	3.1	1.16E+16
S-AC irrigated sunflower	6.17E+09	2.52E+05	1.16	33.34	0.03	6.07	4.76	2.5	1.43E+16

*Farming systems: S-MP, sheep-mountain pastures; S-PC, sheep-permanent crops; S-AC, sheep-arable crops.
[a] Efficiency ratio: emergy required to produce all the food/feed products of the farm, considering the same functional units than transformity of agricultural products.
[b] EYR, emergy yield ratio (*self-sufficiency*); ELR, environmental loading ratio (*environmental stress*); ESI, emergy sustainability index (*sustainability*); EIR, emergy investment ratio (*dependency*); EER, emergy exchange ratio (*delivered emergy*); %Ren, percentage of renewability (*renewability*); ED, empower density (*intensity*).
[c] Functional units of specific emergy: lamb meat (live weight), wool (sheared weight), permanent crops (raw weight) and arable crops (weight of cereal grains, fresh alfalfa and sunflower seeds).
[d] Functional units of transformity: lamb meat (carcass weight), permanent crops (weights of shelled almonds and pressed olives) and arable crops (weights of cereal grains, fresh alfalfa and sunflower seeds).

S-AC (0.97) indicated lower economic and environmental compatibility; i.e., S-MP was 5.1 times more sustainable than S-AC. Lamb meat had the highest *renewability-%Ren* in the S-MP (58.4%), followed by the S-PC (46.7%), and by S-AC (25.7%). The ***intensity-ED*** increased from S-MP to S-PC and S-AC (7.64E14, 9.81E14, 1.42E15 sej/ha/yr, respectively); i.e., S-AC was 1.9 times more intensive than S-MP.

3.2.2. Permanent crop products

Total emergy flow driving the rainfed olive and almond crops per year were 5.53E16 and 6.21E16 sej/yr, respectively (Fig. 2). **Olives** obtained the most of its emergy from the local natural resources (60.4%: 21.5% R, 39.0% NR) and from labor (31.2%) since harvesting and pruning were done manually. **Almonds** obtained 43.1% of emergy from local natural resources (20.2% R, 23.0% NR); 30.7% from purchased inputs, mainly machinery (20.1%); and 26.1% from labor and services.

Pressed olives and shelled almonds had ***transformities*** of 6.83E05 and 2.35E06 sej/J, respectively (Table 3). The olive crop might be considered to have a high *self-sufficiency-EYR*, however it had a high *environmental stress-ELR* that implied a ***sustainability-ESI*** (1.19) that was not very high. Almonds had a lower *self-sufficiency-EYR* and a lower ***sustainability-ESI*** (0.66) because of the higher investments from the economy. Both crops had a *renewability-%Ren* around 20%. ***Intensity-ED*** was lower for olives (4.26E15 sej/ha/ye) than for almonds (7.77E15 sej/ha/yr).

3.2.3. Arable crop products

Total emergy flow used per crops per year (Fig. 2) were 4.52E17 sej/yr for the rainfed barley, 1.86E17 sej/yr for the irrigated barley, 2.33E17 sej/yr for the alfalfa and 1.22E17 sej/yr for the sunflower. The **rainfed barley** obtained 49.8% of its emergy from local natural resources (9.0% R, 40.8% NR); while **irrigated barley**, **alfalfa** and **sunflower** received 22.0% (4.1% R, 17.9% NR), 17.4% (3.1% R, 14.3% NR) and 14.1% (2.5% R, 11.6% NR), respectively. The main purchased input emergy for all of them came from fertilizers: 15.5% and 51.6% mainly from nitrogenous fertilizers in rainfed and irrigated barleys, respectively; 41.0% mainly from phosphorus fertilizers in alfalfa; and 60.4% mainly from slurry and phosphorous fertilizer in sunflower. Water was important in alfalfa and sunflower, while barley irrigation during the monitored year was lower than a normal year to avoid the lodging of the crop. Of the cropping systems, alfalfa required the most labor because of the six-cut per year system.

