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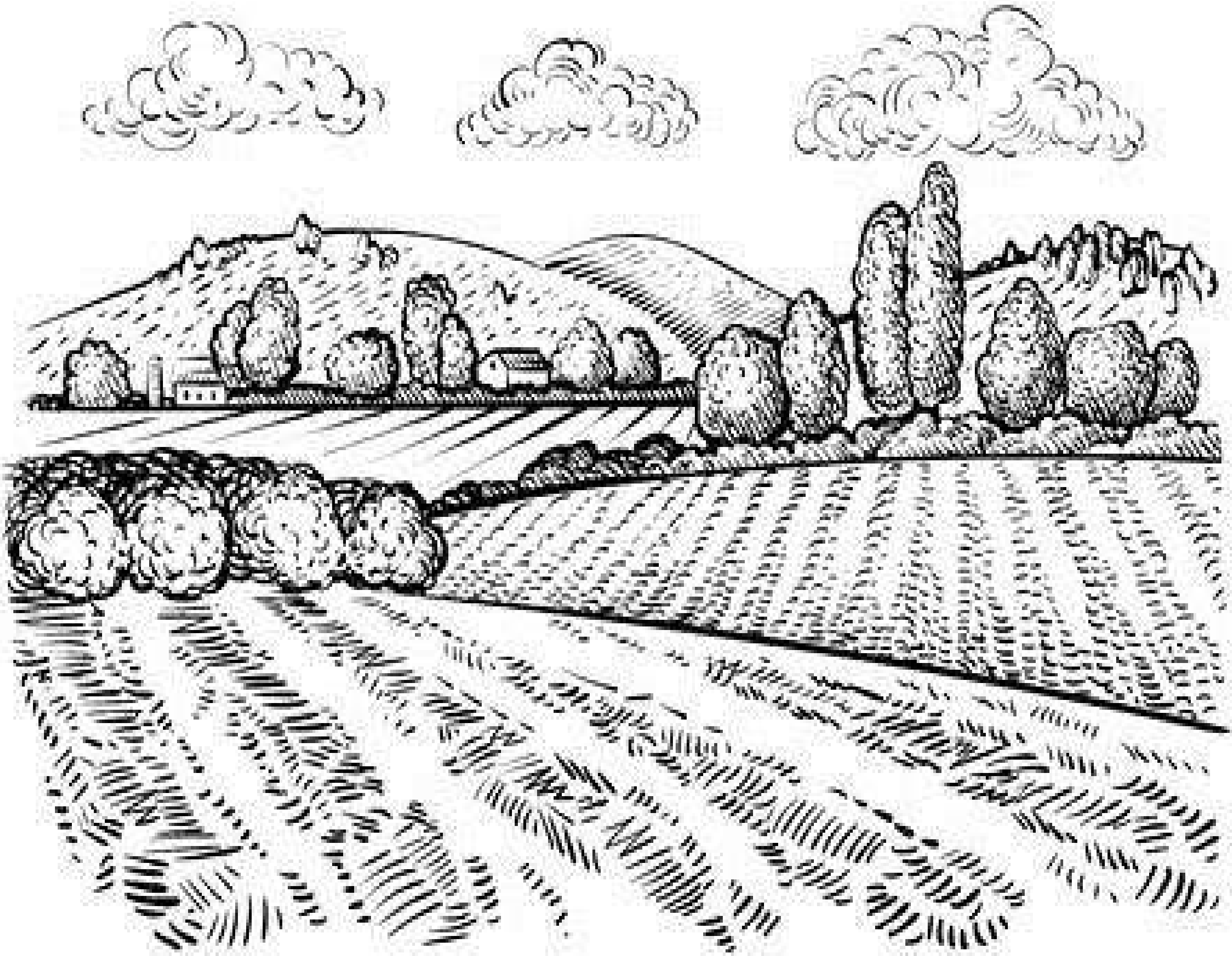

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Par Pietro BARBIERI

La disponibilité en éléments minéraux pourrait-elle contraindre le développement de l'Agriculture Biologique à l'échelle mondiale ?

Can the availability of mineral nutrient be an obstacle to the development of organic agriculture at the global scale?

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“Imagination is more important than knowledge. For knowledge is limited to all we now know and understand, while imagination embraces the entire world, and all there ever will be to know and understand”

Albert Einstein

Abstract

Organic agriculture is often proposed as a promising approach to achieve sustainable food systems while minimizing environmental impacts. Its capacity to meet the global food demand remains, however, debatable. Some studies have investigated this question and have concluded that organic farming could satisfy the global food demand provided that animal product consumption and food waste are reduced. However, these studies have not fully considered the changes in the type of crops grown that occur when conventional farming systems are converted to organic farming. Most importantly, they also have missed a critical ecological phenomenon by not considering the key role that nitrogen (N) cycling plays in sustaining crop yields in organic farming. In this study, we first carried out a global meta-analysis comparing organic *vs* conventional crop rotations. Based on these results, we developed global spatial explicit maps of the type of crop grown if organic farming was to drastically expand. We then estimated organic global food production using GOANIM (Global Organic Agriculture NItrogen Model), a spatially explicit, biophysical and linear optimization model simulating N cycling in organically managed croplands and its feedback effects on food production. GOANIM explores N flows between croplands, livestock animals and permanent grasslands, and with conventional farming systems. The model optimizes livestock populations at the local scale in order to maximize N supply from livestock manure – hence maximizing cropland production –, while minimizing the animals' competition for grain food resources. We used GOANIM to simulate several supply-side scenarios of global conversion to organic farming. We then compared the outcomes of these scenarios with different estimates of the global demand, thus leading to complete exploration of the global production-demand options space. We show N deficiency would be a major limiting factor to organic production in a full organic world, leading to an overall -37% reduction in global food availability. Nevertheless, we also show that lower conversion shares (up to 60%) would be feasible in coexistence with conventional farming when coupled with demand-side solutions, such as reduction of the per capita energy intake or food wastage. This work substantially contributes to advancing our understanding of the role that organic farming may play to reach fair and sustainable food systems, and it indicates future pathways for achieving global food security.

Keywords: *Organic Farming, Conventional Farming, Global Agronomy, Nitrogen Cycling, Organic Livestock, Organic Crop rotations, Global Food System, Modelling, Sustainability.*

Résumé de la thèse

L'agriculture biologique (AB) est souvent présentée comme une alternative prometteuse à l'agriculture conventionnelle, permettant des systèmes alimentaires durables tout en minimisant les impacts environnementaux. La capacité de l'AB à satisfaire la demande alimentaire mondiale reste néanmoins fortement débattue. Plusieurs études ont conclu que l'AB pourrait satisfaire la demande alimentaire globale à condition de réduire simultanément la consommation de produits animaux et les gaspillages. Cependant, ces études n'ont pas pleinement pris en compte les changements d'assolement et de choix d'espèces lorsque les systèmes conventionnels sont convertis en AB. Surtout, ils ont ignoré le rôle clé de la disponibilité en azote (N) dans le maintien des rendements en AB. Dans cette étude, nous avons d'abord réalisé une méta-analyse comparant les rotations de cultures en agriculture biologique et conventionnelle à l'échelle mondiale. Sur la base de ces résultats, nous avons développé une cartographie des espèces cultivées à l'échelle globale sous un scénario de fort développement de l'AB. Nous avons ensuite estimé la production alimentaire grâce au développement de GOANIM (Global Organic Agriculture NItrogen Model), un modèle biophysique et spatialement explicite d'optimisation linéaire simulant le cycle de l'azote (N) et ses effets sur la production alimentaire globale. GOANIM est adapté au cas de l'AB et simule les flux d'azote entre les terres cultivées, les animaux d'élevage et les prairies permanentes, ainsi qu'entre les systèmes agricoles biologiques et conventionnels. Le modèle optimise les populations d'élevage à l'échelle locale afin de maximiser l'approvisionnement en N provenant du fumier, ce qui maximise la production issue des terres cultivées, tout en minimisant la concurrence exercée par les animaux pour les ressources alimentaires. GOANIM a été utilisé pour simuler l'offre alimentaire sous plusieurs scénarios de conversion à l'AB. Ces résultats ont été comparés à différentes estimations de la demande alimentaire mondiale. Nous montrons que la carence en N risque d'être un facteur limitant majeur de la production en AB, entraînant une réduction de -37% de la disponibilité alimentaire à l'échelle globale sous un scénario de conversion à l'AB de 100%. Nous montrons que des taux de conversions inférieurs (jusqu'à 60% des terres agricoles), en coexistence avec l'agriculture conventionnelle, permettent de satisfaire la demande alimentaire mondiale si cette conversion est associée à une évolution conjointe de la demande, telle que la réduction de l'apport énergétique par individu ou du gaspillage alimentaire. Ces travaux contribuent de manière substantielle à mieux comprendre le rôle que l'AB peut jouer dans la transition vers des systèmes alimentaires équitables et durables. Ils indiquent également des voies à suivre pour parvenir à la sécurité alimentaire mondiale.

Mots clés : *Agriculture Biologique, Agriculture Conventionnelle, Agronomie globale, Cycle de l'Azote, Production de Bétail, Rotations des Cultures Biologiques, Systèmes Alimentaires Globales, Modélisation, Durabilité.*

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General introduction – methodologies and objectives

Agriculture and global food security

A fast-growing global population, climate change, natural resources depletion, and the many environmental impacts caused by dumping human activities effluents into our surrounding environment are jeopardizing the Earth System stability and resilience. Human activities are altering Earth System functioning far beyond its Planetary Boundaries (Steffen et al. 2015). Farming activities, among others, have a tremendous impact on the Earth's functioning (Lal 2004; Hertel et al. 2010; Lambin & Meyfroidt 2011) and a large body of literature has shown that current practices are dominant forces contributing to driving the planed beyond this safe operating space (Erb, Haberl, et al. 2009; Steffen et al. 2015).

Not only farming activities contribute to lower planet stability, but they also have consequences on agricultural systems themselves. Hence, humanity is already facing severe biophysical constraints to achieve universal food security (Ehrlich & Harte 2015): (i) climate disruption and unpredictability is slowing down increases in crop yields (Ehrlich & Harte 2015), (ii) the loss of pollinators is threatening yields and nutritional quality of crops in several global regions (Klein et al. 2007), (iii) fertile soils are being lost or degraded due to salinization, erosion or nutrients depletion (Lassaletta et al. 2014), (iv) natural resources like water and mineral nutrients (e.g. phosphate rocks) are increasingly limited due to overconsumption or contamination (Cordell et al. 2009) and (v) the massive application of chemicals and synthetic compounds is contributing to dangerous exposure to toxic substances and to the rise of genetic resistances (Heap 2014; Sharma et al. 2016). All these issues might be worsened by an increasing global population –with higher demand in calories, animal proteins and fossil fuels (Ehrlich & Harte 2015) and might mine our capacity to achieve global food security.

In the last decades, a heated debate on how to achieve universal food security has unfolded. This discussion has been polarized by two main opposite viewpoints. On the one hand, the supporters of the "insufficient food" theory claimed that agricultural productivity has to be unconditionally raised. On the other hand, others claimed that the solution relies on a more equitable distribution of wealth, income and available food (Ehrlich & Harte 2015). In addition to this dichotomy, a parallel debate opposed those who identify the green revolution and the resulting industrial agriculture model as an essential asset to achieve food security in the next future to those arguing that such production system comes with a too high environmental price. This is because intensive systems tend to trade off short-term massive agriculture production for the ecosystem maintenance over the long term (Foley, DeFries, et al. 2005; Badgley et al. 2007; Raudsepp-Hearne et al. 2010). Similarly, recent literature dealing with the preservation of natural ecosystems and their biodiversity is divided into two main positions. On the one hand, stand those who support the intensification of agriculture in restricted areas –i.e. land sparing. On the other hand, others aim at integrating goals for food production and biodiversity protection on the same land –i.e. land sharing (Tscharntke et al. 2012). As with most dichotomies, any of the extremes alone is inadequate to achieve sustainable food systems, while both positions raise valuable issues and possible solutions. Focusing on polarized positions is intellectually unjustified and counterproductive (Ehrlich & Harte 2015). This is because research should not fall into binary positioning; the optimal solutions may often be context dependent (Seufert & Ramankutty 2017).

Achieving sustainable and fair food security becomes even more difficult on a crowded and degraded planet (Godfray et al. 2012). Whether the above-mentioned dichotomies often propose opposing viewpoints, they generally converge on the necessity to increase or maintain food production while preserving Earth System functioning and resilience: agricultural systems have to be managed in a way that allows protecting while using ecosystems services and reducing environmental impacts (Kremen & Miles 2012). Hence, it is now widely recognized that to maintain the Earth's capacity to produce food, we have to shift towards more resilient and sustainable farming models (Garnett et al. 2013; Ponisio et al. 2015; IAASTD 2009). In addition, the social acceptability of current –i.e. conventional[1]- agricultural systems is being mined by agriculture's negative externalities, thus strengthening the call for more sustainable farming systems (Ponisio et al. 2015).

Feeding the world population: which role for organic agriculture?

Several alternative farming approaches have gained interest in the last decades as promising systems with protection, use, and regeneration of ecosystem services. They include sustainable intensification, conservation agriculture, agroecology, as well as organic and biodynamic farming. (Garrett et al. 2017; Wezel 2011). Most of these approaches share the use of techniques based on ecological interactions leading to, e.g., enhanced soil fertility, nutrient cycling closure, and biological pest and diseases control (Muneret et al. 2018).

Among those systems, the most widely studied alternative to conventional –i.e. current– farming systems is organic agriculture. Organics nowadays represents only the 1.1% of the global agricultural land (Willer & Lernoud 2015). Nevertheless, its adoption has rapidly increased in the last years with high annual growth rates up to 64% (India, 2015) and reaching e.g. up to 21% of the agricultural land

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[1] With conventional (or industrial) farming we intend current input-intensive farming systems, with high use of synthetic, chemical fertilisers, pesticides, herbicides, as well as the use of genetically modified crops, heavy irrigation, simplified crop rotations and agricultural landscapes.

in Austria (Willer & Lernoud 2017). This dramatic growth is driven by both increasing policy support and fast-growing consumers' demand (Seufert et al. 2017; Lockeretz 2007). Indeed, most of the consumers in high-income countries buy organic products at least occasionally, motivated by the organic food "healthiness" associated with the absence of chemical residues (Seufert et al. 2017). Due to this increased consumption, global organic market has expanded five-fold since 1999, reaching 62 billion US dollars in 2015 (Willer & Lernoud 2017). In addition, organic agriculture is the only sustainable production system with management practices codified by international recognized principles and by national bodies of laws (Seufert et al. 2017). This makes organic farming a precisely defined agricultural system, in contrast with other forms of agriculture such as 'agroecological' farming (Rigby & Cáceres 2001; Seufert et al. 2017). For this reason, organic farming is probably the most studied alternative agriculture model to current farming within scientific research.

Given both the currently limited extent of organic farming at the global scale and the fast growth of organic markets, a key question is whether organic farming could increase its contribution to fair and sustainable global food systems (Seufert & Ramankutty 2017). In the last decade, an intense debate has started around that question in the attempt to estimate which role organic farming could play for food security in the future. This debate has generated controversies (Muller et al. 2017; Connor 2018) and answering such question will probably largely determine which future is reserved to organic agriculture (De Ponti et al. 2012).

Organic farming expansion and global food security

As previously mentioned, even if the global share of organic farming is still very low (1.1% of the global cropland area in 2016), organic food is one of the fastest growing food sectors globally (Sahota 2016). Given this trend, it is probable that organic farming will continue to gain importance in many world regions in the next decades. Therefore, it is necessary to investigate the possible consequences that organic farming expansion could have for the global food system. Such a question does not have any straightforward answer, in particular because organics may face several issues when expanding at the global scale. We explore those different issues in the following lines.

From an economic point of view, whether organics will keep its profitability for the farmers will strongly influence its expansion in many world regions. Evidence has been provided that current organic systems are more profitable than conventional systems when premium prices are applied (Crowder & Reganold 2015). Such premium prices are due to current limited supply relative to consumers' demand (European Comission 2010), lower yields (Brown & Sperow 2005), and, higher production costs (Crowder & Reganold 2015). The effects that an expansion of organic farming would have on its economic performance does not have a straightforward answer. Indeed, on the one hand, current premium prices may disappear along with organics growth, thus potentially making it difficult for organic farmers to bear the relatively high production costs related to that farming system (Crowder & Reganold 2015). On the other hand, breakeven premium prices necessary to allow organic producers to match the profits of conventional producers are only 5 to 7% (Crowder & Reganold 2015; Seufert & Ramankutty 2017). Hence, if the organic sector is to expand, the higher consumer demand and the lower distribution costs (Seufert & Ramankutty 2017) may be sufficient to stabilize organic prices within an economically feasible range for producers.

From a land resources point of view, organic production systems tend to require more land than their conventional counterpart to achieve the same amount of produced food. This is because organic production systems have overall lower crop productivity and because they generally include more non-food crop species in arable rotations (Lampkin 1990). This higher land demand may jeopardize natural biodiversity, due to the conversion of natural habitats to agro-food systems, especially if organic certification will not prevent deforestations and other forms of habitat conversion (Tayleur & Phalan 2016). Overall, organics should avoid the conversion of natural "High Conservation Value Areas" (IFOAM 2014) and should guarantee a coexistence between food production and biodiversity conservation. Literature suggests that organic management generally benefits the biodiversity of wildlife and species richness (Janne et al. 2005). Nevertheless, some studies also report the existence of trade-offs between biodiversity benefits of organic farming and overall crop yields, thus potentially requiring even more land to achieve the same production (Schneider et al. 2014). Therefore, the effects that an expansion of organic agriculture at the global scale would have on global biodiversity does not have a straightforward answer (Seufert & Ramankutty 2017).

Pest control may also be affected by organic farming expansion, with strong consequences on productivity. Two contrasting hypotheses exist regarding this topic. On the one hand, evidence has been provided that organic farms benefit from the residual effect of pesticides applied by neighbouring conventional farms on their fields, thus contributing to indirect pest control on organic fields (Valantin-Morison et al. 2007). One may hypothesize that such an effect would fade out if organics expands, thus potentially increasing pest and diseases pressure in organic farms. On the other hand, evidence has been provided that organic systems strongly rely on biological pest control (Muneret et al. 2018), an ecosystem service that is weakened by the use of pesticides on neighbouring conventional farms. One may hypothesize that such negative effect on beneficial insect biodiversity may disappear if organics expands strongly.

