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The emergy perspective: natural and anthropic energy flows in agricultural biomass production

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Abstract

Agricultural production (cultivated terrestrial plants grown for nutritional, material and energy provision) is recognised as being a main provisioning ecosystem service. Nevertheless biomass obtained through agricultural activities is not a mere product of natural ecosystems, but requires substantial human input to be obtained. This report presents a further development in disentangling the nature and anthropic contributions to agricultural biomass production by means of energy flows. We identify and quantify the respective natural and human energy inputs into main cropping systems in Europe. The energy quantification is based on the emergy concept, which is the energy needed, directly and indirectly, to make a product. Natural components include sun radiation energy, wind, rainfall, flowing water and groundwater, and topsoil. Human components consist of purchased inputs (e.g. fertilizers, machinery) and human labour. Overall, the emergy results show that the energy used to produce biomass in cropping systems mainly originates from human inputs, particularly from the use of artificial fertilisers and ploughing and tilling, and overall is higher in cropland than in grasslands. By applying the emergy concept we are able to assess the intensity of farming management practices. Emergy helps, therefore, to analyse the provisioning ecosystem services derived from agriculture considering the intensity of their production system. At the same time, it offers a new approach to identify ways to achieve a maximum crop yield considering the balance between natural and human resources, and therefore support resource efficiency in agricultural production. The outcomes of this study should be considered as a first methodological approximation based on the available data and models.

Glossary

Emergy of a product is the energy needed, directly and indirectly, to make that product (initially called 'embodied energy'). The type of energy chosen as reference in this study is solar energy that is the basic energy behind all the processes of the biosphere (Odum, 2000). Emergy considers therefore the economic and ecological (including abiotic and biotic) aspects of a system by converting all inputs, flows, and outputs to a common unit seJ (solar equivalent Joule).

Emergy Yield Ratio (EYR) is an index measuring the ability of a system to use the available local resources. It is the ratio of the output of a system (Y) to the external inputs (feedback) from outside (F): EYR = Y/F. Therefore, it is the ratio of total emergy of the yield to the purchased (economic) inputs. Considering that the total emergy is the sum of all local and external emergy inputs, the higher the ratio, the higher is the relative contribution of the local sources of emergy to the system.

Emergy Investment Ratio (EIR) is an index measuring how much a system depends on the outside rather than on local resources, and how much a system or process uses invested emergy in comparison with alternatives. It is the ratio of external inputs (purchased, feedback) to local resources (renewable and otherwise): EIR = F/(R + N).

Mass-specific emergy is used to evaluate increased organization of concentrated matter, measured in seJ/g.

Energy Return on Investment (EROI) is the ratio of output of the production processes, measured in Joules, over the total of human controlled and manufactured inputs, also approximated in Joules (MJ-out/MJ-in)

Transformity is a factor to convert all inputs of a process, including energy of different types and energy inherent in materials and services into emergy, i.e. the energy of one type, directly and indirectly required, to generate 1 J of another. Solar transformity is currently used in emergy evaluation. Transformity is an intensive quantity, representing the inverse of classical energy efficiency and is measured in seJ/J. It is dimensionless and system specific.

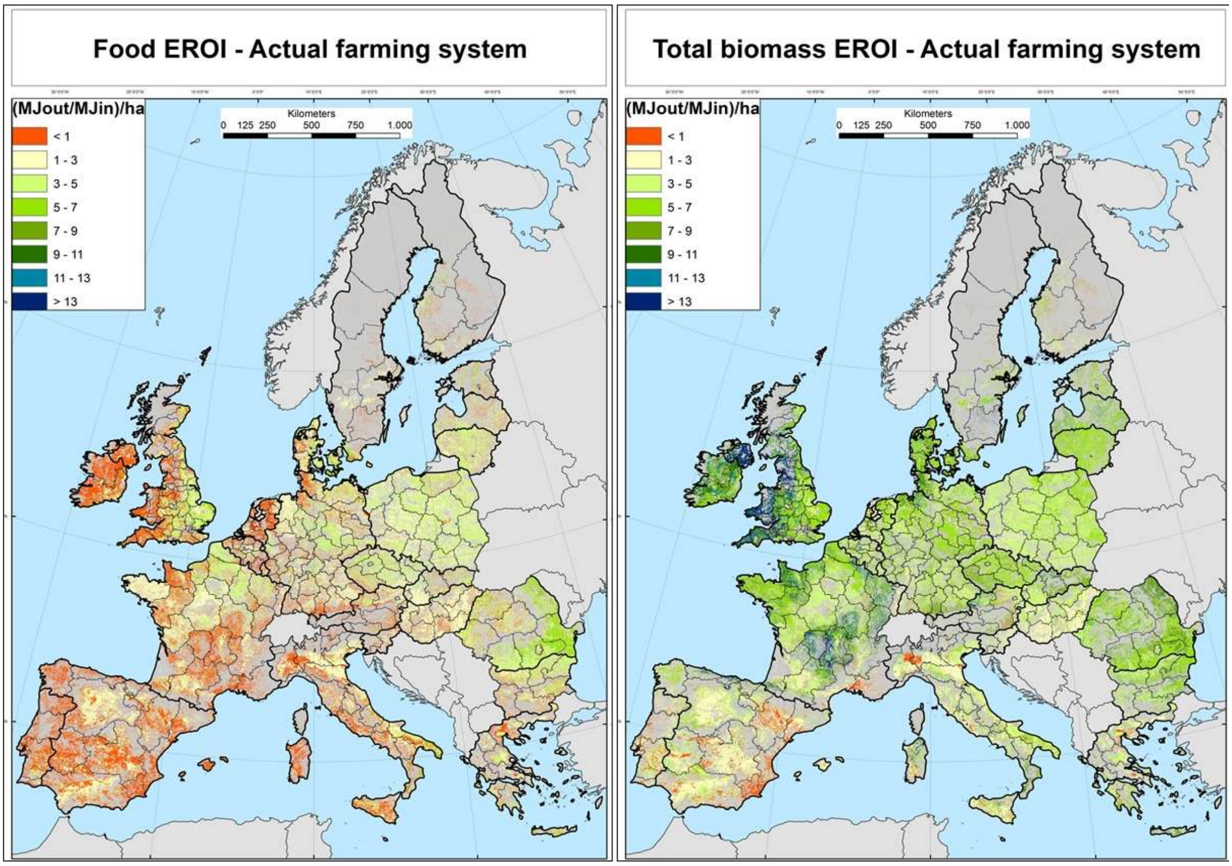
1 Introduction

1.1 Background

Research on ecosystem services has advanced very rapidly in the current decade, and many aspects (nomenclature, reference frameworks, mapping, assessment procedures etc.) have been clarified. Agricultural production (cultivated terrestrial plants grown for nutritional, material and energy provision) is recognised as being a main provisioning ecosystem service (CICES V5.1), nevertheless biomass obtained through agricultural activities is not a mere product of natural ecosystems, but requires substantial human input to be obtained. The main aim of this report is to present a further development in disentangling the nature and anthropic contributions to agricultural biomass production.

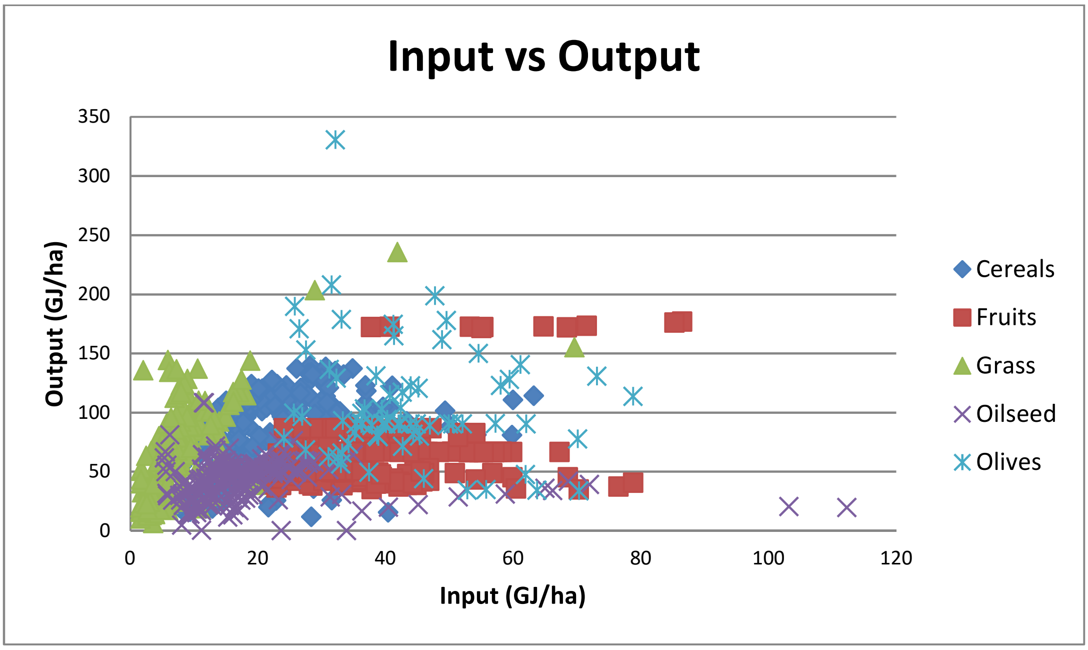
Under this perspective the study completes, in terms of assessment and mapping, the analytical framework presented in the JRC Report "Agricultural biomass as provisioning ecosystem service: quantification of energy flows" (Pérez-Soba et al., 2015), which specifically addressed the anthropic contributions. The study provided the very first assessment carried out at EU level and at a detailed scale, of the flow of human-controlled energy used for food/feed and other biomass production. Furthermore, it related the input-output energy balance to the management intensity of the agro-system. The degree of detail of the analysis is shown in **Figure 1**, which illustrates the spatial distribution of the EROI per hectare (MJ-out/MJ-in) calculated for total and food biomass; and in **Figure 2**, showing the relation between energy input and output per crop category; both figures show the complexity of the analysis and the need to go one step further in the interpretation of results.

Figure 1 Energy Return on Investment (EROI) balance per hectare (MJout/MJin) for food biomass (left) and total biomass (right) at HSMU level.



Source: Pérez-Soba et al. (2015)

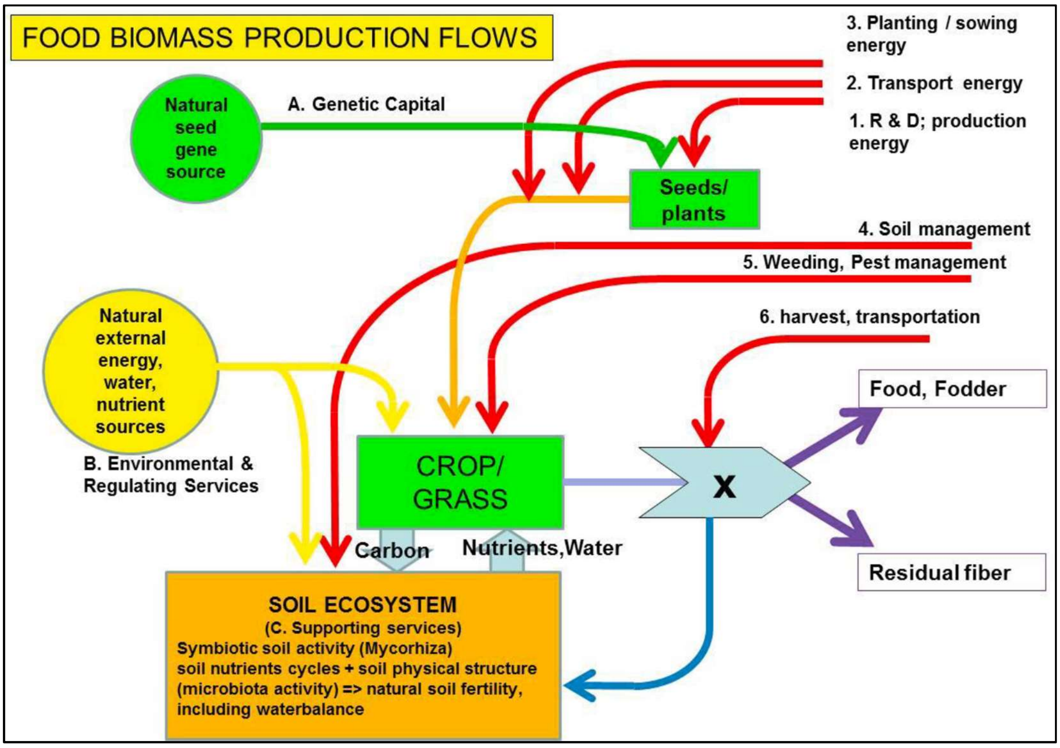
Figure 2 Relation between energy input and output per crop category



Source: Pérez-Soba et al., (2015)

Figure 3 shows, in fact, that other sources of energy are used in crop production and these are mostly linked to the natural ecosystem characteristics of the sites such as solar radiation, rainfall and soil characteristics.

Figure 3 The energy flows involved in food / feed biomass production. Solid lines indicate energy flows. Red lines = human activity; yellow lines = environmental / ecosystem processes; other colours: energy flows resulting from interaction of (natural) ecosystem & human flows



Source: Pérez-Soba et al. (2015)

Therefore in order to have the full overview of the role of the natural ecosystem in agricultural production, the EROI must be referred to, or incorporate, natural energy fluxes. This knowledge allows benchmarking the agricultural biomass production by making explicit the role of the human and natural contributions in the assessment of the provisioning ecosystem services delivered.

1.2 Policy and thematic context

The EU Biodiversity Strategy to 2020 and the current legislative implementation of the CAP 2014-2020 both advocate and set targets to be met by the EU on sustainable agriculture and sustainable management of natural resources. They recognise that society can derive a benefit from the agro-systems only if these are sustainably managed.

In support to achieve these policy goals, the work published in a previous report "Agricultural biomass as provisioning ecosystem service: quantification of energy flows" (Pérez-Soba et al., 2015) focused on the anthropic contributions assessed by means of energy. We calculated the Energy Return on Investment (EROI) for agriculture at 1-km^2 resolution for the EU. The human input into the agricultural system and the yield output were calculated in energy terms to allow for comparison. Their balance was estimated for low-input and high-input farming scenarios and compared to reference situations of naturalness, in order to understand the degree of "human disturbance" reached by current production. Results showed a wide range of variation in EU agriculture both at country and crop system level. The research highlighted how the EROI strongly depends on the cropping system (i.e. cereals versus grasslands), the bio-geographical zone and the levels of energy embodied in the yields. It highlighted as well the 'unsustainable' situations where the human energy input is much higher than the output, resulting in substantial energy loss, or where the total energy output (yields) is not or only partially used.

The first study focused on the energy fluxes that can be controlled by humans. The present study includes the energy provided by the natural ecosystem (sun, soil, rain) to complete the picture.

1.3 Aim and objectives

The aims of this study are:

- To provide an assessment of the relative contribution of natural versus human inputs in agricultural production, which is in fact the core of the concept of ecosystem services (see Braat and De Groot, 2012);
- To trace the critical factors in the production processes, including the natural factors, which allows for focused improvement of the sustainability of the agrosystems;
- To provide a quantitative basis for energy efficiency calculations for (future) studies of the bundles of ecosystem services and their economic and social benefits.

The objectives of this study are:

1. To identify the energy input compartments of the natural ecosystem into cropping systems that can be assessed with available data and models; these compartments should include meteorology, solar radiation and support provided by soil;

2. To quantify the nature and anthropic contributions to agricultural biomass production by means of energy flows;

3. To map the nature and human energy compartments contributions for the main cropping systems at the highest possible resolution for the extent of the EU25.

1.4 Outline of the report

This report consists of five chapters including this first introductory chapter. In Chapter 2 we present the conceptual framework based on ‘emergy’, and its operationalization into indicators of natural and human energy flows in agriculture. In Chapter 3 we present the analytical framework for the quantitative assessment of the energy balance. In Chapter 4 we present the results of analysing and mapping the compartments of the energy and emergy flows. In Chapter 5 we present the main conclusions. Annex 1 provides the literature sources used to derive the transformity values for the different inputs; Annex 2 gives more details on the CAPRI energy module and how anthropic inputs are calculated therein; in Annex 3 results of the calculated emergy indicator are summarised at national level; Annex 4 provides figures on acreage of the crops included in this study at country level.

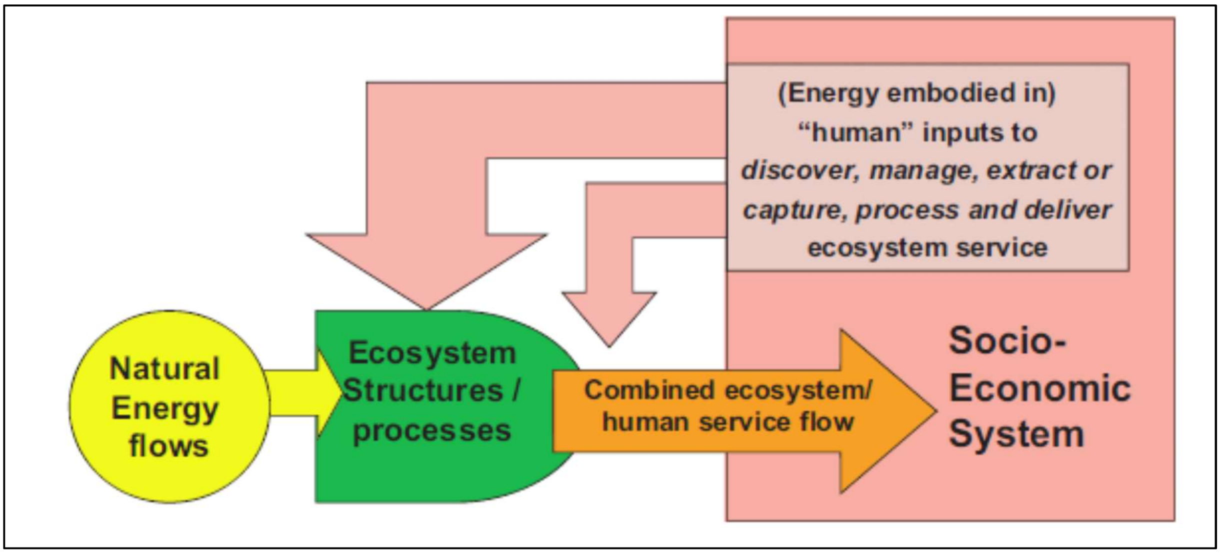
2 Conceptual framework to assess energy flows in agrosystems

2.1 Conceptual approach

The biomass production process in agrosystems is based on the natural and human (socio-economic system) energy inputs sketched in **Figure 4**. In Pérez-Soba et al. (2015) we assessed the human contribution by means of Energy Return on Investment (EROI), i.e. the ratio of output of the production processes, measured in Joules, over the total of human controlled and manufactured inputs, also approximated in Joules. To complete the picture, the present study considers also the inputs from the natural ecosystem. These include:

- Flows generated by external renewable resources (R), i.e. sun radiation energy, wind, rainfall, flowing water and groundwater. "External" is defined as coming from natural sources outside the agricultural system considered;
- Flows generated by internal non-renewable resources, or only partly renewable, (N) in this case represented by topsoil loss.

Figure 4 Ecosystem services as product of ecosystem and human energy



Source: Braat and De Groot (2012)

We distinguish three natural ecosystem sources (sketched in **Figure 4**):

- Natural external (sunlight, water, nutrient);
- Natural seed;
- Natural internal: the soil sources.

The main features of the conceptual framework are summarised below:

- The quantification is based on the emergy concept developed by Odum (1996, 2000), who argued that a more meaningful way to express a system quality is not to consider its energy content (= exergy, or burnable calories), but the energy embodied (emergy) in it. The solar emergy of a product is, therefore, the solar energy needed, directly and indirectly, to make that product. This quantification is underpinned by the findings of the literature review.
- It considers the energy flows of natural and human resources The natural resources include resources outside the production system (solar radiation, wind, rainfall, flowing water and groundwater) as well as internal (soil mineral resources). The human resources, e.g. labour, machinery, fertilisers and irrigation, are those considered in Pérez-Soba et al. (2015).
- It considers transformation of one form of energy to another, at the cost of heat production.
- It delivers three emergy indicators to compare the role of natural energy flows with that of anthropic flows:
    - Emergy Yield Ratio (EYR), which is the ratio of the total emergy of a system to the emergy of anthropic flows
    - Emergy Investment Ratio (EIR), which is the ratio of anthropic energy flows to natural flows
    - The transformity factor expresses the amount of total emergy required to produce one gram of harvested output or one joule of burnable energy. We use the transformity factor to assess the degree of efficiency in the use of emergy in a crop. Transformity can be calculated for the human or natural emergy flows or for both.
- The indicators provide a way to account explicitly the role of the natural ecosystem in the provisioning ecosystem services from agriculture, by identifying the share of natural emergy flows from total emergy of agricultural production.

We provide a detailed description of the different concepts of the framework and their relationships in the next sections of this chapter.

2.2 The emergy concept and methodology

The conceptual approach used in this study is based on Ridolfi and Bastianoni, (2008) and summarised in this subsection. Emergy analysis is a methodology of systems analysis and quantitative assessment, which considers both the economic and ecological (including abiotic and biotic) aspects of a system by converting all inputs, flows, and outputs to the common denominator of solar energy, which is the basic energy behind all the processes of the biosphere. Abiotic sources are often referred to as environmental sources.

An important notion in this analysis is that not all forms of energy are equal. The second law of thermodynamics states that all real processes, including processing of energy and storage of materials, imply a dispersion of part of the energy in the form of heat. Real world systems, natural and human alike, are organized in flows of energy of different qualities. The quality measure is the way energy is concentrated, e.g. solar energy is "concentrated" into chemically bound atoms of water, whereas carbon dioxide and nutrients are concentrated in sugar molecules. This concentration process has a cost, which is measured in solar radiation joules turned into heat (dispersed energy) joules. Odum recognized the implications of these different types of energy quality and introduced the concept and term of emergy (initially called 'embodied energy') to quantify the energy of a given type used directly and indirectly to make a product. The type of energy chosen as reference was solar energy, since it is basically the source of all flows in the biosphere (see e.g. Odum, 2000). The solar emergy (or simply called emergy) of a product is, therefore, the solar energy needed, directly and indirectly, to make that product. Emergy is thus the counter concept of exergy (sometimes called burnable calories).

