Modelling the Scaling Up of Sustainable Farming into Agroecology Territories: Potentials and Bottlenecks at the Landscape Level in a Mediterranean Case Study

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Acknowledgements

This work has been supported by the Spanish research projects RTI2018-093970-B-C32 and C33, and the international Partnership Grant SSHRC-895-2011-1020 on 'Sustainable farm systems: long-term socio-ecological metabolism in western agriculture' funded by the Social Sciences and Humanities Research Council of Canada. The corresponding author was also granted with two scholarships from the Spanish Ministry of Economy and Competitiveness with references BES-2013-06415 and EEBB-I-17-12073.

Abstract

There is a need for a socioecological transition towards sustainable agri-food systems that recover the organic functioning and the closure of socio-metabolic cycles at the lower feasible scales. This implies an agroecology leap forward aimed at scaling up eco-functional intensification practices from the plot to the landscape level, and identifying synergies and trade offs involved in these jump of scale. We present a new methodology to devise feasible, viable and desirable prospective horizons of agroecology landscapes to inform deliberative processes for decision-making: A Sustainable Agroecological Farm Reproductive Analysis (SAFRA). The model is based on biophysical fund-flow integrated and reproductive accounting of the Agrarian Metabolism, which allows to identify the optimal configuration of land uses, livestock densities, diets and the amount of sustainable population to maximize any given societal objective. The results of this SAFRA modelling, run for a Mediterranean case study, identify the potentials of that scaling up processes towards agroecology territories by means of eco-functional intensification practices addressed to the closure of the yield gap with industrial agriculture. These results challenge the concept of sustainability under the current socioecological functioning of nutrient cycles, and help to devise a potential transitionary near-to-sustainable horizon by using the soil nutrients stock, something easily applicable in over-fertilised western agricultural soils as a feasible first step in the socio-ecological transition. Finally, the results also show that shifting from current diets towards local healthy diets would maximize the synergies among the agroecosystem components (livestock, crops, forests, pastures, farmers and society) by recovering complex agro-silvo-pastoral mosaics that have the potential to increase up to 125% the joint organic yields.

1. Introduction

The profound technical, socioeconomic and political changes that global agri-food systems have experienced from the beginning of 20th century have improved land and labour productivity and drastically reduced agrarian prices for producers relative to the raising prices of inputs purchased outside their farms, thus shrinking the share of food spending in the consumer baskets of wealthy consumers (Dorward, 2013; IPES-Food, 2019; González de Molina et al., 2020; IAASTD, 2009; Vorley, Fearne and Ray, 2007). At the same time, the current agri-food regime has failed to reduce environmental impacts, deliver healthy diets, distribute equitable gains and guarantee food security either for many countries of the world and for future generations (Béné et al., 2019). Industrial agri-food systems are both an important driving force of global environmental change (Beylot et al., 2019; Li et al., 2019) and a hazard for environmental justice (Mayer et al., 2015). New solutions are needed to design sustainable agri-food systems capable to recover an organic interaction between society and nature and provide all types of ecosystem services (Gerber and Gerber, 2017). Sustainability sciences are facing the challenge of how to deal with such a complex research issue in order to define feasible transition scenarios bringing to light the barriers, bottlenecks and possible trade-offs entailed (Verburg et al., 2016).

The biophysical accounting of Social Metabolism has been developed in Ecological Economics to quantify the socioecological interdependencies involved in nature-society interaction, in order to assess sustainability challenges through robust systemic models (Gerber and Scheidel, 2018; Hendrix et al., 1992; Lichtfouse et al., 2009). The Material and Energy Flow Accounting (MEFA) allows for a multi-criterial assessment of some pivotal dimensions of sustainability, mainly through a fund-flow analysis that examines whether the relations among the different components of these socioecological systems can meet or not their reproductive requirements (Georgescu-Roegen, 1971; Giampietro et al., 2008; Marco et al., 2020). By self-reproducing funds we mean the elements that provide some amount of flows or services for a certain period in a productive process without being physically incorporated to the product, and whose maintenance requires a regular reinvestment of a certain amount of resources (Giampietro et al., 2013). This analysis can be also applied to agri-food systems, provided that an agroecology analytical frame is adopted to better understand the factors that are most important for the sustainable reproduction of agroecosystems (Krausmann and Fischer-Kowalski, 2013; Toledo and González de Molina, 2014; González de Molina et al., 2020).

The transition to more sustainable agri-food systems involves laying out new agroecology territories. These can be defined as those regions where to scale up organic farming, currently carried out only here and there mainly at the farm level, and where agroecology practices are integrated in the whole food system (FAO, 2018a; Tello and González de Molina, 2017; Wezel et al., 2016). Just adding more organic farms is not enough. A systemic regime shift is needed so that the main agroecology live funds such as fertile soils, land covers, livestock, farm-associated biodiversity, farmers and consumers become tightly interlinked through the closure of their basic biophysical cycles, as well as through socially fair and culturally meaningful food chains connected with cities (Moragues-Faus and Morgan, 2015). This task is key for the advance towards the Sustainable Development Goals of the United Nations for 2030 (Altieri and Nichols, 2012; United Nations, 2016; FAO, 2018b); it is closely related to the FAO strategy for maintaining bio-cultural heritages (FAO, 2017; Agnoletti and Rotherham, 2015); and responds to the growing demands for relocation of agricultural systems to guarantee food sovereignty and resilience raised by the scientific agroecology community and social movements such as Via Campesina, which are beginning to be addressed by some global institutions and local or regional governments (IPES-FOOD, 2019; Silici, 2014; Martínez-Torres and Rosset, 2010; Stoate et al., 2009). Therefore, the time has come for social metabolism to leap from the quantitative assessment of the unsustainable functioning of current agrarian systems to the modelling of potential agroecosystems and agroecology territories, taking advantage of the knowledge acquired at field level in agronomy and agroecosystem levels in agroecology (Gliessmann, 1998; Zhang, 2013).

While there is a clear aim to upscale organic farming into larger and integrated agroecology territories (Wezel, 2016; Nicholls and Altieri, 2018; FAO, 2018; European Commission, 2020; Duncan, Rivera-Ferre and Claeys, 2020), no one knows in advance what they would look like. How large should an agroecology territory be? How many cycles must be closed inside and of what type? What agroecological synergies can be activated to go beyond a simple addition of farms without integrating them as agroecosystems? What trade-offs must be addressed and what barriers must be overcome? The aim of this article is to present the Sustainable Agroecological Farm Reproductive Analysis (SAFRA), a programming model based on social metabolism accounting aimed at prefiguring plausible and practicable scenarios to better inform deliberative processes aimed at achieving more sustainable agroecosystems and agri-food systems within agroecology territories. The model was already used at the farm level for an advanced organic agriculture in mid-nineteenth century in order to reach a counterfactual analysis on the driving forces of farming strategies to differentiate those that won from other possibilities that lost (Padró et al., 2019). In this paper we set up the SAFRA model in a Mediterranean case study for current technological, social and environmental constraints, scaling up the boundaries of the food system at the landscape level. The shift from linear to non-linear programming result in more degrees of freedom and allows defining the optimal Mediterranean diet that maximizes synergies among subsystems following only some broad nutritional criteria that define this diet as well.

A first fundamental question addressed by SAFRA is to make clear what sustainability options can be technically viable, agroecologically feasible and, above all, socially desirable with the resources available and the environmental constraints of a given territory. This means dealing with the multidimensional and multi-scalar emergent properties of agroecosystems brought to light when the analysis goes up from the plot or farm level to the landscape and regional levels. To do so, SAFRA modelling requires going beyond the business-as-usual paradigm to devise future scenarios and new sustainable solutions that only become conceivable, advisable and feasible in larger agroecology territories. It also involves acknowledging from the start that by adopting different socioeconomic goals farming communities, and the society at large, can take different paths leading to different socioecological outcomes (Bai et al., 2016; Popp et al., 2017; van Vuuren et al., 2017). Another important feature of our SAFRA approach is assuming that, in order to highlight the agroecological and technological possibilities that underpin the horizon scenarios foreseen, this modelling must rely on the biophysical constraints of the system analysed without being bounded by current agrarian prices, costs and other economic criteria. This sets a clear difference with other models used in Agricultural Economics that only account monetary flows moved in the market (e.g. Knoke et al., 2015), but also means that SAFRA results have to be further analysed from the economic point of view to consider their market profitability and the public policies required to make the path to the chosen scenario economically viable (Padró, 2018; IPES-Food, 2019).

SAFRA modelling of the functioning of agroecosystems within their socioecological agri-food fabric becomes a first step towards a policy prospective-deliberative Social Metabolism, beyond the current analytical one. It allows to identify the configuration of sustainable land uses, livestock densities, and the amount of human population that can be fed with a given diet, which become optimal under any given objective that society decides to maximize in the functioning of the agri-food system. The results obtained in terms of biophysical flow distribution, and of integration among live funds, are very relevant for land use planning and prospective agri-food system definition for policy deliberative processes. This SAFRA modelling becomes a methodological meeting point between Ecological Economics, Agronomy, Agri-food Systems Analysis and Food Policy that can be particularly useful to identify bottlenecks and help trace new paths towards sustainable landscapes and agroecology territories. All prospective scenarios are obtained by optimizing a social goal, or a set of hierarchical goals, with nonlinear programming whose constraints on the variables and the restrictions established in the relationship between them are always site-specific biophysical data taken from each case study analysed. This makes SAFRA applicable to any agricultural system anywhere in the world while, at the same times, avoids the extrapolation of site-specific solutions found in one place to other locations.

