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Research article

A multiscale integrated analysis of the factors characterizing the sustainability of food systems in Europe

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ABSTRACT

Considering the existing world population, set of environmental impacts, and predicted changes in dietary trends, one can expect that, in the coming decades, food security will remain high on the list of sustainability concerns. In relation to this challenge, Europe's Common Agricultural Policy (CAP) must address a diverse set of goals: (i) guarantee a stable and affordable food supply; (ii) preserve the socioeconomic stability of farmers by guaranteeing their economic viability; (iii) protect the environment by reducing pressures on agroecosystems; and (iv) improve food security by reducing import dependence. Policies related to these diverse goals are likely to generate adverse side-effects. A particularly uncomfortable concern is Europe's massive reliance on imported feed commodities. The European Union (EU) is unlikely to be capable of domestically producing currently imported agricultural commodities and a significant move to internalize imports would dramatically increase pressures on local ecosystems. Faced with that potential predicament, it is essential to have a robust information system capable of simultaneously addressing a variety of policy concerns. In response, this paper presents a novel accounting framework—Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)—capable of generating an integrated set of indicators entangled across different scales and dimensions of analysis. Our versatile approach establishes a set of quantitative relations between: (i) the dietary intake of the society (desirability of the food supply); (ii) processes under human control (viability of the food system); (iii) processes outside of human control and associated with external biophysical limits determined by embedding ecosystems (feasibility of the food system); and (iv) the dependence on imported products (food security). The analysis of such relations can be tailored to the legitimate perceptions of different social actors affected by policies, anticipating potential conflicts and providing useful information for deliberation and negotiation. Our approach is illustrated with an analysis of the European agricultural system, covering the EU-27 plus the UK and Norway.

1. Introduction

Simultaneous concerns about food security, climate change, and loss of biodiversity have received a status of top priority on the international sustainability agenda (FAO et al., 2019; IPBES, 2019; IPCC, 2019). Various government institutions operating at different scales—local, national, and supranational—are adopting and adapting political strategies to address these concerns. Within the scope of the European Union (EU), the resulting sustainability challenge has implied a series of adjustments, continuous since the EU's creation in 1993, to the Common Agricultural Policy (CAP) (Kuhmonen, 2018). This picture is complexified when considering that sustainability concerns are entangled and policy solutions often prove mutually antagonistic. An example of this problem is found in the nine objectives of the CAP. For example, the objectives of *"Increasing competitiveness"* and *"Preserving landscapes and biodiversity"* can be understood as in tension (European Commission, 2019a). Since agriculture is both the main producer of food and the main driver of land use change—a primary driver of biodiversity loss and environmental impact (Charles et al., 2014; IPBES, 2019, 2016)—the tension among such objectives represents a major conundrum: increasing the food supply by increasing agricultural production generally translates into a greater impact on the ecological system. Concerning the attribute of competitiveness, more ecologically friendly production systems tend to have lower yields than conventional systems (De Ponti et al., 2012) while demanding a greater amount of work (European Commission, 2013). Goals of economic competitiveness in

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the international market represent a further confounding aspect of the CAP when contrasted with its objective of "Supporting *generational renewal*"., where in the case of generational renewal, the primary aim is to avoid that rural youth move to urban areas in search of higher-income jobs (European Commission, 2019b).

These few examples of objectives in tension indicate that the simultaneous achievement of all the CAP's objectives is problematic—a realization which may, in part, explain the massive evolution experienced by the EU agricultural sector toward an outsourcing of commodities production through trade. Through outsourcing measures and the externalization of low-value commodity production, such as animal feeds, EU agriculture is able to focus its activities on high-value product chains, such as animal products (Wang et al., 2018). Although this solution reduces the tension over the contrasting goals described in the above, it also elicits two new reasons for concern. First, when looking at existing trends at the world level, one should expect that demand for food will increase by 100–110% by 2050 (Tilman et al., 2011). This scenario is likely to problematize the security of the massive imports of food commodities in the EU (Tukker et al., 2016). In the face of new global economic competitors, resource shortages, environmental deterioration, and geopolitical turmoil, how dangerous is a heavy dependence on imports of food commodities? Second, the massive outsourcing of the production of commodities required by the EU agricultural sector poses ethical concerns since it entails the destruction of habitats and the transfer of environmental pressures to other social-ecological systems.

The issue of food security in Europe is complex and inextricably linked to the issue of food security in the rest of the world. An informed and fair deliberation on this issue would require the availability of robust information about events that are: (i) occurring simultaneously across hierarchical levels and dimensions of analysis, i.e. events that are only observable across different scales and can only be represented using non-reducible metrics; and (ii) relevant in different ways to a diverse array of stakeholders—consumers, traders, farmers, institutions—for different reasons (Munda, 2008).

This paper presents an accounting framework, Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), which allows the quantitative contextualization of narratives about food security in relation to various sustainability concerns. MuSIASEM establishes a set of quantitative relations between: (i) the final food consumption of a society, i.e. the various end-uses of food in the household, industrial, energy, and agricultural sectors; (ii) the set of processes under human control, taking place in the technosphere, i.e. processes related to the viability of the food system; (iii) the processes outside human control, i.e. processes taking place in the biosphere and relevant for the study of biophysical limits both on the supply and the sink side—the feasibility of the food system depends on the preservation of the health of embedding ecosystems; and (iv) the dependence on imported products, which affects food self-sufficiency. After establishing a framework of analysis capable of establishing a set of expected relations over these different aspects of the sustainability of the food system, we can identify the social actors that are or will be affected by a given policy anticipating potential conflicts. In this way, it becomes possible to generate an open and transparent information space that can be used to inform processes of deliberation.

The MuSIASEM approach, illustrated in this work through an analysis of the European agricultural system (EU-27 plus the UK and Norway), allows:

(i) the quantitative operationalization of the formal relations between system components operating both in the technosphere and the biosphere;
(ii) the characterization of the pattern of internal consumption of food, determined by the choices of dietary intake;
(iii) the quantification of the level of commercial openness, relevant for the discussion of food security;
(iv) the characterization of the local requirement of technical and economic resources (land uses, irrigation water, fertilizers, pesticides, etc.) due to both the local production of food and the "externalized" production of imported food (assessed in the form of "virtual quantities" embodied in imports);
(v) the characterization of the externalization of the environmental pressure determined by the use of primary sources in both the local production of food and the "externalized" production of imported food, assessed in the form of "virtual quantities" embodied in imports.

This information space provides an integrated, multi-scale, quantitative representation of the functioning of the food system and its interactions with other social-ecological systems. It can be used: (i) in a diagnostic mode to study critical aspects in the form of indicators that can be tailored on relevant concerns; and (ii) in an anticipatory mode by exploring scenarios based on the adoption of benchmarks.

The rest of the text is structured as follows: Section 2 presents the methodology used to integrate non-equivalent narratives with the integrated representation generating quantitative framework. Section 3 presents the main results. Section 4 presents the discussion and Section 5 the conclusions.