Finally, organic system productivity may be influenced by a potential decrease in nutrient availability -especially nitrogen (N) and phosphorus (P)- due to the ban of synthetic fertilizer in organic guidelines (Muller et al. 2017). This is because organic farming relies only on a few sources of nutrients, namely natural (or inherited) soil fertility, biological nitrogen fixation (BNF), animal manures, recycled crop residues, and atmospheric depositions (Lampkin 1990). In addition, current organic systems import large amounts of both N and P from conventional systems via livestock feed and manure (Nowak et al. 2013a; Oelofse et al. 2010), resources that would fade out if organics drastically expands. These nutrients flows between organic and conventional farming are not limited to exchanges of organic materials. Organic systems are also currently indirectly benefitting from inherited soil fertility –i.e. soil legacy, especially for P- due to the past fertilization practices of conventional farms prior to the conversion to organics (Sattari et al. 2012; Dao et al. 2015). In other words, stronger interactions probably exist between organic and conventional farming, which makes the scaling-up of organic systems a complex issue. Nutrient availability in organic systems may also be further decreased if arable and livestock production basins are geographically segregated, given the economic and environmental unfeasibility of transporting animal manures over long distances (Bartelt & Bland 2007). This is especially true for organic N, due to his highly mobile and volatile nature. That is, the more numerous management steps and the longer transportation distances of organic N resources, the higher are the risk of losses, thus even further jeopardizing N sourcing ability of organic systems. In addition, N management in organic systems is challenging e.g. due to the higher risk of leaching and poor synchronizations between crop demand and N release (Lampkin 1990; Timsina 2018). Due to these reasons, nutrients availability, especially N, may be a clear obstacle to organic farming expansion. Indeed, the centrality of N flows and transfers has been recognized since long (Connor & Mínguez 2012; Ponisio et al. 2015; Muller et al. 2017). This is because, although several production factors can contribute to crop yields (Timsina 2018), N is often considered as the major factor linked to food production (Wetzel & Likens 1991). In spite of all this, currently, no studies have fully addressed and explored such an issue (Seufert & Ramankutty 2017). Hence, the ability of organic systems to source sufficient N still constitutes the central issue of the organic *vs* conventional debate (Timsina 2018). Based on all such considerations, and in particular on the specific literature weaknesses previously evidenced, ***in this dissertation, we will focus on N availability and we will explore the consequences that drastic expansion of organic farming may have for the N cycle and the resulting organic production at the global scale.***

Estimating organic production at the global scale

The yield gap between organic and conventional agriculture

Whether organic agriculture may produce enough to feed the planet is one of the most debated and contentious issues. This question has been addressed by scientific research since long. Since the early ‘90s, research has mainly focused on estimating the difference in crop yields between organic and conventional farming. This difference –often calculated as an organic-to-conventional yield ratio– has been used for long as a direct indicator of organic productivity. The first study dealing with this approach was conducted by Stanhill (1990), who compiled a comparative literature review of organic-to-conventional crop productivity data. In 1997, De Vries et al. concluded that sustainable systems (i.e. replacement of all N in chemical fertilizer by biological N fixation, elimination of biocides, minimal use of energy for transport, local consumption and nutrients recirculation) would have been able to produce food for 9 billion people when coupled with a drastic decrease of consumption of animal proteins. A similar result was found by Lotter et al. (2003). In 2007, Badgley et al. (2007) performed a meta-analysis about organic crop yields by calculating organic-to-conventional yield ratios. As a result, they claimed that organic farming could ‘substantially contribute’ to feeding the world even with a reduction of the global agricultural land. In 2012, the relative yield of organic to conventional agriculture was again estimated by De Ponti et al. (2012) and Seufert et al. (2012b) by using more restrictive data sourcing criteria. Both studies concluded that organic farming productivity at the crop species level was, on average, 25% lower than conventional, discrediting most of the conclusion found by Badgley et al. (2007). Finally, a meta-analysis was published in 2015 by Ponisio et al. (2015), who found organic agriculture being ~19 % less productive than conventional agriculture. In addition, these authors showed how such a gap could be reduced to ~9% when diversification practices –e.g. inter-cropping and complex crop rotations– are used (Ponisio et al. 2015).

These yield-gap coefficients allowed generalizing the current performance of organic *vs* conventional systems at the global scale. In particular, they allowed identifying the organic crop productivity response of different (i) crop species and (ii) management practices in comparison to their conventional counterpart. The yield-gap concept has been then used as an indicator of organic crops’ productivity to estimate organic cropland production at the global scale. Such an approach have been heavily criticized, in particular by Cassman (2007), Connor (2008, 2013), and Goulding et al. (2009). Indeed, the use of these ratios as proxies of organic crop productivity may lead to overestimating organic production. That is, previous studies have considered that the conditions under which such ratios were obtained would remain unchanged when organics expands. This includes assuming, among others, a similar N supply to cropland soils compared to the current situation. Badgely et al. (2007) have even claimed the total N supply in a hypothetical organic world to reach 140 Tg, "which is 58 Tg greater than the amount of synthetic N currently in use" (Badgley et al. 2007). Hence, they suggested that N availability would be enough to satisfy crop N uptake when yields are equivalent to the current –i.e. conventional– ones. This potential N inputs, coming mainly from N-fixing leguminous crop species, was estimated by the authors by multiplying the current global cropland area by the average amount of N available from legumes established during winter fallow or between crops. This estimation was very much simplistic and highly debatable (Connor 2008). This is because the authors assumed that fallow legume crops could be established anywhere, independently from local pedo-climatic conditions and cropping intensity. In contrast, as previously described, N availability in organic systems is likely to decrease compared to the current situation. If this is the case, then these yield-gap ratios would fall to values below current estimates (Connor 2008; Connor 2018) since they do not necessarily account for this decrease in fertilizing resources. In addition to these N availability issues, the yield-gaps introduced evidences of the productivity of organic systems when considering single crop species. Nevertheless, the production of arable systems cannot be deduced simply from the yields of individual crops –i.e. by directly applying crop-specific yield ratios neglecting that organic cropping systems may differ from conventional ones. (Connor 2008; Kravchenko et al. 2017). As last, the reliability of such ratios, especially in developing countries, was highly questioned (Connor 2008). This was due to the fact that data availability for organic systems in developing countries is limited (Seufert & Ramankutty 2017), and that the yield-gap ratios may be distorted due to different nutrient inputs between crops grown under organic and conventional management (Connor 2008).

From a crop-species to a food system analysis

More recently, two studies have taken this question a step forward, by analyzing scenarios of global conversion to organic farming in a broader context. These studies have attempted to switch from simple yield comparisons to a more complex analysis using a food system approach that goes beyond a simple focus on production (Erb et al. 2016; Muller et al. 2017). In 2016, Erb et al. investigated several food system scenarios comparing food supply and demand under a zero deforestation hypothesis. This study included a set of scenarios for organic farming. Nevertheless, organic systems were differentiated from conventional systems by only accounting for organic crop yields. Indeed, the authors did not take into account all the structural differences of organic *vs* conventional systems, namely more complex crop rotations, diversified crop and livestock, and the ban of synthetic fertilizers. Finally, in 2017, Muller et al. simulated scenarios of organic expansion at the global scale and the consequences of such conversion on global food systems. This study made a significant step forward by estimating how the scale-up of organic systems may impact global nitrogen and phosphorus budgets. Although this study was the first to introduce nutrients availability and estimate whether a conversion to organics would lead to positive or negative global budgets, it fell short in fully addressing this question. This is because the authors estimated organic crop yields by using organic-to-conventional yield gaps, without, once again, accounting for nutrient availability feedback on crop yields. In addition, they considered that organic rotations would differ from conventional ones only for the abundance of pulses, assuming that one crop out of five would be a pulse after conversion to organics. Nevertheless, changes in crop rotation and crop diversification practices may be more complex than this simple assumption (Ponisio et al. 2015).

Systemic feedbacks affect nitrogen availability

As underlined above, the expansion of organic farming may lead to systemic feedbacks on crop production and the related food system. These feedbacks are strongly related to nutrient flows and availability (N in particular) and thus influence the final productivity of organic systems. In fact, given the limited N sourcing ability, organic systems have to operate as far as possible within closed N cycles (Lampkin 1990). To do so, organic farmers strongly adapt their system, for instance by adopting more diverse and complex crop rotations. In addition, this lower N sourcing ability may have negative consequences on cropland production, and thus, indirectly on the ability to feed livestock animals. This has some negative resulting consequences on the ability to fertilize soils with animal manure and to sustain crop productivity; a vicious cycle that would then cause even a stronger reduction of organic cropland productivity. In view of all this, estimating crop production in scenarios of large organic farming expansion requires to (i) switch from an analysis at the crop species level to the cropping systems level, (ii) simulate organic yields as a function of N supply to cropland soils and (iii) consider how the systemic adaptation and feedbacks following the conversion to organic systems would finally influence global organic food production. In order to do so, we firstly need to consider how changes in crop rotations would affect N availability and, finally, cropland production. Secondly, we need to estimate N flows between the main compartments of organic farming systems–i.e. soils, cropland, grasslands, and livestock– and to account for the interactions among such compartments. To do so, a modelling approach is required. Therefore, in this dissertation we address these two main knowledge gaps, namely ***investigating the differences in organic vs conventional crop rotations and by consistently simulate organic production at the global scale as a function of nutrients resources*** (according to the current organic production standards)***, focusing on N flows using a modelling approach.*** This modelling approach will, in particular, allow filling the current knowledge gap about N availability and its impact on croplands productivity and organic food production in scenarios of drastic organic farming expansion.

Tools and models for simulating scenarios of global organic expansion as a function of available nitrogen resources

Different datasets, tools, and models can be used to assess N flows in scenarios of organic agriculture expansion at the global scale. Here we provide a short overview of such approaches underlining their relevance to our study.

Global agriculture datasets: during the last decade, several global databases about farming practices, performances, land-use, etc. have been developed. Part of these databases have been developed using a spatially explicit approach. More in details, spatially explicit datasets of the distribution of many crop species and permanent pasture areas (Ramankutty et al. 2008; Monfreda et al. 2008), crop yields (Monfreda et al. 2008), yield gaps (Mueller et al. 2012), fertilizers application rates (Mueller et al. 2012), livestock densities (Robinson et al. 2014), Net Primary Productivity (Zhao et al. 2011), atmospheric N depositions (Dentener et al. 2006), and others have been developed. All these databases represent an interesting tool for global research and modelling of farming and food systems, even if specific global and spatial datasets for organic farming are still lacking (Seufert & Ramankutty 2017).

Nutrients budgets: nutrient budgeting consists of calculating inputs to and outputs from a given system for a given nutrient. Budgets can be calculated at very different scales –i.e. from the plot to the global scale (Watson et al. 2010). In the last decades, a large body of literature has been using budgeting as an indicator of nutrients use-efficiency and of environmental sustainability of agricultural systems at the plot, farm, regional, continental, and global levels (Roy et al. 2003; Watson et al. 2002; Carey et al. 2009; Liu et al. 2010; Watson et al. 2010; Muller et al. 2017). The first step to calculate a nutrient budget is to define the scale and the boundaries of the chosen system. Then, all the input and output flows applied to that system have to be identified, defined, and finally quantified (Watson et al. 2010). The definition of the system boundaries is a key step and it becomes even more important when large scales are considered. This is because the reliability of budgeting calculations decrease with larger spatial scales as a consequence of data aggregation -i.e. the paradox of upscaling and the loss of information are closely connected (Roy et al. 2003).

Mass flow analysis: mass flow analysis (MFA) is another generic method to quantify material flows and stocks for any chosen system. MFA can be used to assess and model nutrients between compartments within agro-food systems (Fernandez-Mena et al. 2016). As for budgets calculations, MFA can be applied at very different scales –i.e. from districts to cities, landscapes, regions, and countries. MFA modelling has been already applied in different disciplines, including agriculture, in order to estimate nutrients flows between the different farming system components (Kleijn et al. 2000; Pfister et al. 2005; Schmid Neset et al. 2008). Overall, both nutrient budgets and MFA are suitable methodologies to quantify and simulate nutrients flows in organic farming at large spatial scale.

Spatial modeling: Numerous studies dealing with nutrients flows at the regional and global scales have used spatially explicit modeling approaches (Bouwman et al. 2013; MacDonald et al. 2011; Liu et al. 2010; Ramankutty et al. 2008; Monfreda et al. 2008; Erb, Krausmann, et al. 2009). These models are based on global raster datasets, which have been increasingly developed in the last decade (Ramankutty et al. 2008; Monfreda et al. 2008; Robinson et al. 2014). Raster datasets are composed of grids –i.e. a regular tessellation of a 2D surface that is divided into a series of contiguous cells– that can then be assigned with unique identifiers and used for spatial indexing purposes. The size of the grid's cells determines the resolution of the raster map. Global gridded maps about crop production –i.e. yield, agricultural land and production (Monfreda et al. 2008), livestock densities and livestock production systems (Robinson et al. 2014), N and P balances (MacDonald et al. 2011; Bouwman et al. 2013), fertilizer application (Mueller et al. 2012) and others- are nowadays available. The resolution of such maps varies from 5 to 0.5 arc-min (about 100 km^2 to 1 km^2 at the equator). Despite spatial modelling has been used to compute global nutrients budget and MFA, it has never been used to explore scenarios of organic farming. This is because retrieving sufficient detailed information at the global scale is challenging. Therefore, no dataset reporting spatially explicit data for organic farming (e.g. about the organic cropland use) had been developed up to now.

Optimization modelling – linear programming: optimization models are mathematical models where an objective variable is maximized under a set of constraints. Optimization models are defined by the type of equations that are used to characterize the problem: linear programming (LP) models, non-linear programming (NLP) models and integer programming (IP) models (Sarker & Newton 2013; Williams 2013). For instance, the theoretical structure of a general LP model could be represented as follows:

Find x to **maximize $\boldsymbol{f(x)}$**

under the constraint that

$$g_i(x) \leq gb_i, \;\; i = 1, \dots, m$$
$$h_i(x) = hb_j, \;\; j = 1, \dots, p$$
$$x \geq 0$$

where the objective function f is a function of a single variable x, and the constraint functions g_i and h_i are general functions of the variable (otherwise expressed as an unknown, decision variable or sometimes as a parameter) $x \in R^n$. The right-hand sides, gb_i and hb_j, are usually the known constants for deterministic problems.

Such an approach has already been used in agronomic research for addressing different topics, ranging from economic analysis to land use exploration and allocation (Makowski et al. 2000), and different geographic scales. In particular, linear programming has already been successfully used to develop models dealing with agriculture production and food systems at the global scale, including studies on organic farming (Smith et al. 2018).

Objectives and research questions

This Ph.D. aims to fill the above-mentioned knowledge gaps about organic farming production in scenarios of a large expansion of this farming type at the global scale. More precisely, ***we aim at estimating the effects that organic farming expansion can have for the global N cycle and its resulting effects on organic food production***. To do so, we need to consider all the farming system adaptations and feedbacks involved when both converting to organic farming and upscaling organics at the global scale. This includes any change in crop rotations, croplands, and livestock compartments. In this dissertation, we aim at (i) characterizing organic crop rotations and simulating the resulting changes in the types of crops grown under scenarios of global conversion to organic farming, and (ii) simulating organic production as a function of N availability using a scenario-based approach. We then aim at comparing the estimated production with different estimates of global food demand. To do so, we developed a spatially explicit global model simulating N flows in organic farming systems, with a specific focus on the systemic adaptation that characterizes conversion to organic farming. We did not aim at considering any economic or trade-related aspects.

More specifically, we will address four main research questions, summarized as follows:

- *To which extent do organic crop rotations differ from conventional –i.e. non-organic- crop rotations?* (Chapter 1)
- *How the types of crop grown would change in scenarios of drastic organic farming expansion at the global scale?* (Chapter 2)
- *How changes in the types of crop grown would impact organic food production at the global scale?* (Chapter 2)
- *To which degree global food production may be limited by N availability to fertilize croplands in scenarios of organic agriculture expansion at the global scale?* (Chapter 3)

In addition to these main research questions, we also formulated the following hypotheses:

HP1: The adoption of organic crop rotations will increase N availability in organic cropping systems through enhanced biological N fixation by leguminous crop species

HP2: Current livestock animal population densities and spatial distribution represent a major limitation to food production in scenarios of strong organic farming expansion

HP3: The allowance of wastewater N resources is likely to raise organic crop yields at the global scale

Modelling and system definition

In this dissertation, we aim to model N flows between three main components, i.e. croplands, pasturelands, and the livestock sector, with a particular focus for N availability for cropland soils (Figure 1). To do so, we developed GOANIM (Global Organic Agriculture NItrogen Model), a spatially explicit biophysical and linear optimization model simulating N budget of cropland soils in organic farming systems and its feedback effects on food production at the global scale. All model compartments are assumed to be at steady-state –i.e. all state variables are constant– and all flows are simulated considering a timeframe of one year.

We considered N flows related to cropland soils that are related to:

1. Livestock manure available for cropland application

2. Biological N fixation (BNF) from leguminous crop species
3. Free-living cyanobacteria N fixation in association with cereals, oil crops, and root crops
4. Crop residues, both recycled to soils and exported from the fields for feed or other purposes.
5. Atmospheric N wet and dry depositions
6. Wastewater as urban sludge spread –or not- on cropland soils
7. N leaching and gaseous losses, during (i) manure management and storage, (ii) application of fertilizers to soils
8. Crop N uptake for harvested biomass and crop residues
9. Fodders from permanent pastures

In particular, GOANIM simulates the N flows and feedbacks between cropland and livestock animals (Figure 1). Livestock populations and cropland productivity are, therefore, optimized at the grid cell scale. The model finally estimates the total food calories available at the global scale by maximizing food energy production in each grid-cell.

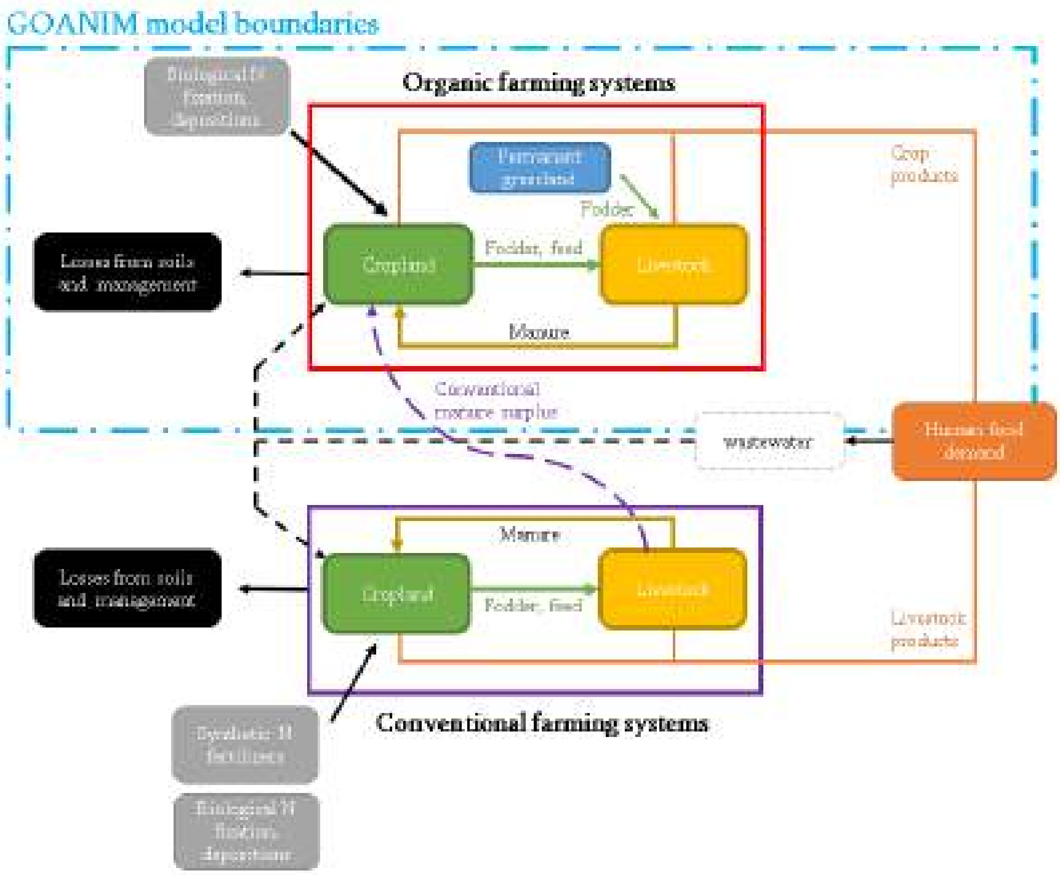

Figure 1. Boundaries, flows, and external nitrogen inputs (from conventional farming and human activities) in the GOANIM model.

