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Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization

Ansel Renner [a,*], Juan José Cadillo-Benalcazar [a], Lorenzo Benini [b], Mario Giampietro [a,c]

[a] Institut de Ciència i Tecnologia Ambientals, Universitat Autonoma de Barcelona, Catalunya, Spain
[b] European Environment Agency, Kongens Nytorv 6, 1400 Copenhagen, Denmark
[c] Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Catalunya, Spain

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ABSTRACT

In the European Union, national-scope efforts to protect local ecosystem services are greatly helped by the externalization of agricultural production. Domestic environmental pressures such as pesticide residue, fertilizer leakage and waterbody overdraft would all significantly increase if European agricultural production were to be re-localized. Those increases would add additional stress on local habitats, soils and freshwater reserves. This work addresses such concerns by anticipating pressure increases associated with a near-complete re-internalization of agricultural production in the European Union. Our results could prove relevant in the event of an end of the era of cheap food imports, or when considering the plausibility of economic circularization efforts (such as suggested by the European Green Deal). Rather than produce quantitative results determined by a given set of supposedly uncontested pre-analytical assumptions, this work presents an innovative approach to scientific representation capable of accommodating several possible results driven by contradictory yet equally legitimate insights. According to our characterization of the option space, which builds on current trade profiles and assumes business as usual change in technical coefficients, a near-complete re-internalization of agricultural production by European Union member states is not environmentally feasible. In relation to social viability, the required changes in social practices would include a significant increase in the share of agricultural workers in the economy and important dietary adjustments.

1. Introduction

Although agriculture in the European Union (EU) contributes minorly to economic factors such as gross domestic product and employment, the environmental pressures it exerts are, by all measures, major. In the EU, half of local non-CO_2 greenhouse gas emissions are produced by agriculture (EC, 2018), one-third of water abstraction is for agricultural use and nearly one-half of land under economic use is agricultural land (Parris, 2001). Since the EU imports substantial quantities of agricultural products (Eurostat, 2019a), considerable externalized environmental pressures—pressures exerted on foreign lands—are also implied. Unfortunately, relatively few studies consider extraterritorial effects of agricultural externalization as associated with the interregional flow of ecosystem services (Koellner et al., 2018; Pascual et al., 2017; Tancoigne et al., 2014).

In this paper, extraterritorial effects of agricultural externalization are considered by taking a broad-scale look at how dependent the good standing of the environment of each EU member state is on ecosystem services located outside of respective national boundaries. In modern times, the openness of the EU agricultural sector is essential to protect the local biodiversity and integrity of EU ecosystems. However, this dependency entails that some ecosystem services, delivered in foreign social-ecological systems, benefit European consumers differently from the way they benefit the people of the social-ecological system in which their production takes place. This disparity opens a new framing of the issue of trade. How threatened are the environments of EU member states by reliance on volatile food imports ("environmental security")? Can we anticipate impending troubles concerning this dependence? How much is the good standing of the environment of importing countries helped by the virtual embodiment of ecosystem services in agricultural imports?

To answer these questions, an innovative accounting approach that adopts the resource nexus lens of analysis is operationalized in this paper. Nexus approaches concern themselves with the implications of

* Corresponding author at: Institut de Ciència i Tecnologia Ambientals, ICTA-ICP Building Z, Campus UAB, 08193 Bellaterra (Cerdanyola), Barcelona, Spain.
E-mail address: ansel.renner@uab.cat (A. Renner).

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biophysical limits to economic growth and the suitability of existing governance structures to put reigns on the complexity inherent to sustainability issues. The nexus lens also expresses dissatisfaction with the reductionist mode of scientific inquiry's approach to the quantification of complex issues (Giampietro, 2018). The questions we aim to explore, questions of resource security confounded by value pluralism, are tricky to assess using the methods of, for example, conventional economics. Building on previous work which presented a diagnostic application of the same accounting framework applied in this study (Cadillo-Benalcazar et al., 2020), this paper presents a long-term anticipation of one possible agricultural future for each of the 27 member states of the EU plus the United Kingdom (UK) and Norway. At the national level, we explore how dependent EU agricultural sectors are on externalization and how patterns of production and consumption amongst EU agricultural sectors affect the biosphere.

For each country, we assess in biophysical terms how much of the total throughput of agricultural products is domestically produced and how much is imported. Following the identification of the various flows belonging to these two categories, we generate information relevant to questions such as: What if the projected 60% increase in global food demand by 2050 (Alexandratos and Bruinsma, 2012) brings an end to the era of cheap food imports? What if growing perceptions of the existence of planetary boundaries result in geopolitical turmoil and force European states to rely more on local resources to guarantee their national food security? What would happen if current EU policy initiatives, such as those related to economic circularity, the Farm to Fork Strategy (EC, 2020) and the European Green Deal (EC, 2019d), inspire a major effort to re-internalize agricultural production? Even if the modern, high-external input model of agriculture is maintained (i.e. massive use of technical inputs on monocultures), are there enough agricultural resources for a full internalization? The main objective of this paper is therefore to improve our understanding of possible biophysical and social limitations to agricultural transformations by exploring what would happen to the remaining natural habitats, soil and aquifers of each EU member state if each member state were forced to locally produce all or nearly all the food that it currently imports.

Section 2 introduces the methods and methodologies used. Although a high degree of uncertainty is present, the anticipations presented in Section 3 indicate significant difficulty in stabilizing social and ecological boundary conditions following an attempt to re-internalize nexus flows in modern EU agriculture. For example, we anticipate that Member States across the EU would require, on average, 2–3x more land for agricultural use in the long-term. We also anticipate that blue water requirements could be as much as 8–9x higher than the status quo in Northern European states. What types of environmental impact would these changes imply? Concerning social-economic factors, countries across the board would require roughly 2–3x more human activity in agriculture. A major bio-economic pressure on society would therefore be expected, implying significant structural adjustments. Finally, in the discussion (Section 4), we highlight how our results are implausible if considered as actual predictions or simulations of *the future*. Instead, we clarify how the results aim to provide a robust exploration of *a possible future* together with a systematic assessment of possible constraints and concerns associated with current forward-looking policy decisions. Using the wording of Beckert (2013) to frame the dialogue, our anticipations aim to present an imaginary of a "future [situation] that provide [s] orientation in decision making despite the incalculability of outcomes" (Beckert, 2013, p. 325; cited by Poli, 2017a).

2. Methods and methodology

The resource nexus paradigm prescribes the adoption of a set of methods that appreciates the complex nature of complex adaptive systems. The address of two epistemological challenges is implied. Firstly, adopted methods must embrace impredicativity, where impredicativity is a difficult admission resulting in contingent results and analyses (Rosen, 1977, 2012). Secondly, adopted methods must embrace the coexistence of non-equivalent descriptive domains resulting from the need to consider multiple scales (Ahl and Allen, 1996; Allen and Hoekstra, 2015). Section 2.1 and Section 2.2 address both of these epistemological challenges. Collectively, they outline an approach to the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) framework (Giampietro and Mayumi, 2000; Giampietro and Ramos-Martin, 2005).

2.1. Methodology

Two causal frameworks are adopted by our methodology, the first of which is the *relational theory of science* (referred to here as *relational analysis*) developed primarily by Rashevsky (1954), then Rosen (2005, 1958), then Louie (2013, 2009) and endorsed for system analysis by, for example, von Bertalanffy in *General System Theory* (1968). Our primary intellectual loan from relational analysis is the *metabolic processor* concept along with related tools useful for the construction of *pathways of causal entailment*. The metabolic processor concept—the possibility of defining an expected profile of inputs and outputs associated with processes that can be integrated across different levels of analysis—is, for our purposes, operationalizable in apparently simple mathematical terms (see Section 2.2.1). It is precisely that aspect that lends itself to the exploration of contingent analyses. Our approach stands in contrast to convoluted dynamical modeling efforts characterized by high degrees of mathematical complicatedness and a high barrier of entry.

Second, we adopt the driving forces ('drivers'), pressures, states, impacts and responses (DPSIR) framework for its ability to inform a *typology of indicators* relevant for the interpretation of environmental accounts (Smeets and Weterings, 1999). The DPSIR framework, proposed by the European Environment Agency (EEA) in 1999 as an extension of a related OECD framework, is supported by a substantial body of literature that has slowly but consistently gained momentum over the years. This work focuses on *drivers*, *pressures* and *states*, with some additional remarks made concerning *responses*. Building on metabolic profiles characterized by Cadillo-Benalcazar et al. (2020), this work anticipates the effects of *drivers* of change on social and environmental *pressures* and discusses their effects on system *state* in the long-term (2050).