The ***transformity*** of rainfed and irrigated barley was 1.45E05 and 1.27E05 sej/J respectively; 8.58E05 for fresh alfalfa and 2.52E05 for sunflower seeds (Table 3). According to the emergy indices (Table 3), arable crops had low ***sustainability-ESI***, nearly zero for irrigated crops, due to their low use of local and renewable natural resources (note also low *self-sufficiency-EYR* and *renewability-%Ren*) and their high *environmental stress-ELR*. Their *dependency-EIR* on external economic inputs was high, especially in the irrigated crops. The sale of arable crops provided low *delivered emergy-EER* to the local and national economies, especially the alfalfa. The ***intensity-ED*** increased from rainfed barley to irrigated barley, alfalfa and sunflower.

4. Discussion

4.1. Emergy as indicator of farming sustainability

Emergy analysis depicts a comprehensive representation of the processes driving the farms with rational computation of direct and indirect materials and energy sources of different qualities embodied in the final products. We found no single emergy values per product, but a range of values according to the different ways of making it, as noted by Brown and Herendeen (1996). We will discuss results per farming system and per their products with the aid of Fig. 3, which constitutes a normalization of three emergy indicators in terms of intensity (ED), efficiency (inverse of efficiency ratio and transformity) and sustainability (ESI).

At the system level (Fig. 3a), specialized S-MP was the most sustainable having the lowest intensity, but it also was the least efficient system. The partially-integrated mixed S-AC had the highest intensity and efficiency, but it was the least sustainable. Finally, the fully-integrated mixed S-PC had intermediate values. Intensity, efficiency and sustainability at the system level are determined by the animal and crop sub-systems and are proportional to their emergy flow. For instance, the intermediate efficiency of S-PC was due to the low efficiency of lamb meat (Fig. 3b) and the high efficiency of permanent crops (Fig. 3c). The high sustainability of S-MP is result of its low dependency on non-renewable inputs and the availability of grazing surfaces. Integration of livestock and crops activities (cash crops and straw for livestock and manure for crops) provides a way of sustainable intensification of agriculture, as already suggested by Ryschawy et al. (2012). Despite straw and manure carried low emergy flows, the lack of this integration might compromise self-sufficiency and entail less sustainable feed and fertilization sources. In this sense, increasing boundaries of emergy analysis at a regional level could give rise to interesting cooperation strategies among farmers in favor of regional sustainability.

At the product level, the higher transformity of grazing lamb meat (S-MP and S-PC) can be seen as a measure of lower efficiency, i.e., more resources are needed to yield the same unit of product (Odum, 1996). Our transformity values for lamb meat seems to be a little bit higher than other values found in literature around 1E06 sej/J for beef cattle (Rótolo et al., 2007), chicken (Castellini et al., 2006) and pig (Wang et al., 2015). These results are in accordance with life cycle assessment studies where lamb meat shows higher carbon emissions than pig, chicken or beef cattle (Ripoll-Bosch et al., 2013). This is because transformity and footprint indicators are sensitive only to the conversion efficiency, which is related to the intensity of production. Therefore, complementary indices are needed to get a more holistic view of agricultural production. The sustainability (ESI) of lamb meat (Fig. 3b) was the highest in the system based on semi-natural vegetation (S-MP), decreased in integrated system (S-PC) and further in the system more dependent on non-renewable resources (S-AC), as occurs with other animal products in the previously mentioned studies of emergy. Lamb meat production was, in general, more sustainable and less intensive in the three systems than crop production (Fig. 3c and d) due to the fact that sheep are able to use more local renewable natural resources than crops.