Dissertation outline

The following dissertation will consider the above-mentioned research questions through the following structure:

- Chapter 1 focusses on the difference between organic *vs* conventional crop rotations at the global scale. In this chapter, we investigate whether differences between organic *vs* conventional crop rotation exist using a meta-analysis approach. We then qualify and quantify these differences at the global scale and for three global regions.
- Chapter 2 focusses on the changes in the types of crop grown in a scenario of 100% conversion of global cropland and livestock production to organic farming. Here, using the information retrieved from Chapter 2, we spatially simulate the changes in the type of crops grown that result from the conversion of croplands to organic farming at the global scale. More precisely, we estimate how the spatial distribution of the harvested area of 38 crop species would be modified. We then estimate how these changes would influence global cropland production without considering any feedback from N deficiency to fertilize cropland soils. That is, we aim at isolating the sole effects of changing the type of crops grown globally on food availability when organic crop rotations are adopted at the global scale.
- Chapter 3 estimates the effects of a large expansion of organic farming at the global scale on the global N cycle and its resulting effects on global food production. More in details, we modelled several scenarios of organic farming expansion at the global scale (supply-side of the food systems) together with their effects on cropland soil N budgets using a spatially explicit, biophysical and linear optimization model called GOANIM (Organic pRoduction GlobAl SiMulator). The different scenarios include different expansion rates of organic farming at the global scale (from 0 to 100% of the global cropland area) in combination with different N sources. We then compare food production with different estimates of global food demand and we assess the feasibility of each combination.
- Finally, Chapter 4 synthesizes the results of the previous chapters and discusses how this dissertation significantly contributes to understanding the role that organic farming could play in feeding the world.

1. Comparing crop rotations between organic and conventional farming

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Abstract

Cropland use activities are major drivers of global environmental changes and of farming system resilience. Rotating crops is a critical land-use driver, and a farmers' key strategy to control environmental stresses and crop performances. Evidence has accumulated that crop rotations have been dramatically simplified over the last 50 years. In contrast, organic farming stands as an alternative production way that promotes crop diversification. However, our understanding of crop rotations is surprisingly limited. In order to understand if organic farming would result in more diversified and multifunctional landscapes, we provide here a novel, systematic comparison of organic-to-conventional crop rotations at the global scale based on a meta-analysis of the scientific literature, paired with an independent analysis of organic-to-conventional land-use. We show that organic farming leads to differences in land-use compared to conventional: overall, crop rotations are 15% longer and result in higher diversity and evener crop species distribution. These changes are driven by a higher abundance of temporary fodders, catch and cover-crops, mostly to the detriment of cereals. We also highlighted differences in organic rotations between Europe and North-America, two leading regions for organic production. This increased complexity of organic crop rotations is likely to enhance ecosystem service provisioning to agroecosystems.

Keywords

Crop rotations, organic farming, conventional farming, meta-analysis, global scale.

Introduction

Land-use activities affect a considerable fraction of the global terrestrial surface (Foley, Defries, et al. 2005; Foley et al. 2011) and are key drivers of habitat and biodiversity loss, water use, global nutrient cycles, greenhouse gas emissions and carbon sequestration (Foley, Defries, et al. 2005). Among all land-use activities, agriculture plays a key role. Because it occupies about 40% of the Earth's terrestrial surface - the largest single use of land on the planet (Foley, Defries, et al. 2005; Ramankutty et al. 2008), agriculture contributes to the large appropriation of net primary production by human societies at the global scale (Haberl et al. 2007). Farming has a tremendous impact on the Earth's functioning (Lal 2004; Hertel et al. 2010; Lambin & Meyfroidt 2011; Tubiello et al. 2015) and a large body of literature has shown that current agricultural practices and related land-use activities are dominant forces that are driving the planet beyond its safe operating space (Steffen et al. 2015).

Cropland-use activities are largely driven by crop rotations (Wibberley 1996). Rotating crops in diverse and complex patterns is one of the oldest agronomic approaches used by farmers to control nutrient and water balances, weed, pest and disease infestations and risk exposure, and to improve system resilience as well as to fulfil human and livestock food and feed needs (Castellazzi et al. 2008; Chongtham et al. 2016). Because they have a significant impact on agroecosystem functioning as well as on the economic and environmental consequences and performances of cropping systems, diversified rotations are essential to design more sustainable agricultural systems (Schönhart et al. 2011). However, crop rotations have been dramatically simplified over the past 50 years (e.g., through the reduced number of crop species in crop rotations and the increased proportion of land farmed under monoculture) (Plourde et al. 2013; R. J. Hijmans et al. 2016) due to the advent of synthetic fertilizers and pesticides (Tuck et al. 2014) and to the increased disconnection between crop and livestock production (Matson et al. 1997). This decrease in the number of crop species in arable rotations has resulted in simplified land-use patterns in modern farming systems, reaching levels that jeopardize the provision of ecosystem services via agroecosystems (Tilman et al. 2002; Sahajpal et al. 2014; Erb et al. 2016; Lamy et al. 2016).

Organic farming represents a promising attempt at reconciling food production with environmental protection and multiple ecosystem service delivery (De Schutter 2011; Reganold & Wachter 2016). Because synthetic fertilizers and pesticides are banned by organic guidelines, rotations are supposed to assume a strategic role in organic production systems. In particular, it is generally supposed that more complex and diversified rotations are adopted in organic systems to sustain crop yields by providing alternative levers for pest control and nutrient management. However, beyond specific local studies, it has never been demonstrated and systematically quantified whether or not crop rotations are more complex in organic farming than in conventional (i.e., non-organic) farming. More generally, because very little systematic data is available about organic rotations, it has never been established to what extent crop rotations and resulting land-use differ between organic and conventional farming. Such knowledge would be critical to assess whether or not organic farming expansion would result in more diversified and multifunctional landscapes than conventional farming. Better understanding of organic crop rotations and land-use composition is also a key – and currently lacking - component to assess the capacity of organic farming to feed the planet (Badgley et al. 2007; Connor 2008; Erb et al. 2016).

Data on crop rotations are scarce, highly dispersed and poorly unified, mostly due to the lack of global datasets. Knowledge gaps are especially large when addressing developing countries and organic systems (Kuemmerle et al. 2013). Crop rotation data are most commonly collected by farm surveys, experimental plots (Lorenz et al. 2013) and field maps (Castellazzi et al. 2007), and are therefore difficult to retrieve at large spatial scales. Remote sensing has been attempted to collect land-use intensity, i.e., cropping frequency and short crop rotation, but only at the regional scale (Spera et al. 2014; le Maire et al. 2014; Estel et al. 2016). To overcome these difficulties, we developed a global database using a meta-analysis approach by collecting data on the composition of crop rotations (i.e. regardless of the temporal sequence of crops within rotations) from the scientific literature about organic *vs* conventional farming performances. Our database is composed of data from 77 publications with information about 238 unique rotations and covering 26 countries worldwide (Supplementary Figure S1). We supplemented this analysis by constructing a database on organic and conventional global land-use using data from FAOSTAT and FiBL (see Methods section). This second database provided information about organic *vs* conventional crop areas for a series of six annual crop categories at the national scale for 50 countries on five continents. Even if the direct comparison of the two datasets has some limitations –because the rotation dataset assesses temporal crop diversity at the field scale, whereas the land-use dataset assesses spatial diversity at the national scale– pairing these two data sources helps to estimate how results from local-scale studies translate into large scale census. By analysing this rotational database, complemented by the land-use information, we aimed to (i) estimate to what extent rotations differ between organic and conventional farming; (ii) investigate whether such differences vary in different global regions; and (iii) verify whether global land-use data were consistent with the rotation results. This study focuses on temporary arable crops (excluding perennial and permanent crops and fodders) that together provide the bulk of calories and proteins to humans and livestock animals and that cover 70 and 92% of the global cropland area in organic and conventional farming, respectively.

Results

Our results showed that rotations are more diversified in organic than in conventional farming. On average at the global scale, we found that organic rotations last for 4.5 ± 1.7 years, which is 0.7 years or 15% more than their conventional counterparts, and include 48% more crop categories (Figure 2), thus resulting in higher crop diversity over space, as well as over time (assessed by the Shannon diversity index). This result is in great part due to the higher abundance of catch (defined as any non-harvested cover crop or green manure between two main crops) and undersown cover crops. Our results also showed that organic farming exhibits a more even distribution of the different crop categories (higher Equitability Index in Figure 2), even if differences between production systems are not significant. In contrast, conventional rotations have a lower diversity, especially in the global region "Others", i.e., in tropical and subtropical countries. However, the land-use dataset did not confirm the higher diversity of organic systems. In fact, land-use tends to be slightly less diverse in organic systems than in their conventional counterparts, in particular for the global tropical and sub-tropical 'Others' region. We found similar results for the equitability of crop categories, although most differences were not significant (Figure 2). This result might be because the land-use dataset does not contain information on some crop categories, i.e., fodders, catch crops, etc., that contribute to the higher diversity in the rotation dataset. Additionally, especially in the tropics, organic farming is strongly focused on a few export commodities such as vegetables, permanent crops, spices and fruits (Willer & Lernoud 2017). Such specialization on a small set of permanent crops might explain the discrepancy between the two datasets when focusing on arable farming systems only.

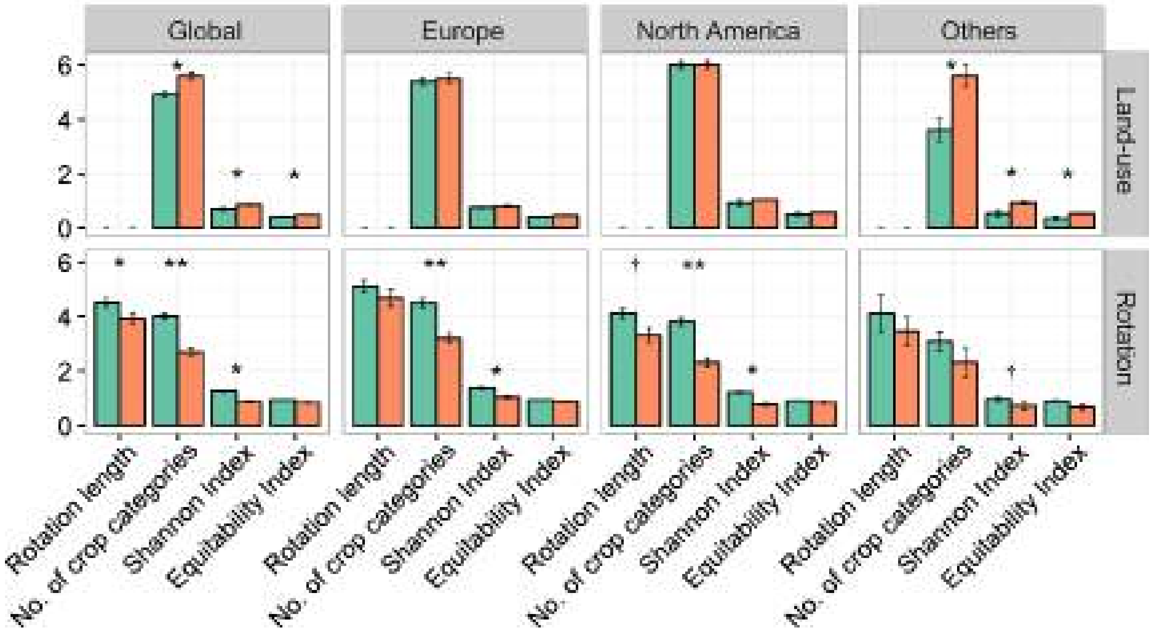

Figure 2. Average (± standard error of the mean) rotation length [in years], total number of crop categories in organic (green), and conventional (orange) rotations and land-use, as well as the Shannon Index (H) and the Equitability Index (EH) calculated at the global scale and by global region using the rotation and the land-use datasets. H and EH are calculated based on the timeshare of each crop in the rotation (for the rotation dataset), or based on the relative harvested area of each crop category (for the land-use dataset). The total number of crop categories considered was n=11 in the rotation dataset and n=6 in the land-use dataset. ** $P < 0.01$; * $P < 0.05$; † $P < 0.1$.

Organic and conventional rotations have different crop compositions

We found that the composition of rotations significantly differed between farming systems (Table S1). Organic rotations are composed of primary cereals (i.e. wheat, maize and rice; 29 ± 2% of the rotation length), secondary cereals (i.e. spelt, barley, rye, triticale, oat, sorghum, millet and pseudocereals; 17 ± 2%), pulses (15 ± 2%) and temporary fodders (24 ± 2%), whereas the remaining 15% is shared among oilseeds, root crops, industrial crops and vegetables (Figure S2). Our results also showed that catch crops and undersown cover crops are 2.4 and 8.7 times more frequent in organic systems compared to conventional systems, respectively, even though their total number in rotations remains low. These rotation characteristics based on our meta-analysis dataset were in good agreement with the land-use data. The latter confirmed that cereals (primary and secondary) compose the greatest fraction of organic cropland use (up to 61 ± 4%) and showed that the share of grain pulses was similar in the two datasets, even though the land-use share of oil crops and vegetables was higher than the rotation dataset (Figure S2).

At the global scale, organic rotations have fewer cereals and more temporary fodders

Our analysis showed that organic rotations have a 10% lower abundance of cereals compared to their conventional counterparts at the global scale (Figure 3). This result was due to a marked decrease in primary cereal species, wheat, corn and rice (that were 1.38 times less abundant in organic rotations), although secondary cereals such as barley, rye and oats exhibited a slight increase of 1.19 times in organic rotations (Figure 3). We also found a higher frequency (4.3 times) of cereal intercropping with legume crops than in conventional systems. In addition, we found that organic rotations have 2.8 times more temporary fodder crops (such as alfalfa, clover, clover-grass, Italian ryegrass, etc.) than conventional systems (Figure 3), which generally occupy land for an entire year. An important share of organic rotations is also dedicated to catch and undersown cover crops, which are 3.2 and 12.1 times more abundant than in conventional rotations, respectively. These results represent critical information about organic systems since most land-use datasets about croplands critically lack data on temporary fodders and non-harvested crops such as cover or catch crops. We also found that, at the global scale, grain pulses (e.g., soybean, beans and peas) are slightly more abundant in organic rotations although the difference was not statistically significant (Table S1). Finally, we found that organic rotations include slightly less oilseed and root crops (Figure 3). These results from the meta-analysis of the scientific literature were confirmed by the global land-use data, which showed 16% lower frequency of cereals in organic compared to conventional systems at the global scale (Figure 4) (although additional details about primary *vs* secondary cereals and intercropping were not available in the land-use datasets). The land-use dataset also confirmed that grain pulses are slightly more abundant, while oilseed and root crops are slightly less abundant in organic farming compared to conventional farming (Figure 4).

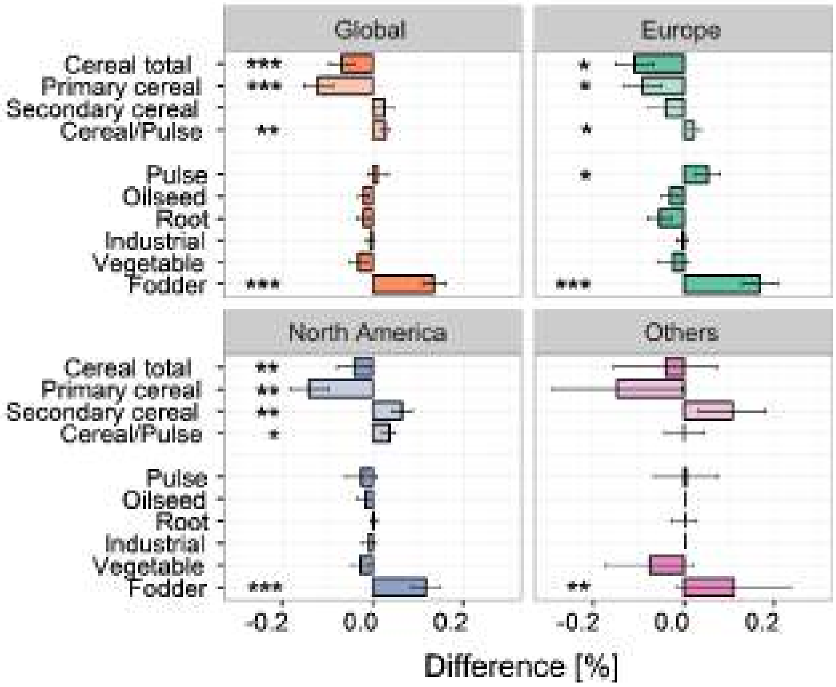

Figure 3. Difference (organic minus conventional, ± standard error of the mean) in crop categories between organic and conventional rotations at the global scale and by global regions (in % of the total rotation length) based on the rotation dataset. The cereal total is the sum of all cereal categories. The shaded sub-categories – 'Primary cereal', 'Secondary cereal' and 'Cereal/Pulse' - refer to primary cereals (wheat, rice, maize), secondary cereals (spelt, barley, rye, triticale, oat, sorghum, millet and pseudocereals), and cereals intercropped with a pulse, respectively. 'Fodder' crops refer to temporary fodder crops (such as alfalfa, clover and ryegrass). Number of observations (organic; conventional): Global (127; 111), Europe (53; 46), North America (63; 54), Others (11; 11). *** P < 0.001; ** P < 0.01; * P < 0.05.

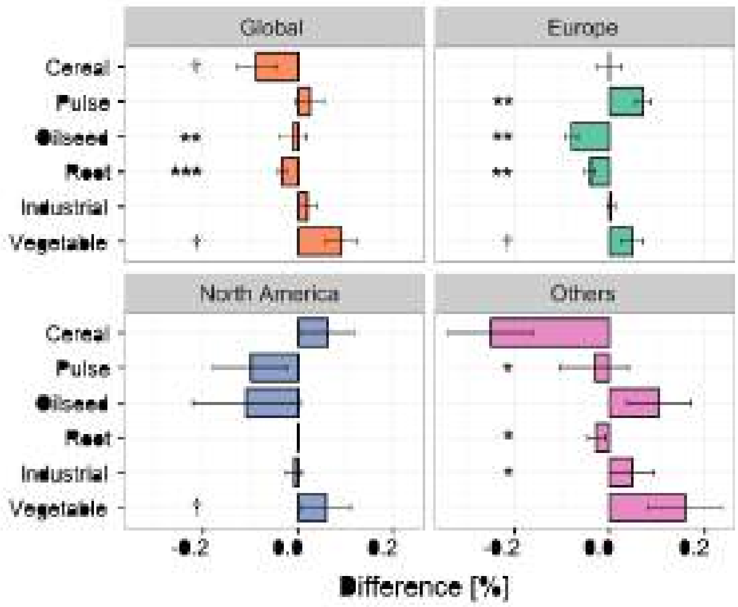

Figure 4. Difference (organic minus conventional, ± standard error of the mean) in crop categories between organic and conventional land-use at the global scale and by global region (in % of harvested area under each crop category in relation to the total cropland area farmed organically or conventionally, respectively) based on the land-use dataset. Number of countries: Global (50), Europe (29), North America (2), Others (19). *** P < 0.001; ** P < 0.01; * P < 0.05; † P < 0.1.