2. Methodology

2.1 Conceptual approach of the SAFRA fund-flow pattern

How agrarian systems can operate at farm or community level by considering their multiple components is an old research issue. From the Chayanovian studies carried out at the beginning of the 20th century (Chayanov, 1925; Ploeg, 2013), there had been many proposals of resource use modelling each one significant to its historical context. In this regard optimization analysis has been mainly used for urban or transport planning, but with very few exceptions (Smit, 1981) it has not been retrieved as an option for agrarian system planning until recently, when the prevailing free market strategies are being called into question. Interesting contributions using this type of approach have been made in the field of agri-food systems that go beyond the purely monetary models, and they have a fertile path ahead. When they are aimed to meet the needs of society relying on the internal agroecosystem capacities, these models incorporate optimizations with a socioecological perspective (Davis et al., 2016; Desjardins et al., 2010; Heck et al., 2018; Meier and Christen, 2013; Peters et al., 2007; Van Kernebeek et al., 2016).

Nevertheless, optimization agricultural models have been mainly focused so far only on the impact of diets at higher scales, or on the food supply capacity at the local level, while remaining within the conventional economic framework for the rest and, therefore, neglecting ecological sustainability criteria. They do not adopt a fund-flow analysis, neither a landscape agroecological approach, nor a reproductive perspective (i.e. they do not attempt to close the biophysical cycles of funds into agroecology territories). The SAFRA socioecological modelling goes beyond monetary flows so as to assess the ecological feasibility, technological viability and societal desirability of agrarian systems in their biophysical and spatial dimensions (Saltelli and Giampietro, 2017). In order to recover a circular organic functioning of agrarian metabolism, land use distribution and livestock densities are not to be independent variables, but the result of prospective analyses which define the best configuration they can have according to given societal goals, by carefully considering the feasible closure of biophysical flows relating one fund to another.

SAFRA programming model is focused on how agrarian systems could be organized from the production and consumption side through a biophysical non-linear optimization of a site-specific fund-flow pattern of agroecosystems in order to generate potential scenarios by considering three main self-reproducing funds: fertile soil, livestock, and farming population. A previous study has demonstrated the usefulness of this socioecological modelling as a counterfactual tool for environmental history using linear programming (Padró et al., 2019). Here we go one step ahead by using a nonlinear SAFRA modelling to define possible agroecological scenarios for agrarian planning and food policy deliberation processes aimed to find out their main bottlenecks, but also the potential synergies for the advance of agroecology transitions at the landscape and regional level.

Focusing the modelling from the landscape to higher levels is also an important issue. We know that the shift from traditional organic to industrial agriculture, when analysed through a biophysical perspective, involved a linearization of agrarian metabolism that altered the cyclical nature of the energy, materials and nutrients flows of agroecosystems and deepened a metabolic rift between society and nature (Krausmann and Langthaler, 2019; Foster, 1999). This has contributed to global environmental changes that crossed planetary boundaries (Steffen et al., 2015). At the regional level it goes hand by hand with the demise of traditional cultural landscapes and the loss of territorial efficiency, which is an important driving force of environmental degradation in biodiversity hotspots like the Mediterranean basin where the case study here used as example on what SAFRA model does is located (Antrop, 2005; Marull et al., 2008, 2019).

A key feature of the former agroforest mosaics of preindustrial organic landscapes currently disappearing is that they were the territorial imprint of how different funds of agroecosystems were kept integrated and managed in order to take advantage of their agroecological synergies (Marull et al., 2016; Nicholls and Altieri, 2018; Font et al., 2020). Those funds were fertile soils, land use patterns and processes, livestock, biodiversity and the farming population as well (Tello et al., 2015). The tight integration of their fund-flow patterns through the circulation of biomass fluxes allowed for those synergies that increase the complexity, internal eco-efficiency and low external dependence of agroecosystems (Ho and Ulanowicz, 2005). This means that in order to change current unsustainable trends we have to deal with multiple scales and dimensions, putting a special focus on the way they interact at landscape level as a key spatial dimension to start closing the basic biogeochemical cycles of agroecosystems and re-define the conditions under which they can operate in a sustainable way (Levidow et al., 2014; Tello and González de Molina, 2017; Wezel et al., 2016). SAFRA modelling also aims at addressing certain open debates regarding the complex concept of carrying capacity of the territories (Murray, 2009).

On the one hand, we want to assess from the production side to what extent a leap from practicing organic farming at the plot scale to creating agroecology territories at the landscape level can give rise to sustainable farm and food systems while considering the regime shift entailed at all levels of societal organization (Tello and González de Molina, 2017). This is relevant for two main reasons: first, because it is known that at the field scale with no limiting factors many crops have a yield gap between organic and conventional management (De Ponti et al., 2012); and second, because recovering an organic circular functioning among society and nature could collide with some bottlenecks that prevent a sustainable closure of the metabolic cycles at present. On the other hand, we also aim at exploring from the consumption side the important synergies that can be set between society and nature to improve agri-food systems. To that aim diets matter and need to be taken into account together with landscape planning. Therefore, our SAFRA model is going to find out in the case study taken as a first example which kind of Mediterranean diet would be the one achieving the highest carrying capacity in the territory considered, once some biophysical constraints for self-reproducing live funds and socially desirable goals have been defined. Other non-living funds, such as machinery or energy converters, are out of the scope of this modelling so far. For the non-domesticated species, we will only infer some boundary conditions due to their inherent complexity when calculating the sustainable requirements for their reproduction .

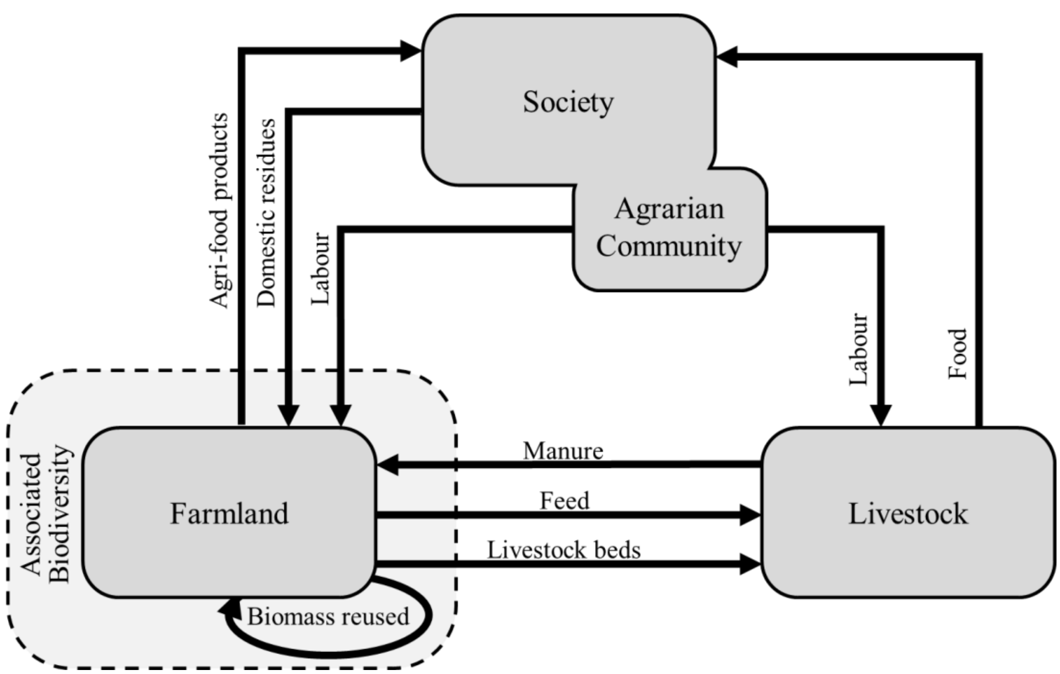

Figure 1. Modelling SAFRA diagram used in the Mediterranean case study for 2009. Squares represent fund elements, and arrows fluxes. Dashed lines mean that this fund is only considered for boundary conditions. Source: Our own.

As seen in Fig. 1, we define a sustainable farm system as that where all self-reproducing funds obtain the biophysical investment needed for their maintenance from the agroecosystem by means of a circular agroecological strategy, and not from external inputs (Gliessmann, 1998; Altieri and Nicholls, 2012; Nicholls and Altieri, 2018). Therefore, we will model their needs and capabilities through balancing biophysical flows among four living funds: agrarian community, society, livestock and farmland. Given that each fund has different needs, each flow will be calculated in the corresponding units for its annual reproductive balance. The time frame of the reproduction requirements in the model is one year. The output of the model are different agricultural scenarios that are feasible (ecologically), viable (technologically) and desirable (socially) according to a specific societal goal, or a list of hierarchical objectives. We are not restricting the model by economic viability, which has to be considered afterwards from a circular bioeconomy point of view (Hetemäki et al., 2017; Raworth, 2017).