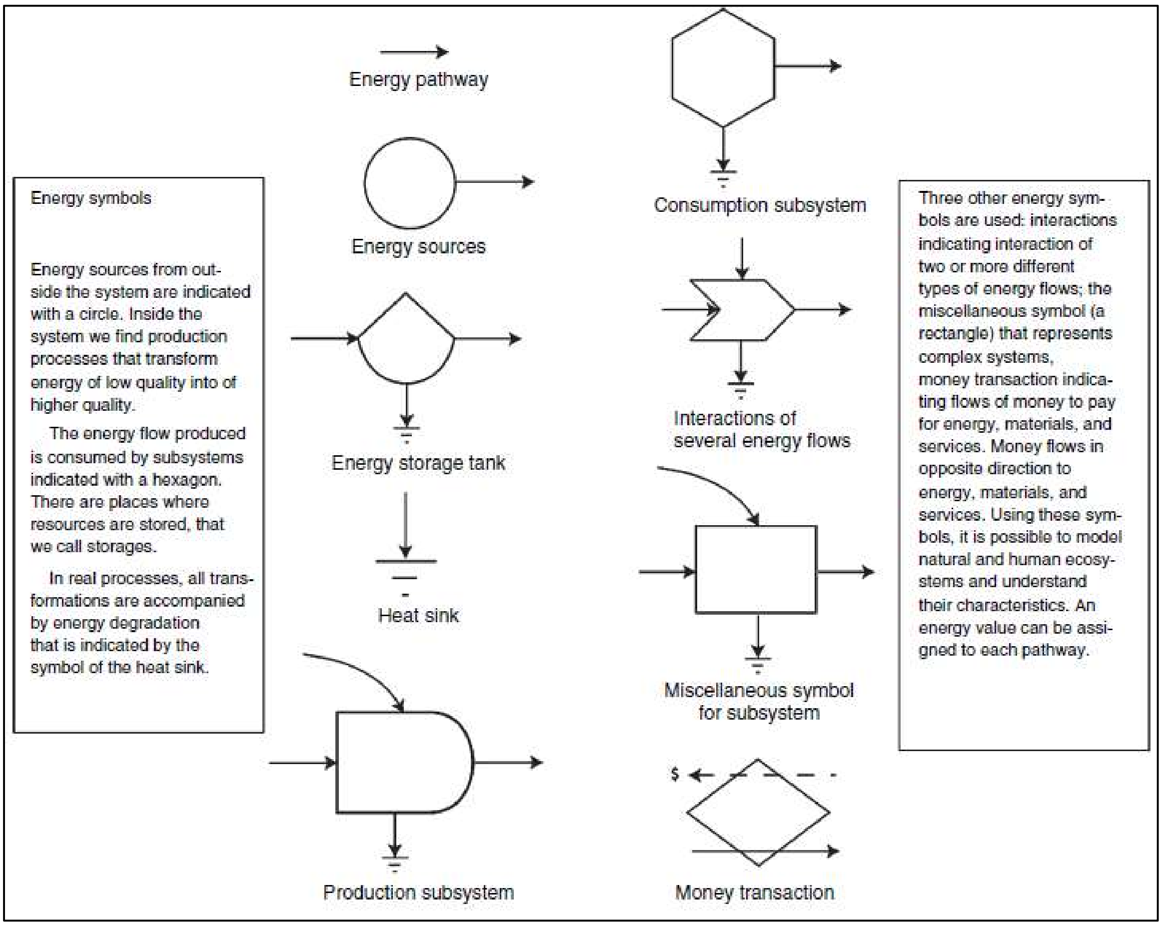
2.2.1 Energy language, energy modelling and hierarchical web

To describe the flows of energy and matter in a system, a modelling language has been developed. Systems are made up of forces and energy pathways: the former are causal actions, the latter represent how and where these forces are directed. The symbols used in energy diagrams are summarized in **Figure 5**.

The emergy concept was developed with hierarchical webs in mind (**Figure 6**). In these webs, the quantity of energy associated with each transformation decreases at each step in the process. Every transformation is accompanied by heat dispersion.

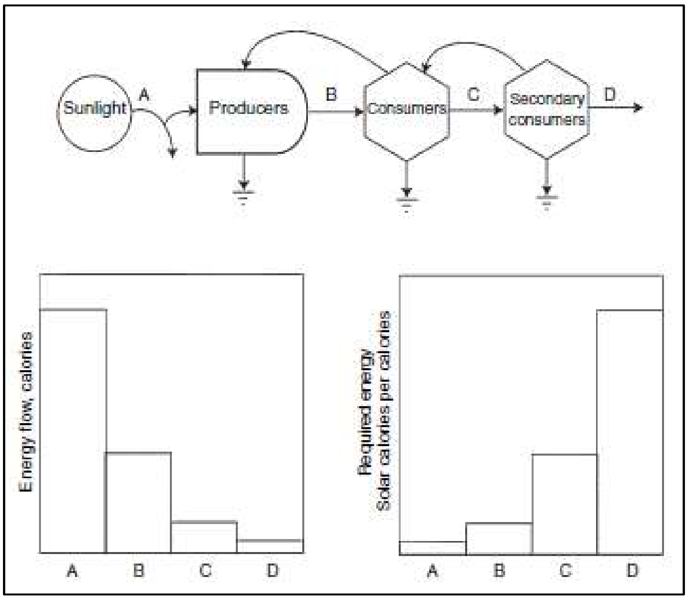
In the energy diagram the productive units on the left produce goods and services for those on the right which return materials and control (= work and information, which are energies of high quality) to the left (also called positive or enhancing feedback). Energy is transformed from left to right and in each transformation the output has less energy (burnable calories) but the remaining energy is concentrated in some form (plant biomass, meat) of higher energy quality and controls other units of the system. In conclusion: to create the high-quality energy products on the right side in the diagram, a great amount of low-quality energy is necessary. The diagrams in **Figure 6** show an energy hierarchy with step-wise convergence from left to right.

Figure 5 Symbols used in emergy analysis



Source: Ridolfi and Bastianoni (2008)

Figure 6 Hierarchical webs and energy flows



Source: Ridolfi and Bastianoni (2008)

In a food web (**Figure 6**), the position in the chain represents different capacities for energy quality and that often implies control of the preceding part of the chain. For example, considering direct and indirect energy inputs, it takes about 1,000 Joules of sunlight to make 1 Joule of spatially dispersed organic matter, about 40,000 Joules of sunlight to make 1 Joule of coal, and usually even more to make 1 Joule of electrical energy. According to this concept, Odum argued that a more meaningful way to express a system quality is not to consider its energy content (= exergy, or burnable calories), but the energy embodied (emergy) in it, that is, how much energy was used to make or sustain the system starting from the lowest level of the web.

Emergy is thus a donor-referenced concept rather than a receiver-referenced one. The basis of emergy evaluation is the conversion of all process inputs, including energy of different types and energy inherent in materials and services, into emergy by means of a conversion factor called transformity. Emergy analysis is a scientific and robust method, elaborated principally by H.T. Odum and his disciples during the last four decades (Brown and Ulgiati, 2004, 2010; Brown et al., 2011; Odum and Arding, 1991; Odum et al., 2000a, Odum et al., 2000b; Odum and Bardi, 2001; Odum, 2000, 1996). Emergy analysis puts a value on all work done by the biosphere and transforms them into a common unit, sun-em-Joule or solar equivalent Joule (seJ).

2.2.1.1 Transformity

Transformity is defined as the energy of one type directly and indirectly required to generate 1 J of another. Solar transformity is currently used in emergy evaluation. Transformity is an intensive quantity, representing the inverse of classical energy efficiency and is measured in seJ /J. It is dimensionless and system specific. To evaluate increased organization of concentrated matter, a mass-specific emergy (seJ/g) is sometimes used. The emergy of a certain type of material is obtained by multiplying its mass with the emergy-to-mass ratio. As with energy-based transformities, matter evaluations are also system and process specific. If in Figure 6 the producers represent forage plants and the consumers (C) are cows, the sun transfers energy to the plants from the boundary of the system, the plants use it by photosynthesis and transpiration, taking up soil nutrients and fertilizers. The transformity of the plants is clearly greater than 1 (i.e. the solar transformity of the sun). The energy (burnable calories) in the forage is obviously much less than that of the incoming solar energy. Similarly, the forage transfers its solar-derived, but concentrated energy to the cow. Since the forage contains energy derived from the sun, so does the cow, and energy embodiment increases while at the same time most of the original energy dissipates (becomes heat) along the steps of the food chain.

The transformities of similar products can be compared to obtain information about production efficiency. If, for instance, the transformity of forage from one field is 4x10*4 seJ/J and that from another field is 1x10*5 seJ /J, the forage from the first field can be said to be more efficient (it has less emergy per unit of product). Transformities of different classes of product (e.g., forage and cow) can also be compared. In this case, transformities indicate the relative 'position' in the global hierarchy of processes.

2.2.1.2 Emergy Algebra

The transformities of two (or more) splits in a chain or web are identical, while their emergy contents are generally different (unless energy is distributed equally among the splits); on the contrary, the transformities of co-products are generally different (unless the same amount of energy went into the various co-products). It is necessary to know the emergy of the inputs in order to calculate the emergy of the output. Apart from the sun, that has a transformity of 1 by definition, it is necessary to calculate the transformity or emergy of natural resources.

All emergy analysis is based on the calculation of a geobiosphere emergy baseline (GEB), defined as the total energy available to the biosphere in a certain period (usually one year). The GEB is the sum of three components: i) solar radiation; ii) geothermal sources; and iii) dissipation of tidal momentum (Brown et al., 2016). As these sources provides energy in different form, it is necessary to convert them to a single unit: since the largest part of the GBE comes from solar radiation, the reference unit used is seJ/year. The reference baseline adopted in this study 15.83x1024 seJ/yr from Odum 2000). The first emergy studies took 9.44x1024 seJ/yr as baseline and can be updated by multiplying the transformities used in the emergy evaluation by 1.68. Other values for the GEB have been recently proposed, e.g. Brown et al., (2016) proposed 12.0x1024

2.2.1.3 Emergy, Sustainability, and Indicators

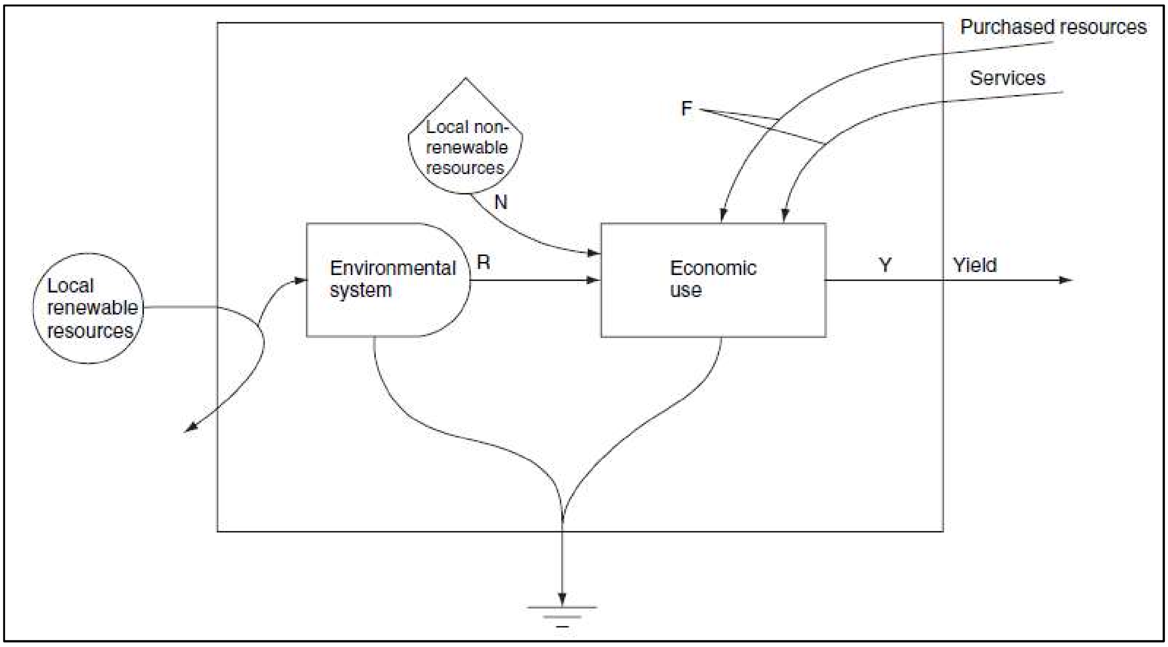
Emergy analysis is useful to check applications of Herman Daly's first rule of sustainable development, 'the sustainable yield principle', that states that resources should be exploited at a rate compatible with their replacement by nature (Daly, 1990). It can be used to define guidelines for consumption of resources compatible with their formation times. Emergy can therefore be used to define guidelines for consumption of resources compatible with their formation times. Emergy can be used to estimate the solar energy necessary to sustain a system; the greater the total emergy flow necessary for obtaining a product, the greater the consumption of solar energy necessary for its re-formation once it has been used, and thus the greater the past and the present environmental cost to maintain it.

The intensive use of the services and products of an ecosystem can degrade its structures and functions, decreasing the capacity of the ecosystem to self-organize efficiently. In order to facilitate the measurement of a system's sustainability, some emergy indicators were introduced. The diagram in **Figure 7** shows them.

Emergy flows to the system are divided into the main categories as given in the following:

- local renewable resources (**R**);
- local non-renewable resources (**N**);
- feedback (**F**): purchased resources and services from outside system; and
- the total output of the system, called yield (**Y**) = (**F+R+N**).

Figure 7 Emergy system diagram of a generic system



Source: Ridolfi and Bastianoni (2008)

These flows can be combined to obtain a set of indicators. The two most common indicators are defined below and will be calculated in this study for the different cropping systems examined in this study.

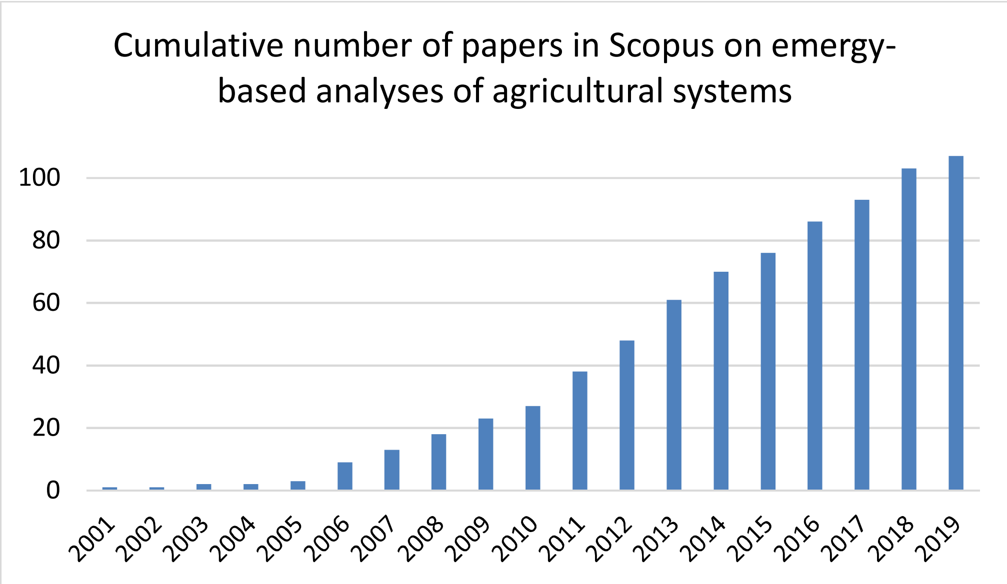
- **Emergy Yield Ratio** (**EYR**) is the ratio of the output of a system (Y) to the external inputs (feedback) from outside (F): EYR = Y/F. Therefore, it is the ratio of total emergy of the yield to the purchased (economic) inputs. Considering that the total emergy is the sum of all local and external emergy inputs, the higher the ratio, the higher is the relative contribution of the local sources of emergy to the system. This index therefore shows the ability of a system to use the available local resources.
- The **Emergy Investment Ratio** (**EIR**) is the ratio of external inputs (purchased, feedback) to local resources (renewable and otherwise): EIR = F/(R + N). It measures how much a system depends on the outside rather than on local resources, and how much a system or process uses invested emergy in comparison with alternatives.

In emergy accounting, the largest of all the related environmental or renewable solar based inputs -such as solar energy, rainfall, wind and evaporation- is used in the calculations of the indicators, to avoid double counting, because all the climatological renewable energy flows are by-products of coupled processes (Lefroy and Rydberg, 2003; Odum, 1996, pp. 51–52).

2.3 Literature review on Emergy studies of agricultural systems

Since the emergy concept was introduced, several emergy-based studies on agriculture have been published, aimed at ascertaining the environmental support provided for free by nature to the agricultural process as well as to the upstream processes delivering needed goods and materials. The first recorded emergy study of agriculture is Odum's (1984) paper about the environmental role of agriculture (Ghisellini et al., 2014). Since then, the literature has grown markedly (**Figure 8**), spanning from local, crop-specific agricultural systems to comprehensive, large-scale analyses at national level[1]. Some studies provide temporal series that allows appreciating the evolution of an agricultural system over decades.

Figure 8 cumulative number of studies on agricultural systems based on emergy in the Scopus database



Source: this study

Emergy indicators used in these studies comprise Y, EYR and EIR as defined in section 2.2.1, as well as other indicators including:

- ELR (Environmental Load Ratio) = (F + N)/R, measuring the stress on the environment in terms of share on non-renewable over renewable resources
- ESI (Emergy Sustainability Index) = EYR/ELR, measuring the process trade-off between the emergy advantage provided by the process and its environmental pressure. The higher the value, the more emergetically sustainable the system is.

Chinese authors account for the majority of emergy-based studies. Chen et al. (2006) present a full emergetic account of Chinese agriculture from 1980 to 2000, showing how in this period the overall EYR decreased from 2.28 to 2.08 and the EIR rose from 0.86 to 1.11, indicating an increased reliance upon external input. This study was complemented by Jiang et al (2007) to cover the period 2000-2004, during which EYR returned to the level of 1980 (2.28), but EIR further increased from 1.11 to 1.17. Tao et al., (2013) use eight emergy indicators to characterize arable cropping systems across 31 Provinces of China, identifying 10 archetypical production systems, for each of which specific policy recommendations were formulated. Zhang et al. (2016) provide a full analysis of the whole crop production in China from 2000 to 2010: in this decade, efficiency in the use of resources (emergy input per unit of yield) increased by 11.5%, EYR remained stable, but EIR also increased from 6.2 to 7.5 and the ratio of non-renewable on renewable input rose from 1.33 to 2.10. Liu et al. (2018) present a similar comprehensive analysis covering the period 1997-2016 and report consistent results, with the share of purchased resources on total emergy output increasing from 70.5% in 1997 to 77.9% in 2016, a trend mainly driven by fertilizers, followed by mechanical equipment, diesel, and pesticides. For the authors, the clear conclusion is that there is a "huge environmental pressure on the local

1 Search done in the Scopus database in March 2019 on papers containing in the title the term "emergy" and one of the following: "agriculture", "agricultural systems", "crop(ping) systems", "farm systems"

ecosystem" and therefore that "China's crop production system is undergoing an unsustainable development pattern" (ibid. pag. 9). Similarly, Liu et al. (2019) provide a detailed analysis of emergy indicators for the 31 Chinese provinces for the period 2006-2015, during which ESI decreased in all of them, though it was higher than in other industrialised countries such as Italy or Japan. They identified the main driving forces underlying this trend in productivity of labour, which mostly contributed to improve the index and in declining use of natural resources, which contributed the most to the overall decrease.

Several Chinese studies were carried out at local or regional scale, and complement the national picture provided by the previously mentioned studies. Wu et al. (2007) studied two agricultural districts in a Province of NE China over 25 years, finding increases in the share of purchased external input of 88% and 8% respectively; Wei et al. (2008) report for another Province a strong decrease of EYR in the period 1980-1990 followed by slight increase in 1990-2000, whilst the ration of renewable on non-renewable resources jumped from 2.5 to 9.2. Wang et al., (2014) report that the EIR of the agricultural system of a NW county jumped from 0.26 to 0.64 in the period 1991 – 2008 with a marked increase after the implementation of the grain-for-green policy (supporting the conversion of marginal cropland to forests or grasslands), pointing out that ecological benefits from land sparing could be offset by increased ecological loads on agricultural land. A more positive evaluation of the same policy in a different region is reported by Lu et al (2017) with regard to the substitution of crop area in sloping terrain with bamboo forest. The latter proved to be more sustainable once assessed with emergy indicator, but also less profitable when assessed with classical economic indicators.

Other studies on specific agricultural systems are Lu et al. (2010) (rice vs vegetables production in a traditional paddy fields region); Zhang et al. (2012) who compared the performances of maize cropping, duck rearing, mushroom production and extensive semi natural pond fish farming; Wu et al., (2015) used emergy to quantify the benefits of waste recycling and improved use of farm by-products in 3 production systems (walnut and grains, pigs and poultry, and biogas). Wang et al. (2015) integrated Life Cycle Assessment calculating "traditionally" emergy indexes and "revised" indexes that account for the additional emergy consumed by the environment to absorb and dilute the harmful by-products of pig production. Wang et al. (2017) further elaborated on how to adequately account for the contribution of recycled matter in emergy algebra, arguing that only the emergy stored in the organic matter of recycled material should be accounted.

Concerning other Asian countries, Gasparatos (2011), analysed the entire Japanese agricultural system in the period 1975-2005 showing a marked increase in the emergetic share of purchased inputs (+57% in EIR) and linking it, among other things, with dietary changes and macroeconomic trends as the collapse of the Japanese economic bubble at the end of the 1980s. Significantly, through this analysis he emphasizes how agricultural systems heavily depending upon external inputs are more vulnerable to market fluctuations and point to a link between energy security and food security.

Ali et al., (2019), examined the whole crop production of India and Pakistan from 2002 to 2011. In this period in Pakistan the share of non-renewable purchased emergy on total emergy increase by 4.3% (being on average around 81%), and it absolute value by 29.3%; in India non-renewable external inputs accounted on average for 75.6% of total emergy and the share decreased by 3.5%: this was however the results of a decrease in labour (considered by authors as purchased non-renewable), whilst the relative emergy contribution those of fertilizers, electricity, mechanical equipment, pesticides and fuels increased significantly. In Pakistan EYR and EIR increased by 13.4%, and 17.5% respectively. Environmental load ratio increased by 25.9% and ESI decreased by 31.2%. Conversely, in India EYR increased by 32.4%, EIR increased by 1.2%, ELR decreased by 14.4% and ESI increased by 54.7%.