Both relational analysis and DPSIR are put to use in an act of quantitative story-telling (QST) (Giampietro and Bukkens, 2015; Renner and Giampietro, 2020; Kuc-Czarnecka et al., 2020) to validate the biophysical plausibility of a dramatic internalization of food and feed imports—a narrative loosely inspired by the "Regional Food" scenario characterized in expert and stakeholder exchange by Mylona et al. (2016). According to Börjeson et al. (2006), such acts of anticipation include the *state* of the system analyzed as well as the set of relationships between factors that are controllable by decision-makers (internal factors) and those which are not (external factors). Both internal and external factors are understood as *drivers* of change in a metabolic pattern (Poli, 2017b). Examples of *drivers* include changes in the composition and size of the components of social-ecological systems, including demographic changes as well as relative and absolute changes in consumptive and productive economic activities. Examples of *drivers* also include changes in production factors, including changes in technical coefficients resulting from technological innovation. In contrast to scenarios based on predicative modeling approaches, anticipation science rejects the forecast-and-control notion that the future is 'there'—that society must simply fashion some sort of objective, optimal route to go 'there'. Instead, anticipation science admits that futures are generated and consumed, that they are co-created by social practices and processes (Poli, 2017a). Following Börjeson et al.'s (2006) typology of scenarios, the anticipatory analysis in this report is based on the questions: *'what can happen?'* and *'what cannot happen?'*. The scenarios are, therefore, exploratory, not predicative.

Futures studies in 'normal science' tend to focus on generating the

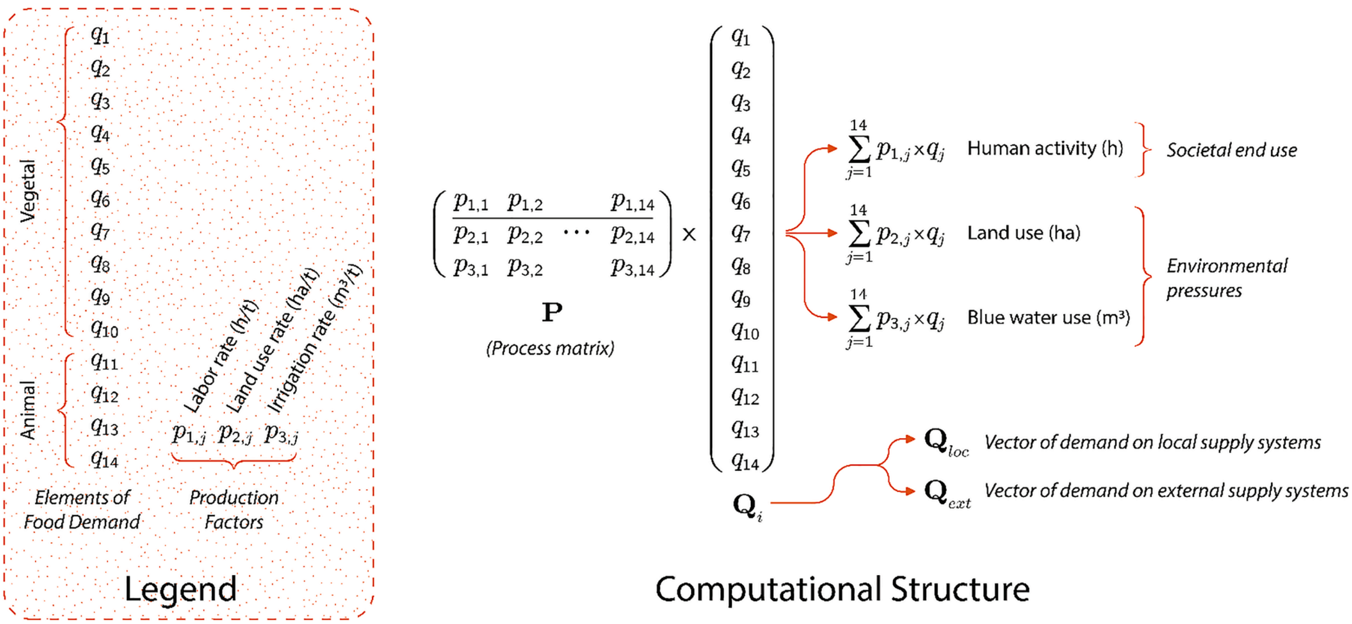

Fig. 1. Graphical summary of the computational structure used in the analysis. Production factor totals for human activity, land use and blue water use are calculated for each of the 29 European countries considered based off both local (Q_{loc}) and external (Q_{ext}) demand for 14 food commodity flows, each associated with bespoke technical coefficients for each of 3 production factors.

highest probability or otherwise optimized prediction of the future, whereas foresight and anticipation consider the future as something which is co-created in the present continuum. Non-predicative approaches to futures studies can still provide substantial decision support utility (Miller, 2007). In this work, we take to heart a foundational assumption in future studies—that the "future can be better confronted by opening our minds and learning to consider different viewpoints" (Poli, 2010, p. 11)—and use it to justify the exploration of biophysical implausibilities (Rhyne, 1981). Coming to our scenario, although a near-complete internalization effort is not likely to be a serious policy proposal in the present-day EU, exploration of that narrative is still a useful exercise in biophysical anticipation in its ability to "help thinking [escape] the constraints of established pathways" (Mylona et al., 2016, p. 16).

The last point worth addressing on methodology is our approach to classifying and communicating constraints. Firstly, we address desirability, a primarily social aspect that explores factors affecting the bioeconomic pressure on society—the need for a high productivity of production factors in order to guarantee a high standard of living (Giampietro et al., 2012; Farrell et al., 2013). Desirability is determined by aspects such as material standards of living (associated with the expected minimum return on agricultural labor), the level of services guaranteed by the society (associated with a low share of agricultural workers in the economy) and the non-material contributions of ecosystems to humans. Secondly, we address viability, a primarily economic aspect that explores factors affecting the productivity of production factors. Viability is determined by aspects such as land availability along with the suitability of that land for expected forms of agriculture (e.g. differences in land productivity filtered by different agricultural regimes) and the profile of costs and revenues (incl. subsidies). Lastly, we address feasibility, a primarily environmental aspect. Feasibility is determined by the severity of external constraints generated by the biosphere. To assess environmental feasibility, environmental pressure flows must be characterized extensively and mapped onto the ecological funds providing the required supply and sink capacity of primary inflows and outflows. The mapping of *pressures* onto ecological funds at the national level yields an imprecise signal. In the

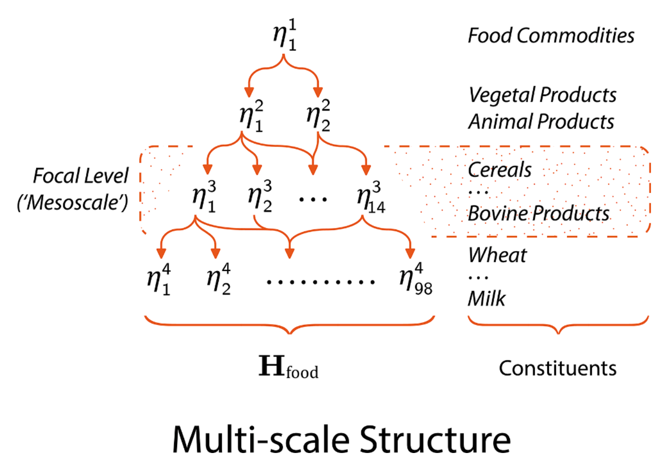

Fig. 2. Structure of the taxonomy of food items (H_{food}) used in the account. The 14 elements of the third level correspond to the 14 elements of the two demand vectors (Q_i) referenced in Fig. 1. Whereas upper indices represent taxonomic level, lower indices distinguish elements within that respective level.

case of 'an elephant in the room' (i.e. a strong signal such as when the internalization of imports would require a tenfold increase in land use or a tenfold increase of fertilizer applications per hectare), a crude mapping of pressures to ecological funds is sufficient to falsify a sustainability narrative or orient a decision-maker.

To clarify the point, the concept of 'fund' used in this paper does not belong to the ecosystem services narrative. The distinction between flow and fund elements was proposed by Georgescu-Roegen (1971) as an alternative to conventional input-output analysis (e.g. Leontief, 1966, 1970; Daly, 1968; Duchin, 1992; Lenzen, 2011; Stone and Croft-Murray, 1959) to avoid confusion in the quantitative representation of the sustainability of economic processes. A fund element is a metabolic agent whose size and identity remain constant during the chosen duration of the analysis. Fund elements and stock elements are not the same. A stock is depleted when a resource is extracted from it (an output flow generating stock depletion) or expanded when a resource is added to it (an input flow generating sink filling). In either case, a change in the size and original identity of the stock occurs. On the other hand, when properly managed (e.g. soil under sustainable agricultural practice), ecological funds can continuously provide a service while maintaining their original identity (both in size and in qualitative characteristics). When not properly managed (e.g. soil under unsustainable agricultural practice), the would-be funds change in size (e.g. soil erosion) and metabolic characteristics (e.g. soil health), and hence are considered stocks.

2.2. Methods

2.2.1. Computational methods

A concise approach to describing the assumptions involved in our analysis is through symbolic blueprints. Two such blueprints are presented in this section. The first blueprint (Fig. 1) summarizes the computational structure used. The second blueprint (Fig. 2) summarizes a crucial aspect of our database: its multi-scale structuring.