2.2 General structure of the model

In the SAFRA modelling both the dimension of funds and the potential interactions among them (flows) are considered. Their units depend on the reproductive process or the fund considered (e.g. hectares, inhabitants or kg of soil nutrients). Constraints are divided into two categories: those referring to the fund-flow relations ensuring reproduction, that is, the balance that has to be maintained in order to sustain each fund year to year (reproductive balances); and those limiting the intrinsic capacities and dimensions of the funds because of ecological, technical or cultural restrictions (boundary conditions). The objective function will maximize the population that can be sustained with a given diet at the boundaries of the agri-food system analysed, and the SAFRA model will provide the resulting landscape in the agroecological territory generated by each prospective scenario according to the prioritized social goal.

In order to set the structure of the model, we first define the variables and the relations among them. Given the complexity of developing a socioecological model, with the experience of the first SAFRA, and following the structure of funds, we define three groups of variables: for population (S, T), for livestock (U, V, W) and a last one for soil fund (M, N, O, P, Q, R, X, Y, Z). For the population fund, we define S and T. Their units correspond to number of inhabitants the first and MJ of metabolizable energy (ME) the second. Regarding livestock, the variables W, U and V represent individuals of animals the first one and days the next two. And lastly, variables X, Y and Z are surface units (hectares), while variables M to R refer to kg of nutrient per ha (as seen in Fig. 2).

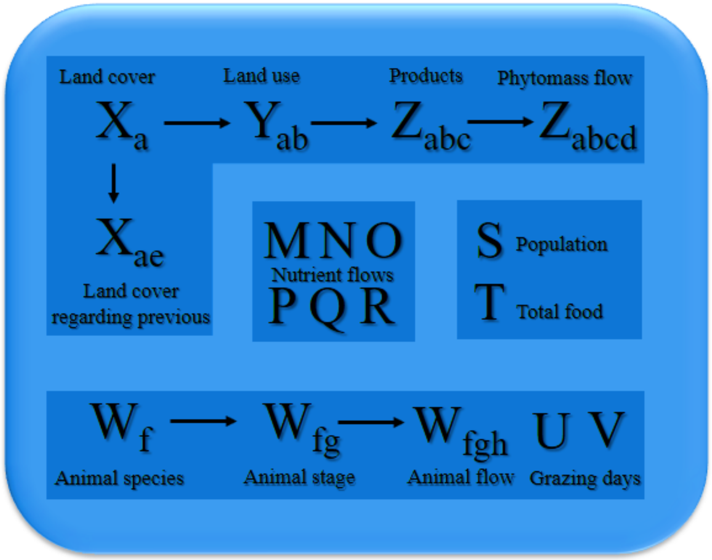

Figure 2. Variables accounted in the SAFRA model. Source: Our own.

While V, W, X, Y and Z represent subgroups of variables, M to U are unique variables. This is why the first ones present subscripts that take consecutive integer values. In order to identify a variable that is part of a hierarchical structure, each subscript indicates its position with respect to its previous variable. For example, for variable Z64212 subscripts read as a = 6, b = 4, c = 2 and d = 12, meaning that it belongs to cover X6 (forest), land use Y64 (oak forest with slope less than 60%, pasturable), by-product Z642 (grass of this forest) and specifically to flow 12, which is the flow of pasture devoted to feed animal stage W411, which in turn are adult sheep for meat production. Arrows in Fig. 2 indicate hierarchical relationships between variables. This implies some first restrictions that refer to the links between hierarchical variables in form of equality (as seen in Eq. 1). Thus, any flow in the agroecosystem is registered by a Zabcd or a Wfgh. The first ones, Zabcd, are representative of a proportional amount of some specific product (Zabc) that comes from a land use (Yab) which is part of some cover (Xa). Therefore, its units are in terms of surface area. For the latter, Wfgh, they reflect an amount of some flows coming from livestock (Wfgh) that depart from an animal stage (Wfg) and therefore belongs to a species (Wf). In this case, then, units are number of individuals.

$$\sum_{b=1}^{b=n} Y_{ab} = X_a \qquad \text{(Eq. 1)}$$

Indeed, we set some constraints to guarantee that the surface of a given cover (Xa) equals the sum of all the surfaces of this one (Xae). The same happens with animals (Wf) with which we set an equality with the sum of all animals in different stages of development (Wfg). From these associations, we obtain a total of 198 constraints.

The mathematical procedure used for running the model is non-linear optimization based on the library NLOPT_LN_COBYLA programmed in R (R Core Team, 2013). The whole SAFRA model, in the version here applied to a first case study used as example, comprises 1,417 variables, 1,977 constraints and 1 objective function (see more detailed explanations and all the datasets used in the Supplementary Material).

2.3 Constraints and data sources

The case study here used only as a first example of what SAFRA modelling can do has been selected for having been used for many years by our research team as testing bench to perform several socio-metabolic and landscape ecology studies (Cussó et al., 2006; Galán et al., 2016; Marco et al., 2018, n.d., Marull et al., 2016, 2008, Tello et al., 2016, 2012). This research effort has provided us with a large array of primary and secondary reliable sources, including data on the agrological suitability of soils for different crops (Olarieta et al., 2008; Rodriguez Valle, 2003). We know in advance that the spatial scope of the study area is likely to become too small to be turned into an agroecology territory, and we expect that the closure of agricultural biogeochemical cycles could only become feasible within this system boundaries, while providing enough food for the resident inhabitants, under very severe conditions. But that precisely allows us to test the capacity of SAFRA modelling to offer solutions in much more demanding conditions than usual. If it is possible to obtain these, that means that it will also be possible under less extreme and more realistic conditions.

The biophysical balances (Table 1) consider the reproductive character of the model, given that all biomass flowing among the different funds of the agroecology landscape departs from the photosynthesis taking place in the farmland over a year, considered as a 'gift from nature' (Tello et al., 2015), as long as farmers ensure the entire reproduction of the agroecosystem. The boundary conditions (Table 2) reflect the site-specific constraints regarding cultural, technological and pedoclimatic conditions (see the sources and datasets used in Tables 1 and 2, and more detailed explanations in the Supplementary Material). We do not allow the return of human excreta as a source of soil nutrients for the biogeochemical balance due to the risks associated with the presence of heavy metals, organic components such as pharmaceutical wastes, and a lack of knowledge about the potential processes of increased antibiotic resistance from the application of sewage sludge in cropland (Bouki et al., 2013; Smith, 2009a, 2009b; Wuana and Okieimen, 2011). This constraint is one of the main socio-metabolic rifts of current unsustainable agri-food regime, and one of the most difficult to solve (Morrissey, Mirosa and Abbott, 2014; Chen and Graedel, 2016; Cordell, Drangert and White, 2009).

Table 1. Boundary conditions of SAFRA modelling. Source: Our own.

Funds	Boundary condition	Procedure and data sources
Farmland	Potential crops	8 different land-uses (and 17 crops) practised in the region (IDESCAT, 2009)
	Crop rotations	3 crop rotations reflect proposals made in a nearby organic agricultural park (Safont i Artal, 2008)
	Cropping and grazing area size	Considering crop suitability (ICC, 2010; Rodriguez Valle, 2003), and subtracting protected areas and old forests, farmland may be increased by 1,879 ha.
	Maximum irrigated land	Based on data of the regional aquifer, and considering an homothetic increase of the extraction, irrigated surface could achieve 2.17 times its 2009 value (ACA, 2004)
Livestock	Livestock species	3 animals: pigs (for meat production); chickens and hens (for meat and egg production); and sheep (for meat and milk consumption)
	Feed limitations	Based on nutritional recommendations we limited certain typologies of feed in livestock diets (FEDNA, 2010)
Society*	Current diet (CD scenarios)	Current diet is obtained from regional information (MAGRAMA, 2009)
	Mediterranean diet (MD scenarios)	Considering food characteristics (Estruch et al., 2013; SENC, 2016) and nutritional objectives (SENC, 2011)
Associated biodiversity	Protected area and old forests	Areas with legal protection status (DGPAMN, 2017) and areas under forest over the past 150 years (CREAF, 2009; Marull et al., 2008) are not subject to land use change
	Organic management	Organic farming is considered to improve condition for associated biodiversity

* Only one of these two boundary conditions are applied at once, so they define the two main different scenarios.