Turning to Central and South America, Ferreyra (2006), examined the evolution of agriculture in the Pampa Region of Argentine over a century (1900-2000). Whilst crops and efficiency increased use of renewable emergy decreased approximately 50%, and ELR increased five times in this period. Ferraro and Benzi (2015) extended the study to cover the period 1984-2010 focusing on three cropping systems: wheat/soybean double cropping, maize and spring soybean. They conclude that these systems are comparatively more sustainable than similar ones in other countries (e.g. Italy and Brazil), but are facing negative trends as demonstrated by the changes in ELR, EYR and ESI; significantly, these index improved in the period 1984-1993 but then declined following the introduction of new production technics, namely no-tillage, genetically modified organisms and the start of systematic fertilization. González-Mejía and Ma (2017) examined the full agricultural system of Puerto Rico from 1960 to 2013 and report an exponential decrease in sustainability in this period. Crop-specific analyses were carried out by Cavalett and Ortega, 2009 (soybean production in Brazil - result showing that by producing raw soybean and soy meal for international markets Brazil loses a great amount of emergy and nutrients); Guillén Trujillo (2003, coffee and sugar cane in Chiapas, Mexico), Cuadra and Rydberg (2006, coffee in Nicaragua), de Barros et al. (2009, banana in Guadeloupe), Goncalves Pereira and Ortega (2009, bioethanol from sugarcane in Brazil), Giannetti et al. (2011, coffee in Brazilian savannah).

In Europe, Ulgiati, Odum and Bastianoni (1994) provided one of the first and most cited study applying emergy metric to agricultural systems. A more recent study by Ghisellini et al. (2014) covers the period 1985-2010 for two Italian Regions, and the results indicate a stable EYR, slightly increasing EIR and a slightly improving of ELR and ESI, which however remain at very unsustainable levels. The authors link these positive trends, though limited in absolute terms, to recent EU policies on rural development. Nevertheless, they claim that the share of renewable emergy is still very small in the two regions, arguing that urgent policy actions are needed to this regard. Land use change, labour productivity, the fraction of population to be fed per hour of agricultural labour and Gross Production Value were identified as the main drivers of total emergy use. Rodríguez-Ortega et al. (2017) investigated three main sheep-crop farming systems in Aragon (NE Spain): specialized, mixed fully-integrated and mixed partially integrated founding that lamb meat production was, in general, more sustainable and less intensive than crop production due to the fact that sheep are able to use more local renewable natural resources than crops. This indicates a trade-off between intensity (and efficiency) and sustainability of production. Fonseca et al. (2019) studied the complex and multifunctional *montado* system (agroforestry and livestock) of Portugal comparing results from emergetic and economic analyses. Results indicate that the *montado* system is very dependent on subsidies that represent 19.1% of the total emergy, whilst local natural resources account for 23.7% of the total emergy and conclude that the current economic evaluation of the system neglects the natural input component and shall be complemented by emergy analyses. Other studies on European agricultural systems include Lagerberg and Brown, 1999 (greenhouse tomato production in Sweden), Bastianoni et al., 2001 (farms in the Chianti area of Tuscany, Italy), Burgess, 2011 (arable crops in Scotland), Jaklič et al., 2014 (dairy sector in Slovenia), and Wright and Østergård, 2015 (pig production system in Denmark), Fonseca et al., 2016 (silvo-pastoral systems in Portugal).

2.4 The soil ecosystem and its underpinned ecosystem services

In the past few years, soil scientists have developed models to assess the ecosystem services for which soil ecosystems are important (see e.g. Dominati et al. 2010 and **Figure 9**).

In agriculture the focus has been on the so-called provisioning services, which in the model of Dominati et al. (2010) are listed as provision of physical support, provision of food, wood and fibre, and provision of raw materials. The model illustrates how these ecosystem services are based on soil natural capital and the various physic-chemical and biological processes. The model uses out-dated classifications of ecosystem services, but the various soil processes identified in the paper remain useful.

Ecosystems functions, such as soil formation, can be related to the combination of several biogeochemical flows (e.g. carbon sequestration, nitrogen biological fixation and water percolation) which are ecosystem processes that indirectly (and in case of carbon sequestration also directly) affect the human perception of welfare. Therefore, biogeochemical processes have an effect on a wide range of ecosystem services, including climate regulation, food and raw material production, soil formation, water supply and flood control (Watanabe et al., 2014).)

The value of the soil ecosystem to the total value of agricultural production can be estimated in different ways (Cohen et al, 2006), including economic valuation and emergy valuation).

Economic valuation methods

They are based on market costs of replacing ‘‘free’’ services, that were provided by soils, after degradation (e.g. fertilizers, organic amendments);

- equate downstream remediation costs (e.g. reservoir dredging) with on-site ‘‘external’’ costs;
- opportunity costs based on the value consumers attach to un-degraded lands;.
- surveys to estimate the ‘‘willingness-to-pay’’ for services provided by soil.

For each, the objective is to estimate value in units that allow comparison with market prices. Methods that assess inherent values of natural capital contingent on perceived human values may fail to capture the full extent of ecosystem services. Methods that complement efforts to quantify the soil resource value in money units by avoiding reliance on human preference may provide an informative benchmark against which derived monetary valuation can be compared (Cohen et al, 2006).

Emergy based valuation

This approach offers a technique for valuing environmental work and natural capital which is based on biophysical processes rather than derived or perceived human value, eliminating preference from the valuation schema. Value is embodied in natural capital (e.g. topsoil) based on the environmental work required to produce it rather than on services provided by that stock.

The loss of topsoil that has resulted from complex system processes and provides several ecological services is valued according to the production requirements for replacement. As such, this so-called "donor-based" valuation offers a useful complement to receiver-based methods for measuring sustainability.

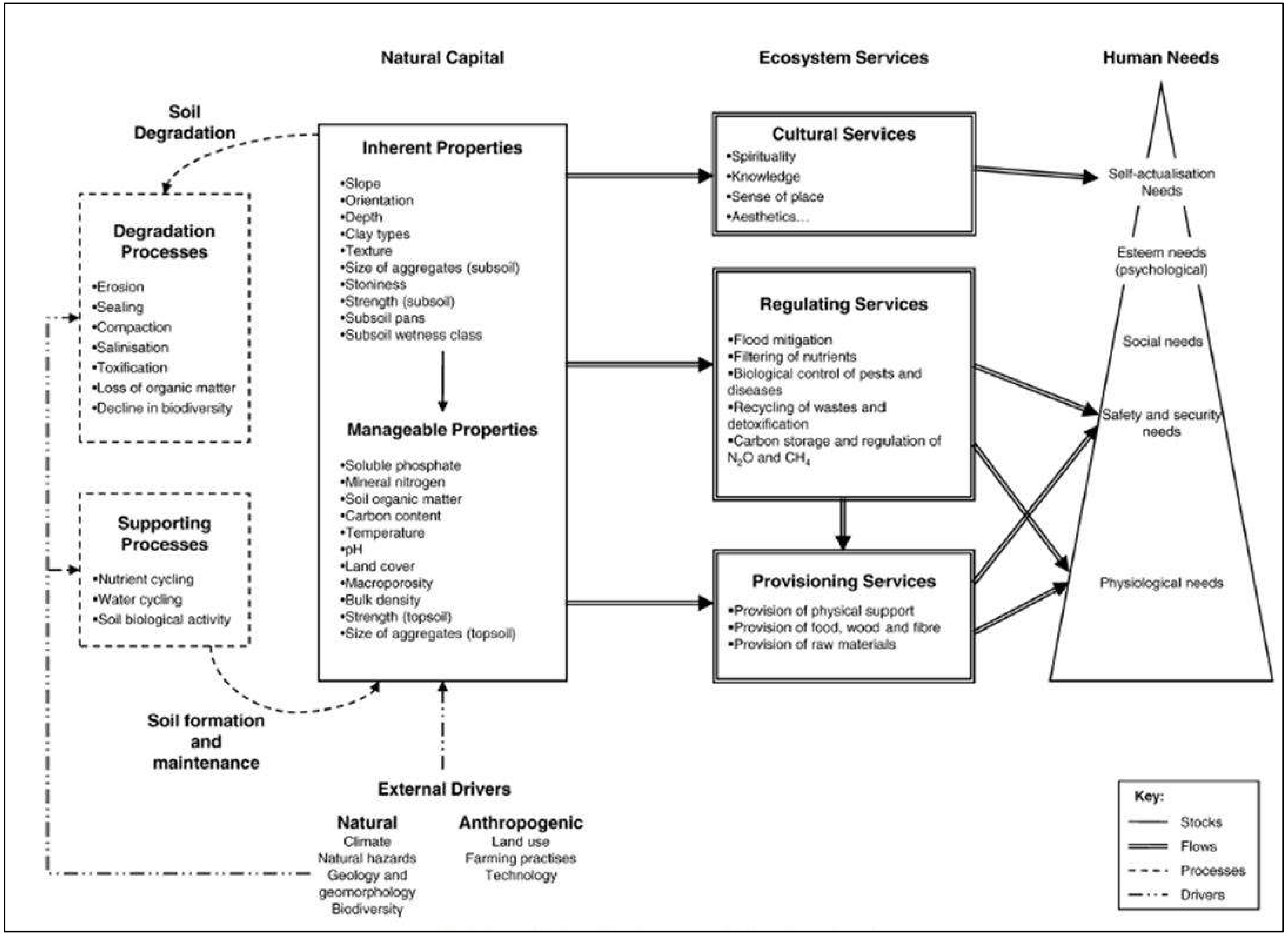
2.4.1 Soil emergy ratio contribution accounting

The contributions from the ecosystem to agricultural production processes are complex but include ultimately:

- internal energy inputs: (1) the nutrients and water provision via the roots systems of the crops (direct matter flows), made available through both microbial activity and physic-chemical processes, and (2) the structure and chemical composition of the soil, again the result of the biotic and abiotic processes;
- external energy inputs:, and (3) outside energy inputs from natural sources such as rain, wind energy (and the resulting evaporation), and deposition of organic and inorganic compounds and (4) inputs from human origin (physical and chemical; including irrigation water, fertiliser, and pesticide residues).

In the emergy accounting the inputs from the soil to the agricultural crops are considered a "soil loss", and typically, soil loss is considered as a non-renewable energy stock depletion (part of N, local non–renewable resources in **Figure 7**).

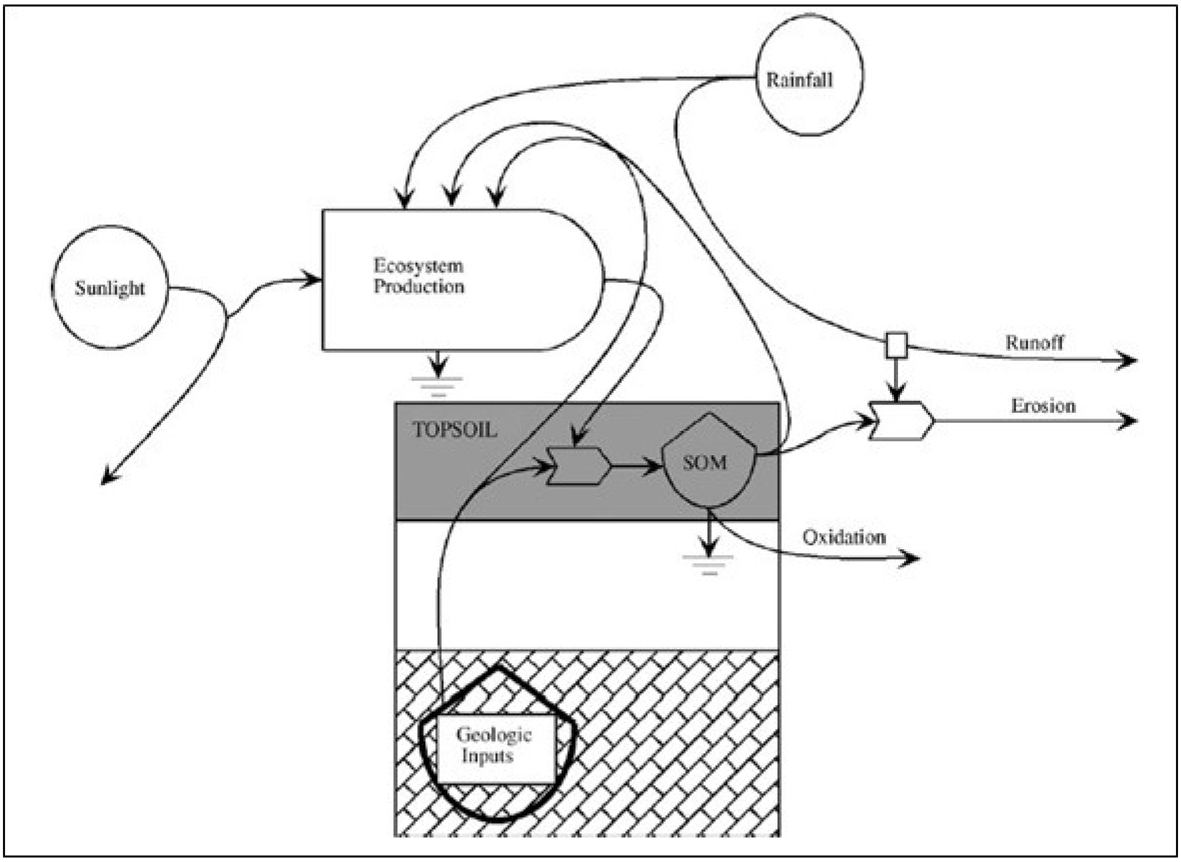
Figure 9 Generalized soil ecosystem services model



Source: Dominati et al. (2010)

In **Figure 10** the inputs to the plant are related to the total "use" of the soil ecosystem in agricultural practice, which may involve tilling, weeding etc. all leading to soil loss. In the calculations the emergy value of the contribution from the soil ecosystem is therefore not estimated per nutrient or water units, but via an estimate of a fraction of total soil loss.

Figure 10 Simplified overview of the topsoil flows



Source: Ridolfi and Bastianoni (2008)

2.5 Emergy values in Agricultural production

In the emergy literature on agriculture the standard approach is to develop an emergy accounting table, which lists the various inputs and outputs in their "traditional" units, and in emergy units. The transformation from traditional to emergy units takes place by multiplication with the transformities, specific for each type of input, and reflecting the energy in solar equivalents needed to produce the type of energy value of the particular input (see **Table 1** below, from Haden, 2002).

Table 1 Emergy evaluation of the S&S Homestead farm

Note	Item, unit	Data (units/yr)	Transformity* (sej/unit)	EMERGY (E14 sej/yr)
RENEWABLE RESOURCES (R)				
1	Sun, J	1.26E+15	1[a]	12.61
2	Wind, J	2.65E+09	1.50E+03 [a]	0.04
3	Rain, evapotranspiration, J	6.68E+11	1.82E+04 [a]	121.65
4	Rain, geopotential, J	9.34E+08	2.79E+04 [a]	0.26
5	Earth Cycle, J	2.50E+11	2.90E+04 [a]	72.50
6	Groundwater, J	2.73E+09	2.27E+04 [g]	0.62
	Largest renewable input			**121.65**
NONRENEWABLE STORAGES (N)				
7	Net topsoil loss, J	2.73E+09	7.38E+04 [a]	2.01
	Sum of free inputs			**124.28**
PURCHASED INPUTS (P)				
8	Fuels and lubricants, J	6.27E+10	6.60E+04 [a]	41.38
9	Electricity, J	2.02E+09	1.60E+05 [a]	3.24
10	Mechanical equipment, g	1.87E+05	4.10E+09 [h]	7.66
11	Buildings, fences, tools (wood), J	1.46E+10	3.49E+04 [I]	5.09
12	Tools, fencing, (steel), g	2.07E+05	3.20E+09 [d]	6.61
13	Ironwood posts (fencing), g	8.50E+03	3.90E+08 [a]	0.03
14	Insulators, ceramic (fencing), g	1.15E+03	1.00E+09 [a]	0.01
15	Plastic (greenhouse and fencing), g	8.85E+03	3.80E+08 [d]	0.03
16	Mineral salt, g	1.58E+05	1.00E+09 [a]	1.58
17	Potash, g K	7.13E+02	1.10E+09 [a]	0.01
18	Phosphate, g P	1.08E+03	1.78E+10 [a]	0.19
19	Nitrogen, g N	1.64E+03	3.80E+09 [a]	0.06
20	Seeds, J	1.81E+08	3.48E+04 [d]	0.06
21	Grocery store culls , g	1.18E+05	6.31E+09 [b]	7.46
22	Soy meal, J	1.70E+09	3.32E+05 [b]	5.64
SERVICES and LABOR (S)				
23	Labor, J	5.77E+09	2.56E+06 [g]	147.80
24	Infrastructure, service component, USD	6.88E+03	1.37E+12 [c]	94.22
25	Services, yearly expenditures, USD	5.56E+03	1.37E+12 [c]	76.21
	Sum of purchased inputs			**396.60**
PRODUCTION, J				
26	Meat, J	3.01E+10		
27	Vegetables, fruit, grain, J	2.51E+10		
28	Eggs, dairy, J	1.02E+10		
28	Hay, J	3.55E+11		

Source: Haden (2002)

Since the early 1990's research groups, particularly in Italy, China, Brazil and USA, and several other countries with help from Odum students, have developed refinements for the transformities. Especially those regarding the soil contribution have been researched extensively. For the real calculation of the emergy flows resulting from human inputs and the natural system, a summary table of transformities has been developed, (see **Table 2**) using the most recent "stable" values, the origin of which is traced in the Annex 1.

Table 2 Transformities used in this study for calculating the emergy values of the different energy flows in agro-ecosystems.

		TRANSFORMITY seJ/J	TRANSFORMITY seJ/g
	unit	average /current estimate	average /current estimate
Renewable Resources			
Sunlight	J	1.00 E00	
wind , kinetic energy	J	2.50 E03	
Evaporation	J	6.00 E01	
Rainfall (chem)	J		
Non Renewable Resources			
Soil erosion/loss	J	Varies with the soil organic carbon content of the soil	
Purchased inputs			
N Fertilisers	g		2.4 E10
K fertilisers	g		1.8 E09
P fertilisers	g		2.2 E10
Manure	g		2.13 E08
Irrigation water	g		7.61 E05
Pesticide	g		1.48 E10
Pesticide	J	1.11 E05	
Herbicide	g		1.48 E10
Insecticide	g		1.48 E10
Fungicide	g		1.48 E10
Seeds	g		1.67 E09
Diesel oil/fuel	J	1.11 E05	
Gasoline	J	1.11 E05	
Lubricants	J	1.11 E05	
Steel Machinery	g		1.12 E10
Human Labour*	J	3.8 E05 - 1.2 E07	
Electricity	J	2.00 E05	

Source: own elaboration based on literature sources presented in Annex 1

Special attention was given to the Renewable Energy flows, as there are different approaches to calculate the contribution of energy in the rain via the processes of evaporation and transpiration.

The approach used in this study is to take the energy involved in evapotranspiration via an approximation by actually applying the "2,260 J/gram water" needed from boiling liquid water to vapour plus some extra Joules for warming up the water, leading to an estimate of 2,500 J/gram. In this case, we cannot apply the transformities published in the literature based on the Odum approach, i.e. ca 3.0E+04, to estimate the emergy, because that transformity value is linked to another way of calculating the Joules involved in evapotranspiration. The recalculated transformity (by comparison to the Odum method) is 60 (6.0E+01).

The Odum approach to this particular energy flow is described in e.g. Haden (2002), and also used in the Brandt-Williams study (2001) which entails the use of the Gibbs Free Energy (= 4.94 J/ gram water) in rainfall as the proxy for evaporation energy, and then via a Transformity of ca 3.0 E+04 calculate the Emergy flow. The use of "evapotranspiration" should be just "transpiration", but since few measurements of T (transpiration) are found in the literature and there is a preponderance of ET (EvapoTranspiration) data, we use ET. So ET is used to derive the water (and the energy associated with it) that is actually "used" by plants (natural or crops) in photosynthesis. The energy in water that plants use is its Gibbs (chemical potential) based on the assumption that the salinity within the plant is close to sea water (35ppt) and the salinity of rainwater is 10 ppm (Pers. Comm. Mark Brown, University of Florida).

We have chosen to use the first method for the EU analysis, which uses a transformity value which is in fact indirectly derived from the Odum approach, and we have done a test with the second method to demonstrate the robustness.

As to the transformity for the non-renewable emergy, i.e. the soil energy loss, no fixed number can be specified in **Table 2**. For this we built on the soil (non-renewable emergy input) emergy calculation approach from Brandt-Williams (2001) as discussed further in the next chapter.

3 Analytical framework for the quantitative assessment of the energy balance

In chapter 2 we show that ecosystem services can be viewed as the flows of energy from natural (or ecological) and human (or social-economic) systems and that their contributions can be assessed through the emergy approach.

In order to proceed with the assessment of the total emergy input into the different cropping systems, we followed this analytical framework:

- We defined the boundaries of the analysis. The assessment focuses on main arable crops and grassland production. It excludes crop production in greenhouses and intensive horticultural systems. The spatial extent is the EU25 at the highest possible resolution;
- All single human energy components were identified and quantified specifically per cropping system per region and HSMU. This had already been done in the former study (Pérez-Soba et al., 2015) in which the focus was on the Energy Return On Investment (EROI), i.e. the ratio of output of the production processes, measured in Joules, over the total of human controlled and manufactured inputs, also approximated in Joules. This assessment was further refined in this study, particularly in relation to the energy flows related to irrigation;
- Each of the human energy input factors were converted to emergy using the transformities presented in Table 2.
- The natural emergy input components were then assessed:
    - The *renewable energy input* that is made up primarily of the evapotranspiration energy. This evapotranspiration energy was derived from the MARS-CGMS model which simulates the crop growth of all major arable crops in the EU taking account of the specific soil and day-to-day weather circumstances. Based on this simulation it is precisely assessed how much water is transpired by the plant and the soil during the full growth cycle. From this the total evapotranspiration energy can be derived;
    - The *non-renewable energy from the soil* which is the soil loss factor, using the specific soil loss and soil organic carbon content factors per crop and soil combination in the EU (details in Box 1).
- All these separate human and natural emergy components were incorporated into the CAPRI energy module (see also section 3.1 and Annex 2), and the total emergy ratio was calculated. Again the spatial resolution at which this calculation was made is the Homogeneous Spatial Mapping Units (HSMU) level (clusters of 1 square Km cells), like in Pérez-Soba et al. (2015).

Further details of the calculations are provided in the next sections of this chapter.