The structure presented in Fig. 1 (endogenous to the model) is populated by parameters (exogenous to the model) as described in Section 2.2.2. Starting on the left of Fig. 1, the 14 elements of food demand (q_1 through q_{14}) represent societal demand for key food groups. Since a central goal of our analysis is to explore changes in externalization, q_1 through q_{14} are defined separately by source—system internal (locally produced) and system external (imported). These two sources are summarized in the respective food demand vectors $\mathbf{Q}_{loc}$ and $\mathbf{Q}_{ext}$ and collectively referred to as $\mathbf{Q}_{i.}$ The two food demand vectors, $\mathbf{Q}_{loc}$ and $\mathbf{Q}_{ext}$, reflect both relative and absolute changes in population and food demand (see Section 2.2.2 for data methods and sources). Moving rightward from demand to the process matrix **P**, production factors ($p_{i,1}$ through $p_{i,14}$) represent technical coefficients defined uniquely for each country in the analysis, each of the 14 elements of food demand and for three critical production factors (human activity, land use and blue water use). Each column of **P** can be interpreted as the structural characteristics of a metabolic processor. Furthermore, changes in the characteristics of production factors (i.e. drivers, characterized both in terms of size and intensity of flows per unit of size) reflect changes in yield as a result of both technological and process innovation as well as climatic changes (see Section 2.2.2 for data methods and sources). The option space defined by these dimensions allows for the exploration of future labor, land and water constraints in both quantitative and qualitative terms. It allows for the exploration of three important agroecosystem dimensions, acknowledging that several additional, likely relevant dimensions such as N-, P- and K-fertilizer, energy carriers, commodity prices and pesticides present further constraints to the option space.

Within each metabolic processor, human activity represents a fund variable, land use represents a fund variable and blue water use represents a flow variable. Human activity may be further classified in the domain of societal end uses and both land use and blue water use may be further classified in the domain of environmental pressures. Once scaled by a food demand vector, all processor variables are related to several agroecosystem services both directly and indirectly. Adopting the Common International Classification of Ecosystem Services (CICES) v5.1 framework (Haines-Young and Potschin, 2018), crop production spans the biomass division of the biotic provisioning service (1.1). A majority of the assessed crop production falls within either cultivated terrestrial plants for nutritional purposes (1.1.1.1) and animals reared for nutritional purposes (1.1.3.1), although other minority classes such as cultivated plants as a source of energy (1.1.1.3) and animal products for processing (1.1.3.2) are included in the mix. All crop production is detailed by class type, i.e. the 14 agricultural commodities defined by the adopted mesoscale. Among the three production factors considered, blue water is considered an abiotic provisioning service. Blue water for vegetal crops comprises surface and ground water as a material, i.e. for irrigation (4.2.1.2 and 4.2.2.2). Blue water for animal crops comprises those same two categories, including service water and water for direct consumption by animals. Land use in agriculture is itself associated with a large variety of ecosystem services and pressures. For example, it is related to soil quality and quantity, land fragmentation and biodiversity levels (Hardelin and Lankoski, 2018).

Although Fig. 1 is a good introduction to the formal foundation for our approach, it misses a crucial aspect necessary to understand agroecosystems. Namely, it lacks a multi-scale perspective (Allen and Starr, 1988; Grene, 1987; Margalef, 1968; Simon, 1962). Fig. 2 provides a summary of the multi-scale structuring of food items used in the analysis (endogenous to the model). The classification used, an excerpt from the FAOSTAT Commodity List (FCL) with some custom top-level aggregation, dictates the analysis's numerical sensitivity ranges—related to the model's underlying uncertainty.

Our assessment of both local and external supply systems occurs at the third level of $\mathbf{H}_{food}$. On account of its location in the middle of $\mathbf{H}_{food}$, we refer to the third level as the *mesoscale*. Data at the mesoscale represents sums (in the case of demand vectors) and weighted averages (in the case of production factors) of *microscale* data (the fourth level in $\mathbf{H}_{food}$). Whereas the assessment of pressures is possible at the mesoscale (level three in $\mathbf{H}_{food}$, 14 supply systems detailed), the assessment of impacts requires a much higher resolution of agricultural products, such as that found at the microscale (level four in $\mathbf{H}_{food}$, 98 production systems detailed). Only at the microscale can environmental pressures be meaningfully contextualized against physically identifiable ecological funds (i.a. aquifers, soils, habitats). At the microscale level, the characterization of the supply and sink capacities of ecological funds, coupled with low-level dynamical modeling approaches, creates the possibility of estimating environmental impacts.

2.2.2. Data and assumptions

The following summarizes the exogenous parameters used to populate the computational model introduced in Section 2.2.1.

2.2.2.1. Technical coefficients. For vegetal products, production factors include: (i) crop yield (tonne/hectare); (ii) blue water use (m^3/hectare); and (iii) human activity (hour/hectare). For animal products, production factors include: (i) crop yield, incl. both meat yield (tonne/head) and milk yield (liter/head); and (ii) blue water use, incl. water for drinking and service water (m^3/head). Changes in technical coefficients in the long-term are proxied by changes in yield, as described later in this section. Feed consumption (tonne/head) minus the import of processed feed is scaled by the demand for animal products and accounted for directly as vegetal matter for animal production. Indirect land uses, blue water uses and human activity embedded in imported/processed feed are included with and scaled by the calculation of vegetal product flows. Disaggregation by use type of the processed vegetal imports proved impossible. Lastly, in the case of animal products, direct (non-feed) land use is considered negligible. Irrigation of grazing lands is also considered negligible. The derivation of the underlying microscale technical coefficients used in the calculation of mesoscale aggregates is based off primary data sources (Chatterton et al., 2010; FAO, 2018, 2017a, 2017b, 2016, 2014b, 2014c, 2014d, 2014a; FAO et al., 2002; Huyghe et al., 2014; Mekonnen and Hoekstra, 2011; Portmann, 2011;

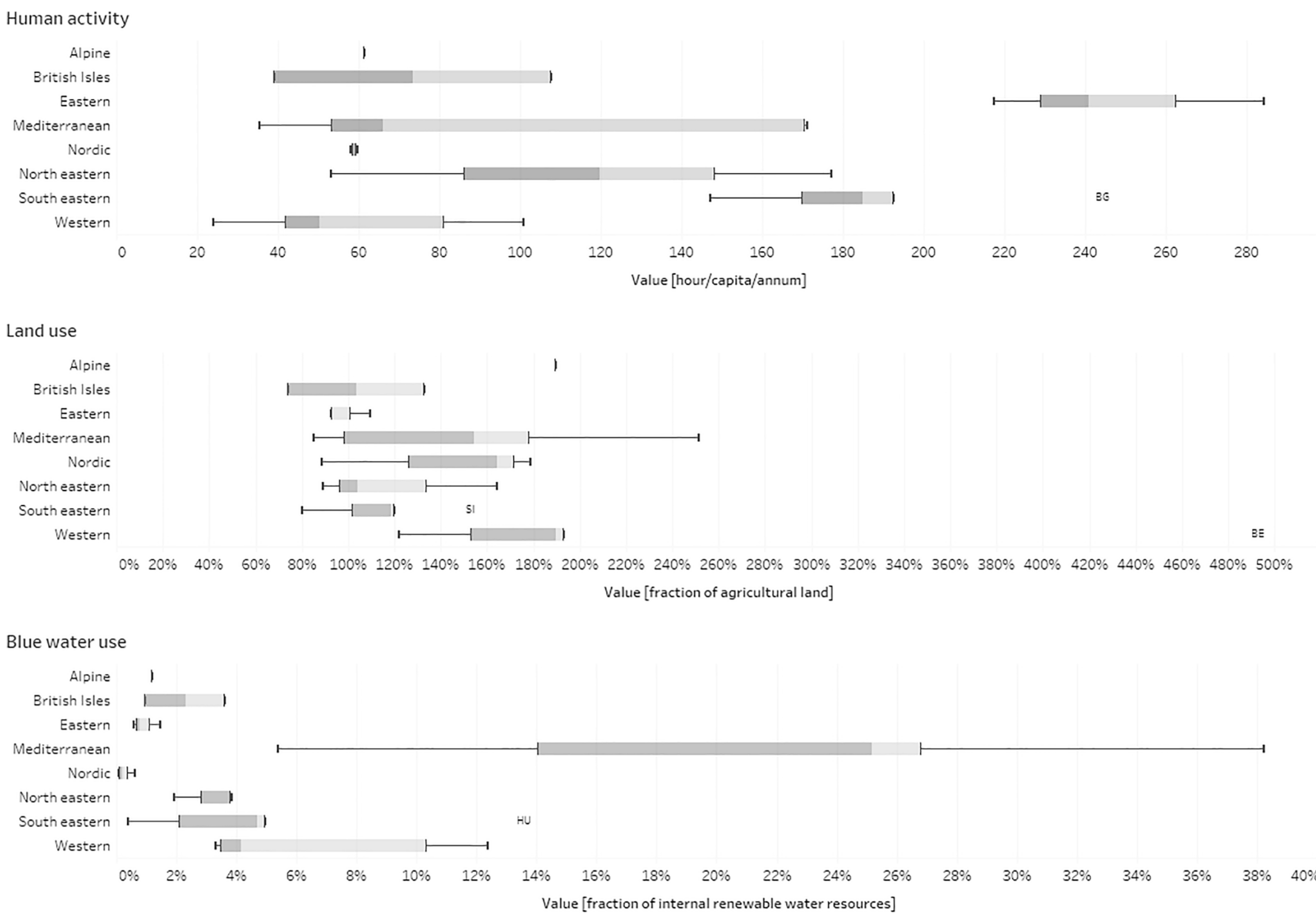

Fig. 3. Overview of the anticipation of three production factors in the long-term (2050) following a 90% agricultural internalization for the EU member states plus the UK and Norway. For land use and blue water use, both Malta and the Netherlands are excluded from the figure for readability purposes and on the basis that they are extreme outliers. Prevailing outliers (more than 1.5 the interquartile range) are labeled with their ISO-2 country acronym.