Table 2. Material and energy flow balance constraints of SAFRA modelling

Balances	Description and units	Associated fluxes, procedure and sources
Phytomass balance (Farmland, Livestock, Society)	The sum of all phytomass used for biogeochemical, feed and food balances must be equal to the harvested net primary production (NPPh)	Fluxes: Farmland food, feed, livestock beds and biomass reused
		Procedure: Productivity of land is obtained from regional statistics (IDESCAT, 2009) adapting the yields to the estimated gap from conventional to organic production (De Ponti et al., 2012; Seufert et al., 2012). Yields of by-products are estimated from Guzmán et al. (2014)
Food balance (Farmland, Livestock, Society)	Food production must fit with food requirements per person to define maximum sustainable population (kg of fresh matter or in carbohydrates, lipids, protein, fibre)	Fluxes: food from farmland and livestock
		Procedure: correction factors for the edible part of farmland and livestock food are considered (Farran et al., 2004)
Feed balance (Farmland, Livestock)	Feed needs of livestock (metabolizable energy and crude protein) are to be satisfied by biomass from land uses. Some by-products are also required as beds	Fluxes: Livestock feed and beds
		Procedure: Each product or by-product from cropping or grazing areas suitable as feed is characterized by its metabolizable energy and crude protein content (Church, 1984; FEDNA, 2010). Before performing feed balances, enough by-products are reserved as beds for livestock stalls
Biogeochemical balance (Farmland, Livestock, Society)	Soil nutrient requirements of each land use (nitrogen, phosphorus and potassium) must be equivalent to organic amendments	Fluxes: Farmland food, feed, domestic residues, manure, biomass reused
		Procedure: soil nutrient extractions plus other nutrient flows (e.g. volatilisation, weathering, leaching, symbiotic and non-symbiotic N-fixation and wet and dry deposition) are estimated for each land-use, and total fertilization requirements are set. Soil nutrient sources are characterized by considering their initial composition and potential composting processes. Data is taken from González de Molina et al. (2010) and IPCC (2006)
Labour balance (Farmland, Livestock, Agrarian Community)	Total labour requirements for maintaining the agroecosystem define the dimension of the agrarian community	Fluxes: Labour to farmland and labour to livestock
		Procedure: Labour needs are calculated by means of the data available at regional level (XCAC, 2010)

Source: Our own.

2.4 Scenarios considered

The conditions of the scenarios studied with SAFRA listed in Table 2 involve the combination of different diets with different agricultural managements that involve different constraints on the closure of agricultural biogeochemical cycles within the system boundaries of the case study. Therefore, we define six scenarios regarding three different types of constraints: diets (current/Mediterranean), management (conventional/organic) and biogeochemical cycles (reproductive/non-reproductive).

Two diet constraints were run in SAFRA, as presented in Table 1 and shown in Fig.3: the current diet (CD), or following nutritional criteria of a healthy Mediterranean diet (MD) based on Estruch et al. (2013) and SENC (2016) (see also Davis et al., 2015; Bach-Faig et al., 2011; and more details in Supplementary Material). The later implies that the food composition of the Mediterranean will be a result of the model based on these nutritional criteria, so that the result will be site-specific and will maximize synergies among funds.

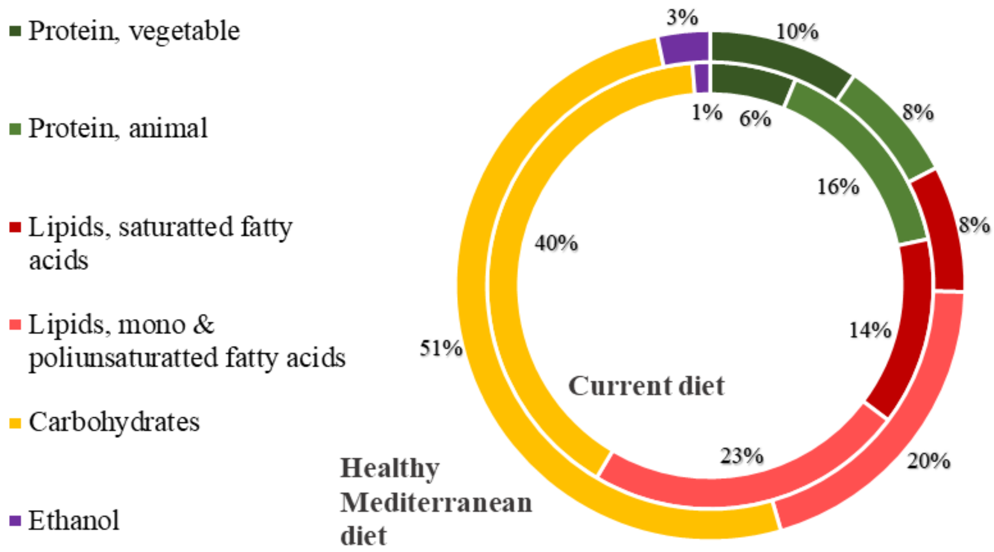

Figure 3. Energetic contribution of different macronutrient sources for CD and MD of the SAFRA 2009. Source: Our own.

In terms of agricultural managements, and in order to have comparable results, we calculate the agroecological scenario (A) where all balances listed in Table 2 are adjusted in the system boundaries of the case study, meaning a total closure of these agricultural biogeochemical flows within that agroecology territory. Then we contrast the results with the ones obtained with the conventional scenario (C) where soil nutrient and feed balances are not locally closed allowing for imports from outside the system boundaries as currently done.

Finally, the third axis refer to the biogeochemical cycles. By applying stricter or laxer criteria in the closure of farming biogeochemical flows within that small agroecology territory, combined with two different types of diets, we can observe the results obtained in terms of the number of inhabitants that can be fed with the local food produced and the landscape entailed.

The objective of this first SAFRA experiment is not only to verify the possibilities of closing the basic biophysical flows on which the reproduction of the agroecosystem funds depends, but to consider at the same time the options that exist to improve the synergies between them by increasing their mutual integration within more complex landscapes. In order to address these synergistic possibilities of eco-functional intensification practices, we will also account for the Land Cost of Agrarian Sustainability (LACAS; Guzmán et al., 2011). LACAS is the amount of land required to provide the vegetal and animal products of a given human diet plus the amount of land needed to close the soil nutrient cycles. We calculate this under current (CD) and improved Mediterranean diet (MD) scenarios for both the conventional (C) and agroecological (A) managements. When including fertilisation in conventional scenarios we do not consider any internal territorial cost associated to the use of mineral fertilizers (Guzmán et al., 2011).

2.5 Sensitivity analysis

In order to ascertain that the results are not biased by the specific meteorological conditions of the reference years of the data used to feed the model (Table 1 and Supplementary Material), we perform a sensitivity analysis to identify the main sources of potential variability in the SAFRA outcomes. The input variables are modified considering the evolution of farm yields at county level between 2007 and 2016 in order to obtain the ranges within which results could vary for the different proposed scenarios. This is a conservative criterion. As other technical factors are not modified (such as harvest indices, soil nutrient content, metabolizable energy intake and nutrients excreted by animals), variations will be higher than expected in reality given that all these biological processes actually respond and adjust to metereological conditions. As long as variations in input variables (yields) remain higher than variations in the output (dimensions of funds), we consider the model to be robust (see further details in Supplementary Material).

3. Case Study

The study area selected covers four municipalities in the Vallès County (Sentmenat, Caldes de Montbui, Castellar del Vallès and Polinyà) in Catalonia (Spain) with some 120 km2 of extent. They are part of the Barcelona Metropolitan Region, 25 km north of the city of Barcelona, located between the coastal and the pre-littoral mountains. The area has a low relief on its southern half and mountainous on the northern half, with a mean annual rainfall ranging from 600 mm in the south to 800 mm in the north. On the southern plain soils are generally moderately deep, loamy, well drained and have a high available water holding capacity. On the northern half soils have been developed on hard parent materials (limestone, dolomite, conglomerate) and steep slopes, so they are relatively shallow, loamy, frequently stony, and have a low available water holding capacity (Olarieta et al., 2008).