Organic rotations have more nitrogen-fixing crops

Although organic rotations do not significantly exhibit a higher share of grain pulses at the global scale (Figure 3), our results showed that nitrogen-fixing crops are more abundant in organic farming than in conventional farming. This is due to temporary fodder compositions (Figure 5) that include more legumes than their conventional counterparts. It is also due to catch and undersown cover crops that are both more frequent and are more often composed of nitrogen-fixing species than in conventional systems (Figure 5), as well as to the higher frequency of cereal intercropping with legume crops. When combined with a simple estimation of the amount of nitrogen (N) fixed by these leguminous crops, we estimate that, overall, leguminous grain pulses, fodders, catch and undersown cover crops provide 2.6 times more nitrogen to soils farmed organically than they do in conventional rotations. Unfortunately, these crop types have not been tracked in the land-use datasets, making it difficult to assess how representative the results from our meta-analysis are for the crops grown on actual organic *vs* conventional farms.

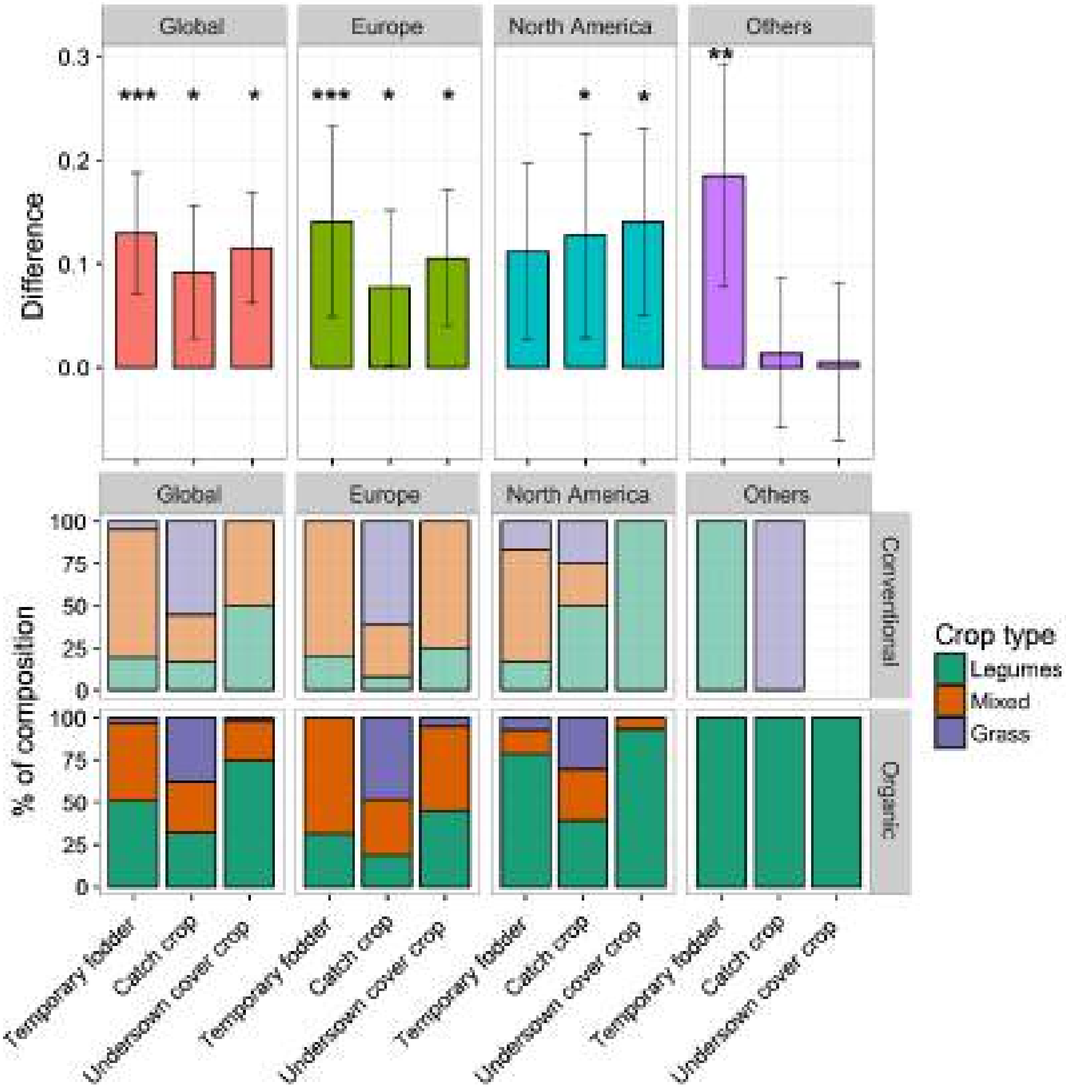

Figure 5. *Above*: Average differences (organic minus conventional, ± standard error of the mean) between the organic and conventional share of fodders, catch and undersown cover crops (in % of the total rotation length) at the global scale and by global region. *Below*: Contribution of grass, mixed (any intercropping of legume and grass) and legume species to temporary fodders, catch crops and undersown cover crop compositions in organic and conventional rotations at the global scale and by global region. Number of observations (organic; conventional): Global (127; 111), Europe (53; 46), North America (63; 54), Others (11; 11). *** P < 0.001; ** P < 0.01; * P < 0.05.

These differences vary among global regions

Beyond the differences highlighted between organic and conventional farming at the global scale, our study also revealed that these differences strongly vary according to the global regions (Table S1, Table S2). For example, we found that cereals were far less abundant in European organic rotations compared to conventional farming, while the difference was much smaller and nuanced in North America (Figure 3, Figure 4). This was due to different behaviours for primary *vs* secondary cereals on the two continents: European organic rotations exhibited lower abundance (compared to conventional farming) of both primary and secondary cereals, while secondary cereals were more abundant in North America (Figure 3). The difference among continents was even more striking regarding pulses: while grain pulses were 65% more abundant in organic rotations and land-use in Europe, we found a 13% lower frequency for these crops in North America. This result is probably due to strong differences in the frequency of these crops in conventional farming – low in Europe, high in North America - largely explained by greater and more stable yield performances of grain pulses in North America and due to difference in both public and economic policies (Cernay et al. 2015).

Discussion

Despite their key role in cropping system performances, crop rotations lack systematic analysis in the scientific literature. Our study made it possible to address part of this knowledge gap by comparing organic *vs* conventional rotations. In particular, our meta-analysis approach allowed to retrieve systematic information on rotations from a large body of scientific papers and reports. In addition, the comparative approach adopted in this study, which also included an assessment of organic *vs* conventional land-use in different crop types at the national scale, was essential to provide information on both organic and conventional production and to highlight system differences between organic and conventional farms. Importantly, our results emphasized the role of temporary fodders, catch and undersown cover crops in organic systems - crops that are typically not included in national land-use databases on organic or conventional agriculture (FiBL 2015; Food and Agriculture Organization of the United Nations 2016). This specific information is of great importance since these non-harvested crops often play critical and multifunctional roles in both organic and conventional farming.

However, our study has some limitations. Firstly, rotation data are difficult to identify based on abstract screening of publications since crop rotations are typically not the focus of a study and information about crop rotations is generally presented in the Materials and Methods section. Some data may therefore have been discarded during our literature search. Secondly, scientific papers mainly report information from experimental field trials, which are not necessarily representative of real farming rotations (Seufert & Ramankutty 2017). In our dataset, 88% of rotations was derived from experimental data, whereas the remaining 12% was derived from on-farm data. Experimental scientific studies today are often focused on crop species that are difficult to manage organically (such as cereals and oilseeds), and cereal-based rotations may therefore be overrepresented. Additionally, the choice of crops within experimental studies may reflect that trials are often carried out in situations where the use of grazing livestock is restricted. Studies addressing a better characterization of real organic farm rotations are clearly necessary. Thirdly, most studies included in our analysis were carried out in North America and Europe, while developing and emergent countries are poorly represented (Figure S1). Additional studies are particularly required in tropical regions where a large proportion of the organic land area and the majority of organic producers are located (Seufert & Ramankutty 2017). Our parallel analysis based on land-use data made it possible to at least partly address these problems since it allowed to include information on the crop types grown in the countries under-represented in the meta-analysis dataset. However, the comparison of the two datasets is not straightforward. Indeed, while most rotation data were extracted from agronomic papers aiming at comparing cropping systems that were designed based on sound agronomic knowledge and that were possibly designed to test new cropping systems, land-use developed by farmers may be driven by non-agronomic drivers, e.g., economic factors. In addition, the rotation dataset provides temporal data from small-scale studies whereas the land-use dataset brings spatial results about the global crop area. Yet, making the parallel between the two datasets is unique to estimate how local results translate into global, spatial census. Despite all the above-mentioned shortcomings, our analysis represents an important – and to our knowledge, pioneering - step in the characterization of organic farming system land-use patterns.

The deep differences in rotations and land-use that we found between organic and conventional production systems are in line with many organic principles and regulations that often require diverse crop rotations (Seufert et al. 2017). Our analysis showed that organic systems represent more diversified farming systems with a higher diversity and evenness of crop categories than conventional systems, and with longer rotations. These more diversified systems are associated with multiple benefits (Kremen et al. 2012). More diverse crop rotations are important management tools for controlling weeds, pests and diseases by creating biotic barriers and interrupting their cycles without the use of synthetic pesticides (Poveda et al. 2008; Kremen et al. 2012; Rusch et al. 2013). Additionally, the fact that we found organic rotations to be longer and more diversified than their conventional counterparts indicates that organic systems are likely to be more resilient to abiotic stresses (Borron 2006) as well, by especially being more capable of buffering the effect of climate stresses such as increased temperature and rainfall variability (Lin 2011). Altogether, these diversification strategies are likely to result in the improved provisioning of ecosystem services to both agroecosystems and the wider environment (Sandhu et al. 2008; Lamy et al. 2016). Specifically, enhanced diversification and the resulting service provisioning may help to narrow the yield gap between organic and conventional farming systems, as suggested by Ponisio et al. (2015) who found lower gaps when diversification practices such as intercropping and diversified crop rotations were implemented in organic systems but not in conventional systems. Adopting strategies to narrow the organic-to-conventional yield gap can, therefore, have the co-benefit of reducing the loss of biodiversity often associated with conventional cropping systems. More diversified agricultural systems could also potentially result in positive impacts on global food security since a higher diversification of food commodities provides more micronutrients than production systems with less diversity (Herrero et al. 2017). Indeed, this higher diversification might also be due to how organic crop rotation might have been affected by the legislative development of organic farming, especially through public subsidies to certain areas and crop types.

The differences in rotations and land-use that we found between organic and conventional production systems show that organic systems have been designed to satisfy the fertilization requirements determined by the different organic principles and regulations. Indeed, meeting crop nutrient demand, in particular for nitrogen, by appropriate and 'organic-compatible' practices is a key lever to close the organic-to-conventional yield gap (Seufert et al. 2012; Ponisio et al. 2015). The greater abundance of nitrogen-fixing crop species found in organic rotations reflects the multifunctional role played by temporary fodders to achieve organic principles, not only to control pests but to fix N in soils as well (Lampkin 1990). In particular, the fact that we very frequently observed the use of legume and mixed legume-grass fodders in organic systems means that cropping practices have been designed to compensate for the lower external supply of N to crops due to the prohibition of synthetic N fertilizers under organic management. Our analysis also showed that this greater use of leguminous fodders is accompanied by a lower frequency of grain pulses found in organic rotations. Such a choice is agronomically sound because temporary fodders provide additional services besides N fertilization (weed control, disease break crop, carbon sequestration in soils, feed production, etc.) (Lampkin 1990) and because the occurrence of several pulse crops in a short timespan can favor problematic diseases such as anthracnose and downy mildew (Baldoni & Giardini 2000). Additionally, organic farms are often mixed farms (especially in Europe), and the greater use of fodders is also in line with the need to produce animal feed within the region, as required, for example, by European organic regulations (European Commission 2008). Finally, the greater use of catch and undersown cover crops found in organic systems suggests that farmers have adopted agronomic strategies to limit N leaching– a problem due to difficulties in synchronizing fertilization practices and crop nutrient uptake (Pang & Letey 2000; Askegaard et al. 2005) - and soil erosion, and to compensate for the high economic cost of external organic N sources.

Finally, this analysis of organic rotation and land-use analysis, although limited by the availability of data at the global scale, represents a necessary step to conduct organic *vs* conventional comparisons at the cropping system rather than at the crop level (De Ponti et al. 2012; Connor 2013). This step is important because estimating the crop production capacity of organic agriculture requires consideration of whole production systems and not just individual crop species (Connor 2013). A better understanding of organic crop rotations is also important to estimate the crop nutrient requirements and ecosystem service provisioning that would result from the expansion of organic farming. The differences in crop rotations under organic management that we observed in our study would result in drastic modifications of crop nutrient requirements and services provided by agricultural landscapes, as well as in possible imbalances in human *vs* animal needs due to the strong differences in the crop categories produced. However, these changes have been poorly captured so far in prospective studies that assess food security in organic production scenarios at large scales. Such changes are indeed more complex than a simple increase in N-fixing crops, a parameter that is supposed to encompass all land-use changes when modeling conversion to organic agriculture up until now (Badgley et al. 2007; Schader et al. 2015). More detailed information about temporary fodders at the global scale and by global region is necessary to better assess food and feed provisioning over the entire organic cropping system (De Ponti et al. 2012; Seufert et al. 2012; Connor 2013). This is because longer rotations that include more fodder crops might undermine food provisioning by competing with grain crop species on the one hand, and have strong consequences for the livestock sector on the other hand. By alleviating these caveats, our results provide a foundation to build more realistic hypotheses about land-use change and to improve future models to assess the contribution of organic farming to feed the planet.

In summary, to our knowledge, this study represents the first comparative analysis of organic *vs* conventional rotations at the global scale. The results of our analysis clearly revealed that the ban of synthetic inputs in organic production forced organic rotations to adopt major changes compared to their conventional counterparts: increased rotation length, higher crop diversity, more frequent temporary fodders, nitrogen-fixing crops and intercropping. The increased complexity and diversity of crop rotations that result from the conversion to organic farming is likely to provide strong environmental benefits and enhanced ecosystem services. Such information is of key importance to guide the conversion to organic farming as a way to achieve global food security without compromising the protection of the environment.

Materials and methods

Rotation dataset

Literature search and publication screening. We collected the data on organic *vs* conventional rotations through both an original literature search and the reuse of existing databases on similar topics. The original literature search was undertaken using the 'Web of Science' portal. We used a complex Boolean search containing (i) the term ecological, biological or organic next to (ii) the term farming, agriculture, cropping or production, in combination with (iii) the term rotation, comparison or conventional. The last search was conducted on October 28, 2016, turning up 431 papers. In addition to this literature search, we retrieved the databases referenced by Seufert et al. (2012), De Ponti et al. (2012), and Ponisio et al. (2015) about organic *vs* conventional crop yields. These databases accounted for an additional 264 publications, leading to a total of 695 papers. The abstracts of these 695 initially retrieved papers were first screened to verify whether crop rotation data were actually present, resulting in the selection of 301 records. These 301 papers were further screened by checking if (i) they provided different organic and conventional treatments, i.e. if equal rotation were reported, the study was discarded, (ii) they reported complete rotation schemes, and (iii) the organic treatment was either certified organic or in line with the definition of organic agriculture given in the Basic Standards for Organic Production and Processing of the International Federation of Organic Agricultural Movement (IFOAM 2014). Papers' methods that provide equal rotations in both conventional and organic cropping systems may -in most cases- be interpreted as a choice to attenuate the difference between the two farming systems, since they might focus on different parameters but the rotation itself. We also excluded multiple publications reporting on the same trials to avoid double counting. Publications reporting rotations in multiple countries were considered as different entries, using the country as the discriminating criterion. As suggested by De Ponti et al. (2012), data prior to 1985 were not included because they were considered outdated, with the exception of long-term trials. Following such criteria, the screening yielded only 77 publications for further analysis, including 238 unique rotations covering 26 countries worldwide (Figure S1). The majority of data came from Europe (42%) and North America (49%). The complete list of studies is provided in the Supplementary Table S4.

Data extraction. Information on rotation length, number of crops, catch and undersown cover crops were recorded from each publication, regardless of their temporal sequence in the rotation. We defined as *crop* any crop species that stands on a field over a cropping season, with a duration of maximum one year. Therefore, if several crop species were grown simultaneously on the same field in the same year, only the main crop was considered (with the exception of cereals intercropped with pulses and temporary fodders that were recorded as such). We also recorded information on non-harvested crops. To derive the total number of crop species present in each rotation (proxy for crop species diversity), we counted only the net number of crops (e.g., if one crop species was present for two or more years in the rotation, it was counted as just one). We also counted the real number of crops to estimate the timeshare of each crop category in the rotation. For instance, if one crop species was present for two years in the rotation, we counted it as one to derive the total number of crop species in the rotation (proxy for crop species diversity), but we counted it as 2 in order to calculate the timeshare of such crop in the rotation. We defined as *undersown cover crop* any relay intercropped species, and as *catch crop* any green manure or winter catch crop. Crops were then classified according to the following crop categories: (i) primary cereals (wheat, rice, maize); (ii) secondary cereals (spelt, barley, rye, triticale, oat, sorghum, millet and pseudocereals); (iii) intercropped cereals with pulses; (iv) pulses (including soybeans); (v) oilseeds; (vi) root crops (potato, sugar beets, cassava, sweet potato); (vii) industrial crops (flax, tobacco); and (viii) temporary fodders. For temporary fodders, catch crops and undersown cover crops, we recorded whether the corresponding species was a legume, a grass or a mixture of the two (e.g., clover-grass mixture). For each rotation, the time share of each crop category was calculated by dividing the number of crops in each crop category by the total rotation length. Finally, the location of each study was retrieved through the country in which the study took place. Countries were grouped according to three main global regions: Europe, North America and Others (Figure S1). Countries other than European and North American were grouped into one single region due to the low number of data retrieved in such countries (n=22, 9% of the dataset), in order to obtain balanced data groups for the statistical analysis. Overall, the number of organic rotations was slightly higher than the conventional one (53% and 47%, respectively). This is because some studies reported one conventional rotation compared to two, or more, organic rotations.

We estimated the nitrogen fixed by pulses, temporary fodders, catch and undersown cover crops by assigning a leguminous species to each crop category (i.e., pea for pulses, alfalfa for fodders and vetch for catch and cover crops) and using the model of Hogh-Jensen et al. (2004). Calculations were computed considering a field size of 1 ha.

Land-use dataset. We created an original database on organic *vs* conventional land-use by collecting country-level statistical data from the Research Institute of Organic Agriculture (FiBL, Switzerland, FiBL 2015) for organic agricultural land-use and from FAOSTAT (Food and Agriculture Organization of the United Nations 2016) for conventional agricultural land-use, for the years 2010-2014. Since the original structure of the two databases differed, datasets were restructured in order to allow data comparability of arable crop categories. To do so, land-use data, i.e., the harvested area for each crop category, were expressed according to the following crop categories: cereals (primary and secondary), pulses (including soybeans), oilseeds, root crops, industrial crops and vegetables. No information on organic temporary fodders was available in either of the databases. Hence, we could not compare the two systems' land-use based on this specific crop category. Information at the crop species level in the FiBL database was not detailed enough to run an analysis at that level.

The data about land-use under conventional agriculture were retrieved by subtracting the area under organic farming (provided by FiBL) from the data on arable land-use provided by FAOSTAT for each country. The across-years land-use average was calculated and used for further analysis. For each country and production system (organic and conventional), the land-use share of each crop category was calculated as the area under the specific crop category divided by the cropland area under the total number of crop categories considered. The data were filtered by removing countries for which the share of organic area was lower than 0.5% of the total agricultural area. Overall, land-use from 50 countries were compared. European and North America countries represent 62% of the dataset, followed by Asian (16%), Latin American (10%), African (10%) and Oceanian (2%) countries. Countries were grouped according to the same three global regions defined for the rotation dataset (i.e., Europe, North America and Others) to facilitate comparisons of datasets as much as possible. Nevertheless, the region "Others" was not directly comparable between the two datasets since the composition of the countries was slightly different.