2. Methodology

2.1. Integrating narratives found in the food system

A food system is determined by the complex interface of different processes taking place simultaneously across different scales, both beyond and under human control. Relevant processes include, for example, natural biogeochemical cycles, ecological processes (when moving from the soil to biomes), agroecological processes on the interface of ecosystems and society, socio-economic processes (in rural communities, urban communities, industrial sectors, the global market), and physiological processes associated with nutrition (of individuals in and outside the household). Thus, relevant features of a food system can only be observed by simultaneously adopting different dimensions (nutritional, economic, social, demographic, technical, agronomic, ecological) and different scales (micro, meso, macro) of analysis. Because of its innate complexity, it is impossible to even imagine a quantitative representation of the functioning of a food system capable of simultaneously characterizing all of the factors determining its sustainability and all the features determining its desirability. From a policy perspective, we can say that any quantitative definition of what is considered to be an "improvement" in the food system is likely to be contested because of (Munda, 2008): (i) the existence of legitimate but contrasting normative values and perceptions found among social actors—referred to as *social incommensurability* in the jargon of Societal Multi-Criteria Evaluation; (ii) the lack of robustness in the quantitative characterization across different dimensions and scales—referred to as *technical incommensurability*; and (iii) the unavoidable presence of heavy doses of uncertainty both in the normative framing and in the chosen quantitative representation.

In this situation, the problem faced by scientists generating an integrated assessment used in governance processes is that dramatic "simplifications" of complexity generate a phenomenon termed "hypocognition"—the unavoidable missing of relevant aspects of the complex system under analysis, aspects that were not included in the chosen set of quantitative indicators (Lakoff, 2010). Another effect of this "simplification" is that, depending on which concerns are neglected, selected policies will generate perceptions of "winners" and "losers" among the set of relevant social actors (May and Jochim, 2013). In fact, even within the same food system, we find different actors that are legitimate carriers of non-equivalent expectations and interests. These social actors can be different types of "consumers", "producers", "post-harvest economic agents" (international food traders, food industry workers, distributors, and retailers), and "policy makers". They operate at different levels and each endorses different narratives about how the performance of food systems should be "improved".

When dealing with the representation of the flows in a food system, conventional analytical approaches would typically assume a linear causation over the definition of the flows controlled by the various social actors, i.e. agricultural production comes first then post-harvest handling then final consumption. However, when adopting a relational analysis, we should expect a different situation in which a system of double causation applies—typical of complex systems (Grene, 1969). There is a *downward causation* (Campbell, 1974) determined by the specification of the required functions—what is wanted—and an *upward causation*, determined by material entailment in sequential pathways and constraining what can be done. The balance between these two forms of causation determines the final quantity and quality of the flows that can be recorded in the set of formal relations.

For example, a change in *downward causation* can be determined by a change in the dietary pattern (e.g. a higher consumption of meat) on a top component (e.g. the step of consumption decided by consumers). This change implies changes in the flows through the lower compartment—the step of agricultural production—that modify the impact of the ecological system (Westhoek et al., 2014). Conversely, a change in *upward causation* could be determined by a collapse in the underlying ecological system. The consequent reduction in local supply—the reduction of the flow of production in the lower component—will force changes in the dietary pattern of society on the top. Modern socio-economic systems, such as the EU, can avoid the negative consequences associated with upward causation by relying on food imports. As discussed earlier, this reliance represents a key factor capable of altering the relations across components considered in an analysis. For this reason, it becomes essential to specify whether the initial production of agricultural commodities either takes place inside society or is imported.

2.2. Conceptual basis of MuSIASEM framework

The quantitative analysis presented here is in the tradition of the input-output analysis of the economic process (Leontief, 1951; Stone, 1981; Stone and Croft-Murray, 1959), with a biophysical focus on the interface of the economic process with the environment (Daly, 1968; Duchin, 1992; Lenzen, 2011; Leontief, 1970). In particular, we implement the concept of "ghost acreage" (Borgstrom, 1965) and the family of indicators of "embedded" or "virtual" environmental services, e.g. "water footprint" (Mekonnen and Hoekstra, 2011) and "land footprint" (Giljum et al., 2013), both of which can be associated with the concept of "phantom carrying capacity" (Catton and Dunlap, 1980).

The MuSIASEM accounting framework has been developed from the perspective of systems theory (Bertalanffy, 1973) to face the challenges associated with the analytical representation of complex systems (Giampietro et al., 2012, Giampietro et al., 2014, Giampietro and Mayumi, 2000). MuSIASEM resorts to hierarchy theory (Allen and Starr, 1982) and relational analysis (Louie, 2009; Rashevsky, 1954; Rosen, 1991) to reinstate the role of the observer in the pre-analytical choices of system definition. At the same time, the framework uses the concept of the metabolism of societies (Giampietro et al., 2012; Lotka, 1956) to interpret, when defining the border between the system and its environment, the interactions between the different structural and functional compartments. System compartments are described in relation to their exchanges of matter and energy necessary to express expected functions and to reproduce structures. Thus, MuSIASEM allows the representation of a metabolic pattern across levels of analysis in quantitative terms. Such evaluation starts from the identification of *what the system is* and *what the system does* through the identification of the constituent components of the system and the rationale of the flow-fund model proposed by Georgescu-Roegen (1971). The framework can be used to identify and characterize three key aspects of sustainability: (i) *desirability*, related to the implications of the normative values of the people in a society; (ii) *viability*, a technical and economic dimension related to the internal characteristics of the system; and (iii) *feasibility*, related to the compatibility between the system and its context. To these three aspects one must add the analysis of the level of openness of the metabolic pattern, i.e. how dependent the food system is on imports.

2.3. Construction of the representation

MuSIASEM uses the theoretical notion of *grammar* for the representation of complex systems. When defining a grammar, the system analyst selects and defines a set of semantic categories and their expected relations in such a way that the representation is adequate for the proposed objectives. The grammar used for the representation of the functioning of the food system of the 27 member states of the EU plus the UK and Norway is shown in Fig. 1.

In this representation, two views of the process co-exist. An *internal view*—the flows metabolized inside the system by the various compartments—and an *external view*—the flows exchanged both with the embedding ecological systems and with other socio-economic systems (trade). The internal view provides an understanding of the purpose of food required with regard to: (i) the supply of nutrients to the population, i.e. final consumption of the household sector; (ii) the supply of feed and seeds for agricultural producers, i.e. flows to the agriculture sector; (iii) the supply of raw materials to the various sectors of the economy, i.e. other uses; and (iv) international trade, including the case of re-export. In this scheme, each one of the components of the system metabolizes a specific flow of food determined by its specific function. Therefore, depending on the component considered, it is imperative to generate different types of relevant information. When dealing with final human consumption, one looks for information relevant to the safety and nutritional composition of food flows. When dealing with international trade, one looks for information about economic values and market regulations.