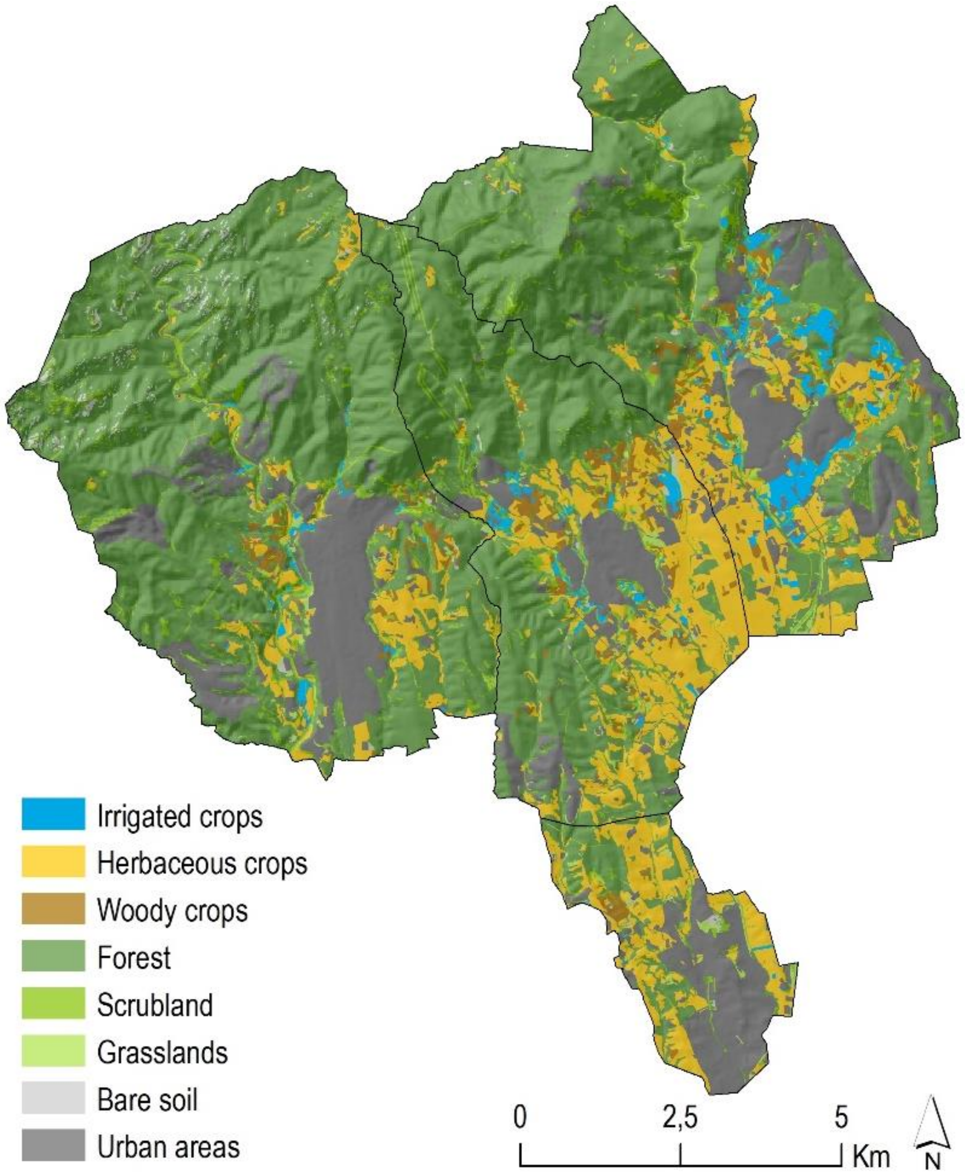

Figure 4. Land-use map for the Vallès case study in 2009. Source: Our own, adapted from CREAF (2009).

The predominant land uses are woodland and scrubland, which covered 62% of the total area in 2009 (Fig. 4). From 1956 to 2009 cropland halved as a result of two main drivers: first, urban areas increased fivefold (being now around 16%), swallowing up formerly irrigated, high-quality cropland; and second, a steady process of forest transition subsumed marginal lands that could not be easily mechanized and were abandoned (Cervera et al., 2019). The decline in cropland has resulted in a subsequent loss of agro-silvo-pastoral mosaics that were the traditional landscape pattern and biocultural heritage of this Mediterranean region (Marull et al., 2016; Padró et al., 2017). The remaining cultivated land mainly grows feed crops (75% of this cropland), and fruit and olive trees to a smaller extent. This is consistent with the exorbitant current animal density of

111 livestock units of a standardized weight of 500 kilos per square kilometre (henceforth LU500/km2), while the figure for the same area was only 7 LU500/km2 in mid-19th century.

The proximity to the Barcelona metropolitan area resulted in an upward population trend until the middle of the last decade, when residents numbered 55,433 and the population density was 462 inhab./km2, with only 0.25% dedicated to farming. This high population density has to be taken into account when drawing conclusions of this example. SAFRA modelling starts from all these local-regional features so as to proceed subsequently to a multi-scalar networked analysis of the capacities for larger regions. Therefore, the results must be taken only as a preliminary case study, always avoiding extrapolating them to other places and scales.

4. Results

In the analysis of the present situation characterized as conventional farming with the current diet (see CCD1 in Table 3 and following figures), total conventional production permits an average degree of food provision within this territory that could only sustain as much as 16% of the population living the study area in terms of metabolizable energy (ME). The enormous amount of animal products (8,964 t compared to 3,223 t of plant products) would drop to 1,882 t of animal products if only the amount of meat produced with local feedstuffs is considered. The current situation presents many other imbalances. Chemical fertilizer is used despite production of composted manure would potentially amount to some 370,000 kg of N, while extractions in crops are just 87,000 kg of N. This huge wastage becomes an indicator of the fund-flow disintegration between livestock and farmland, highlighting a clear metabolic rift (Krausmann and Langthaler, 2019; Foster, 1999). Taking into consideration all imports of soil nutrients embodied in feed and fertilizers, the total amount circulating in the agroecosystem would be 370 kg of N, 111 kg of P and 228 kg of K per agricultural hectare, an enormous surplus that has both internal and external impacts.

Table 3 presents the dimensions of funds for the current situation (with conventional management and current diet; CCD1), as well as for the scenario of increasing agrarian surface under ceteris paribus conditions (CCD2), and for the agroecological scenarios under current diet (ACD1 and ACD2) and the Mediterranean diet (AMD1 and AMD2).

Table 3. Dimensions of funds for the current situation and the scenarios. Source: Our own.

Funds		Units	CCD1 (conventional farming & current diet)	CCD2 (CCD1 & cropland expansion)	ACD1 (agroecology farming & current diet)	ACD2 (fewer NPK constraints than in ACD1)	AMD1 (agroecology farming & Mediterranean diet)	AMD2 (fewer NPK constraints than in AMD1)
Humans	Population	Inhab.	9,080	12,168	1,901	8,124	4,585	18,303
	Agrarian Community	AWU	114	149	35	119	66	226
Farmland	Irrigated crops	Hectares	304	608	29	160	91	406
	Herbaceous crops		1,546	1,372	410	2,166	351	1,254
	Woody crops		268	613	87	524	322	1,280
	Pastures		206	206	206	1,051	206	1,264
	Forests & other		6,801	6,327	9,000	5,831	8,762	5,528
Livestock	Pigs	LU500	8,399	8,399	20	109	3	0
	Poultry		342	342	23	128	0	9
	Ruminant		1,769	1,769	128	706	658	2,568

When considering all constraints set for this SAFRA example, the population that could be fed in the study area by the agriculture carried out in the territory is only of 1,900 inhabitants at present with the current diet (ACD1) and would be of 4,600 with a Mediterranean diet that would involve a demitarian meat consumption compared to the current intake (AMD1) (Table 3; Figs. 5 and 3). Population densities would be 16 and 38 inhab./km2, respectively, far below the sustainable population with current conventional farming.

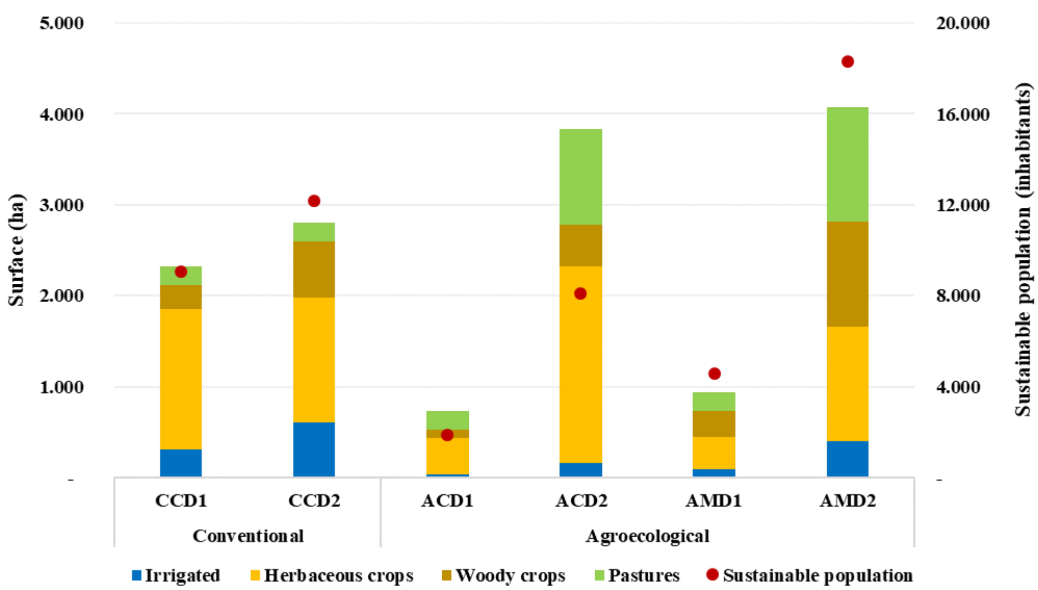

Figure 5. Land-cover dimensions excluding forest area, and amount of equivalent sustainable population in each scenario. Source: Our own.

What appears to be the main limiting factor is the closure of soil nutrient cycles. When the model is run again excluding this constraint, sustainable population increases around 4-fold in each scenario. In that case the population that could be fed with a healthy demitarian diet would even exceed the scenario CCD2 of maximum cropland expansion. This makes apparent to what extent biogeochemical balances affect the potential development of agroecological strategies at the landscape level.

According to the soil nutrient balances (Fig. 6), many nutrients would have to be extracted from forestland in order to maintain current diets and close biogeochemical cycles (ACD1). Conversely, a reproductive Mediterranean diet (AMD1) would not rely on direct nutrient imports and could resort to manure coming from stalls. Nevertheless, phosphorus (P) appears to be the most limiting nutrient, given that nearly half of its soil extraction by crops could not be replenished in a scenario of unrestricted nutrient cycles and current diet (ACD2), and the deficit would amount to 20% of total extraction with a Mediterranean demitarian diet.