USDA, 2014). For supplementary information on the microscale biophysical diagnostic readers are directed to Cadillo-Benalcazar et al. (2020).

2.2.2.2. Population estimates. Three separate population projections are used to derive a spread of estimations in the long-term. The population projections used are the baseline, low-fertility and low-mortality scenarios from Eurostat (2019b). In Section 3, results refer to the baseline prediction. A sensitivity analysis including the high- and low-bound population estimates is found in Appendix A. In the long-term, changes in population have the least effect on the numerical model's output uncertainty.

2.2.2.3. Food demand estimates. The characterization of baseline food demand estimates is based on 2012 data from the FAOSTAT Food Balance Sheet (FBS) (FAO, 2017a). The characterization of drivers of change in crop production mixes, defined at the mesoscale (e.g. for cereals, oil crops, vegetables, bovine products), relies on a forecasting algorithm calibrated to encompass the prediction discrepancies of established food demand forecasts. In general, predicting changes in food demand across decades and including but not limited to changes in dietary demand is a wicked task with hardly any two authorities in agreement (Valin et al., 2014). The uncertainty involved is exceptional. Individual forecasts for each food production mix were first trained on annual FBS data ranging, for 21 of the 29 analyzed countries, from 1961–2013. For the other 8 remaining countries, namely Belgium, Croatia, Czech Republic, Latvia, Lithuania, Luxembourg, Slovakia and Slovenia, less historical data is available and time series start dates range between 1992 and 2000. Growth rate estimates for the demand of marginal food groups—defined as those groups with a consumption of less than 10 kg/capita/annum—are considered negligible. In this way, extreme growth outliers are avoided. Per capita changes in spice and stimulant demand, for example, are considered negligible. In all other cases, the Holt's linear trend forecasting algorithm (additive trend, double exponential smoothing) was used, selected as a general use heuristic and based on its proven effectiveness in the food demand context (Hyndman and Athanasopoulos, 2018; Makridakis et al., 1982). In addition to the baseline forecast, a confidence interval described using a normal distribution is considered as part of the assessment of parameter sensitivity. Specifically, a 50% confidence level was selected—a determination made such that the resulting per capita growth factors encompass the breadth of predictions at the mesoscale described by the following relevant authorities: Alexandratos and Bruinsma (2012), EC (2017), Farm Europe (2015) and OECD and FAO (2017). In this sense, the sensitivity range of food demand changes is conservatively large. Its characterization uses established food demand predictions as a theory of inference, acknowledging that confidence intervals by themselves are neither indices of plausibility nor indices of reasonability (Morey et al., 2016). A major implication to the adopted approach to modeling food demand is that food export is assumed to remain relatively constant even though decreasing imports are explored. In political terms, this assumption is questionable, for example, trade

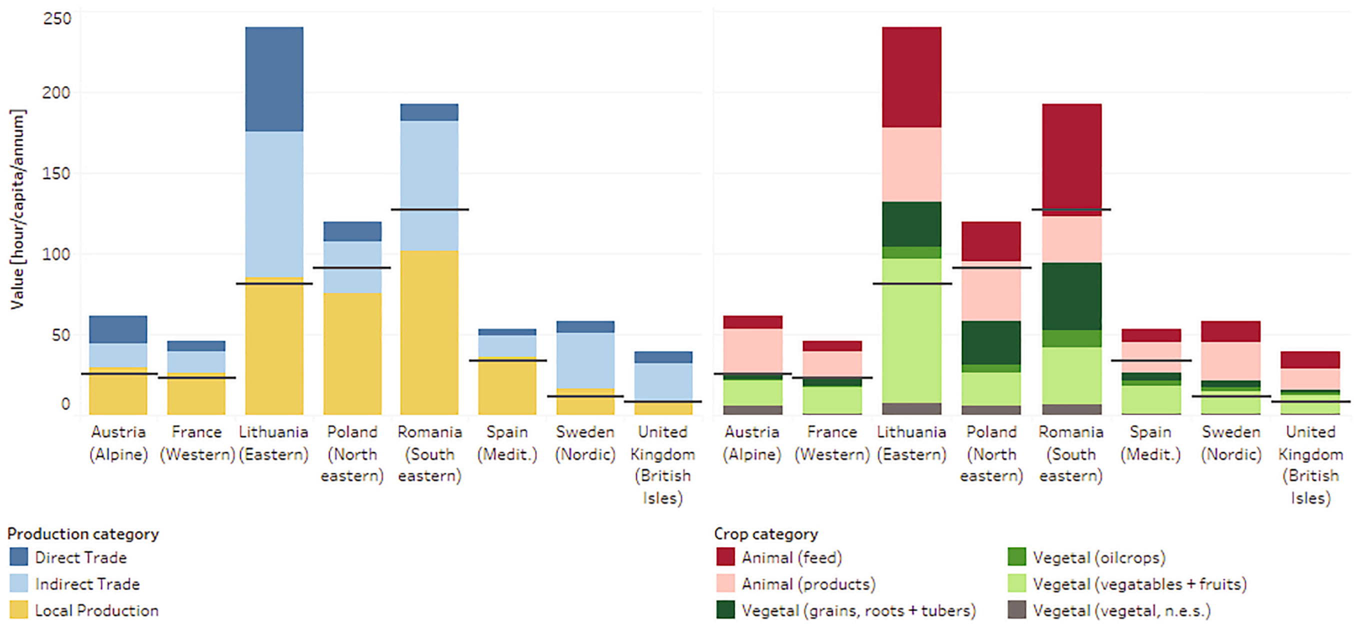

Fig. 4. Anticipated human activity in the long-term (2050). Reference lines show 2012 baseline estimates. Long-term anticipations reflect a 90% re-internalization of imports, where the 'Trade' legend items refer to commodities that were previously received from trade but whose production has been internalized. It should be noted that more than half of agricultural trade in the EU is between EU states.

conflicts would likely erupt. Nevertheless, the exploration of system constraints assuming current economic expectations is a valuable starting exercise. In the event the anticipation results in biophysical implausibilities, a societal discussion can be opened concerning which aspects could or should be changed.

2.2.2.4. Yield estimates. Changes in yield estimates include consideration of: (i) changes in technological efficiency, e.g. innovation-driven advances in technology and techniques; (ii) changes in socio-economic factors, e.g. increases or reductions of subsidies; and (iii) drivers from the biosphere, e.g. climate change and environmental degradation. Constant average annual growth rates (AAGRs) for each of the mesoscale food commodities were characterized following the established literature (Alexandratos and Bruinsma, 2012; EC, 2017; OECD and FAO, 2017). High- and low-estimate bounds describe the discrepancy range among the established estimates (ibid.). As was the case with food demand, designated yield ranges are conservatively large due to substantial discrepancies among existing yield estimates. When describing yield estimates for food commodity groups at the mesoscale, it's worth pointing out that there exists a relatively large nutritional redundancy in food commodities, meaning that many different food commodities may be used to match any given nutritional requirement. In the case that any given food commodity (e.g. almonds or oranges) becomes relatively scarce in the coming years (e.g. due to climate change or an invasive species), a major food security concern generally does not occur. In this sense, the provision of agricultural commodities at an aggregate level is assumed to be protected by commodity level nutritional redundancy. Events such as catastrophic crop failure across commodity types are not included in the estimate's consideration.

2.2.2.5. Internalization target. Re-internalization in the long-term (2050) is set to be 90%. This target translates into an equal 90% internalization for each of the 14 focal level food commodities demanded in each of the 29 European countries assessed. While dramatic, our internalization target is valuable for exploring potential constraints related to increasing concerns over food security in the long-term—concerns largely driven by rapidly rising food demand in developing countries, i.e. an estimated 60% increase in global food demand by 2050 (Alexandratos and Bruinsma, 2012). The internalization target also stands in place of the lack of explicit targets for agricultural trade loop-closing in EU circular economy policies (EC, 2019a; b)—an absence which, we might add, is a significant shortcoming identified in the literature (Giampietro and Funtowicz, 2020; Jurgilevich et al., 2016). Lastly, the assumed internalization target is selected as such to assess the agricultural sectors of the 29 countries against their safe operating space limits. In this sense, the target aims to explore the possibility of downscaling the global safe operating space concept—a concept with currency from the planetary boundary framework (Rockström et al., 2009; Steffen et al., 2015)—to the national scale, where policy efforts have more traction (Häyhä et al., 2016; Hossain et al., 2017).