When adopting the internal view, we can associate the concept of *gross supply* with "what is consumed". When adopting the external view, we can associate *gross supply* with "what is made available". Put another way, "*gross supply*" is a notional category that can be dichotomously interpreted as a biophysical requirement associated with downward causation or as a biophysical supply associated with upward causation.

For characterizing the relevant factors to be considered in the external view, MuSIASEM adopts the concept of a *metabolic processor* from relational analysis (Louie, 2009; Rashevsky, 1954; Rosen, 1991). A metabolic processor is an expected pattern, i.e. a profile of inputs and outputs, associated with a specific physical process of production. In the case of agricultural production, a metabolic processor would include categories such as: (i) the consumption of a profile of inputs (e.g. water, energy, fertilizers, pesticides); (ii) the generation of useful outputs (e.g. wheat, soy, rice); and (iii) the generation of unwanted products (e.g. CO_2 emissions, wastewater contaminated with pesticides). More details on the use of metabolic processors for this type of analysis are available in (Cadillo-Benalcazar et al., 2020).

In this study, 98 unitary processors were built to populate the network of relations over the European food production systems illustrated in Fig. 1. Each processor may be classified in general terms as either a processor of plant products or a processor of animal products—each class is handled differently. Through a scaling process, processors are grouped according to their relevant sequential pathway or parallel component (Cadillo-Benalcazar et al., 2020).

The effect of international trade entails the indirect use of external processors. Such processors must be considered as embodied in imported commodities, as indicated in the "Gross Supply" node—symbol **B** in Fig. 1. Exchanged flow elements refer to quantities of food that will be consumed by different productive sectors within the period of time under analysis. When considering the import and export of live animals—symbol **C** in Fig. 1—we can distinguish two types of elements:

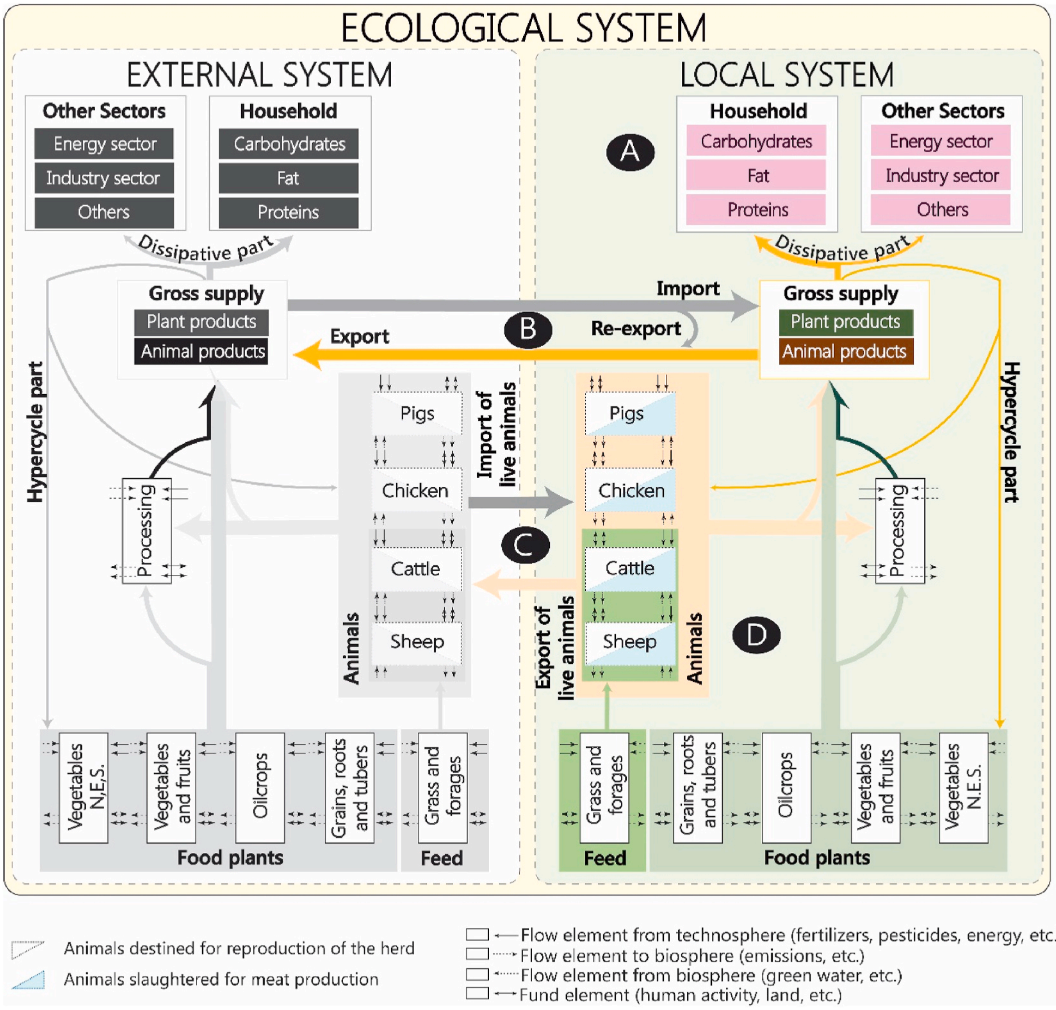

Fig. 1. A grammar illustrating the expected relations over the different structural and functional elements of a food system while considering its interaction with other food systems through trade.

animals that are exchanged for reproducing the herd (fund elements) and those that go directly to slaughter (flow elements).

Finally, this method of accounting allows for the characterization of the environmental pressure exerted on local ecological systems and the environmental pressure externalized to the ecological systems of other countries engaged in the production of imported food. Three methods can be used to estimate externalized environmental pressures: (i) if the source of imports is known, one can calculate "virtual environmental pressures" (consumption of water from the biosphere and technosphere, land uses, fertilizer, and pesticides used) in relation to the country of origin and using the known technical coefficients (yield, hours of work, blue water, green water, etc.) of the exporting country; (ii) if the imports come from a mix of different countries, one can calculate "virtual environmental pressures" as if the imports were produced only by the country that has the major share of production, using for the estimation the technical coefficients of the country; and (iii) if one wants to calculate the biophysical savings (the avoided environmental pressures) that the society under study is enjoying because of imports, one can calculate the "externalized environmental pressures" using estimates of the local technical coefficients of agricultural production of the country under study. In this way, it is possible to calculate the amount of resources that would be needed if imports were produced locally. By applying this last method, we can generate a general understanding of how much local environmental pressure will increase if the importing country were forced to re-internalize the production of imports—to achieve full self-sufficiency, for example. For the purposes of this study, we adopted this third method.

2.4. Assumptions and limitations

Despite great efforts to collect the best information possible for the reference year (2012), some required data remained missing. This issue was particularly relevant in the estimation of labor input divided by crop type and in relation to data on production inputs from EU countries in the Eastern region. In the case of missing processor information, the weighted average technical coefficients of the parent crop category were applied. For example, if it proved impossible to collect data for a wheat processor in a given country, the average technical coefficient of the parent crop group (cereals) was applied. In the event that, in turn, this information (the technical coefficient of cereals) was not available, the weighted average technical coefficient of the parent geographical region was assumed. In other words, "cereals" no longer referring to a specific country, but "cereals" defined at the country-aggregated region level. Lastly, in the case of missing data in time series data sources, data from proximal years was used. Marine food supply was not considered in the analysis. For further details on data assumptions, refer to the Supplementary Material.