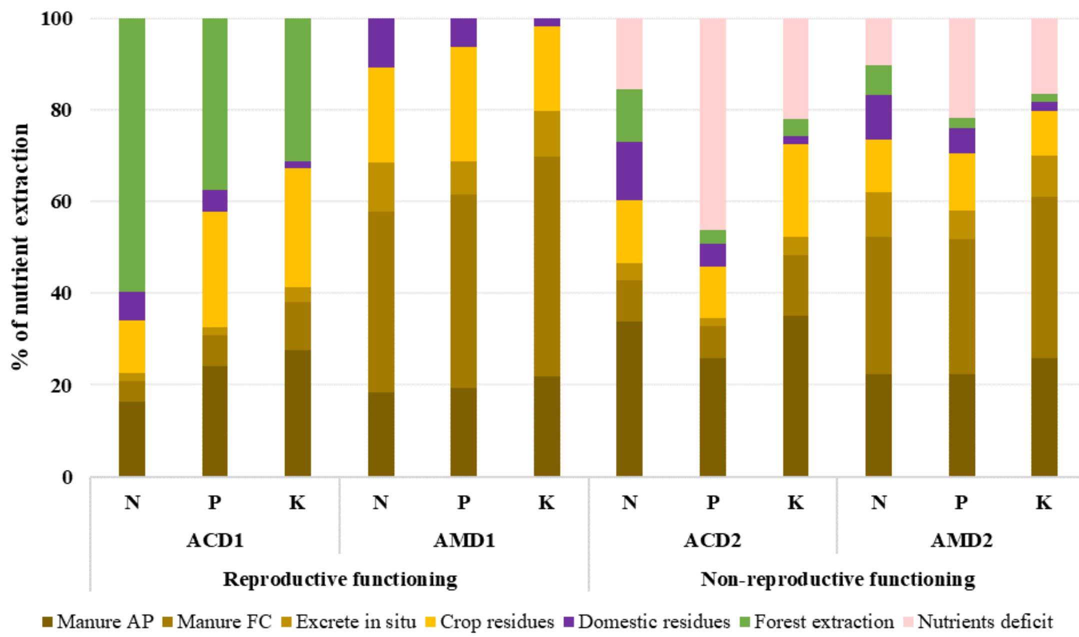

Figure 6. Nutrients available for soil fertility replenishment in pastures and cropping areas in each SAFRA scenario. Reproductive functioning implies a zero deficit for all nutrients, while under non-reproductive functioning no restrictions are applied in terms of soil nutrients. 'Manure AP' is that produced in stalls from the livestock consumption of agricultural products, 'Manure FC' comes from the consumption of forest or grazing products but recovered in stalls, and "Excrete *in situ*" is the amount of nutrients directly excreted by eating by-products *in situ*. Source: Our own.

A very important finding of this SAFRA modelling regarding the total land required to provide the different parts of a diet (LACAS, see Fig. 7) is that the amounts are higher when vegetables (V), animal products (AP) and fertilisation (F) are accounted separately than when combined at the aggregated landscape level (V+AP+F), this time considering the agroecology synergies that can be set in motion (Nicholls and Altieri, 2018). In the agroecological cases, when the maintenance of livestock and the production of plant foodstuffs are accounted separately (the cumulative sum of V and AP) the total cropland needed for the current diet would be 0.47 ha/person, while the amount needed for the healthy diet would be 0.24 ha/person, a reduction of nearly 50%. In the case of diets produced with conventional farming (CCD and CMD), adding together the land cost of plant and animal products is smaller than that for agroecological farming, with the agroecological/conventional ratio being 2.2 for ACD/CCD and 1.3 for AMD/CMD.

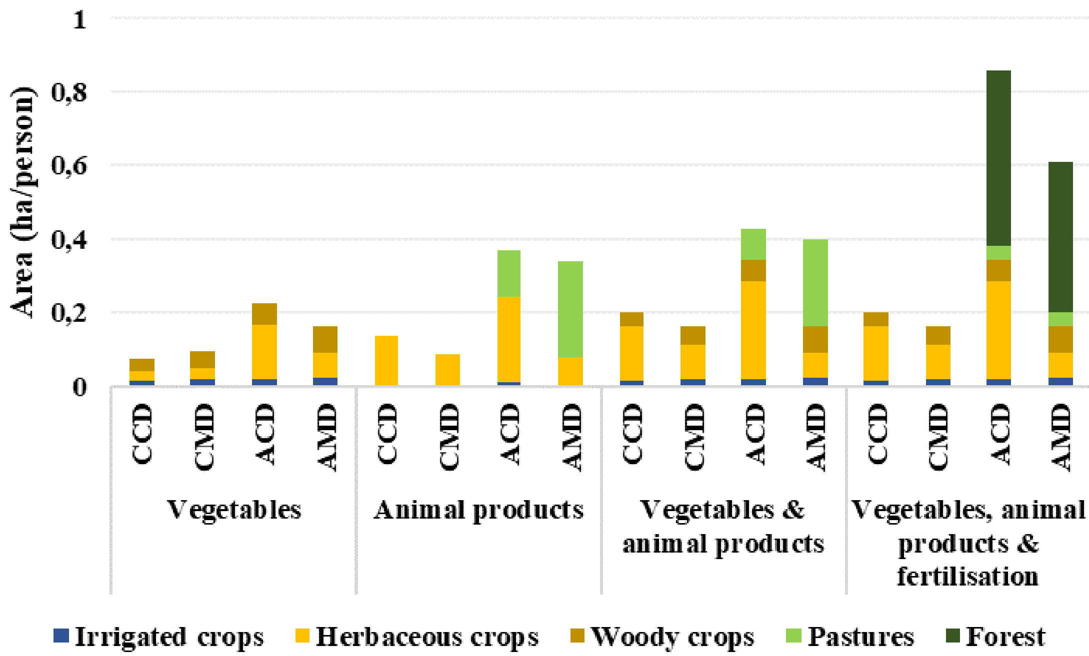

Figure 7. Land Cost of Agrarian Sustainability by fund in each SAFRA scenario. Area required to produce vegetables (V), animal products (AP), the total amount when maximizing landscape synergies (V+AP) and when also applying constraints for nutrient cycles (V+AP+F). Source: Our own.

Considering the cost of soil fertilisation, the maintenance of the current diet would require 0.35 ha of cropland/person, while for the Mediterranean demitarian diet would be 0.16 ha cropland/person. In other words, the land required to provide each satisfied basket unit of the current diet could satisfy 2.2 healthier Mediterranean diets. Changing from the current (CD) to the Mediterranean (MD) diet increases the consumption of legumes, while consumption of potatoes disappears. There is a significant rise in the consumption of wine (only up to a glass a day), while consumption of wheat is similar, although of refined wheat for CD and of whole wheat for MD, which involves a much higher fibre intake. Consumption of pork, chicken and eggs falls sharply, while there is a substantial rise in the consumption of lamb even though the intake of milk declines and, as a result, the proportion of animal protein nearly halves (Table 4).

Table 4. Comparison between current and Mediterranean diets considering annual depletion of soil nutrient pools in agro-ecological non-reproductive SAFRA scenarios. Data is in grams of fresh matter per day and average person for diets, and in percentage for soil nutrient pool depletion. Source: Our own.

		ACD2 (agroecology farming & current diet with fewer NPK constraints)	**AMD2** (agroecology farming & Mediterranean diet with fewer NPK constraints)
Diet (g fm/day·inhab)	**Vegetables**	302.7	400.0
	Fresh fruit	359.3	367.9
	Wheat	201.4	207.7
	Legumes	12.2	40.1
	Olive oil	33.6	31.8
	Almonds	10.3	30.0
	Potatoes	83.9	0.0
	Wine	43.0	120.0
	Pork	86.8	7.2
	Lamb	25.0	43.8
	Chicken	54.4	0.1
	Eggs	28.2	1.8
	Sheep milk	488.0	324.1
	Fish	90.2	90.2
Annual depletion of nutrient pools in crop soils (%)	**Nitrogen**	0.059	0.058
	Phosphorus	0.160	0.088
	Potassium	0.009	0.013

The sensitivity analysis (Table 5) shows that the variations in the values of SAFRA results are higher than input variability when considering whole constraints, especially for AMD1, where population density, land use distribution and livestock densities are far over the 15.2% variability in yields. Conversely, when relaxing the constraints on soil nutrient cycling (scenarios ACD2 and AMD2) we obtain that all variations in SAFRA modelling outputs are below the input variations, which gives a higher degree of confidence on these results.

Table 5. Coefficients of variation for the main inputs and outputs of the SAFRA model (in %). Source: Our own.