Therefore, there is a trade-off between intensity and sustainability at both the scale of the farming system and at the product scale, which is common in agricultural production (Ripoll-Bosch et al., 2012). The trade-off between efficiency and sustainability at the system level can be explained by Odum's Maximum Empower Principle (MEmPP) (Odum, 1996) and its conceptual framework (Odum and Pinkerton, 1955). Simply stated, maximum empower (emergy per time) is not delivered at highest efficiency, nor at lowest efficiency, but at theoretic intermediate efficiency of 50%. We are not suggesting that lower transformity always means higher efficiency of production, since the application of transformity as a measure of production efficiency should only be done when comparing products of similar hierarchical levels (sometimes called trophic levels in ecosystems) (Brown and Cohen, 2007). Nor are we suggesting that high transformity always coincides with high sustainability; in fact, probably just the opposite occurs when

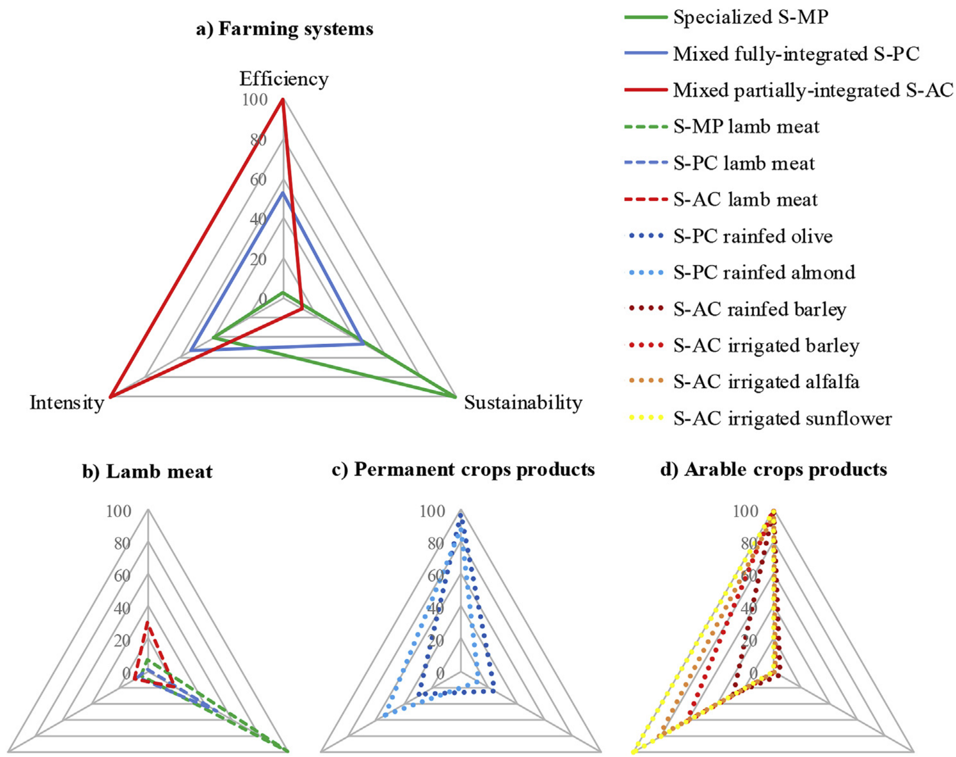

Fig. 3. Relationships among intensity, efficiency and sustainability in farming systems (a) and their individual agricultural products (b, c, d).
Normalization of empower density (as proxy for intensity), system efficiency ratio and product transformity (efficiency) and emergy sustainability index (sustainability). Normalizations were done based on the maximum value of each index per both system and product levels; therefore, diagrams of products (b, c, d) can be compared.

comparing systems of different hierarchical levels due to energy being degraded at upper levels (Brown and Cohen, 2007). It is probably more important to describe our findings in terms of intensification; while yielding more product per unit of emergy input (i.e. lower transformity as a measure of higher emergy efficiency), also results in products having lower self-sufficiency and higher environmental stress, thus contributing to lower sustainability. These findings might also apply to other systems and pose challenges for sustainable intensification. Intensification is the result of higher inputs of non-renewable resources allowing more production in smaller spaces and faster times. Nevertheless, farming intensification does not always result in more production efficiency due to suboptimal farm management or environmental shortcomings (Pérez et al., 2007), as we found for some individual products. This suggests that better management in particular cases could maintain or increase efficiency, while reducing intensity and increasing sustainability.