3.1 Calculation of the human input based energy balance with CAPRI

CAPRI (Common Agricultural Policy Regionalised Impact) is an agro-economical, partial equilibrium model with a focus on European regions (Britz and Witzke, 2012), featuring a global market model and a supply module, iteratively linked. The model simulates the trends of a set of agricultural, economic and environmental indicators for defined scenarios. The simulation occurs at regional level (NUTS2), results (including hectares and yields) are then downscaled to Homogeneous Spatial Mapping Units (HSMU), which are clusters of 1 km^2 cells with similar soil condition, land cover, slope. The modelling framework includes an energy balance model, which was designed for evaluating energy use and energy reduction policies in EU agriculture. In the CAPRI energy module several energy indicators are calculated incorporating the energy requirements for the input quantities of mineral fertilizer, direct energy sources, machinery, buildings, plant protection, seeds, production support systems (such as irrigation) and others. The CAPRI energy module data and methodology enables to calculate various indicators in relation to energy (Kempen and Kranzlein, 2008). An overview of the type of indicators and a description of how the energy balance is calculated, the main data sources and calculation steps used is given in Annex 2 of this report. The energy balance input factors described in Annex 2 are also used in this study, but are further converted into emergy components as will be explained in the next Section. In Annex 3 a further explanation is given of the spatial entity of an Homogenous Spatial Mapping Unit (HSMU). This is the spatial unit used to do all calculations of the human and the natural emergy ratios in this study.

In the former study (Pérez-Soba et al. 2015) the calculation approaches in the CAPRI module, which were applicable to the farm level, were converted to the level of the soil (see Annex 2 for explanation). In the present study the same conceptual boundaries are set. This means that among the available energy indicators at farm level, only those that affect the energy balance at soil level are selected, and aggregated to the energy input. This implies that energy input included is directly linked to crops and to the land management activities of establishment of a crop, management during cultivation (e.g. weeding, spreading plant protection products and fertilisers and irrigating) and harvesting. The processing of the harvest in further end-products for human consumption is excluded. The same applies to the production of meat or milk which is therefore excluded from the balance. So in livestock systems the energy input is assessed including the cutting of grass but excluding the further use of this grass even though this grass may in fact be fed to animals to produce the milk and meat. The latter however need further inputs not linked directly to the soil (e.g. external feed, labour, machinery).

An important difference with the CAPRI energy balance approach in the former study of Pérez-Soba et al. (2015) (see also Annex 3) is that in this study we focus the analysis on a sub-set of crops. This is because the natural energy input from the evapotranspiration processes could only be assessed in detail for the crops incorporated in the MARS-CGMS and LINGRA models used for the quantified assessment of the natural energy components (see Box 2). This therefore implies that the assessment focusses on the crops and crop groups presented in table 3.

The abiotic input such as solar energy water and nutrients from the soil were not considered in the former study (Pérez-Soba et al., 2015). However, in the present study the natural input of the renewable and non-renewable energy components have been taken into consideration and have been added to the CAPRI energy module. For the inclusion of the natural energy components it was necessary to change the methodological approach. This change involved a shift from an energy balance to an emergy ratio as already discussed in Chapter 2. The transformation from traditional energy units (Joules, used in the original CAPRI energy balance) to emergy units takes place by multiplication with the transformities, specific for each type of input, and reflecting the energy in solar equivalents needed to produce the type of energy value of the particular input (see **Table 1**).

In the next section, further details on the assessment of the natural emergy components are provided.

3.2 Quantification of the natural energy components

In the emergy approach discussed in Chapter 2, all energy components are translated into emergy components.

As already explained, the natural components consist of:

- The renewable energy (R) consisting of energy delivered to the crop by radiation, temperature, wind, vapour pressure and rain. All these factors come together in the evapotranspiration process of a crop.

- The non-renewable energy (N), which is represented by the contribution from the soil ecosystem, is an estimate of a fraction of total soil loss.

The first type of natural energy is very much dependent on the type of crop, soil and climate combination. To assess this complex indicator we used the MARS-CGMS models for arable crops (so-called WOFOST model) and for permanent grassland (LINGRA model).

The non-renewable energy, which requires and estimation of the fraction of total soil loss, is assessed using the soil organic carbon fraction of the dominant soil types in every HSMU in combination with the soil loss measure. For the calculation we followed the approach of Brandt-Williams (2001). In this approach the energy contribution to crop growing from the soil system is assessed via measurements of soil loss (erosion), and the organic carbon fraction in the net soil loss (see example of calculation method for different crops and grassland in **Box 1**).

Non-renewable energy = energy of soil used or lost = (net topsoil loss)* (% organic in the top soil loss) * energy content

To make this calculation the crop and specific organic soil content needs to be known together with the amount of top soil loss in a specific crop. This combination of soil loss and organic content was used to make specific calculations following the formula above. The energy content figure in organic soil will be set at **5.4 kcal/g** (=**4186 J/kcal**) (from Ulgiati et al., 1993).

How to calculate the final energy loss is explained in **Box 1**.

Box 1 Example of calculating the soil emergy contribution per crop and soil type combination

Bell Pepper Erosion rate estimated at **850 g/m2/yr** (Pimentel et al., 1995; Moore and Wilson, 1992; Griffin et al., 1988) with 0.04% organics in soil.

Potatoes Erosion rate estimated at **850 g/m2/yr** (estimated from Pimentel et al., 1995; Moore and Wilson, 1992; Griffin, 1988).

Oats Erosion rate estimated at **850 g/m2/yr** (estimated from Pimentel et al., 1995; Moore and Wilson, 1992; Griffin et al., 1988).

Feed Corn Erosion rate estimated at **4700 g/m2/yr** (estimated from Pimentel et al., 1995; Moore and Wilson, 1992; Griffin et al., 1988)

Sweet Corn Erosion rate estimated at **2700 g/m2/yr** (estimated from Pimentel et al., 1995; Moore and Wilson, 1992; Griffin et al., 1988).

Using these erosion rate data in the equation:

Net Top Soil Loss = erosion rate (g/m2/yr) * 0.04* 10000 (m2/ha) *5.4 kcal/g * 4186J/kcal produces:

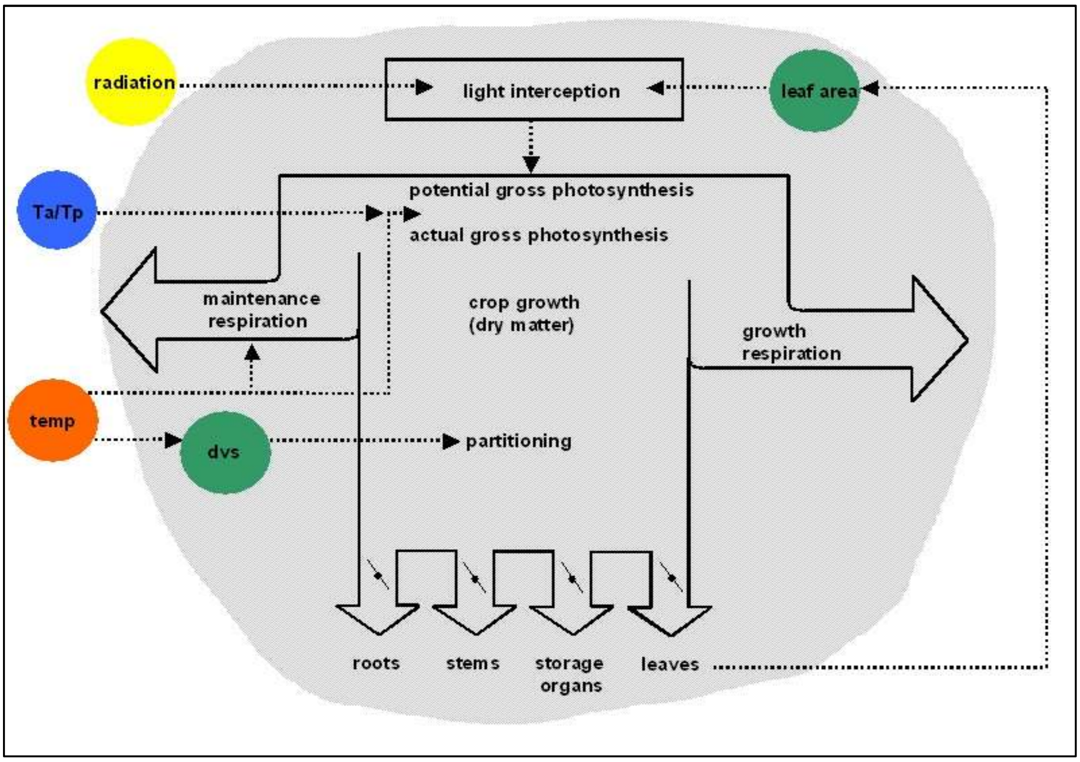
Bell Pepper	7.69 E9 J /ha/yr
Potatoes	7.69 E9 J/ha/yr
Oats	7.69 E9 J/ha/yr
Feed Corn	4.25 E10 J/ha/yr
Sweet Corn	2.44 E10 J/ha/yr
Grassland	2.67 E9 J/ha/yr (from Zhang et al, 2007; grassland Inner Mongolia)

MARS-CGM-WOFOST Models

To assess the evapotranspiration energy a crop uses (=Renewable natural energy) an assessment was done with the Crop Growth Monitoring System (CGMS) as parts of the MARS Crop Yield Forecasting System (MARS-CYFS, Van der Velde et al., 2019) of the Joint Research Centre of the European Commission which consists of a meteorological, soil and crop data base, an agro-meteorological model and remote sensing information on Europe (including Russia, Turkey and Maghreb) and third countries. The system provides indicators of crop yield for specific crops with a resolution of 25x25 km. The system runs on a daily basis to provide to the European Commission with near real time information on the status of arable crop development across Europe in terms of delays and biomass production in the current year and in comparison to the past (1975-2013). The crop biomass production is first simulated using biophysical environmental factors (weather, soil, crops) and agronomic knowledge, and in a second step an analysis is done to relate the simulation results to agricultural statistics. Estimates distinguish total biomass production and harvestable yield, water use in water limited and irrigation situations for 11 arable crops (winter wheat, grain maize, spring barley, rye, field beans, winter rapeseed, sunflower, permanent grassland, temporary grassland, sugar beet and potato). For further details on the MARS-CGMS, see Annex 2

To assess the evapotranspiration for this study, two situations are simulated: that of a water limited yield situation and that of an irrigated situation. In order to estimate the different energy flows from the environment used in the plant growth through evapotranspiration, the intermediate and final results of the WOFOST and LINGRA models in MARS-CGMS are used. The crop simulation is explained for WOFOST in the following focussing especially on the way environmental energy flows are involved in this plant growth processes. WOFOST simulates daily plant growth (see **Figure 11**) where it takes account of the solar energy that is received by the plant through radiation to convert this into biomass i.e. plant matter.

Figure 11 Diagram showing how the WOFOST model simulates plant growth



Source: JRC, 2019

Direct solar energy is received by the plant as its leaves intercept light. The amount of radiation a plant can intercept varies according to its growth stage. The radiation is a crucial input for the photosynthesis of a plant which leads to the production of organic matter (conversion of CO_2 to $C6H12O6$ using solar energy). The newly formed plant matter is distributed over different plant organs: roots, stems, leaves and storage organs (grains/tubers). Depending on the age of the plant the different organs receive different shares (DVS partitioning in **Figure 11**). In the situation that most energy is converted into leaves and storage organs that are harvested one can expect the use of solar energy to be most efficient.

The amount of radiation per day measured by the weather stations, or calculated from alternative measure indicators (such as temperature, sunshine duration and cloud coverage) is daily input into the model. The model distributes the radiation over the day and simulates how the intercepted light is converted into plant matter (potential gross photosynthesis). It should be realised that only half of the incoming radiation is Photosynthetically Active Radiation and thus available for the plant's photosynthesis.

The potential photosynthesis is converted into an actual gross photosynthesis by the model by taking account of two other factors namely the temperature (Temp) and the water availability (Ta/Tp). The daily temperature is input from the weather stations and the water availability is assessed in soil water sub-models.

The Ta/Tp means the assimilation rate is the product of the potential assimilation rate and the ratio of the actual (water-limited) transpiration rate and the potential transpiration rate. This ratio indicates to which extent the crop suffers from drought and it also indicates how efficiently or inefficiently the environmental energy is used to produce plant matter. The potential transpiration rate depends on the leaf area and the evaporative demand of the atmosphere. This evaporative demand is characterised by radiation level, vapour pressure deficit and wind speed.

WOFOST calculates the water availability, related evapotranspiration and yield levels in 3 situations:

- The first sub-model applies to the potential production situation and assumes a continuously moist soil, the crop water requirements are quantified as the sum of crop transpiration and evaporation from the shaded soil under the canopy. So this is basically a condition of irrigation in more arid circumstances or a normal situation in more temperate regions where no water deficit occurs and the soil is always sufficiently moist.
- The second is the water-limited production situation which applies to a freely draining soil, where groundwater is so deep that it cannot have influence on the soil moisture content in the rooting zone.
- The third soil water model is for water-limited production on soils having influence of shallow groundwater in the rooting zone.

In the two water limited situations there is not enough soil water available and the potential plant matter is reduced (actual gross photosynthesis). The reduction share depends on the level at which the crop suffers from a water deficit in every growth stage. When there is a water deficit the radiation energy is not optimally used and this can be assessed by the WOFOST model for every annual crop included in MARS-CGMS for every soil climate situation in Europe.

There are two other processes in the plant growth that consume energy which can be regarded as energy loss, which is however unavoidable. The first is the maintenance respiration (see **Figure 11**). The plant needs to invest energy to perform its basic functions such as resynthesizing degraded proteins and maintaining ionic gradients across cell membranes. It is the energy needed to keep the current plant alive before it can put energy in producing new plant organs. The maintenance respiration is development stage and temperature dependent. It is also crop and organ specific.

The second is the loss in the growth respiration process. Growing, which is the conversion of primary assimilates into plant organs, requires energy in the various biochemical pathways. This energy is provided by the partial combustion of glucose. In the conversion process, CO_2 and H_2O are released that represent the weight loss during growth respiration. The conversion efficiency is crop and organ specific.

Early in the season, most of the plant matter is invested into roots, stems and leaves. With more leaves also more light can be intercepted and plant growth increases rapidly. Towards the end of the season all or most of the plant matter is converted into storage organs and leaves start to decay therefore reducing light interception and thus reducing plant growth. Grains are ripening. This illustrates that the use of available solar energy by a plant is different in different growth stages of the plant. In the beginning of the growth stage most energy goes into production of plant material that is not harvested, so this energy is not gained after harvest.

Indicators delivered by CGMS for the emergy assessment

With the CGMS WOFOST and LINGRA models, the following indicators are calculated per crop per location (in every HSMU-SMU combination) in two situations (optimal situation with a continuous moist soil and water limited with freely draining soil):

- Respiration (by plant)
- Soil evaporation
- Respiration+ soil evaporation = evapotranspiration (ETA)
- Yield level

The total evapotranspiration is converted into energy by using the (latent) heat of vaporization (2,265 J/gram, which is the energy needed to vaporize one gram of boiling water), plus the energy needed for warming up the water from 17.5 °C to 100 °C. This leads to a value of 2,460 Joule/gram (or 2.46 MJ/kg). Since heat of vaporization is slightly dependant on starting temperature, and will therefore differ over Europe, average temperature variations during the growing season over Europe were also checked which resulted in a heat of vaporization between 2.44 and 2.48 MJ/kg (+/- 0.7%). The function is $\lambda = 2.501 - (0.2361 * T)$. Because this local variation is considered minimal, it was decided to use 2.46 MJ/kg as an acceptable average figure for the EU wide situation.

For the conversion into an emergy ratio a transformity ratio was used of 60 (6.0E+01), as already explained in Chapter 2. However, a distinction was made between the evapotranspiration energy delivered in a water limited situation by the natural environment and water additionally added to the natural system through irrigation. In the water limited situation all evapotranspiration energy can be allocated to the natural system. In an irrigated system the evapotranspiration energy of the plant and soil is allocated to the renewable natural emergy component, but the extra energy needed to pump the irrigation water to the plant and the labour involved is allocated to the human energy input component.

3.3 Calculation of emergy balance and main indicators

For the soil emergy balance calculations produced in this study we focused on three main indicators to analyse the provisioning service:

- Emergy yield ratio (EYR) is the ratio of the output of a system (Y) to the external anthropic inputs (feedback) from outside (F): EYR = Y/F;
- The emergy investment ratio (EIR) is the ratio of external inputs (purchased, feedback) to natural input (renewable and non-renewable energy): EIR = F/(R + N);

- The transformity of the different energy input flow as compared to the output (expressed in joule or grams).

The indicators are calculated per crop type and per crop group type as defined in **Table 3**

Table 3 Overview CAPRI of crops included in this study

Crops	Aggregate 1	Aggregate 2	Aggregate 3	Aggregate 4	Aggregate 5
Soft wheat	All Crops	Food	Wheat	Cereals	Other cereals
Durum wheat	All Crops	Food		Cereals	Other cereals
Barley	All Crops	Food	Barley	Cereals	Other cereals
Oats	All Crops	Food		Cereals	Other cereals
Grain maize	All Crops	Food	Grain maize		Other cereals
Rape seed	All Crops	Food		Oil seeds	
Sunflower	All Crops	Food		Oil seeds	
Pulses	All Crops	Food		Other arable crops	
Potatoes	All Crops	Food	Potatoes	Other arable crops	
Sugar beet	All Crops	Food	Sugar beet	Other arable crops	
Fodder maize	All Crops	Fodder	Fodder maize	Fodder crops	
Other forage crops	All Crops	Fodder		Fodder crops	
extensive grassland	All Crops	Fodder	Grass		
intensive grassland	All Crops	Fodder	Grass		

Source: this study

The first step is to convert the soil energy balance from CAPRI into a soil emergy balance. In order to do this all inputs were converted to emergy using the transformities. The crops included in this assessment, which are fewer compared to Pérez-Soba et al. (2015) are given in **Table 3**.

The emergy balance and the three indicators are calculated per crop, and also aggregated to an ‘All crops’ group to produce final results of the analysis. The final emergy ratios are calculated per crop and for the different aggregations presented in **Table 3** at HSMU and NUTS 2 level. The calculation of the emergy ratios is made at the scale of regions (CAPRI regions) and at a more detailed scale of HSMU.

4 Results

The results of the soil energy balance calculations based on the approach described in Chapter 3 are presented in this chapter using the most recent data available in CAPRI at HSMU level. This refers to the years 2007-2009 contained in the COCO (coherent and consistent figures at national level) and Capreg (NUTS2 figures) database belonging to the CAPRI system.

We present an overview of the emergy calculations for cereals (including some crop types), grasslands and all the crops, using four different emergy indicators:

- Emergy yield ratio EYR = total emergy yield (Y)/human input (F);
- Emergy investment ratio: EIR= Human inputs (F)/natural inputs (R + N) for all crops;
- Transformity of all crops for human input as related to the harvested output in joule (SEJ/Joutput);
- Transformity of all crops for natural input as related to the harvested output in joule (SEJ/Joutput).

The same overview is presented at country level in Annex 4.

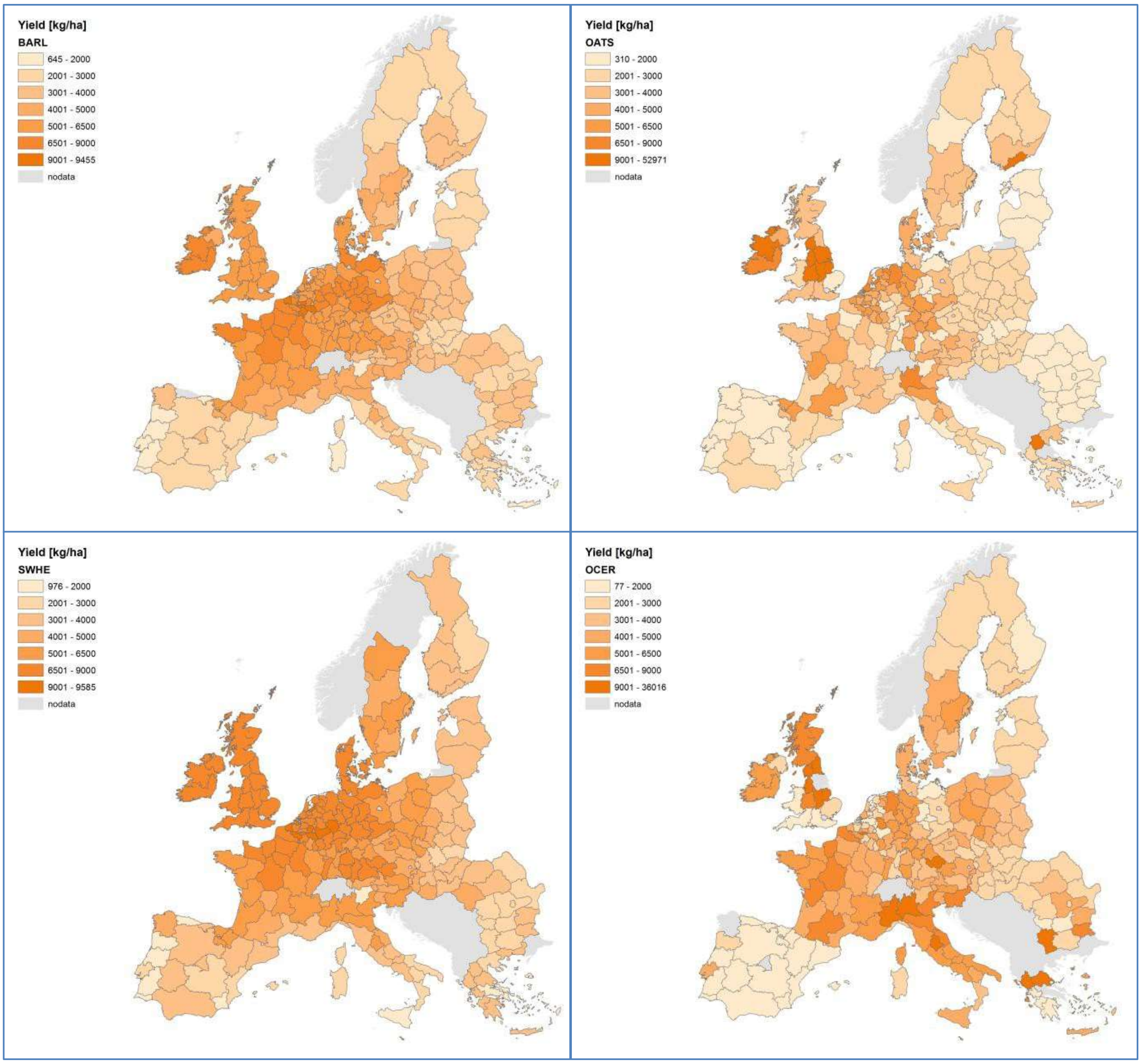
The quantitative analysis provides evidence to understand the differences in input mixes per crop types, as well as how the energy inputs vary among EU regions, environmental zones and within regions.