2.5. Data sources

A summary of the data sources for the quantitative assessment is provided in Table 1. An extended discussion is located in the

Supplementary Material. The database is available at https://doi.org/10.5281/zenodo.3923010.

3. Results

3.1. The local system: an internal view on consumption

In the grammar shown in Fig. 1, the quantification of the required supply in the household sector is indicated by the symbol **A**. Depending on the diet chosen by the population, the grammar allows the calculation of a required supply (production plus import) of a given mix of agricultural products needed to generate the supply of consumed food products. As shown in Fig. 2, different countries present different dietary profiles. For example, Alpine, Western, British Isles, and Nordic countries have the highest caloric intake in total, with grains, roots, and tubers presenting the highest caloric contribution to diets. In addition, those countries also have the highest consumption of animal products in the EU. On the other hand, Romania (South eastern), Poland (North eastern), and Lithuania (Eastern) have a higher consumption of grains, roots, and tubers in absolute terms. That said, when comparing their consumption of oil crops, those same countries consume roughly half or less that of Austria (Alpine). This heterogeneity in dietary profiles is due to the availability of foods and cultural factors, and each country develops its own dietary recommendations (European Commission, 2019c).

In general, we can see that changes aimed at reducing environmental pressures will require changes in consumption patterns. To that end, for example, McMichael et al. (2007) propose a maximum global average consumption of 50 g of red meat per person per day to fight climate change. The question is, who will be willing to accept strategies of this kind? And what about dietary heterogeneity across different scales?

3.2. The interface between the local system and its context (the level of openness)

This section refers to the segment indicated by the symbol **B** in Fig. 1. As illustrated in Fig. 3, there are important differences in the level of self-sufficiency of EU countries. At the country level, Poland (84%) and France (81%) have the highest percentage of self-sufficiency in the production of vegetal products. At the regional level, most Eastern, South eastern, and North eastern countries have a level of self-sufficiency greater than 50% (with the exception of Slovenia at 28%). In contrast, the Netherlands (28%) and Norway (24%) have a low level of self-sufficiency in plant products.

Concerning the production of products of animal origin and in terms of self-sufficiency, the situation appears more worrisome. The highest rates of self-sufficiency are achieved by Poland, Norway, Finland, and Ireland, at approximately 75%, 62%, 60%, and 56%, respectively. Most countries do not reach a 50% self-sufficiency rate for products of animal origin. However, direct analysis of the local production of animal products misses an important part of the story. Such levels of partial self-sufficiency do not address the heavy dependence EU animal production has on imported feed. When considering imported feed in the analysis of food security, we can appreciate a latent state of vulnerability to external factors. Regarding animal feed, Fig. 3 also shows that all EU countries, with the exception of Ireland, have a self-sufficiency rate lower than 30%. By implication, it can be observed that a reduction in the consumption of animal products in the EU diet would also reduce the dependence on imports. To this end, Westhoek et al. (2014) point out that a replacement of 25–50% of food of animal origin would reduce the use of soy meal by 75%. But what will happen to EU producers of animal products? As we have seen before, "desirability" for different social groups also plays an important role.

Another important point to be considered, relevant for another type of dependence on imports, is the trade of live animals. In the grammar presented by Fig. 1, this aspect is addressed by the section indicated by the symbol **C**. Live animals are imported and exported: (i) directly for slaughter (to produce meat); (ii) in a pre-slaughter phase—to be fed in importing countries; or (iii) for reproductive purposes. It is critical to consider these differences when assessing the degree of externalization of national food systems.

For example, all the embedded biophysical resources necessary to produce animals imported directly for slaughter have already been externalized and should, therefore, be accounted as such. In general, the number of cattle imported for slaughter is not significant with respect to current national levels of meat production. Therefore, the movement of live animals simply reflects the specialization of select countries in pursuit of economic gain. For example, Fig. 4 shows that France exports a significant amount of cattle, mainly to Italy. Similarly, the Netherlands specializes in raising pigs, subsequently sent to Germany. This specialization in certain countries has been facilitated by the Treaty on the Functioning of the European Union (TFEU), which facilitates trade between member countries. Such specialization generates a substantial complexification of supply systems.

3.3. The local system: an external view on production

For the component of production (associated with farmers), biophysical processes, socio-economic processes, and ecological processes must be considered simultaneously in order to study overall sustainability. In the grammar shown in Fig. 1, the quantification of the various inputs and outputs is indicated by the symbol **D**. The external view describes the interface between processes within the borders of the system under study and under human control and ecological systems. The effects of those processes can be interpreted as the environmental pressure that agriculture exerts on ecosystems it exploits. That is, in modern high-external input agriculture, the various land uses associated with crop production not only entail the destruction of natural habitat, but also an unnatural pressure of flows—e.g. water abstraction, supply of nutrients, applications of pesticides—on agroecosystems and well outside the "natural" expected pace and density in undisturbed ecosystems (Lomas and Giampietro, 2017). This implies that importing agricultural commodities represents a major release from this pressure for local agro-ecosystems. For example, Fig. 5 shows that, in terms of land use, the internalization of imported products would represent a significant additional pressure on the local ecological system.

Interpreting Fig. 5, the Netherlands and Belgium would have to increase their agricultural land about 14x and 8x, respectively, if they

Table 1
Data sources for the various quantitative assessments.

Production, import, export, gross supply, and consumption of food.	FAO Trade, Food Balance Sheet and the Production Livestock Primary: FAO et al., 2019a, 2019b.
Choice of grouping of food products, related to the FAO Food Commodity List.	FAO, 2014.
Factors for converting derived products into primary products.	FAO (2017a).
Production factors for plant-based food processors.	(i) land: Calculated from yield FAO, 2019b. (ii) green/blue water: Mekonnen and Hoekstra, 2010b. (iii) fertilizer: FAO et al., 2002. (iv) pesticides: Eurostat and European Commission, 2007. (v) human activity: data and assumptions in Supplementary Material
Trade of live animals.	Eurostat (2019).
Production factors for animal-based food processors.	(i) animal production systems, herd, output products, and feed: FAO, 2017b. (ii) blue water: Chatterton et al. (2010) and Mekonnen and Hoekstra, 2010a.
Production factors for grass and silage processors.	(i) land: FAO, 2018; FAO, 2016; Haberl et al., 2007 (ii) water: Portmann (2011).