		ACD1 (agroecology farming & current diet)	**AMD1** (agroecology farming & Mediterranean diet)	**ACD2** (fewer NPK constraints than in ACD1)	**AMD2** (fewer constraints than in AMD1)
Input	**Crop yields**	**12.7**	**15.2**	**14.3**	**15.9**
Output	**Population**	6.7	27.8	11.0	9.4
	Agrarian community	3.2	20.3	11.6	8.1
	Land use distribution	13.6	25.0	13.0	8.1
	Livestock density	9.7	4.5	11.0	9.2

5. Discussion

5.1 Do we need to rethink the concept of agroecosystems' sustainability?

SAFRA results point out to the soil nutrients replenishment, and particularly that of phosphorous, as one of the big bottlenecks to advance towards agroecology territories where the main biogeochemical cycles moved by farming could start to be closed. This is a historical legacy of old metabolic rifts opened long ago (Krausmann and Langthaler, 2019; Schneider and McMichael, 2010; Foster, 1999), and poses a big challenge to the sustainability science (Morrissey, Mirosa and Abbott, 2014; Chen and Graedel, 2016; Cordell, Drangert and White, 2009). A strong dilemma appears: Either having unsustainable agroecosystems, highly dependent on external inputs of mineral nutrients extracted from non-renewable ores and of industrial synthetic fertilizers with large carbon footprints; or, conversely, trying to restart a sustainable nutrient recirculation between different land uses within agroecology territories as was done by necessity in many traditional organic farming systems in pre-industrial times. Different options lead to different capacities to feed human populations. The reproductive scenarios shown in Fig. 5, with population densities that could be sustainably fed of 16 and 38 inhab./km2, are far below the sustainable population densities obtained in counterfactual scenarios for the same case study in the mid-19th century (Padró et al., 2019). The reason for such a sharp decline is the precautionary assumption of avoiding the return of human excreta to the agroecosystem. In mid-19th century human excreta were 12% of the total nitrogen requirements and, even more important, 21% of phosphorus (Tello et al., 2012). In the scenarios ACD1 (agroecology farming with current diet) and AMD1 (agroecology farming with Mediterranean diet) that flow would provide 27 and 24% of nitrogen, 13 and 22% of phosphorus and 10 and 17% of potassium respectively. Losing them is particularly relevant in the case of phosphorus, which is the soil macronutrient most difficult to be replenished in soils by non-human flows except through livestock (Morrissey, Mirosa and Abbott, 2014; Chen and Graedel, 2016; Cordell, Drangert and White, 2009). It is worth noting that the extraction of nutrients from woodland soils would have to play an important role to make the agroecosystem nearly sustainable in the scenario ACD1. About 8 kg N/ha, 0.35 kg P/ha and 15 kg K/ha a year are incorporated in forest soils as natural entries (Tello et al., 2012), so phosphorus again is the most limiting factor.

Strategies to import green biomass from woodlands were not unknown in the traditional organic agricultures of the mid-19th century, but they were always described as very labour intensive (Olarieta et al., 2011; Corbacho et al., forthcoming) and could therefore lead to a non-feasible labour cost for reaching sustainability (Marco et al., 2020) in addition to entailing an unsustainable burden if extraction exceeds natural entries to forest soils. This kind of eco-functional intensification practices use to require higher labour costs than conventional management, and issue that should be considered and is not yet addressed in this study. Just considering the farm-level labour requirements included in the model, the amount of people that could be fed by each farmer remains stable between conventional and organic management ranging from 54 to 82 inhab./farmer depending on the scenario. In any case, those practices can be restarted using other technologies less labour intensive and respecting the limits of natural replenishment of nutrients in uncultivated soils. What matters here is the capacity of SAFRA modelling to identify options, problems and solutions.

Results for ACD1 and AMD1 scenarios stress the importance of the threshold of population living in the territory for a strong sustainability strategy, understanding this sustainability from the reproductive standpoint of the agroecosystem funds. However, while those scenarios would be reproductive, it would be a fantasy to limit the population density to a maximum of 38 inhab./km2 in a territory with a current average density in excess of 450 inhab./km2.

Soils, in addition to being auto-reproducible funds, contain certain stocks of nutrients. There is not great information on the subject, because studies are very often limited in the case of P and K to the amount of ‘available’ nutrients. Using estimations from nearby areas of the study area, we can approximate a total content in forest soils of about 7,000 kg N/ha, 1,600 kg P/ha and 41,000 kg K/ha, compared to 5,000 kg N/ha, 3,000 kg P/ha and 55,000 kg K/ha in agricultural soils (Arán, 2001; Batjes, 1996; Bosch-Serra et al., 2015; Cantero et al., 2012; Kizilkaya et al., 2007; Olarieta, 2017). This greater value in total phosphorus in agricultural than in forest soils is the result of over-fertilization practices during many past decades (Cordell, Drangert and White, 2009; Li et al., 2019; Peñuelas et al., 2009).

By using these stocks of soil nutrients, we would no longer be speaking of a reproducible system ad infinitum. However, it is important to know the impacts that would entail to extract nutrients from forests and use the accumulated stocks in cropland soils. When we run the model removing the constraints of soil nutrient replenishment and establishing that the use of stocks should not be proportionately greater in forest land than in crops or pastures, the agroecosystem of that territory could sustainably provide enough food for a population density of 68 inhab./km2 in the ACD2 scenario (agroecology farming with current diet and fewer NPK constraints) and 153 inhab./km2 with AMD2 (agroecology farming with demitarian Mediterranean diet and fewer NPK constraints).

What would those close-to-sustainable population densities involve in terms of soil nutrient deficits of these scenarios? The decisive element in these possible increases in the carrying capacity of that agroecology territory would be phosphorus again

(Table 4). In the ACD2 scenario (agroecology farming with current diet and fewer NPK constraints), the requirements in agricultural areas become offset by the use of soil nutrient stocks from woodlands and farmland, consuming 0.16% of the agricultural soil pool annually. This generates a horizon of 625 years before total depletion of phosphorus in these soils with annual extractions of 4.2 kg P/ha, and of more than 1,000 years for AMD2 with annual extractions of 2.3 kg P/ha. Although these simple calculations do not consider the gradual soil degradation process, and the ensuing effects on the bioavailability of P, they give us a first picture of the situation. Alternatively, recovering human excreta for agrarian lands would allow for a reduction in the use of soil stocks that would range from 28 up to 92% of the phosphorus requirements. This is another very important result of the SAFRA model that points to the importance of solving the problem of nutrient recovery from human excreta to advance towards sustainable agroecology territories.

The global impact of phosphorus losses to the sea, estimated at about 50% of the total circulation, has been noted in various studies (Liu et al., 2008; Mihelcic et al., 2011; Nesme et al., 2018). But this crucial issue does not appear yet on the political agenda as a priority (Cordell, Drangert and White, 2009), despite having been raised for long time on the scientific literature by Justus von Liebig and others from the 19th century onwards (Foster, 1999; Schneider and McMichael, 2010). The other two soil nutrients are clearly not as constraining as phosphorus. The horizons of soil potassium pool decline are one order of magnitude above phosphorus, whereas for nitrogen there are many other feasible strategies to close the gap, such as increasing the proportion of leguminous plants. When we speak of processes that can be maintained over such a long timescale, the social and environmental costs from pursuing the reproductive scenario would surely be greater than the impacts and risks of depleting the soil nutrient pools inherited from over-fertilization. This is an issue, however, that must be decided socially by putting on the table the various alternatives under discussion.

5.2 Confronting productivity gaps with territorial synergies of recovering agro-silvo-pastoral mosaics

The results obtained also demonstrate that SAFRA modelling can provide relevant insights to a couple of tightly interlinked international debates on sustainability science, namely the big challenge posed by the food-biodiversity dilemma and the alleged need to carry out agroecology intensification strategies as a response (Tilman et al., 2011; Foley et al, 2011; Chappell et al., 2011; González de Molina and Guzmán, 2017). The population that can be sustainably fed with agroecological strategies in the territory studied (ACD2) is only 67% of the one with conventional farming (CCD2) (Fig. 5; Table 3). The gap is due to the 20% difference in crop yields between organic and conventional farming and the longer cycles required in organic animal production. However, these gaps can be largely overridden through agroecological management strategies.

While in the industrial animal feedlots of the CCD2 scenario (extended conventional farming with current diet) only 14% of animal intake are crop by-products or non-competing products for human food such as grazing, this value reaches 65% in ACD2 (extended agroecology farming with current diet) and 99% in AMD2 (extended agroecology farming with Mediterranean diet). Therefore, integration of livestock, and particularly ruminant species, as bio-converters of agricultural products that do not compete with human consumption reduces the land cost of organic farming compared to industrial feedlots (Oltjen and Beckett, 1996; Roos et al., 2016). The active multipurpose management of woodlands as providers of soil nutrients and other resources for farming and livestock feeding stands as another relevant eco-functional intensification strategy (FAO, 2013). These agroecology strategies based on the synergies provided by an integrated diversity of live funds give way, in turn, to functional agro-silvo-pastoral mosaics, which in a Mediterranean context like the territory studied are increasingly valued as a means of preventing forest fires (Fernandes et al., 2014).

Another important result of the SAFRA model is to confirm that the provision of a diet with such great a disproportion between animal and plant production as the current one results in a very high land cost of sustainability (LACAS; Guzmán et al., 2011). Animal products account for 41% of the total energy intake in current diets, and for only 24% in the healthier Mediterranean one— a nearly demitarian outcome (Table 4). As a result, with a Mediterranean diet it is possible to achieve levels of sustainably fed population above those reached in 2009 in that territory with conventional farming (compare AMD2 with CCD2 in Fig. 5). All in all, the differential effect between agroecological and conventional farming has the following result: To produce the current diet under agroecological management requires 75% more land than under a conventional one, whereas to produce a healthy Mediterranean diet (MD) requires the same amount of land under agroecological cultivation as under conventional management (Fig. 7). In MD, the lower productivity of organic production and lower feed-to-meet linear efficiency in livestock production can be overcompensated by means of the synergistic linkage of funds within agroecology landscapes. This explains why the sustainable population density in AMD2 (extended agroecology farming with MD) becomes 28% higher than the maximum threshold that can be fed in the current situation.