Concerning internalization methods, a final note on imputation must be made. In the case that an imported food commodity is not produced domestically, a mean value for each production factor is used for the baseline projection as calculated using all food commodities sharing the imported food commodity's parent element. This is the case for, for example, citrus crops in Luxembourg. In Luxembourg, citrus crops are imported, but there is no significant local production precedent with which to estimate local production factors. In the case of citrus crops in Luxembourg, the mean value of all locally produced fruit crops is, therefore, assumed in the baseline projection. Our analysis's approach to imputation assumes reasonably homogenous production factors within crop categories. In all cases of production factor imputation, high- and low-bound projections in Appendix A are informed by a 50% confidence interval (normal distribution) in the calculation of production factor mean values.

3. Results

3.1. Overview

The presentation of results in this section illustrates example use-values of analyses derived from the methodologies and methods presented in Section 2. In presenting the results, a country classification based on environmental and socio-economic factors dividing Europe

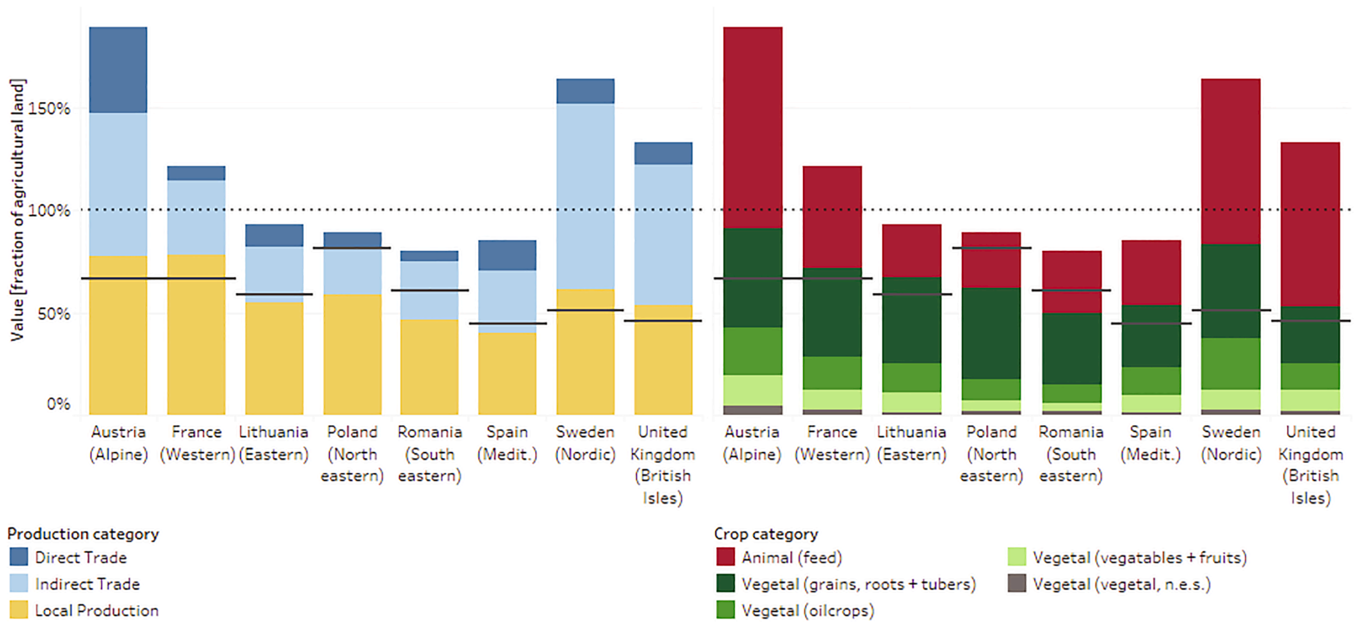

Fig. 5. Anticipated agricultural land use in the long-term (2050). Reference lines show 2012 baseline estimates. Percentage values are conservative estimates, due to varying differences in the definition of agricultural land. Long-term anticipations reflect a 90% re-internalization of imports, where the 'Trade' legend items refer to commodities that were previously received from trade but whose production has been internalized. It should be noted that more than half of agricultural trade in the EU is between EU states.

into eight major agricultural regions is adopted (Olesen and Bindi, 2002). Among the eight major agricultural regions, the North eastern, South eastern and Eastern regions are characterized by a relatively less industrialized form of agriculture and the Nordic, British Isles, Western and Alpine regions a relatively more industrialized form. In the Mediterranean region, a mix of low- and high-agricultural industrialization is found. Fig. 3 provides an overview of the EU countries plus the UK and Norway. In Fig. 3, the Netherlands and Malta are excluded from the land use and blue water use characterizations on the basis that they are extreme outliers. The anticipated land use in the Netherlands in the long-term is 1470%, resulting from the fact that the Netherlands has a very large agribusiness sector and a very small crop area. Although it has 75x less arable land, the export of agricultural products in the Netherlands is roughly equal to that of Argentina and Canada summed (measured in monetary terms and including re-export) (FAO, 2017a). In the case of Malta, the anticipated use of blue water in the long-term is roughly 215% of its internal renewable water resources. This figure is explained by the fact that Malta, a significant importer, is in the lower 4% of countries globally in terms of renewable water resources per capita (FAO, 2016).

3.2. Expansion of results

In this section, human activity (per capita, per annum), land use (fraction of total agricultural land) and blue water use (fraction of total internal renewable water resources) results are further disaggregated. One representative country is selected for each of the eight major agricultural regions and food commodities by source/use-type are presented at the mesoscale level using two distinct color scales. Source categories, depicted in the leftmost subplots, include local production, direct trade and indirect trade. In the case of indirect trade, processed products are represented in terms of primary commodity equivalent.

Fig. 4 addresses the implications of the change in bio-economic pressure resulting from the anticipation of an increase in human activity in agriculture. In countries with very large import quantities, particularly animal products, extra significant changes are observed. This proves to be the case for Sweden (among the Nordic countries) and the UK (among the British Isles), for example. The history of EU agriculture over the past century could be summarized as the elimination of the need for significant labor in the agricultural sector as a result of increasing use of external inputs such as fertilizers and fossil fuels, a glut of farm machinery power capacity (Giampietro, 1997; Arizpe et al., 2011) and a massive process of externalization. From the perspective of social desirability, we anticipate that affluent countries that have come to take a trend of increasingly high external input agriculture for granted would need to come to terms with substantial relative readjustments in the state of their societal metabolic profiles. In Fig. 4, whereas Lithuania, Poland and Romania exhibit relatively low levels of agricultural industrialization and relatively high demand for human activity, Austria, France, Sweden and the United Kingdom represent relatively high levels of agricultural industrialization and relatively low demand for human activity. Spain remains in the middle of those groupings.

In general, far less human activity is required per unit of agricultural product in countries focused on highly industrialized, market-oriented agriculture than in countries with low levels of agricultural industrialization. Indeed, in the long-term and from an absolute perspective, human activity in the agricultural sector in countries performing highly industrialized agriculture remains low. That said, countries performing highly industrialized agriculture would be required to come to terms with a still significant relative increase of human activity in the agricultural sector. In Sweden and the UK, for example, a roughly five-fold increase in human activity per capita is observed. This increase results mostly from the major internalization of animal production and represents a substantial bio-economic pressure. Even so, total levels of human activity likely represent a less-concerning pressure variable than the two other production factors assessed.

Fig. 5 presents an anticipation of the requirement for agricultural-use land as a fraction of total agricultural land. Calculated values are compared against FAO baseline estimates of agricultural land—a class that includes arable land, permanent crops and permanent meadow and pasture. Land that is not used for production purposes but is eligible for subsidy payments is included in the FAO agricultural land estimate. Permanent meadow and pasture include such categories as land crossed during transhumance (seasonal movement of livestock), agroforestry