Statistical analysis

We examined richness and diversity of organic and conventional rotations and land-use by using Shannon's diversity and equitability indices. Shannon's diversity index (H, Eq. 1) helped to assess the relative abundance of crop categories, providing an indication about species diversity, while the Equitability index (E_H, Eq. 2) helped to assess whether the different crop categories have an even share in both rotations and land-use. The two indices were calculated as follows:

$$H = -\sum_{i=1}^{S} p_i \ln(p_i) \qquad \text{(Eq. 1)}$$

Where p_i represents the proportion of crop category i

$$E_H = \frac{H}{H_{max}} = \frac{H}{\ln(S)} \quad \text{(Eq. 2)}$$

Where S is the total number of crop categories. The data expressed as counts (i.e., rotation length, total number of crops and number of catch and undersown cover crops) were analyzed using a Generalized Mixed Model following a Poisson distribution. The production system (organic *vs* conventional), global region and their interaction were included as fixed factors. The 'study' was included as a random effect to account for possible "study effects" and data overdispersion.

The data expressed as percentages (i.e., share of the different crop categories in each rotation and land-use) were analysed using a Permutational Analysis of Variance (non-parametric MANOVA) with distance matrices to test the null hypothesis of no difference between production systems, global regions and their interactions. This made it possible to partition distance matrices among sources of variation and to fit a linear model to the different matrices. The partial R-squared (r^2) obtained indicates the percentage of variance that is explained by the factors. The significance of each explanatory variable was computed from F-tests based on sequential sums of squares from permutations of the raw data (Anderson 2001). The analysis was run using the Bray-Curtis dissimilarity index, and the number of permutations to compute the significance tests was set to 999. We tested the differences in the share of each crop category between production systems, global regions and their interactions using a non-parametric Kruskal-Wallis test, followed by a post-hock pairwise Dunn test.

Differences between production systems in terms of Shannon diversity were tested by using a Linear Mixed Model (production system as the fixed factor; studies' number as a random effect to account for possible "study effects"), and a Linear Model (production system as the fixed factor), respectively, for the rotation and the land-use datasets, followed by a classical analysis of variance. Normality of data was verified through a Shapiro-Wilk test and residual check plots. The equitability indices were far from being normally distributed and their differences between organic *vs* conventional systems were therefore tested using a non-parametric Kruskal-Wallis test. We calculate the Shannon and the equitability indices using both all the data across the 4-year period and the across-year average. Since we did not find any effect due to the variation over time, we finally kept the calculation done using the across-year average.

All the analyses were performed in R Open 3.3.2 (MRAN 2016), using the "lme4" package for mixed models (Bates et al. 2016), the "rcompanion" package for non-parametric models (Mangiafico 2017), the "FSA" package to evaluate the significance of the effects (Ogle 2017), and the "vegan" package for descriptive community ecology (Oksanen et al. 2017).

Data availability

The authors declare that the main data supporting the findings of this study are available within the article and its Supplementary Information files. Extra data are available from the corresponding author upon request.

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Author Contributions

P.B., T.N and S.P. designed the study; P.B. collected the data and performed the statistical analysis; all authors were involved in the interpretation of results and contributed to writing and revising the manuscript.

2. Farming organically, farming differently – how changes in the types of crops grown would impact food production in an organic world

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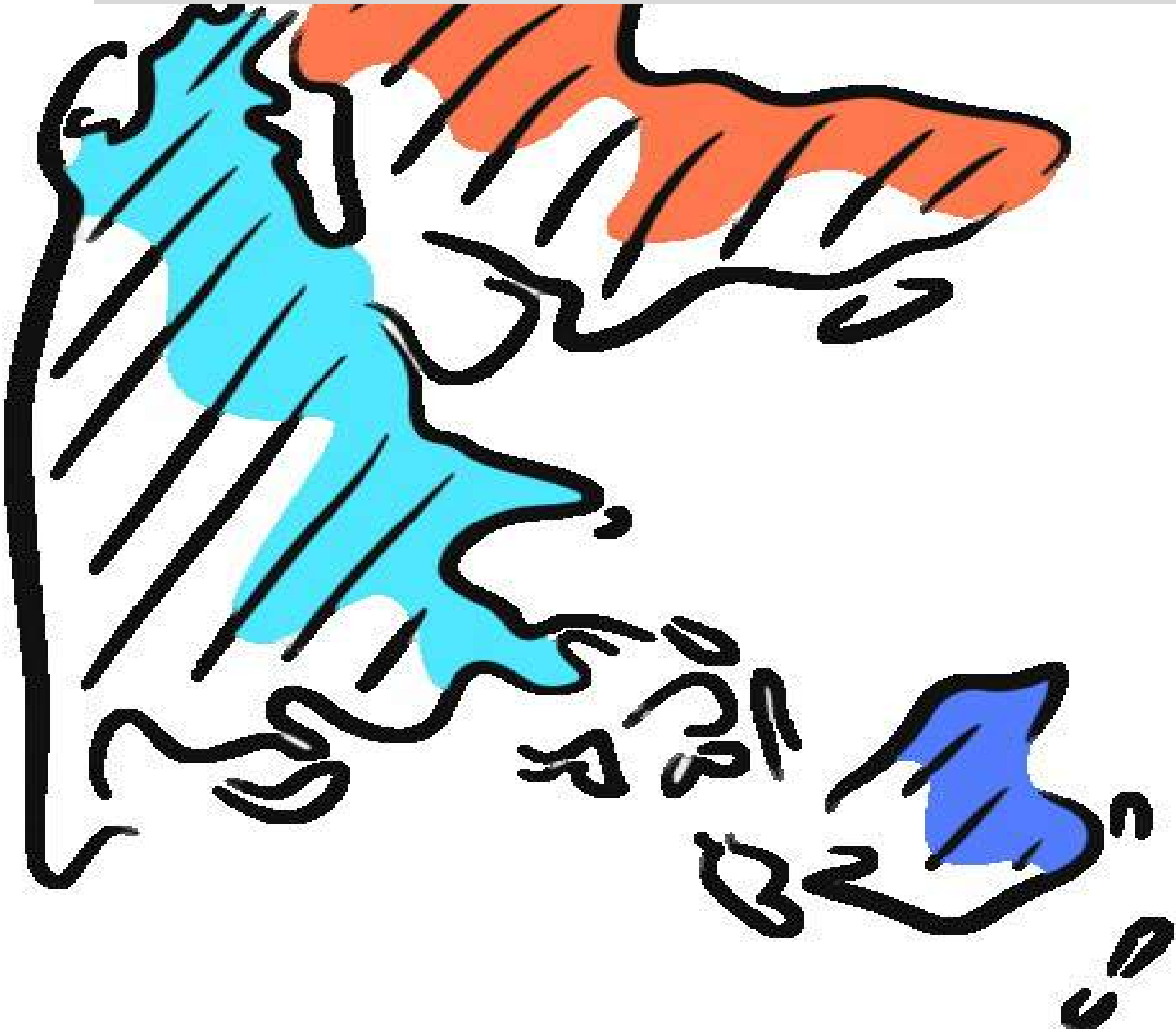
Under review in Nature Sustainability



In the previous chapter, we have showed that organic crop rotations significantly differ from conventional rotations at the global scale. Such differences are complex and involves changes in both (i) the abundance of several crop categories and (ii) the choice of crop species (legume vs non-legume). In this chapter, we propose a modelling methodology to transform such information into global maps of the type of crops grown in a full (i.e. 100%) organic world. We then estimate the impacts that these changes in the type of crops grown cause on global food production. Here, we do not explicitly consider the effects of nitrogen availability on organic cropland productivity.

Abstract

The debate about organic farming productivity has often focused on its relative crop yields compared to conventional farming. A conversion to organic farming does, however, not only result in changes in crop yields, but also in changes in crop rotations, resulting in global, spatially distributed changes in the types of crops grown. To date, the effects of such changes in crop rotation and crop choice on global crop production have never been systematically investigated. We provide here a novel, spatially-explicit estimation of the distribution of crop types grown and crop production in a scenario of 100% conversion of current cropland to organic farming. Our analysis shows a decrease of -31.1% area harvested with primary cereals (wheat, rice and maize), and an increase of the harvested areas with temporary fodders (+62.9%), secondary cereals (e.g. barley, oats) (+27.3%) and pulses (+25.5%) compared to the current situation. These changes, paired with a regionalised organic-to-conventional yield gap, lead to a -27.2% energy and to a -23.1% protein crop production gap compared to current production. While the overall crop production gap depends largely on the organic-to-conventional yield gap, changes in crop choice strongly affect the repartition of total production among different crop types and result in diversification of cropland food production. Being able to feed the world organically would thus require strong adaptations of human diets and animal husbandry.

Keywords

Organic agriculture, conventional agriculture, land management, global food production, yield gap

Introduction

Our planet is confronted with mounting pressure due to the expanding food demands of a growing global population (Augustin et al. 2016). While modern agricultural technologies have resulted in rapid increases in crop yields, they have also caused significant and widespread negative environmental effects (IAASTD 2009) that have driven the planet beyond its safe operating space (Erb, Haberl, et al. 2009; Steffen et al. 2015). Farming the planet and achieving food security in a fair and sustainable manner is urgently needed, thus requiring a switch to efficient and more sustainable agricultural systems.

Amongst more sustainable alternative systems, organic agriculture is often proposed as a promising option (IAASTD 2009; Foley et al. 2011). It is, however, challenged by many critics who claim that organic management would not be able to provide sufficient food to feed the world (Connor 2008; Connor & Mínguez 2012; Connor 2013; Kirchmann et al. 2016). The debate on the relative food provisioning capacity of organic *vs* conventional (i.e., non-organic) systems at the global scale has mostly focused on the comparative productivity of the two systems, i.e., their respective crop yields at the crop species and field level (Erb et al. 2016; Muller et al. 2017). While some recent studies have quantified these differences by considering scenarios of organic expansion in a more systematic way (Erb et al. 2016; Muller et al. 2017), they were not aimed at depicting other management changes under organic agriculture. Converting farming systems to organic agriculture is associated not only with changes in yields, but also with strong structural changes in crop rotations and in the resulting types of crops grown (Bachinger & Zander 2007; Puech et al. 2014). This is due to the need to replace synthetic pesticides and fertilisers with agroecological management strategies such as longer and more diverse crop rotations and increased rotation timeshare[2] dedicated to N-fixing crops (such as leguminous fodders and pulses) in the rotations (Lampkin 1990; Kremen et al. 2012; Rusch et al. 2013). Recent results have confirmed these structural changes, showing that organic crop rotations and the resulting types of crops grown strongly differ from conventional farming and vary between different regions of the world (Barbieri et al. 2017). The large-scale conversion of global cropland to organic farming (which, to date, only covers 1% of the global agricultural area (Willer & Lernoud 2017)) would thus involve drastic changes in global cropland production that go beyond simple yield reductions. Previous studies of global organic scenarios have typically captured such changes

[2] We define the rotation timeshare as the share of the total rotation length occupied by a specific cultivated crop species or crop category.

through a simplistic increase in the share of global cropland under pulses (Badgley et al. 2007; Erb et al. 2016; Muller et al. 2017), despite evidence of much more complex changes in crop rotations. In addition, previous studies of global organic agriculture scenarios have carried out their analysis at regional (Erb et al. 2016) or national resolution (Muller et al. 2017), thus not accounting for sub-regional or sub-national heterogeneity in crop rotations or yields. There is thus a clear need to better account for changes in crop rotations and crop types grown if we want to better estimate the consequences that farming the planet organically would have for the environment and global food security.

In this paper, we provide the first spatially-explicit (5 minute resolution) assessment of both organic crop yields and organic crop rotations and their effects on crop production under a scenario[3] of organic agriculture, taking advantage of the best available high-resolution data on conventional crop choice and crop yields (Monfreda et al. 2008), as well as organic crop rotations (Barbieri et al. 2017) and crop yields (Ponisio et al. 2015). Our objectives are: (i) to estimate the harvested areas of different crops in a scenario of 100% organic farming by accounting for the structural differences between organic and conventional rotations; (ii) to quantify the resulting changes in energy and protein production from crops compared with the current global (conventional) crop production; (iii) to investigate the regional effect of this conversion to organic farming on types of crops grown, crop production and food supply. Our analysis is based on a scenario in which the total harvested cropland area remains constant at current levels (Tayleur & Phalan 2016), thus examining the question how the current world would look like under organic cropland management. We use data on current harvested areas of the 61 most important arable crops by global acreage (representing ~95% of the current global cropland harvested area) (Monfreda et al. 2008), grouped into seven crop categories. These data are then combined with results from a recent global meta-analysis that provides the relative abundance of these seven crop categories in organic *vs* conventional rotations in different geographic regions (Barbieri et al. 2017) to produce a spatially-explicit estimation of the harvested areas of different crop types under a hypothetical scenario of full conversion to organic farming. The resulting organic harvested areas are then combined with regionalised crop-specific data about organic yields – estimated from organic-to-conventional yield ratios (Ponisio et al. 2015) applied to current, conventional yields (Monfreda et al. 2008) - to calculate the potential organic energy and protein crop production. In our analysis, we account for differences in organic crop

[3] We use the term ‘scenario’ here to describe a thought experiment of how the current world would look like under complete organic management. Note that this does not include any analysis of future trajectories.

rotations, as well as crop yields between different regions since organic management differs between different agro-ecological and political zones (Ponisio et al. 2015; Barbieri et al. 2017). We then use FAOSTAT Food Balance Sheet (Food and Agriculture Organization of the United Nations 2016) as well as livestock feed use efficiencies (Cassidy et al. 2013) and food waste estimates (Erb et al. 2016) to estimate the food production from cropland in both the current and our hypothetical organic scenarios. Our analysis shows that the full conversion to organic management leads to deep changes in the harvested areas of different crop categories in many world regions. These changes are likely to provide environmental and dietary diversification benefits – due to substantial changes in the mix of crop products that is produced globally – at the cost of a lower total energy and protein production.

Results

Changes in the types of crops grown in a fully organic world

Farming the planet organically would lead to profound changes in the types of crops grown. In the 100% organic scenario, the harvested area of primary cereals (i.e., wheat, rice and maize, covering 46.1% of the total harvested area in the conventional scenario) would be reduced by 154.7 million ha (i.e., 31.1%) compared to the current situation. The harvested area of oilseed crops (e.g., groundnut, canola, sunflower, covering 6.2% of the total harvested area in the conventional scenario) would also decrease by 15%, and the harvested area of industrial crops (e.g., sugarcane, sugar beet, covering 2.4% of the total harvested area in the conventional scenario) would decrease by 5.8%. In contrast, secondary cereals (e.g., spelt, barley, oat), pulses (e.g., soybean, common bean, pea), root crops (e.g., potato, sweet potato, yam) and, above all, temporary fodders (e.g., alfalfa, clover, ryegrass) (covering 14.3%, 13.0%, 4.4%, 12.4% of the total harvested area in the conventional scenario, respectively) would increase globally by 27.6%, 25.2%, 1.3% and 62.9%, respectively (Figure 6). Asia plays a major role in driving such changes due to both the large size of the continent and the large area dedicated to primary cereal (mostly rice) production, especially in the eastern and south-eastern part of the continent (Figure 7). Overall, these changes in harvested areas result in higher crop diversity in the organic *vs* conventional scenario (global Shannon Diversity index of harvested areas of 1.96 in organic *vs* 1.74 in the conventional scenario, non-parametric Kruskal-Wallis test, $p<0.001$).

These changes in harvested areas are, however, not uniform across and within regions but exhibit strong spatial variations (Figure 7). The higher the area in the conventional scenario under a crop category that declines in organic rotations is (e.g., primary cereals), the stronger the decrease in harvested areas of that crop category in the organic scenario will be (Figure 7, Figure S4). For instance, although the harvested areas of primary cereals decline almost everywhere globally, they exhibit a stronger decrease in North America, where maize and wheat are dominant crops (Figure 7). Temporary fodders increase almost everywhere due to their higher proportion in organic rotations (Barbieri et al. 2017), and this increase is the largest in the same geographic zones that experience strong declines in primary cereals (Figure 7). The changes in harvested areas under pulses and secondary cereals also vary across global regions, depending on the initial extent of these crops in the conventional scenarios, as well as depending on the typical organic crop rotations in each region. In particular, we found a decrease in pulses in North-East America due to the lower abundance of soybean in organic rotations in this region compared to their conventional counterparts (Barbieri et al. 2017), in contrast with some increase in pulses in the organic scenario in Asia and Europe (where pulses - including soybean - do not form an important part of current conventional cropping systems (Monfreda et al. 2008)). Europe is the only global region where the acreage of both primary and secondary cereals decreases due to the low representation of cereals in organic crop rotations in Europe (Barbieri et al. 2017). This reduction, which is also coupled with a decrease in oilcrops acreage, results in a strong increase in the acreage of pulses and temporary fodder (Figure 7, Figure S4).

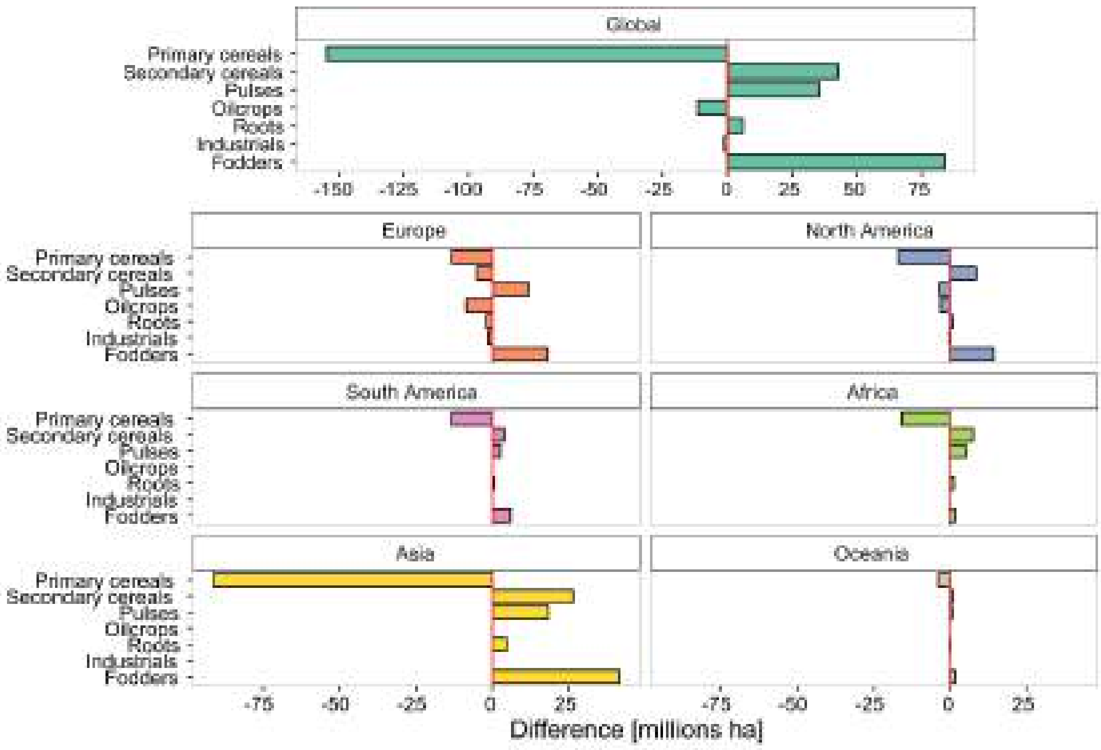


Figure 6. Differences in harvested cropland areas [millions of ha] of the different crop categories (primary cereals, secondary cereals, pulses, oil crops, root crops, industrial crops and temporary fodders) between

the 100% organic minus the 100% conventional scenarios at the global scale and for different global regions.