4.1 Cereals

Different types of cereals are grown in the EU at large scale. The cereal group presented here includes wheat (both soft and durum wheat), rye, oats, barley and less common cereals types such as triticale. Grain maize is not included in this aggregated category. **Figure 12** shows that the yields of different types of cereals are very different in the EU. Yields for barley and soft wheat are highest in north-western Europe and generally decline towards the south and east. For oats this patterns is less strong although the high production areas are mostly found in France, Germany, UK, and Northern Italy. Durum wheat is more limited in geographic extent and are mostly found in Northern Italy and to some more limited extent also in Germany and France.

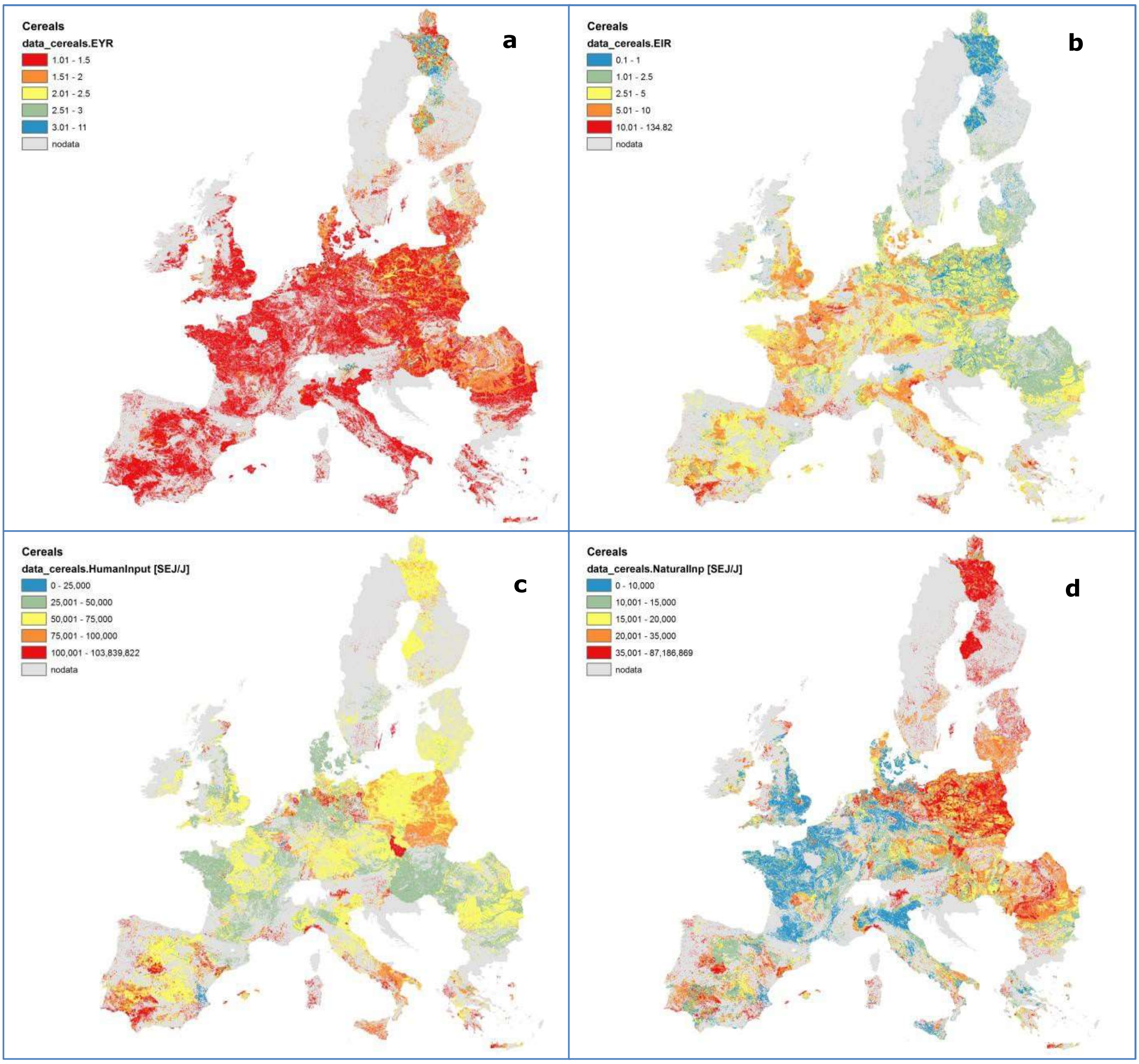
Figure 13 shows the different emergy indicators for cereals. The EYR indicator expresses the total yield of a crop in emergy divided by the human emergy input. Generally, the EYR of cereals is much lower than that of grass which implies a higher human input. However, other arable crops such as grain maize, potatoes, sugar beet have even lower EYR. The oil crops are almost at this same level.

Figure 12 Yield levels (kg/ha) for Barley (BARL), Oats (OATS), wheat (SWHE) and other cereals (OCER) in the EU



Source: this study

Figure 13 Cereals a: Emergy yield ratios (EYR); b: Emergy Investment ratio (EIR); c: Transformity ratio for human input; d: Transformity ratio of natural inputs



Source: this study

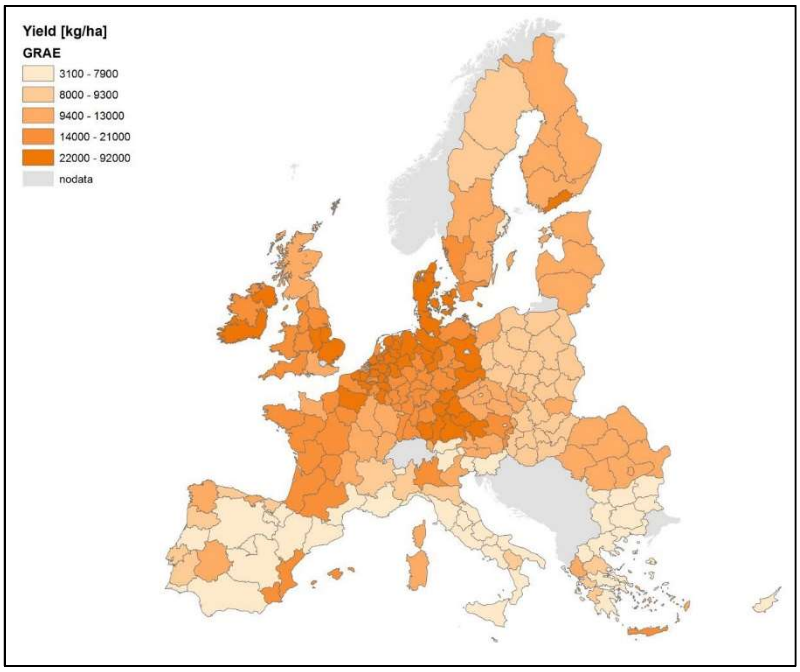
The EYR increases towards the east, particularly in Poland, Romania, Bulgaria, but also in Denmark which implies a relatively lower human input. The main explanation for this is the relatively lower input of artificial fertilisers in these regions as this is the most dominant type of emergy input in the human input class. In Central and Eastern European Countries this happens because the overall nitrogen input level per crop is relatively lower than in the rest of the EU (in reference to the investigated period). In Denmark this is particularly caused by the relatively high level of manure input in the total fertilisation mix. Manure use has a much lower emergy ratio then artificial fertiliser input. Because of this the Emergy Investment level, which expresses the ratio between human and natural emergy input, is also lower mostly towards the east and also in Denmark. However, in France, the UK, Spain the spatial variation in this factor is quite large. A low emergy investment ratio, i.e. with a relatively high share in natural emergy input, does not necessarily go together with a low transformity for human input. In Poland for example this factor is in the average level while it is relatively low in Denmark, large parts of France, Germany and many CEEC countries. Generally, high human transformity goes together with low natural transformity, but this is not necessarily the case as is shown in for example the south of Spain, Italy, Northern Germany, The Netherlands and northeast of the UK. The largest spatial extremes are shown in the transformity of the natural inputs which are considerably higher in the East and also south while they are often very low in the north-western and central parts of the EU.

4.2 Grasslands

Figure 14 shows that the yields of grassland are very different in the EU. Yields for grassland are highest in north Western Europe and generally decline most strongly towards the south and also but less strongly towards the east. This is strongly related to the climate factor, where areas with higher precipitation levels have higher grassland yields. **Figure 15** shows the different emergy indicators for grasslands. Generally, the EYR of grassland is much higher than that of most crops which implies a lower human emergy input then for all other food and fodder crops. The human emergy input is significantly lower because in permanent grassland less emergy for ploughing and tilling is needed, while for annual crops this is the second largest emergy input component. For grass, the EU weighted average EYR is 1.9 while itis 1.3 for cereals, 1.3 for all food crops and 1.4 for fodder maize (See Annex 4). The diversity for this indicator in Europe is however rather large, in comparison to other crops, with scores of 1.3 in countries like Belgium, Denmark and The Netherlands at the one extreme and a score of more than 2.5 in Bulgaria, Hungary and Latvia.

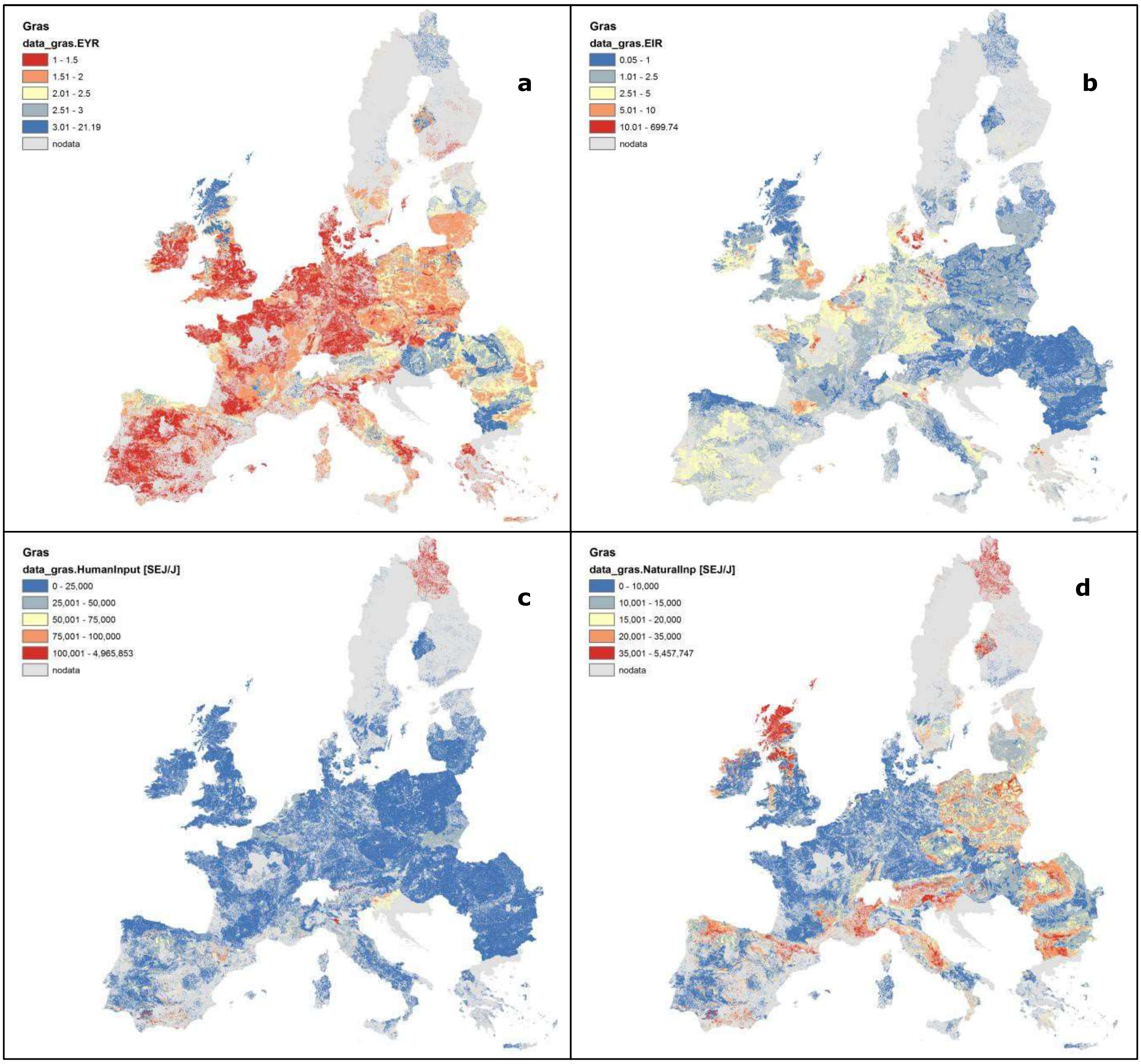
When looking at the Emergy Investment Ratio (EIR) one can see that the human share is dominating (if EIR>1) in most countries, particularly in Belgium, Denmark, The Netherlands, Greece and Portugal. Countries where the natural input is significantly more important than the human input emergy are Austria, Bulgaria, Estonia, Hungary, Latvia, Romania and the UK. Quite surprisingly the average human emergy input in grasslands in the Mediterranean (e.g. France, Spain, Portugal, Italy and Greece) tends to be clearly above the EU weighted average, although scores on these also indicate more extremes within these countries.

Figure 14 Yield level of grassland (kg/ha) in the EU



Source: this study

Figure 15 Grasslands a: Emergy yield ratios (EYR); b: Emergy Investment ratio (EIR); c: Transformity ratio for human input; d: Transformity ratio for natural input



Source: this study

Clearly, the renewable natural emergy is high for these countries as compared to other regions, which is of course related with the higher temperatures leading to higher evapotranspiration at least when water is available at all, but also high non-renewable emergy levels. But especially in several regions in Spain, northern-Italy and Slovenia this goes together with high human emergy levels. In combination with relatively low grassland yield levels this creates the highest transformity levels (seJ/J harvested output) in these three countries.

When looking at the transformities for the natural input categories one can see (from **Figure 15**) and also the country summary tables in Annex 4) that the non-renewable emergy input is very high in countries like Estonia, Finland, Latvia, Poland, Slovenia and UK where much grassland are located on sloping soils with high carbon contents. In countries like Spain, Italy, Slovenia the renewable emergy input per joule harvested output is particularly high

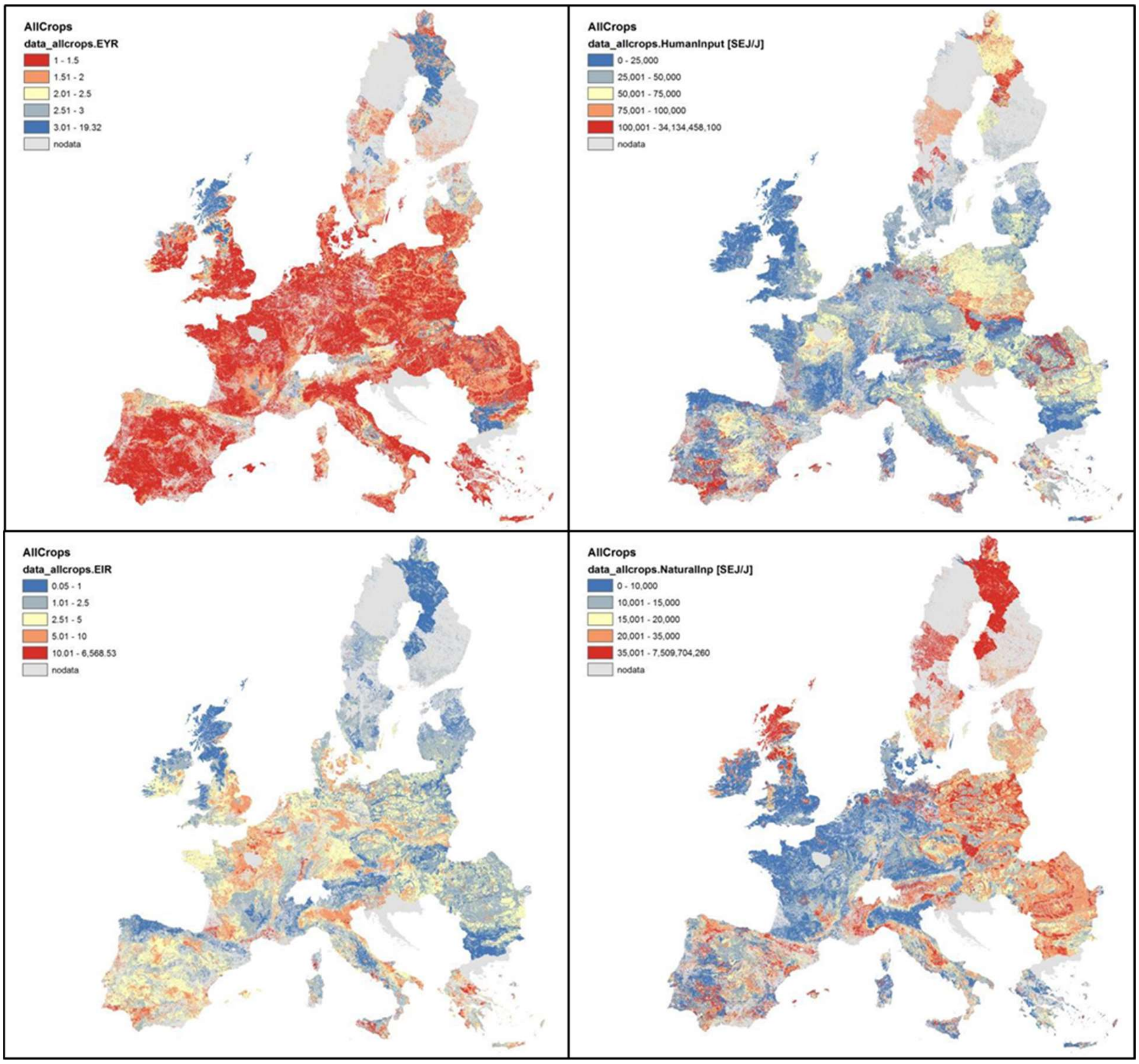
4.3 All studied crops

The spatial pattern of emergy for all crops included in this study is of course very much determined by the relative dominance of certain crops and grassland in the total cropping pattern, but also by the dominating farming practices in every region.

Figure 16 shows the different emergy indicators for all crops. The majority of the regions have a low Emergy Yield Rate for human input, so a high human emergy contribution to the total emergy yield and coincide more often with the regions where arable farming is dominating. The regions with higher human EYR levels, so with relatively lower levels of human input in the total emergy yield are mostly coinciding with regions where grassland is the dominant land use. Examples of such regions are Wales, Scotland and North-western Ireland, Northern Finland, North-western Spain, South-western Romania, Hungary, Massif Central and Alpine regions in France and mountain ranges of Italy. In these regions the EIR indicator is also in the lowest range (EIR<1) which implies a relatively high contribution of natural emergy which is higher than the human emergy input. While the intensive cropping regions have a far more dominating human input. These regions are most often dominated by cereals but also other traditional arable crops such as fodder maize, potatoes and sugar beet in the northwest and central parts of the EU and grain maize towards the south.

Regions where the transformity of the human input is among the highest are spread all over the EU but certainly dominate in Spain, Northern Finland, central Sweden, central and Southern France, Northern but also southern regions in Italy, Poland, Slovakia, Slovenia and Northern Germany. This high level of transformity for human input both occurs in regions dominated by crops and by grassland and is either caused by high emergy input level, or low yield levels or both. Towards the east and south the lower yield levels certainly play an important role, while in the northwest the yield levels are relatively high but go together with very high emergy input levels particularly artificial fertilisers.

Figure 16 Emergy yield ratios (EYR), Emergy Investment ratio (EIR) and Transformity ratio for human and Natural input for all crops



Source: this study.

5 Conclusions

The overall objective of this study was to complete, in terms of assessment and mapping, the analytical framework under which agricultural production should be addressed in the context of ecosystem services. In the previous JRC Report by Pérez-Soba et al. (2015), the human energy components were identified, quantified and mapped. In this study the focus is on the natural input components that have been further identified and quantified.

Based on the assessments of the indicators at the resolution of NUTS2 areas and at a higher spatial resolution of Homogeneous Spatial Mapping Units the following main conclusions on the methodology and the results can be drawn:

- The emergy approach proves suitable to assess the sustainability of agricultural systems as it allows to distinguish and compare the contributions of natural versus anthropic resources, as well as renewable versus non-renewable resources in agriculture. Overall, the higher the dependence upon anthropic and non-renewable resources, the less sustainable the systems is. In addition, calculating emergy flows from the different inputs into the cropping systems allows to identify and quantify the main pressures on agroecosystems. This provides complementary information with respect to other biophysical approaches.
- By applying the emergy concept we are able to assess the intensity of farming management practices. Emergy helps, therefore, to analyse the provisioning ecosystem services derived from agriculture considering the intensity of their production system. At the same time, it offers a new approach to identify ways to achieve a maximum crop yield considering the balance between natural and human resources, and therefore support resource efficiency in agricultural production.
- The energy used to produce biomass in agricultural systems originates mainly from human inputs, as indicated by an overall larger human emergy component compared to the lower natural emergy component. This applies more often to arable crops than to grasslands.
- The main source of human emergy input is artificial fertiliser followed by the emergy required for ploughing and tilling.
- As a consequence of 2) and 3) overall, extensively managed grasslands use lower human emergy inputs than arable crops since the level of artificial fertilisers is low and there is no ploughing involved. However, in intensively managed grasslands the human emergy input can be as high as for arable crops.
- The emergy approach allows to distinguish the energy inputs in substitution processes. For example, it accounts the lower emergy of organic (manure) compared to inorganic fertilization. Therefore a fertilization with a high share of manure accounts less 'human energy' than one with a high share of mineral fertilizer.
- For most crops the optimal transformity is more likely to be reached with some irrigation (given that local water resources are available).
- Crops with high economic benefits, such as potatoes and sugar beet, are usually associated with a high emergy investment ratio (EIR).

The outcomes of this study should be considered as a first methodological approximation based on the available data and models.