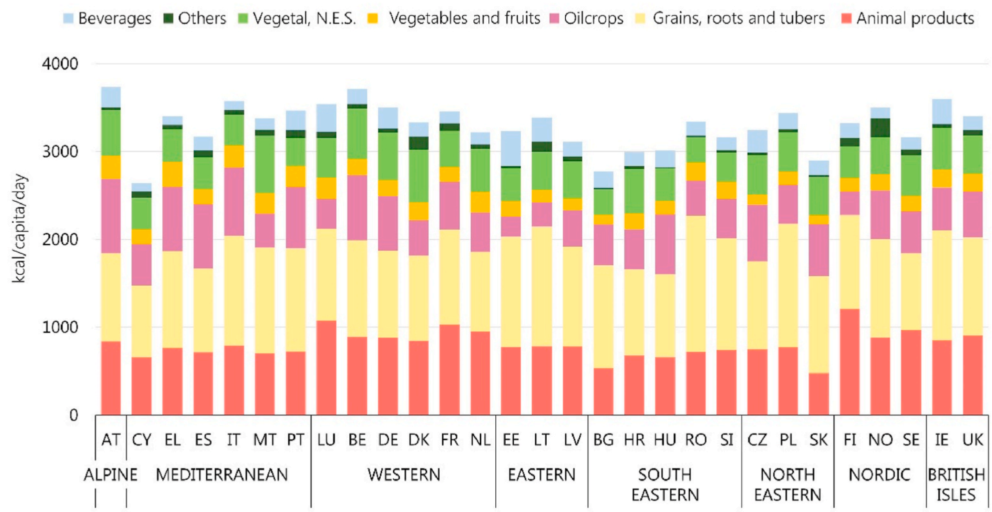

Fig. 2. Absolute caloric intake per person and per crop category in the household sector for 2012. Source: FAO (2019a)

would have to immediately internalize the production of the agricultural commodities they import. In other EU countries, the land requirement for complete internalization is substantially smaller. That said, in nearly all cases, the land requirement for complete internalization is greater than the available agricultural land. As previously mentioned, an important aspect of the issue of internalization is related to the import of animal feed production. This suggests that, if their production cannot be moved to EU countries and if the consumption of meat in the diet will not be reduced, deforestation in tropical areas in the coming years will continue to advance (Carvalho et al., 2019).

It is pertinent to note that agricultural land also includes land that has the potential to become arable in nature, but that is currently not. Therefore, complete internalization would imply an increase in inputs for agricultural production and conversion of fallow lands back into production. Consequently, a full internalization process would, for several reasons, be unrealistic—not only in terms of the shortage of land in absolute terms, but also due to competition for alternative land uses due to intense urbanization (Gardi et al., 2015). At present, around 48% of European territory is considered to be agricultural land (European Comission, 2018), competing with the areas of natural habitat required to preserve biodiversity. Thus, in addition to being unfeasible, an internalization of the production of imported commodities would imply an important impact on biodiversity.

The internalization of food production in the EU would not only imply radical changes in land use, but also an increase in the requirement of production inputs, such as nitrogen, phosphate, and potassium (NPK) fertilizers and pesticides. In relation to this point, Fig. 6 presents the modern situation of EU countries.

Fig. 6 clearly shows that the immediate internalization of imported products would have a significant impact on NPK fertilizer and pesticide demand. Countries such as Romania, Poland, Hungary, and Bulgaria would require, under the current conditions of production and the availability of required land, to increase fertilizer use by less than 50%. On the other hand, countries such as the Netherlands, Belgium, and Malta—countries that have limited land and are substantial food importers—would expect an increase in NPK fertilizer usage of over 90%. Regarding pesticides, only Poland, Romania, France, Spain, and Italy increase their use by less than 50%. Another aspect to consider is that, if EU countries intend to increase the domestic supply of food—for example, to improve food security, they must anticipate the possible effects of that increase in terms of a possible contamination of groundwater. In addition, they must look for alternatives to the vulnerable dependence on imported mineral fertilizers (European Commission, 2019d), due, for example, to a projected shortage of phosphorus—a resource with limited supply availability (Cordell et al., 2009; Neset et al., 2016). Obviously, this increase in input use would not be possible, we report these assessments only to flag the seriousness of the dependence on imports.

Importing food also allows the externalization of other requirements of socio-economically relevant inputs—human labor, for example. This externalization is extremely important in the EU, where the agricultural sector generates an economic return lower than in other economic sectors. In the EU, farmers receive around 40% less income than workers in other sectors, a situational variable in turn motivating the CAP to go through great effort to maintain the economic viability of farmers (European Commission, 2019b). Assessing the externalization of the requirement of labor in agriculture, as depicted in Fig. 7, the existence of differences between EU countries is observable, as determined by the level of technical capitalization of their agricultural system.

To contextualize the data reported in Fig. 7, one can calculate the equivalent Annual Work Units imported in this way by multiplying the numbers of virtual hours per capita embodied in imports by the size of the population and dividing the resulting number by the yearly workload. In the case of the Netherlands, use of an approximated value would have: 145 h per capita multiplied by 17 million people and divided by 1800 h of workload per year, resulting in about 1.4 million farmers equivalent. The countries in the Western, Mediterranean, Nordic, Alpine, and British Island regions use fewer work hours per capita per year than the other EU countries. It should be noted that economic growth tends to reduce the fraction of working time that a country allocates to agriculture (Giampietro, 2018). This is why, despite a large effort in terms of subsidies, the number of farmers has been seen to continuously shrink in Europe over recent decades. Human activity represents another important point to be considered when running scenarios of massive internalization of the production of imported agricultural commodities. Further insight into the anticipation of the internalization of EU agriculture, including the relevance of such anticipations for policy and using similar logic and methods as this work, are made by Renner et al. (2020).

4. Discussion

The results presented aim to illustrate the potential of an innovative accounting framework generating an integrated information space capable of handling different criteria of performance in relation to different sustainability concerns. By using this information space, different groups of social actors can visualize the relations through which an improvement of the situation, according to their own