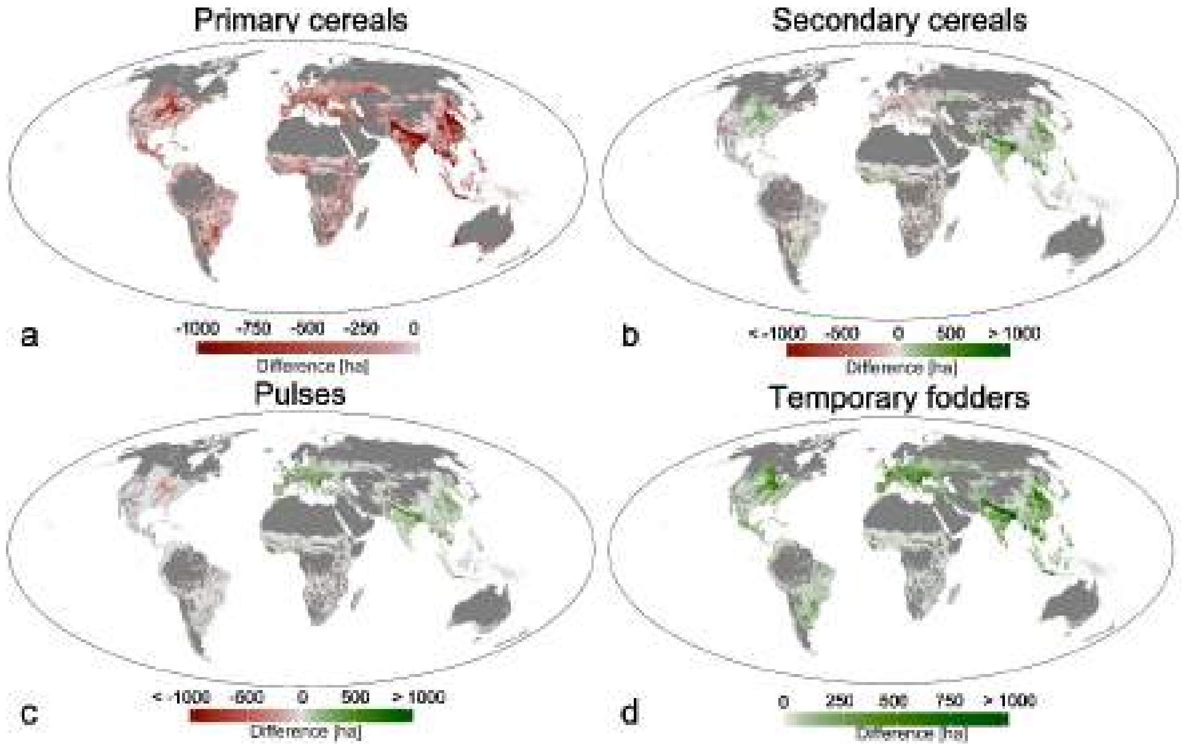


Figure 7. Difference in harvested cropland areas [ha per gird-cell] for major crop categories such as primary cereals (a), secondary cereals (b), pulses (c), and temporary fodders (d) between the 100% organic minus the 100% conventional scenarios. Grid-cells size at the equator is ~10 km x 10 km.

Our results also show that the area under nitrogen-fixing crops (i.e., pulses and leguminous species in temporary fodders) exhibits a large increase in the organic scenario (up to 30% more harvested areas compared to the current scenario), with the exception of regions with large soybean production in the current scenario, such as the eastern part of the US and some spots in Argentina and Brazil (Figure S4).

Change in crop types grown influences global crop production and food supply

The strong changes in the types of crop grown induced by organic farming have important repercussions for crop production as well as potential implications for food supply. Using data on current organic and conventional crop yields (see Materials and Methods), we globally found an organic-to-conventional energy and protein production gap of 27.2% and 23.1%, respectively, when considering all crop categories that might provide food products (i.e., excluding temporary fodders and minor crops like tobacco, cotton and rubber; see Figure 8b). These energy and protein gaps decreased to 19.9% and 8.6%, respectively, when including non-food crops (Figure 8a), showing that temporary fodders compensate for about ~8% and ~15% of total energy and protein production gaps. Interestingly, our results show that the overall organic-to-conventional production gap for food crops is somewhat in agreement with the average global yield gap between organic and conventional farming (~25%, ~19%, ~20% according to the different previous estimates) (Seufert et al. 2012; De Ponti et al. 2012; Ponisio et al. 2015). This suggests that changes in the types of crops grown in the organic scenario have minor effects on total crop production at the global scale. This result is confirmed by our sensitivity analysis, which shows that varying the harvested area values of different crop types results only in limited variation in the total energy and protein production estimates (see Appendix II).

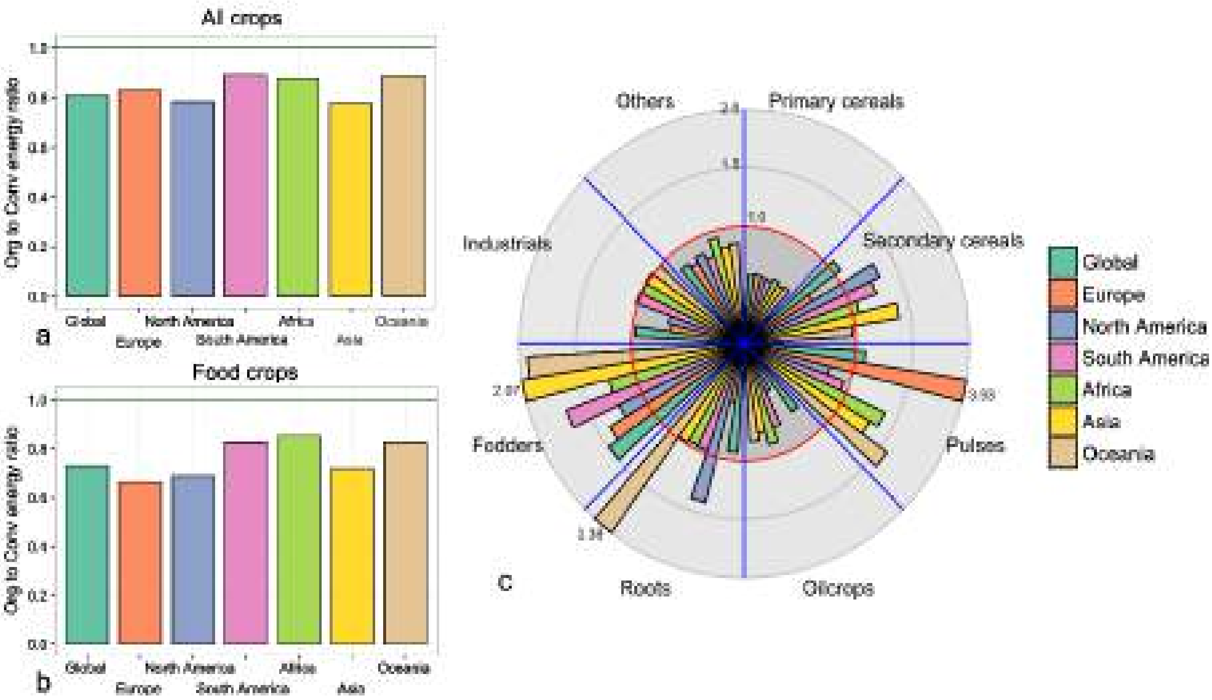


Figure 8. Ratio of organic-to-conventional energy production from crop products at the global scale, for each global region and by crop category (considering all of the 61 crop species). (a) Global organic-to-conventional energy production ratio for all crop categories; (b) Global organic-to-conventional energy production ratio for food crops (i.e., all crops that could be used directly for human food); (c) Organic-to-conventional energy production ratios for each global region and each crop category. Ratios exceeding 2 are not depicted but their values indicated. Precise estimated values are reported in Table S11.

However, the global average of energy and protein provisioning again mask important variations among different global regions and crop categories. In particular, we found that the 100% organic scenario would result in far-reaching changes in energy and protein provisioning between and within different world regions (Figure 8c, Figure S6c) and that the impacts of a conversion to organic farming would strongly vary depending on local characteristics. Food production gaps would be high within highly productive agricultural areas, e.g., the north-eastern US and Canada, northern India/Nepal, and West Asia (Figure 9, Figure S7). In contrast, organic food production would be similar or even higher compared to the conventional baseline in low productive zones, like in some parts of Sub-Saharan Africa, Central Asia, and Central and South America (Figure 9), especially in terms of protein provisioning (Figure S7). In these areas, temporary fodders are often the crop type driving the increase in cropland production in the organic scenario, in particular regarding protein production, due to their high protein density (Figure S8).

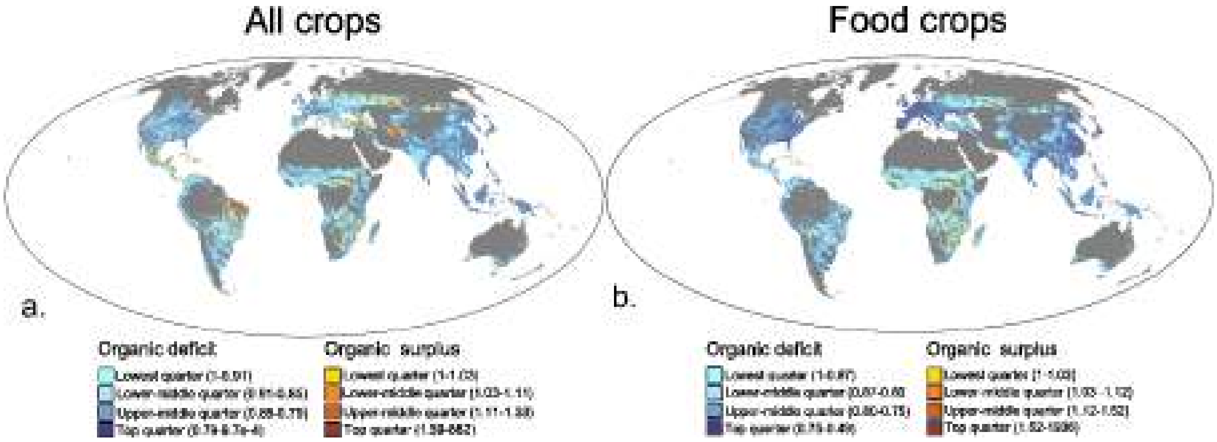


Figure 9. Organic-to-conventional production ratios (expressed in quarters) between the 100% organic and the 100% conventional scenarios for (a) total energy production (i.e., considering all 61 crop species) and (b) energy production per food crop category (i.e., considering only crops that could be used directly for human food). Numbers in brackets refer to the organic-to-conventional production ratios of the corresponding quarter.

In addition, we found profound changes in energy and protein provisioning among different crop categories (Figure 8c, Figure S6). The energy provided by primary cereals would decline by 41% globally, partly compensated by a 14% increase in energy provisioning from secondary cereals and pulses. Oil crops, root crops and industrial crops also contribute to the overall decline in energy and protein provisioning (Table S10, Table S11). Additionally, driven by the increase in harvested area, the energy provided by temporary fodders increases by 54% globally. Such changes among crop categories are likely to result in important consequences for human and livestock diets and food supply chains. Assuming no changes in the proportion of crop products used for food versus feed versus other uses (e.g. biofuels or industrial purposes) compared to current conditions (see Materials and Methods), we estimate an energy and protein production gap of 32% and 27% for food, and of 17% and 16% for other uses. Interestingly however, we estimate that feed energy and protein production would increase by 9% and 23%, respectively (Table 1), mainly due to the increased production of temporary fodders (+54%) compared to the conventional baseline. Converting crop production to an estimate of the number of people fed (see Materials and Methods for further details), based on a dietary requirement of 2700 kcal per capita (11.29 MJ) per day that accounts for food household wastage (Erb et al. 2016; Gustavsson et al. 2011; Cassidy et al. 2013), we found that croplands in the organic scenario would deliver calories to feed about ~6 billion people, which is 25% lower than the estimated capacity of current conventional croplands to feed ~8 billion people (Table 1). This difference in food availability is due to both lower yields and changes in the type of crop grown at the expense of food crops, despite a slight increase in animal products availability. The latter results from the higher feed availability (+11%) due to enhanced temporary fodder production compared to the current baseline (Table S12). This simple estimation assumes that livestock conversion efficencies (Cassidy et al. 2013), as well as livestock species raised stay the same between organic and conventional agriculture.

Table 1. Total number of people fed on current cropland and pasture area, based on a 2700 kcal per capita per day diet. See Materials and Methods for further details on calculations.

	Food supply from crop products (nr. of people fed)	**Food supply from animal products (nr. of people fed)**	**Total food supply (nr. of people fed)**
Conventional scenario	7.1 billion	0.8 billion	7.9 billion
100% organic scenario	5.0 billion	0.9 billion	5.9 billion

Our simple estimate of the number of people that could be fed in a fully organic world is both optimistic and conservative at the same time. On the one hand, it is optimistic as it assumes no changes in grassland productivity, as in fact, organically raised livestock on temporary grassland often have lower productivity than conventional livestock (Wilkinson 2011). On the other hand, it is conservative, as it assumes that people in a fully organic world would actually eat more animal products than under current conditions. In our calculations, we estimate food supply based on production. This means that we do not keep diets constant, but, instead, we keep the crop use constant between the organic and conventional scenarios.

Discussion and conclusions

Several recent studies have provided some estimates of global food production under full conversion of agriculture to organic management (Erb et al. 2016; Muller et al. 2017). However, these global assessments have mainly represented organic agriculture as a lower yielding farming system, without taking the other fundamental structural difference between organic and conventional farming systems into account – that is differences in crop rotations under organic management (Barbieri et al. 2017). Although the importance of assessing organic farming performance at the global scale by accounting for differences in cropping system structure as well as crop yields has been duly recognised (De Ponti et al. 2012; Seufert et al. 2012; Connor 2013; Ponisio et al. 2015; Seufert & Ramankutty 2017), our analysis is the first to propose a spatially-explicit estimation of the types of crops grown under organic farming at the global level. By combining this estimate with data on organic-to-conventional crop yield gaps, our modelling approach made it possible to estimate the global and regional consequences for crop production and food supply that would result from a conversion to 100% organic management at high spatial resolution. This approach is much needed to accurately account for changes in the types of crop grown that are observed in organic farming systems, including the introduction of new crop species such as temporary fodders and secondary cereals in areas where they are currently absent (Table S7).

In our analysis, the 100% organic scenario results in a 31.1% decrease in the harvested area of primary cereals. Such a decrease is caused by the need for organic systems to diversify their cropping structure and to incorporate organic management principles (Seufert & Ramankutty 2017). In particular, the diversification of organic cropping systems and the decrease in primary cereals reflect the need to introduce break crops and waiting periods in order to control biotic stresses (Kremen et al. 2012; Poveda et al. 2008), with benefits for disease and animal pest control at both the plot and the landscape scales (Muneret et al. 2018). Cropping system diversification is also a strategy to allow an increase in nitrogen-fixing crops that are essential to counterbalance the absence of synthetic nitrogen fertilisers (Lampkin 1990; Ponisio et al. 2015; Seufert et al. 2012). Our approach enables us to include new crops – especially leguminous species – in the organic scenarios to better reflect organic rotations and particularly the need for nitrogen fixation in organic systems. In the organic scenario grain legumes are increased by 25% and leguminous temporary fodders by 42%. However, it is important to note that organic crop rotations and crop choice might undergo even more dramatic changes if organic farming is to be scaled up. For instance, nitrogen limitation might require the organic rotation to adapt even more in order to better take advantage of the N-fixing capacity of leguminous crops (Connor 2008; De Ponti et al. 2012), as currently a considerable portion of N inputs to organic systems comes from conventional systems (Nowak et al. 2015). This increase in N-fixing crops would also allow to decrease the global agricultural reliance on external N inputs, offsetting N_2O emission, but might result in higher risks of N leaching (Seufert & Ramankutty 2017). Our study does not address the question of whether the nutrient demand for a world with 100% organic agriculture would be able to be met by existing organic nutrient sources (e.g., from animal manure, composts, green manures) or whether it would require inclusion of additional leguminous crops in rotations or as cover crops, or the use of human waste (which is currently not allowed in most organic regulations (Seufert et al. 2017)). Examining nutrient availability for the large-scale expansion of organic agriculture is an important next step to assess the potential of a fully organic world (Connor 2008; Connor 2013; Muller et al. 2017).

Changes in the types of crop grown, paired with drops in yield, would have far-reaching consequences for food supply and the wider food system under a full conversion to organic management. Overall, we found an organic-to-conventional energy and protein crop production gap of 27% and 23%, respectively, when excluding non-food crops. This energy production gap is large but could be partly offset by improving the efficiency of our food systems, e.g., by decreasing food waste, reducing consumption of animal products or reducing human over-consumption (Muller et al. 2017; Alexander et al. 2017), without the need for an increase in agricultural land. Some estimates suggest that 48% of harvested crop production is currently lost prior to human consumption (Alexander et al. 2017). These losses include one third of agricultural production lost due to food waste (Cassidy et al. 2013; Lin et al. 2013), meaning that halving food waste could compensate for about half of the production gap estimated in our full organic scenario. Additionally, by shifting the allocation of crop products from biofuels and animal feed towards direct human consumption (e.g., through more vegetarian or vegan diets), food availability would dramatically increase (Cassidy et al. 2013). Changing diets from animal products to plant products could be supported by the increase in the production of pulses and secondary cereals (which have high protein contents) in the organic scenario, with large potential benefits for human health in many world regions (Smith & Haddad 2015).

In addition to the global gap in energy and protein supply, we also observe a large change in the types of crop categories grown in a fully organic world (Figure 8). The variations in biomass provisioning by the different crop categories that we estimated would have global repercussions for human diets and would require considerable changes in consumers' habits and behaviours in several global regions. These dietary changes required by a fully organic world would, however, most likely result in more nutritious diets and positive health impacts, e.g., by switching from primary cereal-based diets to more diversified diets (including, e.g., more secondary cereals and grain legumes), in addition to the potential general health benefits from organic production (Mie et al. 2017). In particular, the higher diversity in cropland harvested areas that we found in the organic scenario is likely to result in more balanced diets by providing a more diversified food basket. For example, such an organic food basket would include a higher share of non-staple crops that are often reported as good proxies for dietary quality (Smith & Haddad 2015), particularly when considering micronutrients (Ahmed & Blumberg 2009; Mitchell et al. 2009; Pellegrini & Tasciotti 2014), one of the rising problem of our food systems (Halberg et al. 2006).

The changes in the types of crops grown globally and regionally would also have strong repercussions on livestock production. The increased inclusion of temporary fodders in organic rotations would lead to an overall increase in feed availability (when assuming that the relative use of crops for food *vs* feed would not change) but it would also lead to changes in livestock diets, requiring a shift away from using primary cereals (e.g. maize) and pulses (e.g. soybean) as livestock feed towards increased use of fodder crops (e.g. alfalfa and clover). This result is in line with the studies by Schader et al. (2015) and Muller et al. (2017), who illustrate that providing enough food to feed the planet organically would require major changes in the use of food-competing feedstuff (like cereals) for livestock feed. In particular, ruminant livestock species might be favoured due to the strong increase of temporary fodder production, while grain-fed non-ruminant livestock such as chicken and pigs might decrease due to the lower availability of cereal production under the organic scenario.