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List of abbreviations and definitions

CAP: Common Agricultural Policy

CAPRI: Common Agricultural Policy Regionalised Impact model

CEEC: Central and Eastern European Countries

CGMS: Crop Growth Monitoring System

CICES: Common International Classification of Ecosystem Services

CYFS: Crop Yield Forecasting System

EIR: Emergy Yield Ratio

ELR: Environmental Load Ratio

EROI: Energy Return on Investment

ESI: Emergy Sustainability Index

ETA: Evapotranspiration

EU: European Union

EYR: Emergy Yield Ratio

GJ: Gigajoule

GMO: Genetically Modified Organisms

HSMU: Homogeneous Spatial Mapping Units

J: Joule

JRC: Joint Research Centre

K: Potassium

LINGRA: LINTUL-Grasslands, Light Interception and utilization simulator for grasslands)

MARS: Monitoring Agricultural Resources (former JRC Unit, now D.5 – Food Security Unit)

MJ: Megajoule

NEB: Net Energy Balance

N: Nitrogen,

P: Phosphate

seJ: solar equivalent Joule

SGDBE: Soil Geographical Database of Europe

SMU: Soil Mapping Units

STU: Soil Typological Units

SUCROS: Simple Universal Crop Growth Simulator

USA: United States of America

WOFOST: World Food Studies crop simulation model

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Annexes

Annex 1. Origin of Transformity values in publications

		average /curent estimate	Ghaley et al 2013		Coppola et al 2009		La Rosa et al 2008		Zhang et al 2007		Martin et al 2006		Brandt-Williams 2001		Ulgiati et al 1994	
		TRANSFORMITY	TRANSFORMITY		TRANSFORMITY		TRANSFORMITY		TRANSFORMITY		TRANSFORMITY		TRANSFORMITY		TRANSFORMITY	
		SEJ/J, or SEJ/g	SEJ/J, or SEJ/g		SEJ/J, or SEJ/g		SEJ/J, or SEJ/g		SEJ/J, or SEJ/g		SEJ/J, or SEJ/g		SEJ/J, or SEJ/g		SEJ/J, or SEJ/g	
			WHEAT		WHEAT		Oranges		Crops		CORN		CORN		SUGAR BEET	
	unit		DENMARK		DENMARK		Sicicly		China(north)		KANSAS		FLORIDA		ITALY	
Renewable Resources																
sunlight	J	**1.00 E00**	1.00 E00	3,4	1.00 E00	5	1.00 E00	6	1.00 E00	4	1.00 E00		1.00 E00	3,4	1.00 E00	2
wind , kinetic energy	J	**2.50 E03**	2.45 E03	3,4	2.52 E03	5	1.5 E03	6	2.45 E03	4	1.50 E03	3				
evaporation	J	**3.00 E05**							3.06 E04	4			*1.54 E04*	3		
(corrected by 1.68)													2.85 E05			
Rainfall (chem)	J	**3.05 E04**	3.02 E04	3,4			1.82 E04	3			1.82 E04	3			1.82 E04	2
Non Renewable Resources																
Soil erosion/loss	J	**1.24 E05**	1.24 E05	7	1.24 E05	5	1.24 E05	3,4	1.92 E05	12	6.25 E04	2	*7.38 E04*	4	*6.25 E04*	2
(corrected by 1.68)													1.24 E05		1.05 E05	
Purchased inputs																
N Fertilisers	g	**2.4 E10**	4.05 E10	7	2.42 E10	7	4.0 E10	4	2.41 E10	7	2.41 E10	7	2.41 E10	4	4.62 E09	2
K fertilisers	g	**1.8 E09**	1.85 E09	7	1.47 E09	7	3.01 E9	4	1.74 E09	7			1.74 E09	3,4	2.96 E09	2
P fertilisers	g	**2.2 E10**	3.70 E10	7	2.02 E10	7	3.69 E10	4	2.20 E10	7	2.20 E10	7	2.20 E10	4	1.78 E10	2
Manure	g	**2.13 E08**	2.13 E08	10	2.13 E08	10										
irrigation water	g	**7.61 E05**					5.12 E5	9			13.3 E05	9				
Pesticide	g	**1.48 E10**			1.85 E09	4	1.48 E10	7	1.48 E10	7			1.48 E10	1		
Pesticide	J	**1.11 E05**													*6.60 E04*	2
(corrected by 1.68)															1.11 E05	
Herbicide	*g*	***1.48 E10***	*2.52 E10*	*7*							*1.48 E10*	*7*				
Insecticide	*g*	***1.48 E10***									*1.48 E10*	*7*	*1.48 E10*	*1*		
Fungicide	*g*	***1.48 E10***	*2.52 E10*	*7*									*1.48 E10*	*1*		
Seeds	g	**1.67 E09**	1.20 E08	13	1.20 E09	orig					3.64 E05	8				
Seeds	J														*6.60 E04*	2
(corrected by 1.68)															1.11 E05	
Diesel oil/fuel	J	**1.11 E05**	1.11 E05	7	1.10 E05	4			1.6 E05	4	*6.60 E04*	3	*6.60 E04*	3,4	*6.60 E04*	2
Gasoline	J	**1.11 E05**					1.1 E05	3,4							*6.60 E04*	2
Lubricants	J	**1.11 E05**			1.10 E05	4									*6.60 E04*	2
Steel Machinery	g	**1.12 E10**	1.12 E10	7	1.13 E10	5									*6.60 E04*	2
steel & iron	g	**5.31 E09**														
Human Labour	J	**3.8 E05 - 1.2 E07**			1.24 E07	5	7.38 E6	2	3.80 E05	11			4.50 E06	2	7.38 E06	2
Electricity	J	**2.00 E05**			2.00 E05	2	1.43 E05	14	2.69 E05	4	2.00 E05	2	1.60 E05	3,4	2.00 E05	2

1	Brown & Arding, 1991	8	Trujillo, 1998
2	Ulgiati 1994	9	Buenfil 2000
3	Odum 1996 Env Accounting	10	Bastianoni et al 2001
4	Odum, Brown & Brandt Williams 2000 Folio#1	11	Lan et al, 2002
5	Odum 2000 Folio#2	13	Coppola et al. 2009
6	Brown , Bardi (2001) Folio#3	14	Bastianoni et al ? Italian Electicity prod.
7	Brandt-Williams 2002 Folio #4	15	Tiezzi, Italian calculation

Annex 2. Detailed description of the MARS-CGMS model simulation and data

CGMS-Europe contains a meteorological data base with historic daily meteorological data from weather stations. For the EU15 and neighbouring countries data from approximately 380 stations with data since 1976 are available, in some cases back to 1930. Since about 1990 the data set was extended with stations from Eastern Europe, western Russia, Maghreb and Turkey, while the station density increased over the entire area. Presently, data from about 7000 stations is available. Of these stations about 3000 receive daily meteorological information. The historic data were converted into consistent units and scanned for inconsistencies and non-realistic values. Variables covered are global radiation, air temperature, dew-point temperature (humidity), pressure at sea level, wind speed, amounts of precipitation, clouds, and sunshine duration.

Although crop simulations can be applied at station level, weather data are first interpolated to a 25 by 25 km grid to have a uniform and full spatial coverage of weather data over Europe. The spatial variability of the crop parameters is also available at this resolution. The weather variables needed as input are: precipitation, minimum and maximum temperature, global radiation, wind speed and vapour pressure. The data interpolation is based on the averaging of values from weather stations surrounding a given grid cell, with a preference for similar stations. Similarity is expressed as a score based on distance between grid centre and station, difference in altitude and, distance to the coast, position relative to a climatic barrier and the distribution of the used stations around the grid cell.

The interpolation is executed in two steps: first, from the list of suitable stations a set of stations is selected that is most suitable for the interpolation. Second, a simple average is calculated for most of the meteorological parameters, with a correction for the altitude difference between the station and grid cell centre in case of temperature and vapour pressure. As an exception rainfall data are taken directly from the most similar station. This empirical interpolation method is robust and accurate.

CGMS is based on a number of crop physiological responses to weather and soil conditions which is the case for a family of crop growth models, of which SUCROS, WOFOST, LINGRA and ORYZA are the best known members. These models are used to explain or predict the potential and attainable yields of crops under the environmental and management conditions, and to compare these yields against actual yields in a field, farm, or a region, to quantify the yield gap and to identify the constraints limiting crop production. The WOFOST model (see Keulen van and Wolf, 1986; Diepen van et al., 1989; Supit et al., 1994; Vossen and Rijks, 1995) is the weather driven crop engine of CGMS. The WOFOST model covers all main annual crops in Europe and LINGRA simulates the growth and yields of grasslands. Like WOFOST, LINGRA also calculates light interception and converts it into plant matter which in turn is converted into leaves and roots.

In WOFOST first, instantaneous photosynthesis (calculated at three depths in the canopy for three moments of the day) is integrated over the depth of the canopy and over the light period to arrive at daily total canopy photosynthesis. After subtracting maintenance respiration, assimilates are partitioned over roots, stems, leaves and grains as a function of the development stage, which is calculated by integrating the daily development rate, described as a function of temperature and photoperiod. Assimilates are then converted into structural plant material taking into account growth respiration. Leaf area growth is driven by temperature and limited by assimilate availability.

Above ground dry matter accumulation and its distribution over leaves, stems and grains on a hectare basis are simulated from sowing to maturity on the basis of physiological processes as determined by the crop's response to daily weather: (rainfall, solar radiation, photoperiod, minimum and maximum temperature and air humidity), soil moisture status (i.e. Ta/Tp, alike the FAO models) and management practices (i.e. sowing density, planting date, etc.). Water supply to the roots, infiltration, runoff, percolation, capillary rise and redistribution of water in a one-dimensional profile are derived from hydraulic characteristics and moisture storage capacity of the soil.

Detailed physiological information is also included, such as heat sums to reach various phonological stages, energy conversion, portioning of assimilates over various plant organs. For specific crop varieties grown in certain regions some crop parameters are modified. Since new crop varieties are constantly introduced, crop parameters that describe crop growth and development, such as for example the temperature sums to reach the flowering stage, are regularly updated and calibrated as new information comes available.

The need for soil data is twofold. Rooting depth and water retention characteristics determine the maximum available water that can be stored by the soil. Important system aspects like initial available water at the start of the growing season and the soil capacity to buffer infiltrated rainfall are influenced by these soil properties. Further, soil data are used to define whether a crop has to be included in the simulation for a given soil type. For instance shallow soil types are excluded as these soils are not be cropped in reality. The current CGMS is based on the Soil Geographical Database of Europe (SGDBE) version 4 covering pan Europe. The resolution available for geographical representation is 1:1,000,000 for most countries. The SGDBE contains list of Soil Typological Units (STU), characterizing distinct soil types that have been identified and described. The STU are described by attributes specifying the nature and properties of the soils, for example texture, the moisture regime, the stoniness etc. Because it is not technically feasible to delineate each STU on the map, the STUs are grouped into Soil Mapping Units (SMU) to form soil associations. Soil attributes like rooting depth and water retention required in the crop water model of CGMS have been derived from basic properties like soil name and texture applying so called pedotransfer rules.

This SMU's are intersected with the (25km) grid for which weather data and crop parameters are available. The crop models are run for each unique combination of grid cell and STU within a SMU. Since the HSMU is an intersection of SMU (in addition to other spatial layers) the CGMS results calculated at STU-GRID level and aggregated to SMU-GRID level can easily be allocated to the HSMU level in terms of area shares.

Annex 3 Calculation of the anthropic input energy balance with CAPRI

The CAPRI energy module data and methodology enables to calculate various indicators in relation to energy (Kempen and Kranzlein, 2008). An overview of the type of indicators and units is given in **Table A 1**.

Table A 1 Overview of parameters produced in the CAPRI energy module and the related units.

Parameter	Parameter Unit	Description
Energy per CAPRI activity unit	MJ/ha; MJ/head	Covers all energy requirements necessary for one CAPRI activity unit per year
Energy per CAPRI output unit	MJ/kg	All energy requirements for one CAPRI activity unit are divided by the output level; allocation between main product and by-products is carried out for a number of activities
Energy efficiency – Type "energy"	MJ/MJ	The output level of a CAPRI activity is assessed by its energy content, whereas allocation between main product and side-products is done for some activities. The result is divided by all energy requirements of the CAPRI activity unit. In short: Energy output (per kg) divided by energy input (per kg)
Energy balance	MJ	The output level of all CAPRI activities of a region are assessed by its energy contents (See Chapter 7.3.3) whereas allocation between main product and side-products is done for some activities and then sum up over the region. The input energy requirements for all CAPRI activities are multiplied with the relevant activity levels and then sum up over the region. The result shows energy requirements (INPUT) and energy output (OUTPUT). Imports and exports of energy can be shown separately.
Energy requirements-overview	MJ/ha; MJ/head	On an activity-based, regional level, the composition of total energy requirements can be shown on an aggregated level.
Energy requirements-detail	MJ/ha; MJ/head	On an activity-based, regional level, the composition of total energy requirements can be shown on in detail.
Energy input units	Input unit/ha; Input unit/head	On an activity-based, regional level, the composition of input units driving the energy needs can be shown in detail.
Energy content products	MJ/kg product	On an activity-based level, the energy content for products can be shown; energy assessment of output is based on this parameter; Energy content is assumed being equal throughout all NUTS-II regions.

Source: CAPRI model systems, Pérez-Soba et al., 2015

For the assessment of the energy balance in Pérez-Soba et al. (2015) it was first necessary to convert the calculation approaches in the CAPRI module which were applicable to the farm level to the level of the soil. This meant that among the available energy indicators at farm level, only those that affect the energy balance at soil level were selected, and aggregated to the energy input and output at soil level. This implies that energy input and output included in the balance has to be directly linked to crops and to the land management activities of establishment of a crop, management during cultivation (e.g. weeding, spreading plant protection products and fertilisers and irrigating) and harvesting.

For the soil energy balance calculations the focus was on two main indicators:

Energy Return on Investment (EROI) MJout/MJin per ha.

Net Energy Balance (NEB) per ha=MJout-MJin per ha

The calculation of the energy balance are done at regional (NUTS 2) level (Capri regions) and to take account of the diversity in agro-environmental diversity also at the level of Homogenous Spatial mapping units (HSMUs)

The following factors are considered in the energy balance calculation:

- On the input side we consider energy input in relation to machinery, seeds, fertilisers (including nitrogen from manure), irrigation and labour.
- On the output side biomass production and related energy output is taken into account in produced food, feed and other biomass potentially used for fibre, fuel and other products. To determine the total biomass output, the starting point is the biomass which can be removed sustainably.

The crops included in the total energy balance calculation with CAPRI and presented in Pérez-Soba et al. (2015) are given in **Table A 2**. The energy balance is calculated per crop, but then aggregated to different clusters of crops to produce final results of the analysis.

Table A 2 Overview of crops included in CAPRI energy balance calculation

Crop acronyms	Crops	In/excluded
SWHE	Soft wheat	in
DWHE	Durum wheat	in
RYEM	rye	in
BARL	barley	in
OATS	oats	in
MAIZ	Sugar maize	in
OCER	other cereals	in
RAPE	oil seed rape	in
SUNF	sunflower	in
SOYA	soya	in
OOIL	other oil crops	in
OIND	other industrial crops	ex
NURS	nursery crops	ex
FLOW	flowers	ex
OCRO	Other crops	ex
MAIF	fodder maize	in
ROOF	fodder root crops	in
OFAR	fodder other on arable land	in
GRAE	extensive grassland	in
GRAI	intensive grassland	in
PARI	paddy rice	in
OLIV	olives	in
PULS	pulses	in
POTA	potatoes	in
SUGB	Sugar beet	in
TEXT	flax and hemp	in
TOBA	tobacco	in

TOMA	tomatoes	in
OVEG	other vegetables	in
APPL	apples	in
OFRU	other fruits	in
CITR	citrus	in
TAGR	table grapes	in
TABO	table olives	in
TWIN	wine	in
FALL	fallow	in
ISET	Set aside obligatory - idling	in
GSET	Set aside obligatory used as	in
TSET	Set aside obligatory - fast	in
VSET	Set aside voluntary	in

Source: Pérez-Soba et al., 2015

On the input side there are two dimensions of energy inputs:

- Input per resource (e.g. fertiliser, machinery, fuel)
- Input per activity/process (e.g. cultivation, irrigation)

The difference between these dimensions can be illustrated with the following example. Ploughing a field requires 4,000 MJ for fuel and 3,000 MJ for energy used to produce the machinery (tractor and trailed machinery). The latter is allocated to the crop according to the hours of machinery use in the crop and the depreciation of it. Irrigating the plot requires 2,000 MJ for fuel and 1,000 MJ for energy used to produce the pump in the factory which is again allocated to the crop according to the hours of irrigation and the depreciation of the pump. In total the energy input is 10,000 MJ, which can be allocated to the crop and aggregated in two ways:

- in 6,000 MJ fuel and 4,000 MJ machinery (resource dimension) , or
- 7,000MJ for cultivation and 3,000 MJ for irrigation (activity dimension).

An overview of all energy input indicators per crop per resource and per activity is given in **Table A 3**. The energy input per resource refers to all the energy that is used to produce the resource that is further used in the establishment, cultivation and harvesting of a crop.

Plant protection products, seeds and mineral fertilisers all need energy when produced. The input of this energy can directly be linked to the crop as it is known how much of these inputs are used per crop. So these can also be linked easily to the land on which these crops are grown and therefore expressed in an input per hectare.

For the energy input used in the production of machinery this is more complicated as the machinery is not only used for a single crop, furthermore some crops need more, while others less of machinery input. For this CAPRI uses the (average) operation time of machinery per crop as a distribution factor which are based on data derived from national machinery inventories. In case of data gaps, values of countries are used which have most similar farming characteristics.

Table A 3 Input indicators included in the soil energy balance

Indicator	Unit	Description
Plant protection products	MJ/ha	Energy that is needed to produce the plant protection products that are needed per hectare per crop
Electricity	MJ/ha	Energy input as electricity
Diesel	MJ/ha	Energy input as diesel fuel (energy content of diesel + energy used in processing)
Other fuels	MJ/ha	Energy input as other fuel (energy content + energy used in processing)
Machinery	MJ/ha	Energy that is needed to produce the machinery that is used during the planting, cultivation and harvesting of the crop.
Seed	MJ/ha	Energy used during production of the seed
Mineral fertiliser (Nitrogen, Phosphates and potassium)	MJ/ha	Energy used during production of the mineral fertiliser
Seeding/planting	MJ/ha	Energy used for planting/seeding the crop.
Cultivation management	MJ/ha	Energy used in mechanisation (tractor use) and fuel for managing the crop once established (e.g. weeding)
Application of fertiliser	MJ/ha	Energy used for applying the fertilisers
Application of manure	MJ/ha	Energy used for applying manure
Application of plant protection products	MJ/ha	Energy for plant protection products
Application/pumping of irrigation water	MJ/ha	Energy used in mechanisation (e.g. pump) and fuel for applying irrigation water
Processing harvested goods	MJ/ha	Energy used to conserve harvested good, mainly drying of cereals
Labour	MJ/ha	Energy needed by humans to perform all the crop production related activities

Source: this study

To calculate the energy contents of fertilizers both artificial and manure fertilisers need to be included and allocated to a crop. The incorporation of manure fertiliser required additional processing as in the CAPRI farm energy balance calculation all manure fertilizer was (indirectly) allocated to animal production, while for the soil energy balance this needs to be allocated to the cropping activities (including grasslands).

Since CAPRI calculates input of nitrogen (N), phosphate (P) and potassium (K) in kg per crop, the energy input used for spreading the manure also needs to be allocated to the nitrogen, phosphate and potassium contents of the manure. How this is calculated is explained in the following. The reason why the energy input only includes the fuel consumption of the tractor and other machinery use, and not the energy used in the production of the machinery, is because according to the logic of the CAPRI energy model this part of the energy input is completely allocated to the 'cultivation' part of the cropping activities.

Data used for estimating the energy input of manure spreading were based on German average figures (available at http://www.llh-hessen.de/landwirtschaft/vtec/text63.htm). According to these it is assumed that a spreading tank contains on average 16m3 of manure (average 11 – 22 m3). It takes 30 minutes to drive, fill and spread the tank (own estimate). This means that 32m3 are spread per hour which implies that 1.67 litres of diesel are used to spread 1 m3 manure (32/19.2 = 1.67 l).

1 m3 manure contains 12 kg Nitrogen, Phosphate and Potassium (NPK) in equal shares (based on “rough” average of nutrient content in different types of manure see e.g. http://www.lfl.bayern.de/iab/duengung/organisch/09556/). To link the fuel input to the separate NPK contents the following formula is applied: 1.67/12=0.139 l per kg NPK Where 0.139 is the amount of diesel needed to spread 1 kg of nutrition. As the energy content of diesel is 45,71 MJ/l we arrive at about 6,4 MJ/kg (nutrition).

When the calculation results on the energy input for manure spreading is combined with the fertiliser spreading, the following coefficients for energy input for mineral and manure spreading are the result:

N mineral: 58.99; P mineral: 40.06; K mineral: 9.25. N, P, K manure: 6.4

For **irrigation** figures from different sources were used to get a most up to date and spatially detailed overview of irrigation share per crop and total irrigation water consumption per crop. Several of these sources were already included in the in the CAPRI model. They are based on various national sources providing information on irrigated crop area and/or water use combined with crop specific expert information. However as part of this project these CAPRI irrigation data were further up-dated with more spatially detailed irrigation data based on Wriedt et al. (2008) in which irrigation shares per crop area and total irrigation water consumption are provided at 10*10 km grid.

The **labour** input estimate builds on a German study which is based on the average energy intake for a person (see **Table A 4**) doing light physical work

Table A 4 Overview of average energy in-take per day for males and females

Age	Males	Females
15-18 years	3100 kcal	2500 kcal
19 < 24 year	3000 kcal	2400 kcal
25 -50 years	2900 kcal	2300 kcal
51 - 64 years	2500 kcal	2000 kcal
>= 65 years	2300 kcal	1800 kcal

Source: D-A-CH: Referenzwerte für die Nährstoffzufuhr. Available at: http://www.ernaehrung.de/tipps/allgemeine_infos/ernaehr10.php

For heavier work, the following additional energy in-take is needed:

- Moderately heavy physical work: plus ca. 600 kcal
- Heavy physical work: plus ca. 1,200 kcal
- Very heavy physical work: plus ca. 1,600 kcal

Examples of these working categories are given in Table A 5. In this study we assume that a farmer operates at the same physical work level as a roofer or construction worker and that on average he is male and is in the age of 25-50 years

This implies that his caloric needs are: 2,900 + 1,200 = 4,100 kcal.

Per working hour it needs:

4,100 / 8 hours of work = 500kcal per hour (approximately)

Conversion to MJ:

1kJ = 0.239kcal; this implies that:

500 kcal/0.239= 2,092kJ = 2.092 MJ per hour

In the study presented in this report a differentiation was further made between skilled and unskilled categories of labour.