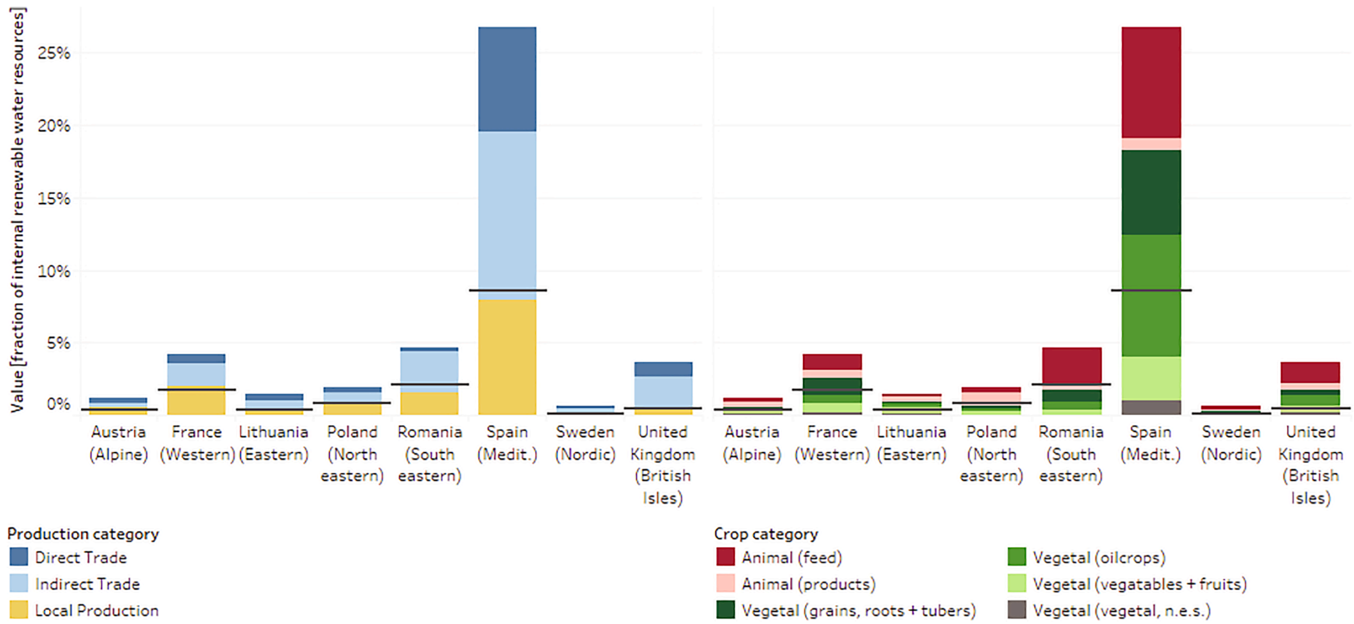

Fig. 6. Anticipated blue water use in the long-term (2050). Reference lines show 2012 baseline estimates. Long-term anticipations reflect a 90% re-internalization of imports, where 'Trade' legend items refer to commodities that were previously received from trade but whose production has been internalized. It should be noted that more than half of agricultural trade in the EU is between EU states.

land used for grazing and land out of production for extended periods of time (more than 5 years) but maintained in good agricultural condition. These marginal categories are generally either not considered or underestimated in our data calculation, which is based on standard yield values. For this reason, we repeat, the calculated land-use estimates in this work are conservative. It should be noted that the suitability of 'marginal land' for agricultural production—land considered as inappropriate for agriculture due to its low or non-existent levels of profitability—is highly dependent on agricultural paradigm, agricultural technology and product prices. Intensive, highly industrialized agriculture generally requires high-quality land and the industrialization of agriculture and associated land marginalization is seen as the leading driver of strong trends of farmland abandonment in Europe since the 1950s (Buttrick, 1917; Li and Li, 2017). Agricultural land such as the iconic terracing on the steep slopes of Machu Picchu would certainly not be considered suitable for agricultural use in the modern, highly industrialized sense. Still, that land functioned perfectly well for the Inca in centuries past. Notwithstanding, an increased use of marginal land for agricultural activities may or may not be desirable in environmental terms as buffer zones prove essential for the management of effects on downstream ecosystems.

In general, expansive, low population density countries such as Sweden (among the Nordic countries) are unlikely to be faced with serious internalization issues regarding land use. On the other hand, highly urbanized countries such as France (among the Western countries) and the UK (among the British Isles) would be faced with an insurmountable task when attempting to internalize. According to FAO estimates, France is roughly 45% agricultural land and the UK is roughly 75% agricultural land (FAO, 2017a). Assuming a 90% internalization rate in the long-term, we anticipate the need for roughly 65% of France's *total land* and roughly 95% of the United Kingdom's *total land*, both impossible changes in system state. Translated, these figures represent roughly 120% of total agricultural land for France and roughly 130% of total agricultural land for the UK. Austria, the singular Alpine country, would likely also be faced with acute difficulties in internalization concerning land requirements on account of relatively high levels of import and a relatively low percentage of agricultural land (32%, by FAO standards) (FAO, 2017a).

As indicated on the left side of Fig. 6, most of the anticipated increase in blue water use derives from the internalization of direct and indirect vegetal trade. Blue water use in feed production is low in relation to the actual mass of feed consumed because a majority of feed crops are not irrigated. For example, roughage, pasture and silage are typically non-irrigated. Nordic countries such as Sweden (illustrated) or Norway (not illustrated) are unlikely to be presented with serious issues on account of them having ample freshwater resources and relatively low irrigation rates. In other regions, such as the Mediterranean and the British Isles, serious issues arise. In the Mediterranean, the mixture of an arid climate and high levels of irrigation have already led to critical freshwater over-exploitation in several agrarian provinces. For example, this is the case for numerous agrarian provinces in Spain and Portugal (EEA, 2018). Spain's current water exploitation index of roughly 30% already translates into acute impacts at the regional scale (Eurostat, 2018a). Assuming a 90% re-internalization in the long-term, we would anticipate Spain to require a blue water abstraction rate roughly 350% higher than its baseline value. Although our national-level data is not spatially resolute enough to calculate watershed impacts, we anticipate that virtually the entire country would be in an acute water crisis on account of such a strong pressure signal. In other countries with substantially lower blue water usage, significant adjustments in ecosystem interactions would still be required, largely as a result of the internalization of processed animal feed components. For example, this is the case for the UK and Romania.

4. Discussion

4.1. Main findings

In the EU, the total import of agricultural products is greater than the total export of agricultural products (in aggregate physical terms) (Eurostat, 2019a). The existence of important ecosystem impacts associated with the EU but taking place outside its borders is, therefore, implied (Peeters, 2013). This work presented one possible characterization of those ecosystem impacts by anticipating a 90% re-internalization of food and feed imports by each of the 27 member states of the EU plus the UK and Norway. The characterization indicated severe limitations.

For example, human activity in the agricultural sector, the first of the three production factors addressed, would prove to be a significant economic constraint. In the event of a near-complete re-internalization effort, we anticipate a 2–3x increase in human activity in the agricultural sector (hours of labor per capita per year). Social desirability concerns would confront with, and need to be checked against, social norms and social practice expectations. Indeed, the modern EU economy operates with a small fraction of farmers in the workforce and a historically unprecedented three-quarters of the population live in urban areas (Schuh et al., 2019). The role of farmers in European society has become, in a sense, to feed cities (Renner et al., 2020). This trend of reduction of farmers in the workforce, although developed very recently in human history, will not be easy to revert.

Furthermore, our anticipation of environmental pressures showed that current and foreseeable technological development rates would not alone be sufficient to match the challenges provided by re-internalization. On top of business as usual expected improvements, land use and water efficiency would need to improve on average 3–4x, entailing that environmental pressures would be incompatible with existing biophysical constraints. Therefore, our results show that an emphatic re-internalization of agricultural production—otherwise maintaining the current economic structure—is out of the picture in environmental terms for many if not most the EU countries regarding land use and blue water use. 26 of the 29 countries assessed were anticipated to require more than 100% of their currently available agricultural land, often considerably more. In each of the 29 countries assessed, pressure on internal renewable water resources was anticipated to more than double. Although our assessment of biophysical constraints was not comprehensive—it lacked consideration of factors such as NPK fertilizer disaggregated into its N, P and K constituents, energy carriers such as various liquid fuels and electricity and plant protection products such as pesticides and insecticides—the magnitude of the incompatibility of the two environmental pressures characterized raises concerns across the environment dimension.

4.2. Implications for policy

The need to transform the EU food system to halt the loss of biodiversity and enhance natural capital while providing a secure and equitable supply of food is recognized by many world leaders as per the Sustainable Development Goal (SDG) framework (UN, 2015). In particular, the European Commission has indicated that sustainability 'from farm to fork' (EC, 2020) is one of the key policy foundations for a sustainable future in Europe in which a modernized Common Agricultural Policy (CAP) is likely to play a crucial role (EC, 2019c). In a similar albeit broader vein, the Commission has presented the European Green Deal, which calls for a deeply transformative change in food and agriculture, specifically endorsing digital technology and precision agriculture techniques as crucial enablers (EC, 2019d). Beyond those policies, concerns over EU food system transformation are further justified along the lines of national-level food security and resilience in the face of an uncertain future characterized by strong drivers of increasing global food demand (Alexandratos and Bruinsma, 2012) shaped by emerging economic powers, changes in global leadership and the resulting tensions in international trade governance (EPRS, 2018). Therefore, national-scale pathways could respond to calls for safe operating space regionalization within the planetary boundaries discourse (Häyhä et al., 2016; Hossain et al., 2017), and towards the achievement of the EU long-term vision of 'living well within the limits of the planet' (7th Environment Action Programme) (EC, 2013).

In light of the above and in combination with the biophysical concerns highlighted by our analysis, countries should carefully consider pathways for at least a partial re-internalization of their agricultural sector. The EU should also consider a more careful integration of the agricultural sectors of Member States. The elaboration of a sound transformation pathway is not possible without an accounting approach that is rooted in multi-scale, biophysical analysis. The analysis presented in this paper is one example of such an approach. Given the many non-trivial, impredicative causal relations among the complex components of social-ecological systems, quantifications can easily lead to problematic oversimplifications.