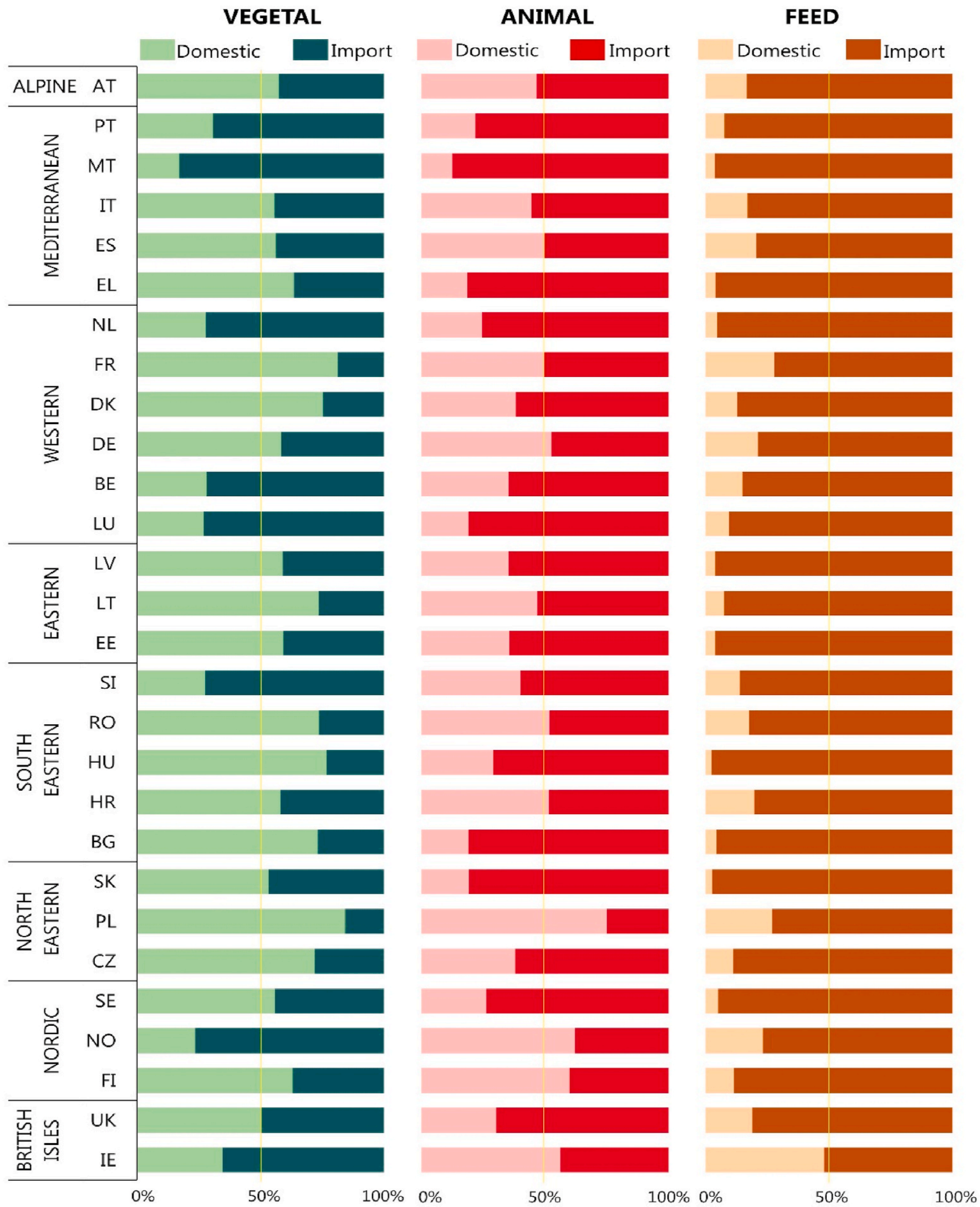

Fig. 3. Level of openness (dependence on import) for animal feed (right graph), animal products (central graph), and vegetal products (left graph) for EU countries for the year 2012. Percentages based on physical quantities.

legitimate perspective, may imply negative consequences in relation to other concerns prioritized by other social actors. A transparent information space that allows an anticipation of potential troubles and conflicts can dramatically increase the quality of the deliberation over the sustainability of food systems (Halpern et al., 2019). For example, the information contained in Fig. 2 is available in the FAO FBS (FAO et al., 2019a, 2019b). However, when this information is used within the MuSIASEM accounting framework, it can be related to the technical characteristics of the production systems, their natural resource basis, and the pressure they exert both on the local ecological system and on other ecological systems affected by the production of imports. Without this integration, it is very difficult to use the indications of the FAO FBS and food-based dietary guidelines for a systemic analysis of the sustainability of the food systems of European countries (Bechthold et al., 2018). More in general, we can say that the more holistic an analysis of "hidden relations" is, the greater the ability the analysis has to avoid the expression of contradictory behaviors. For example, in 2019, European countries and civil associations complained to the Brazilian government for its inaction in relation to the fires in the Amazon rainforest. However, those fires can be related to the need of increasing the production of agricultural commodities destined for export in the face of a growing demand (Pendrill et al., 2019). In relation to this point, in 2012 (the reference year of this study), Brazil and Argentina represented the two most substantial sources of soybean cake import for the EU (FAO et al., 2019a, 2019b). At the same time, those two countries are currently being targeted by social protests in the EU over the deforestation of the Amazon rainforest (Brazil) and the problems caused by the use of pesticides (Argentina), both related to the production of soybean.

A second strength of the proposed approach is its semantic openness. This approach has been used to assess the pros and cons of the production of alternative feeds for salmon in Norway (Cadillo et al., 2020) and to study the performance of a complex of electricity production-desalination of water used to irrigate greenhouses in the Canary Islands (Serrano-Tovar et al., 2019). The choice of the accounting categories for food—e.g. "Grains, roots, and tubers"—may include products that have different production requirements (the

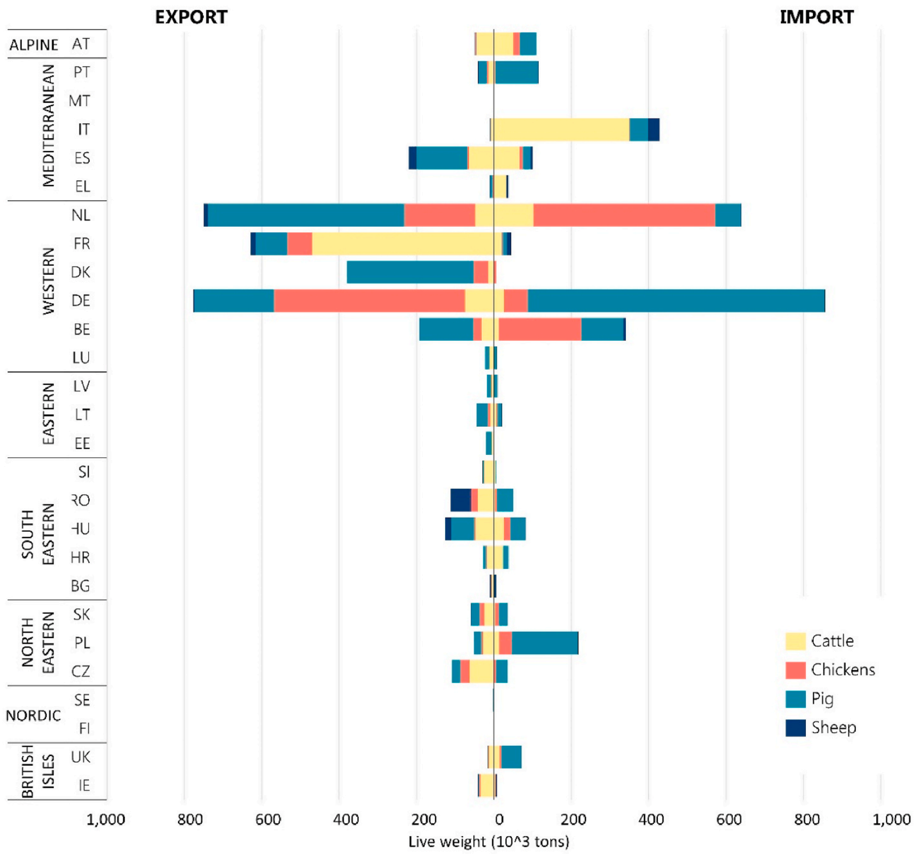

Fig. 4. Export and import of live animals in EU countries (2012). Source (Eurostat, 2019).