These are extremely important results of SAFRA modelling, because they confirm that it is possible to compensate the yield gap between organic and conventional farming at the plot scale by implementing low-entropy internal loop strategies through a more complex integration of agroecosystem funds at the landscape scale (González de Molina and Guzmán, 2017; Marco et al., 2018; Padró et al., 2019). The key is how the art of farming (Ploeg, 2013) can shape more efficient agroecology landscapes by dealing with the information that rules the complexity of their fund-flow patterns (Font et al., 2020). Knowledge-intensive farming of agroecology territories can be an alternative to increasing land intensity to meet the world's growing food needs (IAASTD 2009). This also means connecting, in turn, the way out to the food-biodiversity dilemma with another information-driven societal shift: the change of diets (Tilman and Clark, 2014; Westhoek et al., 2014; Van Kernebeek et al., 2016; Willett et al., 2019).

5.3 Healthy diets to improve sustainability

The shift from the current diet to a nearly demitarian Mediterranean one (MD) would involve a fall in the contribution of monogastric- livestock from 36% to 4% of animal products. This is consistent with the situation observed in countries without industrialized farming, where ruminants are the dominant livestock because of their ability to mobilize nutrients without competing for land with humans (Eisler et al., 2014; Haberl, 2015). The result is that a MD would reduce livestock density from the 6 LU500/km2 necessary in agroecological terms for the current diet to 4 LU500/km2, similar to the value that existed in 1860 in the same study area (Marco et al., 2018). These livestock densities are not that low. In a study done for the Netherlands, the ideal sustainable proportion of animal protein over total intake was estimated at 12% (Van Kernebeek et al., 2016), while in our MD the proportion reaches 45%.

It is also true that the potential of ruminants as efficient bio-converters clashes with their role in greenhouse gas emissions (GGE) (Herrero et al., 2013). Nevertheless, when accounted as a net balance within the whole basket of GGE of Mediterranean agriculture the methane enteric contribution is very small and can easily be offset by other farming improvements (Sanz-Cobena et al., 2017). In our SAFRA case study, when the MD agroecology scenario is compared with the current situation in 2009, aggregate GGE would be lower because livestock density of ruminants would fall from 11 LU500/km2 to 3 LU500/km2. Once again, systemic eco-efficiencies achieved through agroecology synergies outperform the lower linear input-output efficiency of a single component (in this case animal bioconversion) thanks to knowledge-intensive, low-entropy loop strategies that increase the internal agroecosystem complexity at the landscape level (Marull et al. 2016; Font et al., 2020).

If we analyse these diets in terms of the contribution of different macronutrients to total metabolizable energy (Fig. 3), we find an imbalance in current diet (CD). Carbohydrate intake is only 40% (below recommended 50-55%), while fats exceeds 37% (over 35% recommended). Saturated fats are 38% over total fats, against the recommended 25%. These imbalances, therefore, stem from the high consumption of animal products. For both type of diet protein consumption is over the minimum of 15%. However, plant protein is only 27% of total protein in the current diet, far below the recommended minimum of 50%. Lastly, in terms of macronutrients, both diets can provide the nutritional requirements of the population. It is clear, therefore, that the current diet does not only limit the potential carrying capacity to feed human population in the territory studied. Better diets can improve the health of the environment together with human health (Willett et al., 2019). SAFRA results confirm that current diets have a significantly higher land cost than diets with lower animal intake (Peters et al., 2007; Van Kernebeek et al., 2016), which in turn would also provide a positive health impact (Tilman and Clark, 2014; Westhoek et al., 2014). Furthermore, they show that healthier demitarian diets help improve agroecology synergies among funds as well, which would be a key factor to optimize the use of the site-specific resources of each territory and reduce the land required per each final consumption basket of agri-food products that society needs helping to advance towards a higher closure of soil nutrients (Billen, Le Nöe, Garnier, 2018).

5.4 Limitations of SAFRA model and pending research

After discussing the outcomes obtained by running the SAFRA model, and their implications, we want to point out some limitations that become sources of uncertainty and restrain the robustness and applicability of the results. They have a lot to do with cross-disciplinary issues. Institutional dimensions and social relations are not incorporated in the study. SAFRA modelling assumes freedom of access to resources and societal feasibility of changing their use. The results obtained are decontextualized from the social reality of private property and other prevailing rules of access and use of them. These factors limit the establishment of new farmers and impede crop diversification that would be required to pursue these strategies. However, precisely because of that our results also highlight how those entitlement rules become social barriers to achieve technically feasible agroecological alternatives. The study of how to overcome these institutional barriers can be addressed through other types of modelling, such as agent-based models aimed at providing better guidance to public policies designed to fostering land exchange (Bakker et al., 2014).

It is also critical to delve more deeply into the analysis of farm-associated biodiversity kept in agroecology territories. In this first SAFRA example we have limited the modelling of alternative scenarios to the change in land use distributions, not including other fundamental aspects of landscape ecology such as the role of patch fragmentation or ecological connectivity. These aspects can be either incorporated in future SAFRA enlarged versions, or subsequently addressed through other models such as ELIA and IDC ones (Marull et al., 2019).

Other aspects which entail a land use competition, such as firewood extraction for energy use, water metabolism, greenhouse gas emissions and the management of stocks such as machinery, should also be included even though that would entail changing the scale of analysis to a larger regional or country scope (Billen, Le Nöe, Garnier, 2018; Aguilera et al., 2015; Madrid-López and Giampietro, 2015). In this sense, further studies should focus and refine the dimension of agrarian labour as a key element to understand and evaluate the time cost of more sustainable food systems, its potentials and limitations. The same applies for the potential increases of urban or industrial built-up areas that have not been considered. For the sake of simplicity, we limited the analysis to only three animal species. Although the inclusion of other livestock types would imply more detailed results, the big picture would probably remain similar. It would also be advisable to incorporate more time-use limitations than the ones considered, e.g. for the availability of labour or specific grazing resources.

Finally, it is important to bear in mind the site-specific character of the constraints, restrictions and capacities taken into account to foresee the potential development of landscape strategies towards desirable scenarios. The results cannot be extrapolated in any way to other places and scales. This is the strength but also the weakness of the SAFRA model. Results are restricted to the system boundaries analysed in each case, but the model can be applied at various scales successively. We believe that further research and diversification of case studies will lead to a better understanding of the potential of these agroecological strategies to upscale current sustainable agriculture in true agroecological territories.

6. Conclusions

By using the SAFRA model to generate prospective scenarios, based on the feasible capacities set by the biophysical constraints of the variables and the restrictions among them for upscaling organic farming, we have found that the main bottleneck lies in the closure of biogeochemical cycles into agroecology territories. Strong sustainability faces here a dilemma raised by the founders of Agronomy. Even recovering an organic functioning, agricultural sustainability needs to address the difficult challenge of closing the metabolic rift of soil nutrient cycles opened long ago in the industrial society (Foster, 1999; Schneider and McMichael, 2010). The precautionary principle we have applied in this first SAFRA case study concerning the return of human excreta to the agroecosystem strongly limits the ability to attain a totally reproductive system at the landscape scale, with phosphorus being the most limiting factor. Our society will have to consider other kinds of transitional solutions for soil fertility management that would be only nearly-sustainable, such as relying on the stock of nutrients accumulated into cropland soils by over-fertilisation during recent decades (Cordell, Drangert and White, 2009), minimizing its depletion rate, while deploying a big effort in the development of new procedures for a safe recovery of nutrients from human excreta.

We have also been able to verify the high agroecological potential underlying the synergies between land uses and livestock feeding through diversification and integration management strategies (Nicholls and Altieri, 2018). SAFRA has revealed that a new organic farming integration of crop rotations with livestock at the landscape level could provide a healthier diet with a similar amount of land than producing the same diet under an industrial agriculture. This means that agroecology can confront the yield-gap at plot and farm level by means of the eco-efficiency potential provided by the synergies that can be carried out at the landscape level. This is a very relevant result for eco-functional intensification practices. The agroecology synergies required can be obtained recovering various land-saving strategies largely used by many ingenious organic farm systems of the past: i) farm-integration of livestock, especially ruminant animals as bio-converters of non-edible resources by humans; ii) active use of forestland as provider of soil nutrients for cropland, animal feeding for livestock, and fuel; and iii) keeping land-use diversification strategies, such as crop rotations, associated crops, agroforestry and wood pastures.

We have also showed that diets become a fundamental issue to determine what the potential of an agroecosystem to feed human population is. Choosing a healthy and sustainable diet is a basic condition to improve land use distributions keeping a synergic integration with livestock and forests. In turn, sustainable diets also help improve the landscape efficiency to provide all types of ecosystem services to society through those agroecological synergies of a biodiversity-based farming (Duru et al., 2015).

Despite the limitations of this first attempt, the agroecological SAFRA modelling has proven its usefulness for defining scenarios and transition horizons that are agroecologically feasible, technically viable and socially desirable. For deliberative purposes, this goes far beyond the conventional cost-benefit analysis in which market criteria takes precedence shadowing the rest as externalities. SAFRA results allow stakeholders to engage in multi-criteria deliberative processes where all sustainability dimensions start to become integrated. The ultimate aim is to resort to the various scientific disciplines that contribute to Sustainability Science as a whole, in order to inform public policy-makers, citizens and rural communities willing to advance towards new agroecology territories capable to globalize –i.e. recirculate— sustainable foodscapes through local-regional integration anywhere in the world.

7. References

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