For example, the allocation of 'fair shares' of environmental burdens to countries on the basis of planetary boundaries, as a means for the re-internalization of trade footprints and through scaling based on variables such as GDP, population and land cover (e.g. Dao et al., 2015), typically lacks considerations regarding feasibility, viability and/or desirability and fails to address in context multiple scale and pressure criteria. The same criticism applies to more sophisticated approaches involving economic modeling of trade in agricultural commodities, e.g. the CAPRI model (Britz et al., 2014). In such models, economic and environmental variables including biophysical constraints are often dealt with at a single scale and dimension at a time. Such models thus seem more suitable for short-term assessments rather than long-term transformations and societal reconfigurations, as the assumptions underpinning model equations are very likely to fall apart under anticipations which entail radical changes in existing patterns. Similarly, dynamical modeling simulations can only meaningfully reflect small oscillations in the proximity of current conditions, and therefore cannot represent and be used to explore possible long-term reconfigurations of national food systems or agricultural sectors. This aspect implies that standalone econometric analyses based on forecasts of aggregate production and consumption are fully insufficient for producing robust indicators, contrary to what is presented in this work.

Instead, the biophysical lens proposed and applied to this paper's prospective assessment can provide a complementary approach relevant for agroecosystem accounting. Indeed, the outcomes presented in Section 3 already provide a much richer picture than that provided by an aggregate indicator. While an aggregated indicator provides useful insights on overall trends, its usefulness is largely limited as it cannot convey messages concerning interrelations and related context-dependence (Kuc-Czarnecka et al., 2020). Prospective assessments must allow for the identification of which system elements and which biophysical vectors contribute most to specific pressures (e.g. in the column charts presented in Section 3), thereby allowing decision-makers and stakeholders to identify critical points associated with a specific mix of concern and anticipation. All these indicators are informative and relevant, though they speak differently to different stakeholders and inform different aspects of decision processes as dependent on stakeholder interest (Saltelli and Giampietro, 2017). Evaluating whether policies have had or are likely to have significant impacts (positive and/or negative ones) or have reached prefixed objectives necessitates a sound, multi-dimensional knowledge base and robust biophysical accounting methodology. In the context of studies of ecosystem services and disservices, different stakeholders and cultural groups have different, equally legitimate preferences (van Zanten et al., 2016) and the use of methods capable of integrating value pluralism proves essential (Jacobs et al., 2016). To this end, the exploration of alternative scenarios towards the transformation of social-ecological systems represents promising material for further work.

The approach proposed in this paper can contribute to the improvement of the knowledge base underpinning policies and measures targeting the agricultural sector and its transformation. Moreover, the contextualized information provided by these indicators serves as a basis to highlight a variety of (positive) ecosystem services and (negative) ecosystem disservices under the theme of societal food security—especially when these services originate outside the borders where they are used. Therefore, this type of information improves the discussion on the importance of protecting ecosystem services, creating an environment conducive to overcoming the structural and functional deficiencies that limit the adoption of this concept in EU environmental policies (Bouwma et al., 2018; Keenan et al., 2019). As illustrated in the sections above, the strongest asset of this approach is its internal biophysical consistency—an aspect well suited for assessing trade-offs, burden-shifting and inherent limits associated with alternative configurations of the system under investigation.

The relevance and soundness of the approach proposed in this paper can serve at least two different operational goals in policy. Firstly, it can be used to derive a robust set of interdependent biophysical indicators for monitoring progress and *ex-post* evaluations. Secondly, when used in a prospective mode—as illustrated in this paper—it can prove very useful for *ex-ante* impact assessments. As from the focus of this paper, an indicator tracking the level of openness of various resources and commodities would prove highly relevant for tracking EU loop-closing efforts in agriculture and the food system at large. Indeed, without such an indicator, a perverse incentive for European countries to further open their agricultural sector (relying on foreign imports and markets) may be created. Moreover, when used as an *ex-ante* impact assessment tool, this approach is able to show whether transformation scenarios and pathways aimed at minimizing impacts on natural capital are within the realm of feasibility, could lead to viable socio-economic reconfigurations and could open-up debate concerning the overall desirability of the proposed changes across different sustainability goals.

5. Conclusions

In this paper, a set of novel methods was applied in anticipatory fashion to explore an imagined agricultural future for 29 European countries in the long-term. The methods used were selected based on their ability to coordinate the biophysical accounting of agricultural sectors understood as social-ecological systems and viewed through the lens of complexity. Specifically, the near-complete re-internalization of agricultural production was explored (90% in the long-term). Our results show that if, in pursuit of resilience or national security agendas, a significant re-internalization of food supply inside the respective borders of the 29 countries explored is considered to be a long-term goal or necessity, major social, economic and environmental challenges would be need to be overcome. For example, significantly more employment and land-use in the agricultural sector would be required and changes in agricultural paradigm away from market-oriented agriculture would need to be explored.

Although an extreme level of agricultural re-internalization in the EU may currently seem an unrealistic future, its plausibility cannot be ruled out *a priori*. As the foresight approach to exploring the future asserts, exploration of the repercussions of 'improbable' scenarios allows to stretch-out thinking and supports the identification of 'blind spots', which can be of relevance for current policies. Coupling anticipation science with biophysical accounting methodology, as developed in this paper, provides unique insights for policy-makers by exposing and exploring implausibilities—questioning the possibility of 'living well within the limits of the planet' (EC, 2013) without a fundamental reconfiguration of production and consumption patterns if not society at large. These insights are relevant for the policy debate occurring in the EU on policies and strategies such as the Common Agricultural Policy, the Farm to Fork Strategy (EC, 2020) and the European Green Deal (EC, 2019d).

As levels of agricultural openness have risen over the years, inter-regional assessments of ecosystem service flows have increased in importance. Notwithstanding, many studies continue to neglect them. Our integrated approach to assessing cross-boundary ecosystem service flows provides a novel perspective on the complex issues involved—issues such as resource security and value pluralism, which would otherwise have been tricky to explore using methods of conventional economics. But the approach demands a major shift in thinking away from reductionist sustainability. Overall, the adopted approach responds to the necessities demanded by combining insights from methods and theories including the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) framework (Giampietro and Mayumi, 2000; Giampietro et al., 2020), anticipation science (Poli, 2017a; Rosen, 2012), the relational theory of systems (Rosen, 2005) and the DPSIR causal framework (Smeets and Weterings, 1999).

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.

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Appendix A

The following three figures accompany the figures presented in the results section (Section 3) and present long-term anticipations individually for each of the EU member states plus the UK and Norway. High- and low-bounds (the sensitivity ranges) are determined following the methods described in Section 2.2. Uncertainty emerging from parameter sensitivity is found not to be great enough to affect the analysis conclusions significantly.

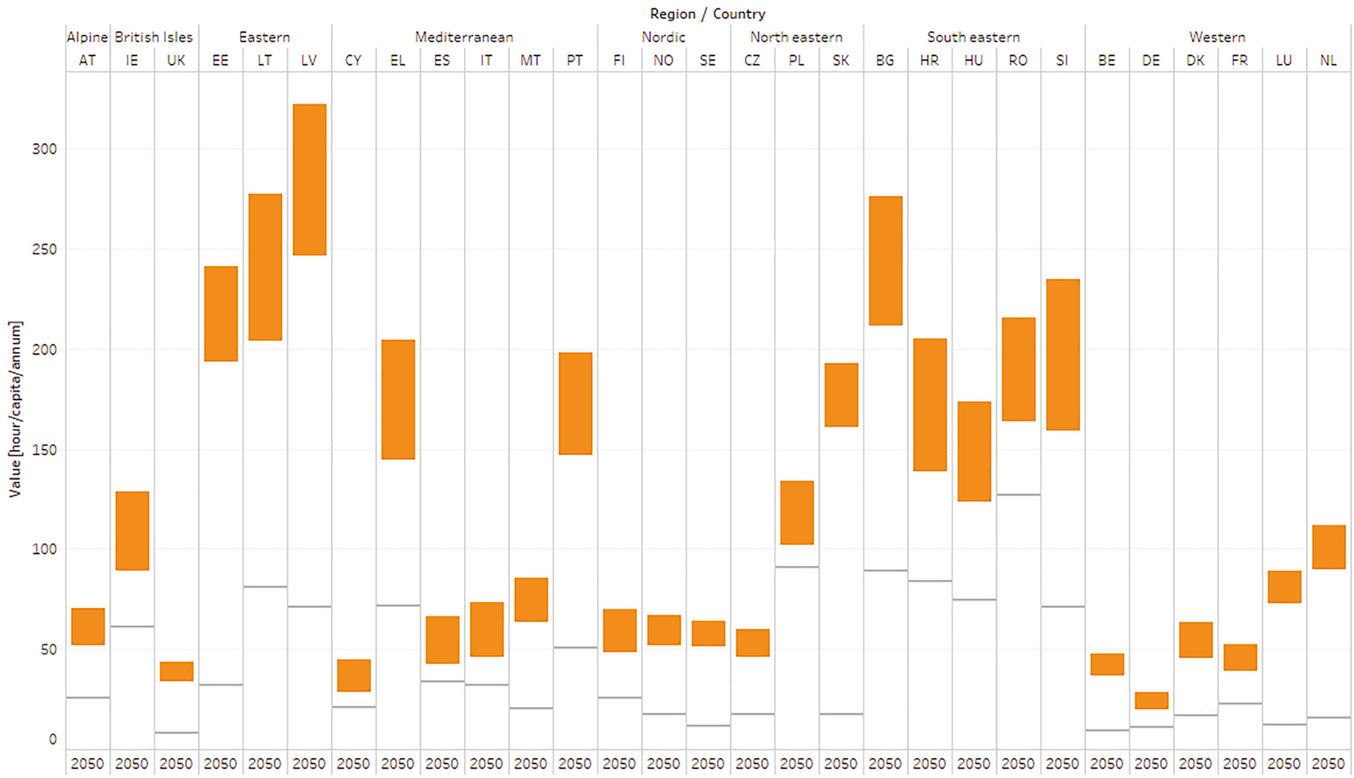

Fig. 7. Anticipation of human activity in the agriculture sector over the long-term for the EU member states plus the UK and Norway. A re-internalization of 90% is anticipated in the long-term. Cell reference lines represent the estimated value for 2012.