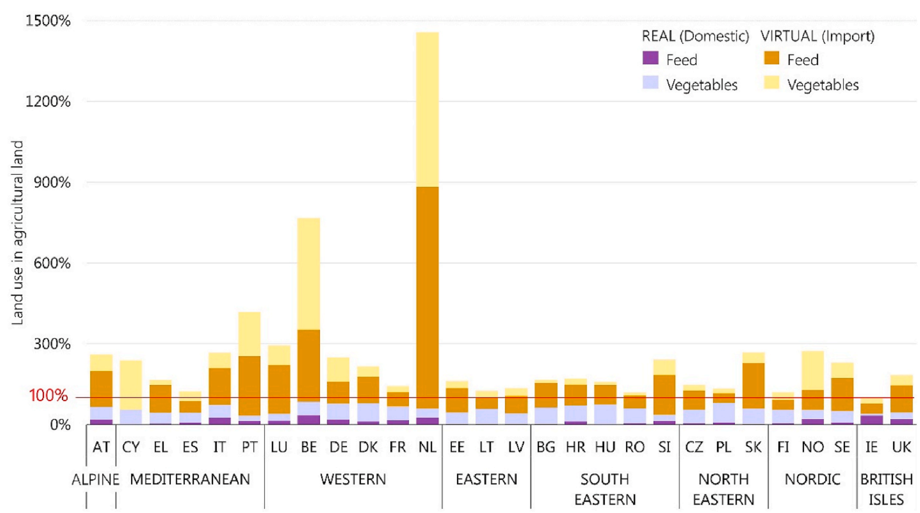

Fig. 5. Actual use of land (purple gradient) and land saved (yellow gradient) per agricultural land in EU countries. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

inputs for producing corn are different from those required by potatoes). For this reason, depending on the purpose of the analysis, the pre-analytical choices of the accounting categories must always be discussed and agreed upon with the users of the results. That is, the flexibility of this accounting system and its semantic openness in the pre-analytical phase, when deciding what and how to account for flows, guarantees a total transparency in the process of the choice of an accounting grammar. When done in a participatory way, this choice translates into a "co-production" of the accounting framework with the users of the results.

A third strength of MuSIASEM is that it allows to contrast between what is desired and what can be done. In this sense, its approach to biophysical accounting generates descriptions of the state of the system analyzed across different levels and dimensions of analysis, by which it provides the necessary elements to explore the possible consequences of actions to be taken. In this way, MuSIASEM can be used to complement economic analysis by checking the quality of proposed narratives in terms of their biophysical feasibility and viability. Of particular relevance is the accounting of human activity, expressed in hours per year and used to contextualize the size of the various components of relevant

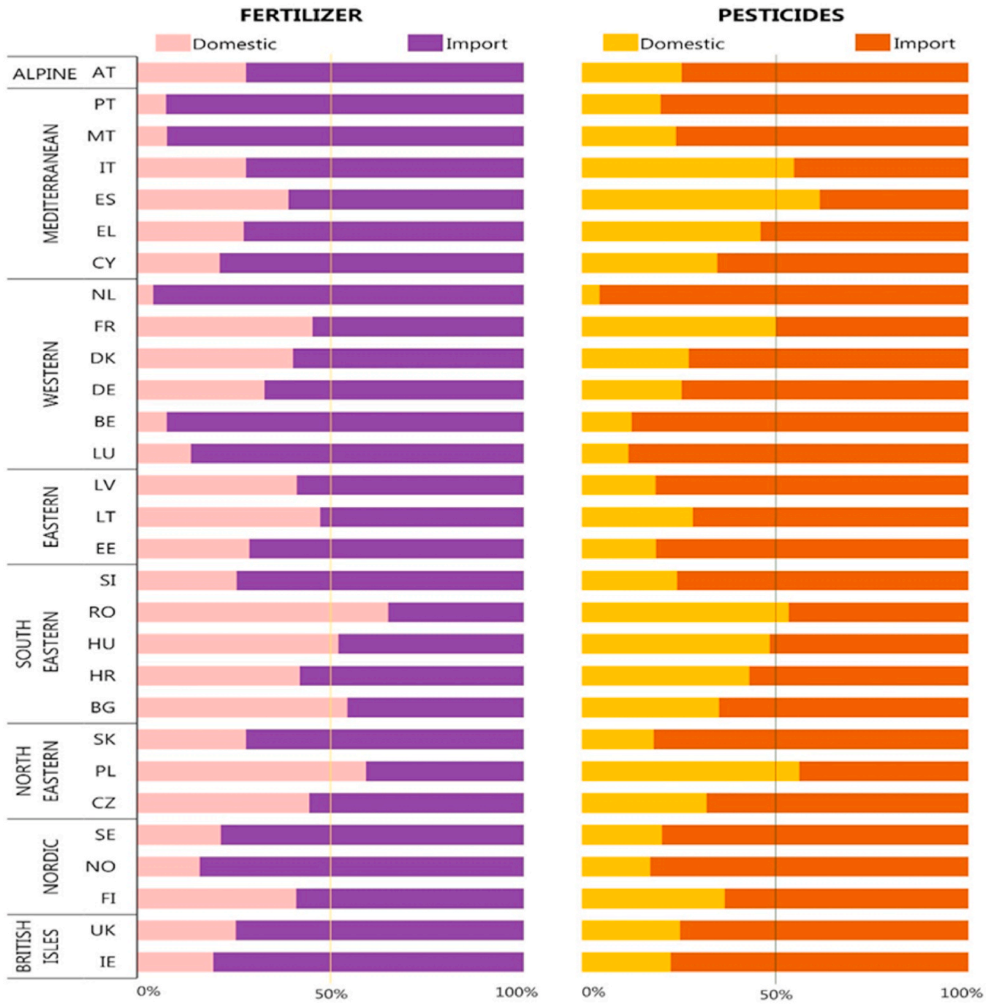

Fig. 6. Percentage mass of fertilizers and pesticides used for food production versus that avoided due to importation.