The impact of the large-scale adoption of organic management on energy and protein provisioning is even more complex when the spatial distribution of crop rotations and of organic-to-conventional yield gaps is considered. At the local scale, the joint effect of changes in crop choice and yield gap under organic management can cause hotspots of either energy and protein deficit or surplus, relative to current conventional production (Figure 9). While the deficit hotspots are located in areas characterised by a current relatively high productivity (e.g., in Europe and North America), the few hotspots of higher energy and, especially, protein production in the 100% organic scenario are interestingly located in areas currently characterised by low productivity, e.g., in Sub-Saharan Africa, showing that organic farming could be beneficial for local food provisioning in such areas (van Ittersum et al. 2016; De Ponti et al. 2012). For instance, in Botswana and Zimbabwe the 100% organic scenario would result in a 9% and 69% energy provision increase, respectively. This is mainly due to the combined effect of changes in crop types grown (i.e. when the energy density of the crop species grown in the 100% organic scenario is higher than the one in the current conventional baseline), as well as the absence of an organic-to-conventional yield gap in these regions (see Materials and Methods section for more details). Some studies suggest that organic management might be able to increase the productivity of some low-input systems (van der Werf 1993; Panneerselvam et al. 2011), due to its often positive impact on soil and water conservation, as well as better biological pest control (Halberg et al. 2006). Organic management has thus sometimes been suggested as a promising tool to potentially increase food production and security in these regions (Pellegrini & Tasciotti 2014). The potential impact of organic (or agro-ecological) management on food supply and food security in low-income countries is, however, still highly disputed (Lotter 2014) for example, due to concerns about phosphorus deficiency under organic management (Halberg et al. 2006; Lotter 2014) or due to shortages of organic inputs, which are often already used for alternative purposes (Fermont et al. 2008), and a final verdict on this topic is thus still out.

In summary, this study represents the first spatially-explicit assessment of a scenario of 100% organic agriculture at the global scale that simulates changes in crop rotations, as well as crop yields and that assesses the potential consequences for food provisioning. Our study shows that the organic-conventional yield gap is more important than changes in crop rotation in driving total energy and protein production at the global scale in an organic scenario. However, the crop rotation changes under organic management have major repercussions on the production of different crop categories and differences between global regions. Such changes in the types of crops grown, especially the large decrease in overall cereal production, implies that, in a fully organic world, the delivered food basket would have higher diversity compared to the current baseline, with benefits on both agricultural ecosystems and population health, at the expense of overall lower energy and protein delivery. Farming the world organically and the resulting changes in the type of crops grown would strongly impact our food system and would entail profound changes in our food consumption habits.

Materials and methods

Our approach consisted of two major steps. First, we estimated the changes in the types of crop grown on croplands that would occur in a scenario of 100% conversion of global cropland to organic farming. Second, we combined the resulting harvested areas with data on the organic-to-conventional yield gap retrieved from the literature (Ponisio et al. 2015) to estimate the global crop production (in both total energy and protein provisioning). The resulting crop production was then compared with current crop production, which we consider as a scenario of conventional crop production, given that 99% of global cropland area today is managed conventionally (Willer & Lernoud 2017). All calculations are performed at the grid-cell scale, and our analysis thus assumes only changes (e.g., distribution of crops species or yields) within but not between grid cells. We carried out our analysis on the 61 most important crop species from Monfreda et al. (2008), accounting for ~95% of the global harvested area, thus excluding 114 crop species of minor importance. The total harvested cropland area in our analysis thus represents the total harvested area of the crop species considered.

Estimation of the type of crops grown

We estimated the harvested areas in the 100% organic farming scenario at a 5-min resolution based on the maps provided by the EarthStat project for the years circa 2000 (Monfreda et al. 2008). We assumed that EarthStat's maps represent the baseline (i.e., 100% conventional) distribution of crops. We performed our estimation under the hypothesis of constant total harvested cropland area at the global scale.

We based our assessment on the evidence that some crop categories (e.g., primary cereals and oil crops) are less frequent in organic rotations – and, hence, in organic cropland use – than in their conventional counterparts, and that these discrepancies vary across global regions (i.e., Europe, North and South America, Africa, Asia and Oceania) (Barbieri et al. 2017). We thus applied ratios of the shares of crop categories in organic compared to conventional crop rotations from the scientific literature (Barbieri et al. 2017) to the conventional harvested areas of these crop categories from Monfreda et al. (2008), thereby freeing up some land in grid cells from crops that are less frequent in organic compared to conventional rotations. In the next step, we allocated this freed-up land to those crop categories that are more frequent in organic than in conventional rotations. We performed this allocation so that the rotation timeshare of all 'expanding' crop categories (based on Barbieri et al. 2017) are maintained in the organic rotations. For instance, consider 100 ha of land conventionally cultivated with only primary cereals. According to the data synthesized by Barbieri et al. (2017), organic rotations globally have 27% less primary cereals in their rotation compared to conventional rotations. The resulting harvested area under primary cereals in the 100% organic scenario would thus be 73 ha, while the remaining 27 ha can be allocated, e.g., to temporary fodders and pulses that exhibit higher abundance in organic rotations compared to their conventional counterparts. Given that empirical data suggests that – on average - organic rotations include 30% fodder crops and 15% pulses, 18 ha of the 27 ha (i.e., 30/(30+15)) that are freed-up due to reduction in primary cereals will then be allocated to fodders and the remaining 9 ha (i.e., 15/(30+15)) to pulses.

This estimation of the types of crop grown under a 100% organic scenario was carried out for only 38 out of the 61 arable crop species covered in the energy and protein production estimation (representing 85% of the global harvested area) (). For the remaining 23 crop species (vegetables and permanent crop species), we assumed that harvested areas remain constant in the organic farming scenario compared to the current baseline since we lacked the information necessary to determine a land allocation rule for these crop species (as data on the rotations of these crops under organic management is not readily available, (Barbieri et al. 2017)). The 38 crop species from Monfreda et al. (2008) were further aggregated into seven crop categories: primary cereals (maize, rice and wheat), secondary cereals and pseudocereals (e.g., barley, oat, millet), pulses (e.g., bean, soybean), oil crops (e.g., sunflower, rapeseed), root crops (e.g., potato, sweet potato, cassava, yam), industrial crops (e.g., sugarcane, sugar beet) and temporary fodders (e.g., alfalfa, clover, ray-grass), in order to combine them with the data from (Barbieri et al. 2017) presented at the level of crop categories.

To be able to combine the estimated harvested areas per crop category with crop-species level data on yields, the estimated harvested areas occupied by each crop category were then disaggregated to the crop species level. To do this, we assumed that the relative abundance of the different crop species within a given crop category was similar in the current baseline and in the 100% organic scenario. Notable exceptions are temporary fodders, for which the disaggregation to the crop species level was based on the relative share of leguminous *vs* grass fodder species (Barbieri et al. 2017). More details about land-use calculations are reported in the Supplementary Methods as well as in Table S5, Table S6, and Table S7.

Our estimation of the types of crop grown under organic agriculture is based on the assumption that the relative harvested areas of different crop types can be directly derived from the data concerning current organic crop rotations. Given that organic farming currently only accounts for 1% of the global agricultural area (Willer & Lernoud 2017), crop rotations under large-scale organic agriculture might not correspond to current organic crop rotations as described in the scientific literature (and summarized by Barbieri et al. 2017). Despite this, our approach represents the only transparent method to estimate harvested areas in a fully organic scenario since data pertaining to organic rotations and types of crop grown are scarce and highly scattered. It is also important to note that our disaggregation of organic harvested areas from the crop categories to the crop species level was based on the current shares of crop species within each crop category, as observed in conventional agriculture [20], even though this distribution is likely to differ between organic and conventional farming. Given that detailed and accurate data about types of crop grown in organic farming are very limited at the global scale, we were unable to find any explicit, alternative approach for such disaggregation. We examined richness and diversity of organic and conventional harvested areas by using Shannon's diversity Index $H = -\sum_{i=1}^{61} p_i \ln(p_i)$ calculated at the grid-cell scale, where p_i represents the proportion of the area harvested under the crop species i. We verified data normality through a Kolmogorov-Smirnov test and we tested differences between the organic *vs* conventional scenarios using a non-parametric Kruskal-Wallis test.

Estimation of crop production

We estimated the production of the 61 crop species considered in the 100% organic scenario by multiplying the harvested areas of each crop species (i.e., the 38 crop species for which the harvested areas are calculated as explained above, plus the 23 vegetable and permanent crop species for which we assumed constant harvested areas) by its respective yield in organic farming (derived from data on the organic yield gap by Ponisio et al. 2015).

Organic crop yields were estimated by applying crop-specific organic-to-conventional yield ratios to current, conventional yields (Seufert et al. 2012; De Ponti et al. 2012; Ponisio et al. 2015). As in a previous study (Erb et al. 2016), we applied the organic-conventional yield gaps from Ponisio et al. (2015) only to industrialised agriculture with high conventional yields, which we define as regions where conventional yields are higher than 55% of their potential attainable value (based on the conventional yield gap analysis by Licker et al. (2010) and Mueller et al. (2012); see Supplementary Methods and Table S8). We made this assumption because the data collected by Ponisio et al. (2015) are largely restricted to developed countries and high-yielding conventional systems and we currently do not have sufficient scientific data on relative organic yields in developing countries with low-input conventional agriculture (Seufert & Ramankutty 2017). In regions where current yields are far below their yield potential, it is, however, likely that a conversion to organic farming would not result in lower productivity (Erb et al. 2016;

Kilcher 2007), and we thus assume no difference between conventional and organic yields for these regions.

We then calculated the global production in terms of biomass, metabolisable energy and proteins for each grid cell according to Equation *1*.

Equation 1. $Production = \sum_{i=1}^{61} A_i \times Y_i \times k_i$

where: A_i represents the harvested area for crop species i [in ha], Yi is the yield [in tons DM ha^{-1}] of the crop species i, and k_i is the metabolisable energy or protein density for the crop species i, [in kcal (kg DM)$^{-1}$ and kg protein (kg DM)$^{-1}$, respectively]. Global crop production was then estimated by summing crop production across the 9.2e5 grid cells having a non-zero harvested area. The same approach was adopted for the current (i.e., conventional) scenario by accounting for the current cropland use and crop yields (based on Monfreda et al. 2008). Energy and protein density values for different crop species were retrieved from different sources, including Monfreda et al. (2008), INRA et al. (2016), INRA (2007), and the *Food Standards Agency* (2002) (Table S9). We assumed that energy and protein densities were similar for conventionally or organically grown crops (Seufert & Ramankutty 2017).

In order to estimate the food supply from cropland production, we retrieved data about the current (year 2016) use of crops products as food, feed and other uses from the FAOSTAT Food Balance Sheets (Food and Agriculture Organization of the United Nations 2016). We calculated the respective amount of energy and protein production that would be allocated to these three categories in both the current baseline – i.e. the 100% conventional scenario – and in the 100% organic scenario, assuming that the current feed-to-food repartition would remain constant. We then calculated the number of people that could be fed from crop food products by dividing the amount of crop food by a demand of 2700 kcal day^{-1} cap^{-1}, including food household wastage (Erb et al. 2016; Gustavsson et al. 2011; Cassidy et al. 2013). The amount of energy provided by livestock products in the current baseline was estimated by retrieving current livestock production data from FAOSTAT (in tons) (Food and Agriculture Organization of the United Nations 2016) that we multiplied by the energy density (in kcal tons^{-1}) of each animal product (Food Standards Agency 2002). Note that FAOSTAT data include livestock produced on permanent grassland. In order to calculate the energy provided by livestock products in the 100% organic scenario, we compared the estimates of the total crop production allocated to feed in the current conventional baseline and in the 100% organic scenario. The total amount of feed produced in the 100% organic scenario was higher than the one observed in the conventional baseline due to increased temporary fodders in organic rotations. We therefore assumed that the organic scenario produced the same amount of livestock products as the conventional baseline, plus the additional livestock produced with the surplus feed in the organic scenario. The additional feed produced in the 100% organic scenario was converted in energy from livestock products by being multiplied by a conversion coefficient (average coefficient across all livestock types) of feed crop products into livestock products retrieved from Cassidy et al. (2013) (equation 2). Note that we assumed that the livestock conversion efficiency would remain constant as currently observed:

Equation 2: $$\boldsymbol{E_{organic\_livestock} = E_{conventional\_livestock} + \left(E_{organic\_feed} - E_{conventional\_feed}\right) * k}$$

where: $E_{organic\_livestock}$ is the total energy provided by livestock products in the 100% organic scenario, $E_{conventional\_livestock}$ is the energy provided by livestock products in the conventional baseline, $E_{organic\_feed}$ and $E_{conventional\_feed}$ are the amount of energy contained in feed products in the 100% organic scenario and in the current baseline, respectively, and k is a conversion coefficient of feed crop products into livestock products (retrieved from [25]).

Sensitivity analysis

Given the uncertainty in translating data on current organic crop rotations (when organic management makes up only 1% of global cropland) to global harvested areas under a scenario of 100% organic agriculture, we tested the influence of variations in types of crop grown on crop production through a sensitivity analysis (see Appendix II). We also examined how our assumption that crop species distribution within crop group categories are the same under organic and conventional management influences our results through a sensitivity analysis (see Appendix II).

Software used

All calculations were performed using R Open 3.3.2 (MRAN 2016, https://mran.microsoft.com/), the “raster” (R. Hijmans et al. 2016), “rgdal” (Roger Bivand et al. 2017), “rgeos” (R. Bivand et al. 2017), “GISTools” (Brunsdon & Hongyan 2015) and “ncdf4” (Pierce 2017) packages for spatial analysis, and the “doparallel” package for parallel computation (Calaway 2017). All calculations were run using the Avakas cluster managed by the University of Bordeaux. The full code is available upon request.

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Author Contributions

P.B., S.P., V.S. and T.N. designed the study; P.B. collected the data, coded the cropland-management model and performed the calculations; all authors were involved in the interpretation of results and contributed to writing and revising the manuscript.

3. Farming organically, farming differently – effects of nitrogen availability on organic production at the global scale

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To be submitted to Nature

In the last chapter, we showed how the global distribution of the harvested area under different crop species would change when organic farming is adopted. Based on such changes, we showed how global food production would drop by ~27 %, and that food delivered by different crop-based commodities would strongly change. Here we introduce and use the GOANIM model to estimate global food production under different scenarios of organic expansion at the global scale. The model simulates organic food production as a function of the available N resources. Therefore, information from Chapter 2 are combined with N flows to simulate cropland and livestock production in organic systems. This chapter will be submitted, in a modified version, to Nature.

Abstract

Organic agriculture is often proposed as a promising approach to achieve sustainable food systems while minimizing environmental impacts. Its capacity to meet the global food demand remains, however, debatable. Some studies have investigated this question and have concluded that organic farming could satisfy the global food demand provided that animal product consumption and food waste are reduced. However, these studies have missed a critical ecological phenomenon by not considering the key role that nitrogen (N) cycling plays in sustaining crop yields in organic farming. Here we estimate organic productivity using a global spatial N cycling model. Our simulations show that a 100% conversion to organic agriculture would lead to a large gap (-37%) in global food calorie production compared to the current –i.e. non-organic- production. In such a scenario, organic food availability would thus not be sufficient to match global food demand (34% gap). Nevertheless, we also show that lower conversion shares (up to 60%) would be feasible in coexistence with conventional farming when coupled with demand-side solutions, such as reduction of the per capita energy intake or food wastage. These scenarios are achievable only with a complete redesign of the livestock sector which plays a fundamental role in sustaining organic food availability in several global regions. These results are critical to explore the option space of the global food system in a sound and systemic manner.

Keywords

Organic agriculture, conventional agriculture, nitrogen cycling, global food production, organic livestock, linear programming, food security

Introduction

Feeding the world with current agricultural systems is facing numerous challenges. Global food systems need to guarantee sufficient food production while curbing the environmental impacts caused by intensive agricultural practices (Muller et al. 2017; IAASTD 2009). Adopting more holistic and sustainable farming approaches such as organic agriculture represents a promising option (Mäder et al. 2008; Foley et al. 2011; Reganold & Wachter 2016).

The role that organic farming could play in feeding the world has been investigated for a decade now, but this question still generates controversial positions (Badgley et al. 2007; Seufert et al. 2012; Connor 2008; Connor 2013; Muller et al. 2017). Recent studies have introduced important advancements, claiming that organic agriculture can contribute to providing sufficient food for the 2050 population (Erb et al. 2016; Muller et al. 2017), while simultaneously reducing the environmental impacts. Such results would be achievable only by decreasing the consumption of animal products. However, these studies have missed a critical ecological process by not considering if the availability of nitrogen (N) resources would be enough to satisfy crop N requirements, globally and locally. Indeed, the ban of synthetic N-fertilisers and the exclusive reliance on organic N sources in any organic production guidelines are likely to limit the amount of N resources available to fertilize agricultural soils globally (Muller et al. 2017). In addition, organic systems source a large part of the N resources from conventional farming systems in many regions, in particular as organic manure and fertilizing materials (Nowak et al. 2013a; Oelofse et al. 2010; Oelofse et al. 2013). Those resources that will mechanically fade out if organics drastically expand. Accounting for the limitation in N resources to fertilize soils and its possible negative effect on crop yields is therefore critical to get an accurate estimate of global crop production under scenarios of large organic agriculture expansion. Such an estimate may significantly differ in comparison to up-to-date results (Muller et al. 2017; Connor 2018). Therefore, the role that organic farming may play in feeding the world is still very much an open question (Connor 2018).

In this study, we investigate whether N availability can limit organic food production, expressed as the total calories and proteins produced at the global scale, in scenarios of large organic farming expansion. We address this knowledge gap by adopting a farming system approach that accounts for the structural differences between organic and conventional management, including differences in crop rotations, cropland use, and animal husbandry. We complement this analysis by considering additional supply-side measures to increase N resource availability in organic systems, notably (i) through redesigning of the organic livestock sector in terms of geographic distribution and animal species composition, and (ii) by allowing the use of additional external N-resources –i.e. organic manures from conventional farming and wastewater N resources–. We then estimate the impacts that a 100% conversion to organic farming would have on global food systems at high spatial resolution. Our analysis is based on the assumption that the total harvested cropland area remains constant at the current level (Tayleur & Phalan 2016), thus examining how the current world would look like under organic management. We then complement this analysis by comparing the estimated food production with different estimates of the global food demand, expressed in calories and proteins, including a reduction of food wastage, a recognized strategy to reduce global food demand. Hence, we assess whether and to which extent a combination of organic farming with these different demand-side measures is appropriate to satisfy the global food demand. We further develop the relationship between food supply and demand by investigating the consequences that a conversion to organic farming would induce for the global food baskets.