Table A 5 Examples of light to very heavy work categories

Light physical work	Moderately heavy physical work	Heavy physical work	Very heavy physical work
Clerk	Garage employee	Construction worker	Steel worker
Housewife/ma	Painter	Sports instructor	Kohl miner
Teacher	Gardener	Physiotherapist	Top sportsmen/women
Lorry driver	Salesman/women	Roofer	Forest worker

Source: this study

On the output side a distinction was made between:

- output of harvested products used for food and feed and
- output of biomass that can be used for production of non-food products including bioenergy.

The latter category includes all biomass that can be harvested sustainably and which is already partly harvested as part of regular crop management activities such as pruning and cutting activities.

The CAPRI model calculates crop yield in kg fresh weight. The CAPRI energy module was fed with data on energy content of the output products (food, feed and other biomass) which were collected from literature. As a starting point, coefficients are estimated from the energy of forage (as defined in animal science literature) and heating value of biomass.

As values are typically given per kg dry matter, all the coefficients had to be converted to fresh weight. For an overview of the energy content factors used for food products see **Table A 6**. An overview of the energy contents of forage crops is given in **Table A 7**

Table A 6 Energy content of the food products

Crop	MJ per kg fresh weight	Crop	MJ per kg fresh weight
Soft wheat	11.38	Olives	36.81
Durum wheat	11.38	Pulses	14.00
Reye and meslim	12.06	Potatoes	2.74
Barley	11.46	Sugar beet	2.38
Oats	10.19	Tomatoes	0.81
Grain maize	11.02	Other vegetables	1.12
Other cereals	11.46	Apples	1.70
Rape (seed)	15.28	Other fruits	1.75
Sunflower (seed)	15.28	Citrus fruits	1.18
Soya (seed)	10.19	Table grapes	2.86
Other oil (seed)	37.07	Tobacco	4.07
Paddy rice	15.88	Wine	2.85

Source: Pérez-Soba et al., 2015

Table A 7 Energy content of forage or biomass output

	Energy (MJ per kg dry matter) ****	Dry matter content (g/kg)	Energy (MJ per kg fresh weight)
Silage Maize*	11,2	352	3,75
Fodder root crops**	7,9 – 8,3	140 - 190	2,00
Other fodder from arable	10.2 – 10.7	390 – 406	3,75
Grass*	10,0 - 10,6	423 – 431	3,75
Straw***	18	890	16,00

Sources:
* http://www.landwirtschaftskammer.de/landwirtschaft/tierproduktion/rinderhaltung/
** https://www.fibl-shop.org/shop/pdf/mb-futterrueben.pdf
*** Elbersen et al. (2012)

To derive the potential biomass output of non-food (e.g. wood cuttings as by product of apple trees) specific biomass coefficient estimates were used first to estimate the total volume for cuttings and pruning from vineyards, citrus and other fruit trees, nuts and olives and for straw. These volumes were then converted to energy content according to their lower heating values and their dry matter content.

In order to estimate the residue potential the permanent cropping areas derived from CAPRI the average harvest ratios per type of permanent crop was taken. The harvest ratios were derived from several publications (see underneath) and their averages are summarised per crop category in **Table A 8**

Table A 8 Average residue harvest ratios per type of permanent crop

Land use category	Residue yields Ton	Source
Fruit and berry plantations – total	2.15	1
Temperate climate fruit and berry plantations		
Subtropical climate fruit and berry plantations		
Nuts fruit and berry plantations	2.15	2
Citrus plantations	2.75	3
Olive plantations - table olives	1.77	4
Olive plantations - oil production		
Vineyards - quality wine	2.81	5
Vineyards - other wines		
Vineyards - table grapes		
Vineyards – raisins		

Sources:

1 -Di Blasi et al., (1997), M. A study on the production of agricultural residues in Italy; Biomass and Bioenergy Vol 12 No 5 pp 321-331 (1997)

2 - Bernetti et. Al. (2004). A methodology to analyse the potential development of biomass energy sector: an application in Tuscany; Forest Policy and Economics 6 (2004) 415-432

3 - Figures taken from powerpoint presentation "Bioenergy market in Greece" by Despina Vamvuka (15/12/2006): http://www.enveng.tuc.gr/Downloads/ABES_LAB/05%20Vamvuka.pdf

4 - Siemons et al. (2004). Bioenergy's role in the EU energy market. A view of developments until 2020. http://ec.europa.eu/environment/etap/pdfs/bio_energy.pdf

5 - Mladen et al., (2004). The state of biomass energy in Serbia; BIBLID: 0354-9836, 8 (2004), 2, 5-19; http://www.doiserbia.nb.rs/ft.aspx?id=0354-98360402005I

For the conversion of this biomass to energy the following conversion factors were used:

- Lower heating value: Energy (MJ per kg dry matter) = 11.7
- Dry matter content (g/kg) = 890
- Energy (MJ per kg fresh weight) = 10.41

A methodology for estimating the straw biomass potential is available from a JRC study (JRC and CENER, 2006 and Scarlat et al. 2009). In this work the methodology for estimating a sustainable potential applies to a wide range of crops delivering straw including all cereals, rice, and maize, sunflower and oil seed Rape. Based on a wide range of EU expertise the straw yield ratios per type of crop are provided together with sustainable harvest levels. The latter relate to harvest practices aimed at maintaining the soil carbon levels in the soil. These were estimated to be at 40% for wheat, rye, oats and barley and at 50% for the other 4 crops. The JRC approach was applied to all crop area and yield levels in the Capri database to arrive at a final straw biomass energy output. For conversion of the straw biomass to energy the figures provided in Table 7 for

Annex 4 Results for emergy indicators at national level

In the following tables two values for EYR are provided: Y/F and Y/(R+N)

All crops	EIR= human input(F)/natural input(R+N)	EYR= output (Y)/human input (F)	EYR= output (Y)/natural input (R+N)	AREA	All Input	Human Input	Natural energy input Non Renewable	Natural energy input renewable	All Input transformaty	Human Input transformaty	Non Renewable input transformaty	Renewable input transformaty
	Ratio	Ratio	Ratio	*1000 ha	SEJ	SEJ	SEJ	SEJ	[SEJ/J]	[SEJ/J]	[SEJ/J]	[SEJ/J]
Austria	2.5	1.4	3.5	2641	4.E+15	3.E+15	5.E+14	5.E+14	41372	29648	6415	5310
Bulgaria	2.1	1.5	3.1	4182	2.E+15	2.E+15	4.E+14	4.E+14	58539	39602	9576	9361
Belgium-Luxembourg	5.4	1.2	6.4	1372	6.E+15	5.E+15	5.E+14	5.E+14	42259	35677	3149	3433
Czech Rep.	2.0	1.5	3.0	15108	3.E+15	2.E+15	4.E+14	4.E+14	63823	42315	11149	10359
Germany	2.6	1.4	3.6	3140	4.E+15	3.E+15	7.E+14	4.E+14	61957	44546	10866	6545
Denmark	3.5	1.3	4.5	13631	6.E+15	4.E+15	8.E+14	5.E+14	45634	35404	6314	3916
Estonia	3.4	1.3	4.4	1854	5.E+15	4.E+15	7.E+14	4.E+14	36879	28411	5532	2936
Greece	0.9	2.1	1.9	639	4.E+15	2.E+15	2.E+15	4.E+14	67389	31799	29497	6093
Spain	4.8	1.2	5.8	1343	3.E+15	2.E+15	2.E+14	2.E+14	45380	37549	3802	4029
Finland	2.6	1.4	3.6	14173	4.E+15	3.E+15	3.E+14	9.E+14	96336	69719	5951	20666
France	0.6	2.6	1.6	1371	8.E+15	3.E+15	5.E+15	2.E+14	110178	42492	64586	3100
Hungary	3.7	1.3	4.7	23245	5.E+15	4.E+15	4.E+14	6.E+14	49823	39169	4735	5919
Ireland	3.0	1.3	4.0	4428	5.E+15	4.E+15	7.E+14	5.E+14	77383	58002	11764	7617
Italy	2.0	1.5	3.0	4053	4.E+15	3.E+15	9.E+14	5.E+14	30447	20335	6312	3800
Lithuania	2.8	1.4	3.8	8376	5.E+15	4.E+15	3.E+14	9.E+14	73604	54420	4641	14544
Latvia	2.3	1.4	3.3	1752	4.E+15	2.E+15	7.E+14	4.E+14	61616	42660	11592	7364
Netherlands	1.0	2.0	2.0	1597	3.E+15	2.E+15	1.E+15	3.E+14	48333	24729	18949	4655
Poland	3.6	1.3	4.6	1687	7.E+15	5.E+15	1.E+15	4.E+14	46557	36407	7080	3071
Portugal	2.6	1.4	3.6	11657	5.E+15	4.E+15	1.E+15	4.E+14	81411	58857	16205	6349
Romania	2.9	1.3	3.9	1950	3.E+15	2.E+15	2.E+14	5.E+14	50657	37681	3884	9092
Sweden	1.9	1.5	2.9	10926	3.E+15	2.E+15	5.E+14	4.E+14	65914	43389	11771	10754
Slovenia	1.6	1.6	2.6	2288	5.E+15	3.E+15	2.E+15	3.E+14	59265	36632	19203	3430
Slovakia	3.2	1.3	4.2	421	4.E+15	3.E+15	5.E+14	5.E+14	88607	67550	11120	9936
UK	2.6	1.4	3.6	1789	3.E+15	2.E+15	5.E+14	3.E+14	50210	36324	8707	5179
EU-27	**2.8**	**1.4**	**3.8**	**133621**					**62989**	**45026**	**9245**	**8717**
Minimum	*0.6*	*1.2*	*1.6*						*30447*	*20335*	*3149*	*2936*
Maximum	*5.4*	*2.6*	*6.4*						*110178*	*69719*	*64586*	*20666*

Cereals							Natural energy input					
	EIR= human input(F)/natural input(R+N)	EYR= output (Y)/human input (F)	EYR= output (Y)/natural input (R+N)	AREA	All Input	Human Input	Non Renewable	renewable	All Input transformaty	Human Input transformaty	Non Renewable input transformaty	Renewable input transformaty
	Ratio	Ratio	Ratio	*1000 ha	SEJ	SEJ	SEJ	SEJ	[SEJ/J]	[SEJ/J]	[SEJ/J]	[SEJ/J]
Austria	3.9	1.3	4.9	318	5.1E+15	4.0E+15	5.0E+14	5.2E+14	61839	49327	6150	6362
Bulgaria	3.2	1.3	4.2	1159	3.7E+15	2.8E+15	4.8E+14	4.0E+14	68840	52622	8877	7341
Belgium-Luxembourg	7.5	1.1	8.5	248	9.0E+15	7.9E+15	5.2E+14	5.4E+14	75449	66571	4337	4541
Czech Rep.	3.5	1.3	4.5	926	5.9E+15	4.6E+15	8.1E+14	4.9E+14	74868	58312	10326	6229
Germany	4.6	1.2	5.6	3451	7.4E+15	6.1E+15	8.0E+14	5.1E+14	61041	50210	6619	4212
Denmark	3.9	1.3	4.9	766	5.3E+15	4.2E+15	5.7E+14	5.1E+14	44375	35268	4789	4318
Estonia	1.2	1.8	2.2	140	6.5E+15	3.5E+15	2.6E+15	3.9E+14	118828	64752	46952	7124
Greece	4.8	1.2	5.8	202	3.7E+15	3.1E+15	3.1E+14	3.3E+14	93800	77747	7725	8328
Spain	4.0	1.2	5.0	2191	4.3E+15	3.4E+15	3.9E+14	4.6E+14	94388	75691	8599	10098
Finland	0.8	2.3	1.8	607	9.6E+15	4.2E+15	5.2E+15	2.6E+14	156986	68446	84334	4206
France	5.6	1.2	6.6	4688	7.0E+15	5.9E+15	5.3E+14	5.3E+14	60177	51022	4612	4543
Hungary	2.1	1.5	3.1	1178	4.1E+15	2.8E+15	8.4E+14	5.1E+14	57535	38848	11641	7045
Ireland	3.9	1.3	4.9	118	6.8E+15	5.4E+15	8.7E+14	5.2E+14	70490	56160	8974	5356
Italy	6.4	1.2	7.4	777	5.4E+15	4.7E+15	3.1E+14	4.2E+14	71682	61953	4117	5612
Lithuania	2.5	1.4	3.5	518	5.2E+15	3.7E+15	1.0E+15	4.9E+14	79895	57038	15416	7440
Latvia	1.5	1.7	2.5	334	5.1E+15	3.1E+15	1.6E+15	4.6E+14	89873	54267	27494	8112
Netherlands	5.1	1.2	6.1	154	1.1E+16	9.0E+15	1.2E+15	5.4E+14	96195	80307	11098	4790
Poland	2.9	1.3	3.9	4253	6.3E+15	4.7E+15	1.2E+15	4.5E+14	103514	77243	18906	7365
Portugal	3.3	1.3	4.3	126	2.7E+15	2.1E+15	2.7E+14	3.6E+14	128252	98141	12968	17142
Romania	2.0	1.5	3.0	2312	3.1E+15	2.1E+15	5.8E+14	4.5E+14	74067	49208	14001	10858
Sweden	2.2	1.5	3.2	597	6.4E+15	4.4E+15	1.6E+15	3.6E+14	73265	50465	18677	4123
Slovenia	4.5	1.2	5.5	33	8.7E+15	7.1E+15	1.2E+15	4.2E+14	130890	107164	17345	6381
Slovakia	2.8	1.4	3.8	397	4.2E+15	3.1E+15	5.9E+14	5.3E+14	61273	45116	8485	7672
UK	**5.9**	**1.2**	6.9	**2088**	**7.61E+15**	**6.5E+15**	**6.1398E+14**	**4.9255E+14**	**62373**	**53304**	**5033**	**4037**
EU-27	**3.9**	**1.3**	**4.9**	**27581**					**76145**	**57898**	**11821**	**6426**
Minimum	*0.8*	*1.1*	*1.8*						*44375*	*35268*	*4117*	*4037*
Maximum	*7.5*	*2.3*	*8.5*						*156986*	*107164*	*84334*	*17142*

Fodder maize	EIR= human input(F)/natural input(R+N)	EYR= output (Y)/human input (F)	EYR= output (Y)/natural input (R+N)	AREA	All Input	Human Input	Natural energy input		All Input transformaty	Human Input transformaty	Non Renewable input transformaty	Renewable input transformaty
							Non Renewable	renewable				
	Ratio	Ratio	Ratio	*1000 ha	SEJ	SEJ	SEJ	SEJ	[SEJ/J]	[SEJ/J]	[SEJ/J]	[SEJ/J]
Austria	2.9	1.3	3.9	83	5.1E+15	3.8E+15	8.5E+14	4.6E+14	29557	21909	4943	2705
Bulgaria	2.1	1.5	3.1	41	3.1E+15	2.1E+15	5.4E+14	4.6E+14	115091	77750	20187	17154
Belgium-Luxembourg	2.6	1.4	3.6	195	4.2E+15	3.0E+15	6.3E+14	5.3E+14	25627	18508	3861	3257
Czech Rep.	2.3	1.4	3.3	199	4.4E+15	3.1E+15	8.0E+14	5.5E+14	40214	27993	7219	5002
Germany	2.3	1.4	3.3	1604	6.0E+15	4.2E+15	1.3E+15	5.5E+14	36093	25204	7562	3326
Denmark	2.8	1.4	3.8	159	3.1E+15	2.3E+15	8.0E+14	1.1E+13	21138	15559	5503	76
Greece	4.4	1.2	5.4	2	3.0E+15	2.4E+15	3.0E+14	2.6E+14	51764	42120	5150	4494
Spain	4.1	1.2	5.1	111	6.3E+15	5.1E+15	7.0E+14	5.4E+14	46380	37288	5120	3972
France	2.4	1.4	3.4	1395	3.6E+15	2.5E+15	5.1E+14	5.5E+14	22628	15898	3225	3505
Hungary	1.3	1.8	2.3	108	3.3E+15	1.9E+15	9.1E+14	5.3E+14	37796	21459	10308	6029
Ireland	3.0	1.3	4.0	22	6.5E+15	4.9E+15	1.6E+15	9.3E+12	166708	124648	41823	238
Italy	3.2	1.3	4.2	269	9.1E+15	6.9E+15	4.0E+14	1.8E+15	46477	35406	2026	9046
Lithuania	1.9	1.5	2.9	22	3.0E+15	2.0E+15	1.0E+15	1.1E+13	40114	26157	13815	142
Netherlands	1.9	1.5	2.9	235	5.4E+15	3.5E+15	1.3E+15	5.0E+14	34204	22517	8512	3175
Poland	1.5	1.7	2.5	413	4.2E+15	2.5E+15	1.2E+15	5.1E+14	25459	15224	7109	3126
Portugal	4.2	1.2	5.2	91	4.5E+15	3.7E+15	4.0E+14	4.8E+14	35448	28576	3097	3774
Romania	1.8	1.5	2.8	40	3.3E+15	2.1E+15	6.4E+14	5.2E+14	47159	30590	9147	7421
Slovinia	4.8	1.2	5.8	17	8.2E+15	6.8E+15	9.0E+14	5.2E+14	32454	26836	3553	2065
Slovakia	3.1	1.3	4.1	80	4.4E+15	3.3E+15	5.5E+14	5.4E+14	47038	35461	5850	5728
UK	2.4	1.4	3.4	158	4.0E+15	2.8E+15	7.5E+14	4.2E+14	28722	20218	5453	3052
EU-27	**2.4**	**1.4**	**3.4**	**5244**					**32783**	**22989**	**5982**	**3811**
Minimum	*1.3*	*1.2*	*2.3*						*21138*	*15224*	*2026*	*76*
Maximum	*4.8*	*1.8*	*5.8*						*166708*	*124648*	*41823*	*17154*

Food crops	EIR= human input(F)/natural input(R+N)	EYR= output (Y)/human input (F)	EYR= output (Y)/natural input (R+N)	AREA	All Input	Human Input	Natural energy input		All Input transformaty	Human Input transformaty	Non Renewable input transformaty	Renewable input transformaty
							Non Renewable	renewable				
	Ratio	Ratio	Ratio	*1000 ha	SEJ	SEJ	SEJ	SEJ	[SEJ/J]	[SEJ/J]	[SEJ/J]	[SEJ/J]
Austria	6.9	1.1	7.9	674	8.0E+15	7.0E+15	5.6E+14	4.5E+14	85045	74267	5956	4821
Bulgaria	3.0	1.3	4.0	2238	3.5E+15	2.6E+15	4.7E+14	4.1E+14	82452	61699	11140	9613
Belgium-Luxembourg	8.6	1.1	9.6	472	9.9E+15	8.9E+15	5.1E+14	5.2E+14	77914	69835	4000	4079
Czech Rep.	3.5	1.3	4.5	1561	5.8E+15	4.5E+15	8.3E+14	4.6E+14	85859	66703	12315	6841
Germany	4.8	1.2	5.8	6200	7.7E+15	6.4E+15	8.2E+14	5.0E+14	73857	61189	7883	4786
Denmark	3.7	1.3	4.7	1021	5.2E+15	4.1E+15	6.1E+14	4.9E+14	48637	38361	5698	4578
Estonia	1.2	1.8	2.2	227	6.1E+15	3.4E+15	2.4E+15	3.6E+14	140011	76685	55021	8305
Greece	7.8	1.1	8.8	374	5.4E+15	4.8E+15	3.0E+14	3.0E+14	83897	74403	4755	4739
Spain	3.6	1.3	4.6	3995	6.6E+15	5.2E+15	3.6E+14	1.1E+15	153252	119910	8310	25033
Finland	0.8	2.3	1.8	687	9.5E+15	4.1E+15	5.2E+15	2.4E+14	168124	72097	91824	4203
France	6.1	1.2	7.1	8945	8.2E+15	7.0E+15	5.2E+14	6.3E+14	81973	70381	5238	6355
Hungary	3.6	1.3	4.6	3153	6.2E+15	4.9E+15	8.4E+14	5.1E+14	101465	79383	13802	8280
Ireland	4.0	1.3	5.0	143	6.9E+15	5.5E+15	8.8E+14	5.0E+14	75410	60245	9655	5509
Italy	4.4	1.2	5.4	2110	9.6E+15	7.8E+15	3.2E+14	1.5E+15	113366	92494	3746	17126
Lithuania	2.9	1.3	3.9	771	5.5E+15	4.1E+15	1.0E+15	4.1E+14	99485	73986	18096	7403
Latvia	1.8	1.6	2.8	465	5.5E+15	3.5E+15	1.5E+15	4.2E+14	107069	69037	29860	8172
Netherlands	5.2	1.2	6.2	409	1.2E+16	1.0E+16	1.4E+15	5.0E+14	105252	88298	12611	4343
Poland	3.6	1.3	4.6	6247	7.2E+15	5.6E+15	1.1E+15	4.4E+14	120776	94313	19148	7315
Portugal	3.8	1.3	4.8	305	6.2E+15	4.9E+15	3.3E+14	9.7E+14	155728	123181	8212	24334
Romania	2.5	1.4	3.5	6199	3.6E+15	2.6E+15	5.8E+14	4.5E+14	107627	77118	17143	13367
Sweden	2.2	1.4	3.2	779	6.1E+15	4.2E+15	1.6E+15	3.2E+14	73722	50940	18941	3840
Slovenia	5.2	1.2	6.2	80	8.8E+15	7.4E+15	9.7E+14	4.5E+14	113927	95545	12529	5853
Slovakia	3.4	1.3	4.4	822	5.0E+15	3.8E+15	6.1E+14	5.0E+14	82807	64153	10223	8431
UK	5.2	1.2	6.2	3128	6.8E+15	5.7E+15	6.1E+14	4.8E+14	64548	54122	5819	4606
EU-27	**4.2**	**1.3**	**5.2**	**51004**					**97823**	**76474**	**12130**	**9219**
Minimum	0.8	1.1	1.8						48637	38361	3746	3840
Maximum	8.6	2.3	9.6						168124	123181	91824	25033