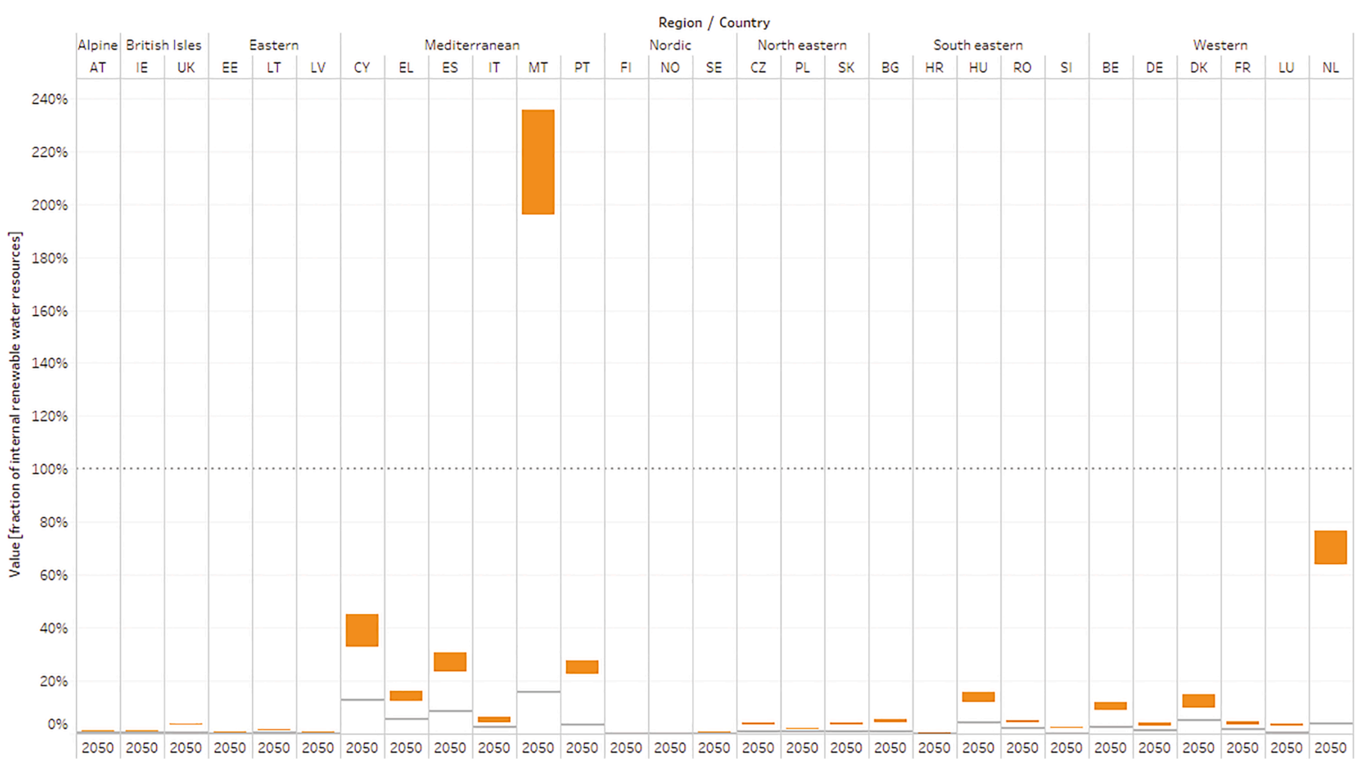

Fig. 8. Blue water use in the agriculture sector per total internal renewable water resources over the long-term represented as a percentage of water use in the 2012 baseline estimate. A re-internalization of 90% is anticipated in the long-term. Cell reference lines represent the estimated values for 2012, the table reference line represents a value of 100%. A deep understanding of this chart requires additional knowledge on water recharge rates—an aspect not readily available in a reliable form for all countries analyzed. In general, water recharge rates are just a small fraction of total internal renewable water resources. In the case of many countries (Malta, the Netherlands, Cyprus, Spain, Portugal, for example), the anticipation is certainly infeasible.

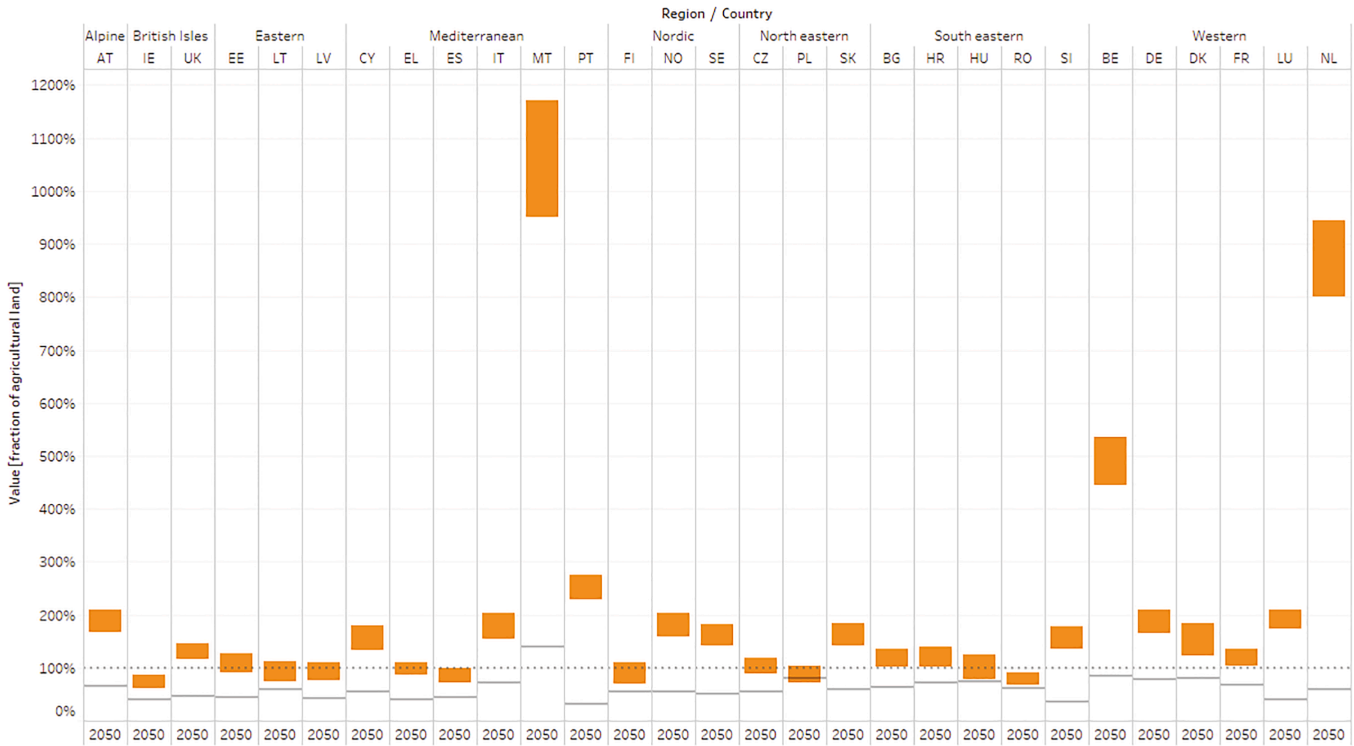

Fig. 9. Anticipation of land use in the agriculture sector as a fraction of agricultural land (baseline 2012 FAO estimate) over the long-term for the EU member states plus the UK and Norway. Percentage values are conservative estimates, due to varying differences in the definition of agricultural land. A re-internalization of 90% is anticipated in the long-term. Cell reference lines represent the estimated values for 2012, the table reference line represents the absolute feasible maximum (100%). Some small error in calculated baseline values is present, resulting both from this work's analysis and from official estimations. In the case of many countries (Belgium, Malta and the Netherlands, for example), the anticipation is clearly infeasible, resulting largely from animal trade.

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