4.2. Implications for policy decision making

Although public demands and policy efforts respond to environmental concerns, the continuity of environmentally-friendly farming systems might be compromised if short-term production and economic targets are the only priorities. Regarding natural resources, despite systems highly dependent on them are economically more resilient to external market instabilities, they are also more vulnerable to environmental instabilities, such as droughts or greater weather variability (Bernués et al., 2011). Additionally, free local emergy embodied and exchanged in marketed products is not recognized in the price. It has been suggested that the economy does not value the environmental emergy in nature and primary sector as high as in tertiary and quaternary economic sectors (Campbell and Tilley, 2014) and that the prices of agricultural products should be higher than those determined by the market (Cavalett et al., 2006). This, together with the lack of internalization of negative externalities, results in green products not having a trade advantage over the cheap conventional ones (Nguyen et al., 2016).

Therefore, it is important that policy truly rewards sustainable farming systems, compensating their lower efficiency in production. We suggest two complementary ways that can influence both consumers' and farmers' decisions. First, embodied emergy of products could be included in food labels alone or in combination with other environmental footprints. Emergy should be presented in a clear and meaningful unit for consumers, for example “equivalent solar joules”, and should be accompanied by a sound sustainability index such as the “percentage of renewability”. Second, a policy of incentives could be developed for those farming systems that are more based on local and renewable natural resources, which are the ones with greater potential to deliver ecosystem services. Actually, some authors argued that emergy analysis could be used to establish a system of payments for ecosystem services based on an “eco-price” that would assign monetary value to previously unvalued ecological work, incorporating this work into the economy (Campbell and Tilley, 2014).

4.3. Limitations of the study and future research needs

In addition to the shortcomings of the emergy methodology (see Hau and Bakshi (2004) for a review), our work presents a number of limitations that also indicate research gaps that need to be addressed. First, we monitored and checked only one agronomic year and it differed slightly from the average weather conditions. Second, an accounting for renewability in inputs from outside the system boundary by distinguishing local and non-local inputs would have improve our emergy analysis. Third, it was difficult to know whether or not labor and services were included in the UEVs obtained from the bibliography; so we assumed that this was the case when authors used UEVs with labor and services. Despite these limitations, we made the same assumptions across all evaluations, which assure comparability across farming systems and products. Finally, we think that future research efforts should combine diverse methodologies for environmental footprinting of agricultural products with the valuation of ecosystem services delivered by agro-ecosystems.

5. Conclusion

Specialized pasture-based sheep systems are highly sustainable when they are low-input and use local renewable natural resources. Further integration of livestock and cropping activities at farm level may be a way to increase self-sufficiency and a pathway towards sustainable intensification of agriculture. Partially-integrated mixed sheep-crop farming systems have highest production efficiency and intensity, but the lowest sustainability.

Sheep sub-systems are comparatively less efficient but more sustainable than crop sub-systems, because they are able to use more local and renewable natural resources than crops. The sustainability of meat production is linked to the use of semi-natural vegetation through grazing, which prevents the purchase of off-farm feeds and fertilizers. Permanent and arable crops can increase significantly their sustainability with better protection of their non-renewable soils and by reducing the use of chemical fertilizers.

The trade-offs between intensity and sustainability and between efficiency and sustainability at different scales can compromise the continuity of low-input farming systems and the ecosystem services they deliver. Therefore, further support of farms based on a sustainable use of local and renewable natural resources is necessary to compensate their lower economic performance, and, globally, ensure long-term farming sustainability and social welfare.

Acknowledgements

We are grateful to the project INIA RTA2011-00133-C02-02, the pre-doctoral fellowship from INIA for the first author. We also acknowledge the support and collaboration of farmers.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.12.089.

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