Grain Maize	EIR= human input(F)/natural input(R+N)	EYR= output (Y)/human input (F)	EYR= output (Y)/natural input (R+N)	AREA	All Input	Human Input	Natural energy input		All Input transformaty	Human Input transformaty	Non Renewable input transformaty	Renewable input transformaty
							Non Renewable	renewable				
	Ratio	Ratio	Ratio	*1000 ha	SEJ	SEJ	SEJ	SEJ	[SEJ/J]	[SEJ/J]	[SEJ/J]	[SEJ/J]
Austria	11.3	1.1	12.3	181.4	1.5E+16	1.4E+16	7.3E+14	5.2E+14	115507	106148	5480	3879
Bulgaria	3.0	1.3	4.0	287.6	3.9E+15	2.9E+15	4.9E+14	4.7E+14	100356	75273	12805	12278
Belgium-Luxembourg	12.8	1.1	13.8	66.4	1.6E+16	1.4E+16	6.0E+14	5.3E+14	121036	112236	4682	4118
Czech Rep.	7.6	1.1	8.6	116.1	1.2E+16	1.0E+16	8.2E+14	5.5E+14	178718	157958	12438	8322
Germany	8.8	1.1	9.8	478.2	1.6E+16	1.4E+16	1.1E+15	5.6E+14	148650	133464	9936	5250
Greece	12.4	1.1	13.4	117.6	7.7E+15	7.1E+15	3.0E+14	2.7E+14	71499	66161	2840	2498
Spain	3.9	1.3	4.9	395.7	1.6E+16	1.3E+16	3.4E+14	2.9E+15	161437	128651	3436	29349
France	7.8	1.1	8.8	1599.5	1.5E+16	1.3E+16	5.0E+14	1.1E+15	143117	126933	4908	11276
Hungary	6.2	1.2	7.2	1150.6	1.0E+16	8.8E+15	8.8E+14	5.3E+14	155093	133638	13364	8091
Italy	4.1	1.2	5.1	984.2	1.4E+16	1.1E+16	3.1E+14	2.4E+15	134138	107649	3124	23365
Lithuania	6.1	1.2	7.1	6.5	7.4E+15	6.4E+15	1.0E+15	1.5E+13	146438	125712	20438	289
Netherlands	7.0	1.1	8.0	20.4	1.6E+16	1.4E+16	1.3E+15	6.2E+14	140057	122616	11917	5524
Poland	6.8	1.1	7.8	289.9	1.2E+16	1.0E+16	1.0E+15	5.2E+14	169561	147686	14529	7346
Portugal	3.5	1.3	4.5	106.7	8.8E+15	6.8E+15	3.7E+14	1.6E+15	123566	95951	5155	22460
Romania	1.8	1.5	2.8	2395.7	3.0E+15	2.0E+15	5.8E+14	4.9E+14	99603	64629	18830	16144
Slovenia	5.8	1.2	6.8	38	8.62E+15	7.35E+15	7.42E+14	5.23E+14	95320	81330	8211	5779
Slovakia	*7.4*	*1.1*	8.4	*153.8294*	*9.21E+15*	*8.11E+15*	*5.58E+14*	*5.37E+14*	*132606*	*116838*	*8029*	*7738*
EU total	**5.2**	**1.3**	**6.2**	**8389**					**129960**	**105410**	**10845**	**13705**
Min	1.8	1.1	2.8						71499	64629	2840	289
Max	*12.8*	*1.5*	*13.8*						*178718*	*157958*	*20438*	*29349*

Grass	EIR= human input(F)/natural input(R+N)	EYR= output (Y)/human input (F)	EYR= output (Y)/natural input (R+N)	AREA	All Input	Human Input	Natural energy input Non Renewable	renewable	All Input transformaty	Human Input transformaty	Non Renewable input transformaty	Renewable input transformaty
	Ratio	Ratio	Ratio	*1000 ha	SEJ	SEJ	SEJ	SEJ	[SEJ/J]	[SEJ/J]	[SEJ/J]	[SEJ/J]
Austria	0.8	2.2	1.8	1717	1.8E+15	7.9E+14	4.9E+14	4.9E+14	22821	10195	6264	6362
Bulgaria	0.6	2.6	1.6	1903	1.0E+15	3.8E+14	2.8E+14	3.4E+14	26270	9998	7360	8912
Belgium-Luxembourg	3.9	1.3	4.9	594	3.9E+15	3.1E+15	2.8E+14	5.3E+14	26687	21208	1922	3558
Czech Rep.	1.2	1.9	2.2	1054	1.8E+15	9.7E+14	3.9E+14	4.5E+14	34858	18690	7521	8647
Germany	2.1	1.5	3.1	4967	3.1E+15	2.1E+15	5.1E+14	5.1E+14	23499	15842	3832	3826
Denmark	3.3	1.3	4.3	217	2.7E+15	2.1E+15	4.0E+14	2.4E+14	20972	16104	3033	1835
Estonia	0.9	2.1	1.9	252	2.2E+15	1.0E+15	8.0E+14	3.6E+14	33687	15771	12326	5590
Greece	2.6	1.4	3.6	718	1.3E+15	9.0E+14	1.3E+14	2.2E+14	25920	18632	2731	4557
Spain	2.1	1.5	3.1	9133	3.2E+15	2.2E+15	2.0E+14	8.4E+14	72483	49046	4604	18833
Finland	1.0	2.0	2.0	57	2.8E+15	1.4E+15	1.4E+15	3.9E+13	39565	19401	19618	546
France	1.7	1.6	2.7	9496	2.3E+15	1.5E+15	2.9E+14	5.5E+14	30842	19595	3882	7365
Hungary	0.5	3.1	1.5	985	1.2E+15	3.7E+14	3.4E+14	4.5E+14	19195	6150	5607	7438
Ireland	2.0	1.5	3.0	3287	3.9E+15	2.6E+15	7.8E+14	5.4E+14	28570	18948	5691	3931
Italy	1.7	1.6	2.7	3935	2.6E+15	1.6E+15	2.6E+14	7.3E+14	55583	34647	5406	15530
Lithuania	1.4	1.7	2.4	958	2.0E+15	1.2E+15	4.0E+14	4.5E+14	33946	19734	6669	7543
Latvia	0.6	2.8	1.6	715	1.7E+15	6.3E+14	7.1E+14	4.1E+14	28593	10231	11676	6687
Netherlands	3.1	1.3	4.1	849	4.8E+15	3.7E+15	6.7E+14	5.1E+14	32396	24499	4492	3406
Poland	1.1	1.9	2.1	3474	2.2E+15	1.2E+15	5.9E+14	4.7E+14	40234	20973	10648	8613
Portugal	2.6	1.4	3.6	1144	1.8E+15	1.3E+15	1.2E+14	3.8E+14	34374	24947	2314	7112
Romania	0.7	2.4	1.7	4688	1.2E+15	4.9E+14	3.0E+14	3.8E+14	25457	10645	6564	8248
Sweden	1.2	1.9	2.2	450	2.4E+15	1.3E+15	7.9E+14	3.1E+14	29140	15716	9646	3778
Slovenia	1.9	1.5	2.9	292	2.6E+15	1.7E+15	3.5E+14	5.2E+14	91940	60492	12687	18762
Slovakia	1.1	1.9	2.1	720	1.1E+15	5.8E+14	3.6E+14	1.5E+14	18348	9730	6057	2561
UK	0.8	2.2	1.8	10145	3.0E+15	1.4E+15	1.1E+15	4.7E+14	31076	14236	11909	4931
EU-27	1.4	1.9	2.4	61749					36512	21242	6598	8672
minimum	0.5	1.3	1.5						18348	6150	1922	546
maximum	3.9	3.1	4.9						91940	60492	19618	18833

Oil seeds	EIR= human input(F)/natural input(R+N)	EYR= output (Y)/human input (F)	EYR= output (Y)/natural input (R+N)	AREA	All Input	Human Input	Natural energy input Non Renewable	Natural energy input renewable	All Input transformaty	Human Input transformaty	Non Renewable input transformaty	Renewable input transformaty
	Ratio	Ratio	Ratio	*1000 ha	SEJ	SEJ	SEJ	SEJ	[SEJ/J]	[SEJ/J]	[SEJ/J]	[SEJ/J]
Austria	3.3	1.3	4.3	81	4.3E+15	3.3E+15	5.3E+14	4.7E+14	97068	74601	11894	10573
Bulgaria	2.4	1.4	3.4	763	2.9E+15	2.1E+15	4.5E+14	4.1E+14	108279	76370	16743	15167
Belgium-Luxembourg	6.0	1.2	7.0	16	7.4E+15	6.4E+15	6.0E+14	4.5E+14	131480	112758	10657	8064
Czech Rep.	1.6	1.6	2.6	390	3.6E+15	2.2E+15	9.3E+14	4.5E+14	90475	55967	23265	11243
Germany	3.8	1.3	4.8	1519	6.0E+15	4.7E+15	8.0E+14	4.4E+14	105061	83227	14161	7673
Denmark	3.2	1.3	4.2	171	4.6E+15	3.5E+15	7.0E+14	4.0E+14	82321	62673	12471	7178
Estonia	0.7	2.5	1.7	77	4.2E+15	1.7E+15	2.2E+15	3.3E+14	169125	67868	87811	13446
Greece	4.1	1.2	5.1	1	2.8E+15	2.2E+15	3.1E+14	2.3E+14	163285	131370	18541	13374
Spain	2.9	1.3	3.9	945	6.9E+15	5.1E+15	2.9E+14	1.5E+15	546519	405444	22802	118274
Finland	0.6	2.7	1.6	80	8.9E+15	3.3E+15	5.5E+15	9.1E+13	403626	149285	250194	4147
France	4.8	1.2	5.8	2008	5.5E+15	4.5E+15	4.9E+14	4.6E+14	117209	96943	10420	9846
Hungary	1.6	1.6	2.6	779	3.3E+15	2.1E+15	7.9E+14	4.7E+14	92044	57001	21966	13078
Ireland	2.7	1.4	3.7	7	4.1E+15	3.0E+15	6.6E+14	4.7E+14	75038	54516	12063	8459
Italy	3.4	1.3	4.4	133	5.1E+15	4.0E+15	3.2E+14	8.4E+14	143747	111119	9091	23538
Lithuania	1.2	1.8	2.2	180	3.0E+15	1.6E+15	9.9E+14	3.4E+14	98979	54830	32914	11235
Latvia	1.1	1.9	2.1	93	3.6E+15	1.9E+15	1.3E+15	3.3E+14	105009	55885	39311	9812
Netherlands	2.6	1.4	3.6	3	8.6E+15	6.2E+15	2.0E+15	4.0E+14	154924	111583	36146	7195
Poland	2.8	1.4	3.8	811	5.7E+15	4.2E+15	1.1E+15	4.3E+14	134069	98776	25120	10173
Portugal	2.8	1.4	3.8	22	2.6E+15	1.9E+15	2.8E+14	4.0E+14	267258	197013	28507	41739
Romania	2.3	1.4	3.3	1201	3.0E+15	2.1E+15	5.1E+14	4.1E+14	130577	90550	22215	17811
Sweden	1.5	1.6	2.5	92	4.6E+15	2.8E+15	1.5E+15	3.3E+14	102638	62366	32862	7410
Slovinia	4.6	1.2	5.6	4	8.4E+15	6.9E+15	1.1E+15	4.0E+14	177567	145896	23231	8439
Slovakia	1.8	1.6	2.8	240	3.2E+15	2.0E+15	7.0E+14	4.6E+14	93259	59465	20338	13456
UK	2.3	1.4	3.3	582	3.4E+15	2.4E+15	5.7E+14	4.6E+14	64426	44919	10877	8630
EU-27	3.0	1.4	4.0	10198					152920	111287	20203	21430
minimum	0.6	1.2	1.6						64426	44919	9091	4147
maximum	6.0	2.7	7.0						546519	405444	250194	118274

Potatoes	EIR= human input(F)/natural input(R+N)	EYR= output (Y)/human input (F)	EYR= output (Y)/natural input (R+N)	AREA	All Input	Human Input	Natural energy input		All Input transformaty	Human Input transformaty	Non Renewable input transformaty	Renewable input transformaty
							Non Renewable	renewable				
	Ratio	Ratio	Ratio	*1000 ha	SEJ	SEJ	SEJ	SEJ	[SEJ/J]	[SEJ/J]	[SEJ/J]	[SEJ/J]
Austria	17.4	1.1	18.4	22	1E+16	9E+15	5E+14	4E+13	114749	108499	5751	499
Bulgaria	7.3	1.1	8.3	21	8E+15	7E+15	7E+14	3E+14	213467	187677	17051	8739
Belgium-Luxembourg	7.6	1.1	8.6	71	8E+15	7E+15	5E+14	4E+14	62998	55636	3946	3416
Czech Rep.	11.0	1.1	12.0	36	8E+15	8E+15	6E+14	5E+13	119400	109475	9151	773
Germany	4.2	1.2	5.2	271	8E+15	7E+15	1E+15	5E+14	75815	61196	10247	4372
Denmark	3.4	1.3	4.4	40	8E+15	6E+15	1E+15	5E+14	75310	58307	12383	4619
Estonia	5.9	1.2	6.9	9	2E+16	1E+16	2E+15	3E+14	398656	341023	51450	6182
Greece	14.2	1.1	15.2	29	8E+15	7E+15	3E+14	2E+14	119180	111337	4426	3417
Spain	4.0	1.3	5.0	96	2E+16	2E+16	4E+14	4E+15	315132	251669	6682	56781
France	6.2	1.2	7.2	154	1E+16	9E+15	5E+14	9E+14	84668	72932	4462	7274
Hungary	5.6	1.2	6.6	24	9E+15	7E+15	9E+14	4E+14	125750	106709	12821	6220
Ireland	6.3	1.2	7.3	13	9E+15	8E+15	9E+14	4E+14	107979	93219	9988	4771
Italy	5.1	1.2	6.1	70	1E+16	1E+16	3E+14	2E+15	188393	157655	5135	25603
Lithuania	14.3	1.1	15.3	53	2E+16	2E+16	1E+15	1E+13	462967	432772	29803	392
Latvia	5.8	1.2	6.8	38	1E+16	1E+16	2E+15	3E+14	304050	259575	38690	5785
Netherlands	5.9	1.2	6.9	153	1E+16	1E+16	2E+15	4E+14	141257	120882	16313	4063
Poland	7.6	1.1	8.6	546	1E+16	1E+16	1E+15	4E+14	244684	216311	21834	6539
Portugal	5.7	1.2	6.7	32	1E+16	1E+16	4E+14	2E+15	368236	313409	10425	44403
Romania	13.5	1.1	14.5	265	2E+16	2E+16	9E+14	2E+14	414459	385862	22312	6285
Sweden	2.5	1.4	3.5	29	6E+15	5E+15	2E+15	2E+13	73363	52469	20706	188
Slovinia	7.9	1.1	8.9	4	1E+16	1E+16	1E+15	2E+14	162845	144465	16122	2258
Slovakia	10.4	1.1	11.4	15	8E+15	7E+15	6E+14	1E+14	176482	161067	13010	2405
UK	9.7	1.1	10.7	148	1E+16	1E+16	7E+14	5E+14	116918	105964	6310	4644
EU-27	7.8	1.2	8.8	2141					207011	182986	15226	8799
minimum	2.5	1.1	3.5						62998	52469	3946	188
maximum	17.4	1.4	18.4						462967	432772	51450	56781

Sugar beet	EIR= human input(F)/natural input(R+N)	EYR= output (Y)/human input (F)	EYR= output (Y)/natural input (R+N)	AREA	All Input	Human Input	Natural energy input: Non Renewable	Natural energy input: renewable	All Input transformaty	Human Input transformaty	Non Renewable input transformaty	Renewable input transformaty
	Ratio	Ratio	Ratio	*1000 ha	SEJ	SEJ	SEJ	SEJ	[SEJ/J]	[SEJ/J]	[SEJ/J]	[SEJ/J]
Austria	11.0	1.1	12.0	43	6.9E+15	6.3E+15	3.9E+14	1.8E+14	41869	38373	2389	1107
Bulgaria	3.0	1.3	4.0	0	3.9E+15	2.9E+15	9.7E+14	2.1E+13	119410	89358	29418	634
Belgium-Luxembourg	10.3	1.1	11.3	69	1.1E+16	1.0E+16	4.1E+14	5.7E+14	60879	55489	2266	3124
Czech Rep.	4.7	1.2	5.7	59	6.0E+15	5.0E+15	6.1E+14	4.4E+14	56675	46799	5762	4113
Germany	5.1	1.2	6.1	387	7.6E+15	6.3E+15	6.2E+14	6.2E+14	49545	41463	4034	4048
Denmark	3.8	1.3	4.8	38	4.3E+15	3.4E+15	3.8E+14	5.1E+14	32663	25801	2931	3931
Greece	11.9	1.1	12.9	6	9.0E+15	8.3E+15	3.0E+14	4.0E+14	52978	48858	1765	2355
Spain	4.4	1.2	5.4	60	1.9E+16	1.5E+16	3.6E+14	3.1E+15	106636	86988	2040	17608
France	7.5	1.1	8.5	313	1.2E+16	1.0E+16	6.9E+14	6.9E+14	57386	50653	3360	3373
Hungary	3.4	1.3	4.4	21	5.7E+15	4.4E+15	9.8E+14	3.2E+14	50992	39319	8757	2917
Ireland	4.2	1.2	5.2	1	8.8E+15	7.1E+15	1.2E+15	5.0E+14				
Italy	4.4	1.2	5.4	69	1.2E+16	1.0E+16	3.1E+14	2.0E+15	86475	70433	2161	13881
Lithuania	5.5	1.2	6.5	14	8.6E+15	7.2E+15	1.0E+15	2.9E+14	83553	70713	10011	2829
Latvia	2.3	1.4	3.3	0	1.0E+16	6.9E+15	2.7E+15	3.7E+14	113795	79120	30503	4171
Netherlands	3.6	1.3	4.6	75	8.8E+15	6.9E+15	1.4E+15	5.4E+14	60062	47059	9312	3691
Poland	5.5	1.2	6.5	218	1.0E+16	8.8E+15	1.1E+15	5.4E+14	87602	74100	9012	4490
Portugal	3.9	1.3	4.9	1	2.2E+16	1.7E+16	2.6E+14	4.2E+15	104980	83487	1247	20246
Romania	4.1	1.2	5.1	24	6.8E+15	5.5E+15	7.0E+14	6.3E+14	90201	72651	9281	8269
Sweden	6.6	1.2	7.6	40	4.7E+15	4.1E+15	5.8E+14	3.5E+13	35988	31279	4441	269
Slovakia	3.9	1.3	4.9	16	5.5E+15	4.4E+15	5.2E+14	5.9E+14	40687	32446	3877	4364
UK	3.7	1.3	4.7	125	5.9E+15	4.6E+15	7.1E+14	5.5E+14	42306	33224	5140	3943
EU-27	5.8	1.2	6.8	1581					60770	51158	4886	4725
minimum	2.3	1.1	3.3						32663	25801	1247	269
maximum	11.9	1.4	12.9						119410	89358	30503	20246

Wheat	EIR= human input(F)/natural input(R+N)	EYR= output (Y)/human input (F)	EYR= output (Y)/natural input (R+N)	AREA	All Input	Human Input	Natural energy input Non Renewable	renewable	All Input transformaty	Human Input transformaty	Non Renewable input transformaty	Renewable input transformaty
	Ratio	Ratio	Ratio	*1000 ha	SEJ	SEJ	SEJ	SEJ	[SEJ/J]	[SEJ/J]	[SEJ/J]	[SEJ/J]
Austria	4.1	1.2	5.1	284	5.2E+15	4.2E+15	4.8E+14	5.4E+14	61778	49744	5655	6379
Bulgaria	3.3	1.3	4.3	1137	3.7E+15	2.9E+15	4.8E+14	4.0E+14	68507	52452	8768	7286
Belgium-Luxembourg	7.6	1.1	8.6	240	9.1E+15	8.0E+15	5.1E+14	5.4E+14	75026	66317	4204	4505
Czech Rep.	3.6	1.3	4.6	870	6.0E+15	4.7E+15	8.1E+14	4.9E+14	75579	59276	10113	6190
Germany	4.8	1.2	5.8	3237	7.6E+15	6.3E+15	7.9E+14	5.2E+14	60634	50104	6358	4173
Denmark	4.1	1.2	5.1	694	5.4E+15	4.3E+15	5.4E+14	5.3E+14	43955	35276	4375	4304
Estonia	1.3	1.8	2.3	104	7.0E+15	3.9E+15	2.6E+15	4.2E+14	119363	66724	45393	7246
Greece	5.1	1.2	6.1	137	4.1E+15	3.4E+15	3.1E+14	3.6E+14	88002	73587	6753	7661
Spain	4.6	1.2	5.6	1569	4.5E+15	3.7E+15	4.1E+14	4.0E+14	89086	73314	7996	7775
Finland	0.9	2.1	1.9	218	9.6E+15	4.6E+15	4.7E+15	3.0E+14	141305	68021	68820	4464
France	5.6	1.2	6.6	4529	7.1E+15	6.0E+15	5.3E+14	5.3E+14	60239	51177	4545	4517
Hungary	2.1	1.5	3.1	1120	4.2E+15	2.9E+15	8.4E+14	5.1E+14	57525	39111	11408	7006
Ireland	4.1	1.2	5.1	95	7.1E+15	5.7E+15	8.6E+14	5.4E+14	70688	56830	8486	5372
Italy	7.0	1.1	8.0	632	5.8E+15	5.1E+15	3.1E+14	4.3E+14	69397	60683	3645	5069
Lithuania	2.7	1.4	3.7	432	5.7E+15	4.1E+15	1.0E+15	5.2E+14	78088	57080	13815	7194
Latvia	1.7	1.6	2.7	261	5.4E+15	3.4E+15	1.5E+15	5.0E+14	85977	53826	24146	8005
Netherlands	5.1	1.2	6.1	152	1.1E+16	9.1E+15	1.2E+15	5.4E+14	96078	80315	10986	4777
Poland	3.8	1.3	4.8	2300	7.3E+15	5.8E+15	1.0E+15	5.2E+14	102427	80926	14150	7351
Portugal	3.5	1.3	4.5	70	2.9E+15	2.3E+15	2.6E+14	3.9E+14	120136	93682	10675	15779
Romania	2.0	1.5	3.0	2106	3.1E+15	2.1E+15	5.8E+14	4.6E+14	72095	47851	13442	10803
Sweden	2.8	1.4	3.8	370	7.0E+15	5.1E+15	1.4E+15	4.1E+14	69296	51146	14056	4094
Slovenia	4.6	1.2	5.6	31	8.9E+15	7.3E+15	1.2E+15	4.3E+14	131984	108437	17226	6320
Slovakia	2.9	1.4	3.9	378	4.3E+15	3.2E+15	5.8E+14	5.4E+14	60846	45044	8220	7583
UK	6.0	1.2	7.0	1945	7.8E+15	6.7E+15	6.1E+14	5.0E+14	62606	53713	4886	4007
EU-27	**3.0**	**1.4**	**4.0**	**22909**					**152920**	**111287**	**20203**	**21430**
	0.9	1.1	1.9						43955	35276	3645	4007
	7.6	2.1	8.6						141305	108437	68820	15779

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