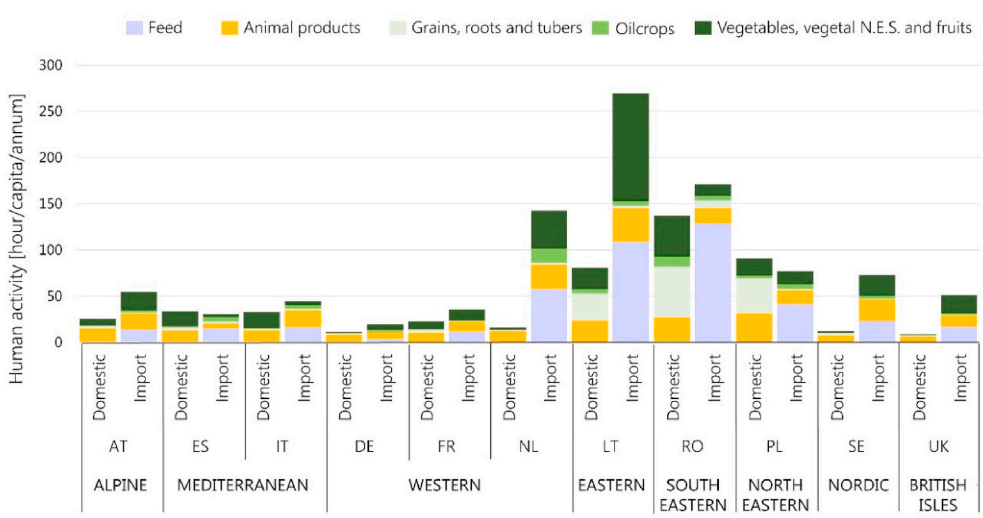

Fig. 7. Actual use of working hours per capita per year in agriculture (left bar) and saved working hours per capita per year in agriculture through imports (right bar) in eleven EU countries.

socio-economic systems. This aspect is especially important for the analysis of food systems. When considering the demand side, quantities of human activity—mapped against the characteristics of age classes and demographic structure—can be used to explore dietary requirements in both qualitative and quantitative terms. When coming to the supply side, quantities of human activity—mapped against the characteristics of production systems and the structure of the agricultural system—can be used to explore the share of the workforce required to be allocated to food production. As shown in previous applications of MuSIASEM (Giampietro, 1997a, 1997b; Giampietro et al., 2012), the contemporary mode of socio-economic development entails a massive movement of workers away from the agricultural sector. Workers in the agricultural sector of developed countries generate less added value per hour of labor than workers in other sectors of the economy. Simultaneously, they require a larger economic investment in terms of technical capital (Giampietro, 2009; Giampietro et al., 1999; Velasco-Fernández et al., 2020). For this reason, despite the massive use of subsidies, the fraction of the workforce in agriculture is seen to be continuously shrinking in developed countries (Giampietro, 2018). We should not expect an inversion of this trend any time soon. These considerations flag the existence of a dilemma between a strategy aimed at the maximum generation of added value (including agribusiness, i.e. imports and re-export of agricultural commodities), which has generated a situation where developed countries exhibit a major dependence on imports, and a strategy that attempts to maintain a system-internal production of food. This second strategy is becoming more and more difficult to maintain in developed countries due to the growing economic burden of agricultural subsidies and growing concerns for the protection of the environment, which is already severely stressed by modern techniques of agricultural production—a result of so-called high external input agriculture. The analysis provided by MuSIASEM can assist social deliberation efforts at this crossroads.

The creation of the EU has increased the exchanges of goods and services between EU member countries. However, at the same time, it has made the EU an attractive market to other countries through the signing of several free trade agreements. This process of globalization has complicated the interactions among social-ecological systems and groups of social actors within and across the borders of the EU. In the existing situation, when considering the “big picture”, it has become more and more difficult to maintain coherence in the use of the narratives about the performance of “food systems” (which food systems?). The co-existence of a diversity of concerns, criteria, and targets defined across different scales and dimensions of analysis generates a systemic muddling in the framing of sustainability problems. For example, the CAP invests an important amount of economic resources to generate an affordable supply of animal products in the diet. At the same time, in the EU, there is now a discussion over the need to impose taxes on animal products in order to increase their price (Sagener, 2017). This paradox shows the importance of avoiding simplistic framings of sustainability issues generating “silo analysis” and leading to “silo governance” blunders. We do not wish to “fix” a sustainability problem (e.g. reducing meat consumption) while worsening another one (e.g. importing more refrigerated fresh vegetables and exotic fruits arriving in airplanes from all over the world).

5. Conclusion

The CAP deals with a wicked problem (Rittel and Webber, 1973; Kuhmonen, 2018)—the sustainability of the EU food system. Even defining such a problem is difficult. An acceptable solution requires guaranteeing an affordable and safe food supply to European citizens, protecting the welfare of farmers and rural communities, and preserving the health of the environment while guaranteeing food sovereignty (European Commission, 2019a). The simultaneous achievement of these goals is a formidable challenge entailing the generation of frictions and undesirable side effects at the moment of implementing policies. The growing dependence on imports of agricultural commodities (esp. feed) in the EU has gained increasing attention in recent decades; however, conventional analytical tools based on reductionism seem to not be capable of producing the effective analyses needed to deal with the problem. Without a holistic perception and representation of the complexity of the relations found in the food system, scientific advice risks to reinforce the current “silo governance syndrome”—solving one problem at a time while ignoring negative side effects on other aspects of the sustainability issue in question.

The examples given in this study show that it is possible to integrate the analysis of four pillars of food security: (i) the quality of dietary intake; (ii) the economic viability of the agricultural sector; (iii) environmental security; and (iv) food self-sufficiency. Data on the final consumption of food products can be related to nutritional intake data. At the same time, they can be related to socio-economic factors. The interface between the internal and external views provides a frame of reference for analyzing the factors determining the availability of food supply—domestic production versus imports. This interface allows the analyst to define which fraction of the final consumption of food products is due to the activity of local farmers. The analysis of the domestic production of food products can be related to the economic viability of various processes in relation to: (i) the availability of local resources; and (ii) the competitiveness of local producers on international markets. These two points determine the capacity of the agricultural system under analysis to carry out the production of expected outputs. Finally, the identification of processes of internal production—that which can be geo-localized—allows the analysis of the environmental pressures they exert on local ecological systems, i.e. feasibility in relation to biophysical limits outside human control.

The versatility of the proposed approach allows to connect different narratives—relevant for different social groups—and to develop different indicators relevant for them. The novelty is that the values of the various indicators generated in this way are entangled in the accounting framework. They are kept in coherence through congruence constraints over a quantitative analysis carried out using different metrics defined across levels and dimensions. Because of its philosophy, the proposed framework cannot be used to identify the “best course of action” but, rather, it can be used to explore the existence of limits, bottlenecks, and trade-offs. It allows for a more transparent and better-informed deliberation about the sustainability of food systems. For example, the results shown here illustrate the existence of heterogeneity among the EU countries not only in relation to production patterns, but also in consumption patterns. These differences are due to differences in resources, cultural heritage, and levels of economic openness. Another source of heterogeneity is the level of direct or indirect dependence on imports, a dangerous vulnerability in terms of food security in the face of new global economic competitors, resource shortages, environmental deterioration, and geopolitical turmoil.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Juan José Cadillo-Benalcazar: Conceptualization, Methodology, Writing - original draft, Investigation, Validation, Formal analysis. **Ansel Renner:** Conceptualization, Methodology, Software, Visualization, Funding acquisition, Writing - review & editing, Formal analysis. **Mario Giampietro:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Resources, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110944.

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