To do so we apply a mass-flow and N cycling model (GOANIM – Global Organic Agriculture NItrogen Model) that optimizes organic crop and livestock production at a spatial resolution of 5 arc-min (~10 km × 10 km at the equator) as a function of nitrogen supplied to soils. Because livestock animals play a critical role in organic farming systems (both as suppliers of manure to fertilize soils and as consumers of crop productions), an optimization procedure is necessary to adjust the livestock population to each specific location, i.e. to maximize N supply from livestock manure – hence maximizing cropland production –, while minimizing the animals' competition for food resources. Our model is based on simple, linear, crop species-specific N-response yield curves, combined with regionalized data about organic yields, and assumes no transportability nor exchange of resources (i.e. manure and feed) between grid-cells. These assumptions are in line with the organic principles of local sourcing of animal feed (IFOAM 2018) and low transportability of livestock manure. We assess the feasibility of 52 supply-side and 6 demand-side options for a total of 312 supply-demand combinations. We compare all combinations with the conventional –i.e. non-organic– baseline scenario, which represents current farming systems since organics accounts nowadays for only ~1% of the global agricultural area (Willer & Lernoud 2017). Our analysis shows that N deficiency would be a major limiting factor to organic production at the global scale, leading to an overall -37% reduction in global food availability. This reduction would be limited by a complete redesign of the livestock sector. A better management of fodder resources would value ruminant livestock species, thus strongly reducing livestock *vs* human competition for grain crop resources. In addition, we show how a conversion to organic farming would lead to an increase in the availability of livestock food commodities (+22%).

Materials and Methods

The above-mentioned question was addressed by designing different scenarios of organic farming expansion at the global scale and by assessing those scenarios with the GOANIM model, simulating soil N budget in organic farming. We present the GOANIM model and the considered scenarios in the following sub-sections.

Model framework and databases

The GOANIM (Global Organic Agriculture NItrogen Model) model is a spatially explicit, biophysical and linear optimization model simulating cropland soil N cycling in organic farming systems and its feedback effects on food production at the global scale. It is based on the overall assumption that the global harvested cropland area remains constant at current levels (Tayleur & Phalan 2016). GOANIM includes different compartments (organically managed croplands, livestock animals and permanent grasslands) and accounts the biomass and N flows among these compartments (as feedstuff, grazed biomass and animal manure) as well as the N flows between cropland soils and the environment as represented in Figure S9. GOANIM uses high resolution (5 arc-min) spatially explicit databases for the year ~2000, providing consistent data on agricultural biomass flows (see Table S16 for the full list of the variables used), encompassing the 61 most important crop species by global acreage and 5 livestock animal species. The model respects the thermodynamic law of conservation of mass and energy it embraces all countries and geographic territories (164) covered by FAOSTAT. GOANIM simulates the supply side of the global food system –i.e. food production–, by maximizing organic production from both cropland and livestock food commodities. Cropland production is maximized in each grid-cell as a function of N supply to cropland soils from different sources, including organic manure from livestock animals, biological N fixation, atmospheric depositions, and additional external inputs. The floating variables in the optimization model correspond to the local livestock animal population and the allocation of animal manure to the different crop species; both floating variables are optimized at the grid-cell scale (Figure S10). Any use of cropland resources other than food and feed is not directly considered here, apart for crops like rubber and cotton, whose production may be used for industrial purposes. All model compartments are assumed to be at steady-state –i.e. all state variables are constant in spite of ongoing processes that strive to change them– and all flows are simulated considering a timeframe of one year. The model assumes that each raster's grid-cells is independent, i.e. resources are not transportable or exchangeable outside grid-cell boundaries. This choice is in line with organic farming principles aiming at a local sourcing for both feed and fertilizers (IFOAM 2018; European Commission

2008). Additionally, the resolution of our datasets (10×10 km at the equator) represents a feasible distance for livestock manure sustainable transportability (Bartelt & Bland 2007).

Nitrogen and biomass flows

The core aim of the GOANIM model is to simulate the N budget of the organically managed cropland soils (Figure S9).

Inputs to organically managed cropland soils include N in manure and in crop residues, N fixation from biological N fixation (BNF) and free-living cyanobacteria, and N atmospheric wet and dry depositions. Outputs from organically managed cropland soils include N in the harvested crop products and crop residues and N losses to the environment (Dong et al. 2006; De Klein et al. 2006). The overall soil N budget is calculated as follows (Eq. 1):

$$N\ surplus\ = \left(OUT_{crop} + OUT_{res} + OUT_{loss}\right) - \left(IN_{fix} + IN_{man} + IN_{res} + IN_{dep}\right)\quad \text{(Eq. 1)}$$

where: OUT_{crop} , OUT_{res} and OUT_{loss} are the N outputs in harvested crop products, crop residues and through environmental losses (NO_3 leaching and N_2O , N_2 and NH_3 gaseous losses, estimated following IPCC Tier 1 (De Klein et al. 2006)), respectively; IN_{fix} is the N fixed by leguminous crop species (through BNF) and by free-living cyanobacteria in soils, IN_{man} is the N in manure from livestock animals, IN_{res} is the N input from recycled crop residues to soils, and IN_{dep} is the total dry and wet N atmospheric deposition.

Organic crop and crop residues yields are simulated as a function of the total N supplied to cropland soils via a crop species-specific linear N-response curve, as in Eq. 2. Note that our assumption of a linear crop yield response to N, although often reported to have a good fit to experimental data (Cerrato & Blackmer 1990; Godard et al. 2008), may underestimate crops yields at low fertilization rates since yields tend to increase more than linearly at low fertilization rates, while the opposite behavior is observed at high fertilization rates.

$$IF\ N_i < N_{max_i}, THEN\ \ Y_i = \frac{N_i}{N_{max_i}} Y_{max_i},\ ELSE\ \ Y_i = Y_{max_i}\quad \text{(Eq.2)}$$

where Y_i is the simulated crop yield [in tons DM ha^{-1}], N_i is the N input to soils [in tons N], N_{max_i} is the N input to soil that allows Y_{max_i} [in tons N], and Y_{max_i} is the maximum attainable yield in organic farming [in tons DM ha^{-1}], for crop species *i*. The details about how the maximum attainable yield in organic farming is determined are provided in SI.

Inputs to cropland soils as animal manure (IN_{man}) are determined by multiplying organically managed livestock densities by livestock species-specific N excretion rates (Sheldrick et al. 2003). N losses due to housing and manure management are accounted (IPCC Tier 1 procedure (Dong et al. 2006)). Livestock population is estimated as a function of animal feed availability at the grid-cell scale.

Nitrogen fixation inputs (IN_{fix}) are estimated using the model proposed by (Hogh-Jensen et al. 2004), and the free-living cyanobacteria fixation coefficients reported by (Liu et al. 2010). Atmospheric depositions (IN_{dep}) are estimated from (Dentener et al. 2006), while crop residues inputs (IN_{res}) are estimated multiplying crop residues' biomass by a recycling factor (Liu et al. 2010; Smil 1999; Sheldrick et al. 2003). N outputs from soils as harvested crop products and crop residues is estimated multiplying the respective biomasses by their N density. Losses (OUT_{loss}) are estimated following the IPCC Tier 1 procedure (De Klein et al. 2006), and encompass leaching (NO_3) and gaseous losses (N_2O, N_2, NH_3).

Input to livestock production is represented by feed, which is differentiated into three categories: (a) feed derived from human-edible crop products (e.g. grains, pulses) grown on arable land, (b) fodder from temporary grassland grown on arable land and from permanent grasslands, (c) fodders from crop residues. The feed from grains grown on arable land (hereafter referred to 'food-competing feedstuff') is in competition with food production, while permanent grassland-based feed and crop residues-based feed are not. Livestock density is estimated for each animal species and in each grid cell as a function of both animal species specific feed requirements (expressed in energy and protein) and the feed availability in the specific grid cell, as in Eq. 3:

$$\sum_{\mathrm{i,j}=1}^{9,3} LIV_i \times F_{j,i} \leq \sum_{k=1,\mathrm{j}=1}^{z,3} A_k \times Y_k \times [D]_{j,k} \text{ (Eq. 3)}$$

where: LIV_i is the number of heads for animal species *i*, $F_{j,i}$ is the feed requirement [in energy and protein] for feed category *j* (grain, fodder, or crop residues, retrieved from Herrero et al. (2013) and for animal species *i*, A_k is the harvested area [in ha] under crop species *k*, Y_k is the dry matter yield of crop species *k* [in t ha^{-1}], and $[D]_{j,k}$ is the energy and protein density of feed category *j* for crop species *k* [respectively in MJ tons DM^{-1} and tons tons DM^{-1}].

Outputs from livestock production include human-edible (meat, milk, eggs) and inedible products (skins, hides, bones, etc.), and manure excretion. We estimated individual livestock animals' production by multiplying livestock animals' individual productivity (retrieved from FAOSTAT) by the energy densities of each food commodity. It is important to note that livestock production has a dual effect on organic crop food production. On the one hand, livestock population is positively related to cropland productivity, since livestock animals provide N resources to croplands as manure inputs to cropland soils. On the other hand, livestock population is negatively related to food production because animals, especially monogastrics, are direct competitors for crop products (in particular for grains) with humans. Therefore, an optimization procedure is necessary to find the best appropriate compromise between (i) enhancing manure input to cropland soils, while (ii) minimizing the use of food-competing feed resources. Note that livestock population is also positively related to global food production by providing important, nutrient-dense food commodities. GOANIM-model is thus able to capture and simulate the systemic feedbacks between cropland production, animal feeding, livestock population, manure production, and cropland soil fertilization.

GOANIM finally estimates the total food calories available at the global scale by maximizing food energy production in each grid-cell. Food production is calculated as the sum of the food calories produced on croplands at the net of the calories used as animal feed, plus the food calories from animal food commodities.

Organic agriculture parametrization

For the livestock sector, we assume no differences between organic and conventional productivity, as reported by the literature (Muller et al. 2017). Similarly, we assume no differences in animal feeding rations between those two production systems. Indeed, although differences in animal feeding might exist between these production systems (Srednicka-Tober et al. 2016), the data are too scarce and scattered to derive any sound conclusion related to the inputs of our model.

Organic agriculture is characterized by the ban of synthetic N fertilizers. Therefore, soil fertility relies on organic N inputs, atmospheric depositions, and N-fixing crops. This essential characteristic of organic crop production is captured by the GOANIM model by considering a modified frequency of N-fixing crops (i.e. pulses and temporary leguminous fodders) in organic crop rotations and cropland use (Barbieri et al. 2017). In particular, we made use of global gridded maps that accounted for the structural differences in the types of crop grown between organic and conventional farming, at a high spatial resolution (Barbieri et al., submitted for publication).

Organic yields are simulated as a function of the total N supplied to soils (Eq. 2). We assume no difference in the N density between organic *vs* conventional crop products as is commonly assumed (Erb et al. 2016; Muller et al. 2017). However, because some nutritional studies have recently reported consistent 10% lower N densities in several organic products compared to conventional products (Mie et al. 2017), we considered a scenario where N density is reduced by 10% in all crop products compared to conventional farming. We estimate the organic maximum attainable yield in equation (2) by multiplying the current –i.e. conventional- yields (Monfreda et al. 2008) by an organic-to-conventional yield gap (Ponisio et al. 2015). We corrected this organic-to-conventional yield gap in order to account for a yield reduction due only to pest and diseases, i.e. not accounting for the yield reduction due to N deficiency (see Appendix IV for further details). This is because the GOANIM model itself simulates the yield reduction due to N limitation. As in a previous study (Erb et al. 2016; Barbieri et al., submitted for publication), we applied the organic-to-conventional yield gaps (Ponisio et al. 2015) only to industrialised agriculture with high conventional yields, which we define as regions where conventional yields are higher than 55% of their potential attainable value (based on the conventional yield gap analysis by Licker et al. (2010) and Mueller et al. (2012)). We made this assumption because the data collected by Ponisio et al. (2015) are largely restricted to developed countries and high-yielding conventional systems and we currently do not have sufficient scientific data on relative organic yields in developing countries with low-input conventional agriculture (Seufert & Ramankutty 2017).

Losses and emission factors for manure management and emissions from cropland soils (NO_3 leaching and N_2O, N_2 and NH_3 gaseous losses), are assumed to be identical between organic and conventional farming systems due to the lack of robust data supporting a different parametrization of the two production systems.

External N inputs to organically managed cropland soils

We consider two additional external N input sources for organically managed cropland soils: (i) N in wastewater from human activities and (ii) N in conventional animal manure. We estimate the N available in wastewater sources following the procedure described by Van Drecht et al. (2009), i.e. considering the global population density of 2015 (United Nations 2015), and the current per-capita N excreta estimated based on the protein consumption for each considered country. We then spatially allocated, the total N in wastewater proportionally to the total harvested area within each country. Regarding conventional manure application to organically managed cropland soils, we assume that only the conventional manure in excess compared to conventional cropland N requirements was made available for organic cropland soils (see Appendix III for details on conventional N-budgets calculations). We considered two possible variants for the use of the conventional manure by (i) considering that conventional manure is available only in the locations (i.e. grid-cells) where it is originally produced ('un-redistributed variant'), or by (ii) spatially allocating conventional manure proportionally to the total harvested cropland area at the country scale ('redistributed variant'). These two variants correspond, respectively, to local utilization of N fertilizer resources assuming that (i) conventional livestock densities and spatial distribution are left unchanged or that (ii) conventional livestock is re-located with cropland production compared to the current, conventional livestock production.

Scenario analysis

Fifty-two scenarios were assessed by the GOANIM model in terms of cropland soil N budget, crop production and food availability. These scenarios differed in terms of global share of production under organic farming (0, 20, 40, 60, 80 and 100% of the global cropland and grassland areas, and of livestock populations in each grid-cell), recycling of N from wastewater on organically managed croplands (no recycling and nationally distributed recycling), use of conventional animal manure on organic croplands (no use, local use, nationally distributed use), and animal livestock population redesign through the above-mentioned optimisation procedure (no redesign -i.e. animal population is kept as observed in current, conventional systems- *vs* redesign of the animal population in terms of species specific number of heads and spatial distribution). In addition, we also tested a scenario without any livestock production (corresponding to a vegan-diet scenario). For each scenario, food availability from both cropland production and animal derived products is estimated (expressed as calorie and protein supply per capita per day) and compared to the global food demand. We estimate global food demand considering the calories demand for two specific human diets – i.e. business as usual (Erb et al. 2016) and a reduced energy demand (Ahmed & Blumberg 2009) –. Furthermore, we subdivided such demand into 10 commodity groups –e.g. cereals, pulses, ruminant meat, and eggs- (from Erb et al. (2016)). Fish and seafood are outside the scope of the GOANIM model and the food demand for fish and seafood products is assumed to be fulfilled at the global scale. More in details, global food demand is estimated multiplying the per capita food consumption by each country population estimates (United Nations 2015), including household food waste (Erb et al. 2016; Alexander et al. 2017). Finally, we combine the two global food demand estimates with a food wastage reduction of 50% and 100%, i.e. by reducing the current food wastage estimate for each commodity group (from Erb et al. 2016). The feasibility of the different considered scenarios – i.e. match between food supply *vs* demand – is assessed at the global scale, and trade is assumed to balance regional discrepancies between food demand and supply, assuming no trade barriers prevail (Table S17). Note that our scenario does not include any analysis of future trajectories. Furthermore, the model does not take into account economic aspects or restrictions, as well as any market effects relating changes in quantities to changes in prices.

In the following Results section, we pay particular attention to the scenario reporting full (100%) conversion of cropland to organic farming due to its specific contribution to the global food security debates. Note that the baseline scenario correspond to the current situation where all croplands, grasslands and livestock animals are considered as conventional agriculture.

Software used and code availability

The model and all calculations were coded using R Open 3.3.2 (MRAN 2016, https://mran.microsoft.com/), and making specific use of the "raster" (R. Hijmans et al. 2016), "rgdal" (Roger Bivand et al. 2017), "rgeos" (R. Bivand et al. 2017), "GISTools" (Brunsdon & Hongyan 2015) and "ncdf4" (Pierce 2017) packages for spatial analysis, the "doparallel" (Calaway 2017) package for parallel computation, and the "ROI" (Hornik et al. 2018) package for optimisation programming. The linear optimization problems were solved using the COIN-OR CLP solver, via the "clpAPI" (Fritzemeier & Gelius-dietrich 2016) and "ROI.plugin.clp" (Thieurmel 2017) R packages. All calculations were run using the Avakas cluster managed by the University of Bordeaux.

Results

Full conversion of global croplands to organic farming results in large crop production gaps

Farming the planet entirely organically would lead to important cropland production gaps. Our results show that global cropland production, expressed in energy and including temporary fodders, would drop by -58% compared to the current, conventional baseline in a 100% organic scenario, corresponding to a decrease of ~6.7e+15 kcal (28e+12 MJ) (Figure S11). This overall large gap in cropland production masks, however, large variations among global regions (Figure 10). In particular, we found that organically managed croplands would deliver much fewer calories in the south east of the US and Canada, North Europe, East Asia, and in South East Asia. In contrast, we also found that the full conversion of croplands to organic farming would help to increase crop production in a few, but nonnegligible regions including some areas of Brazil and Mexico, and a few hotspots in the south part of Africa and in Eastern Europe. The increase in crop production, especially in terms of protein provisioning (Figure S12) in these locations is mainly driven by higher shares of pulses and fodder crops in organic crop rotations compared to the conventional baseline, due to their higher energy and protein densities (Barbieri et al. 2017; (Barbieri et al., submitted for publication).

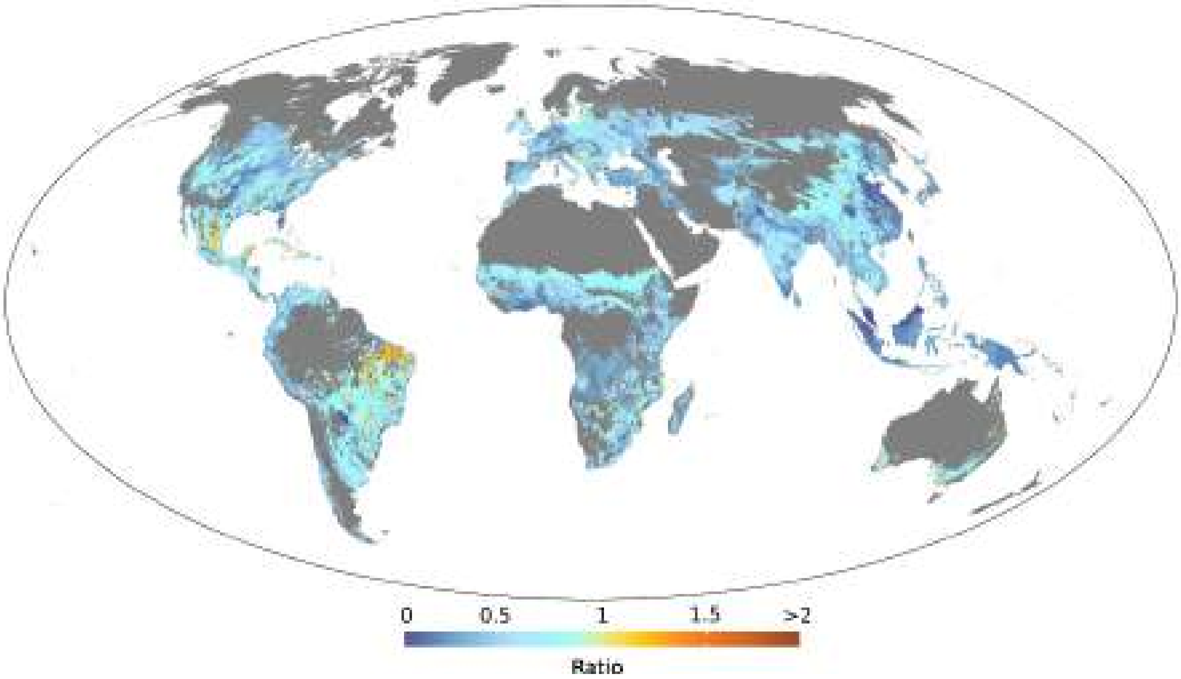

Figure 10. Ratios between cropland energy production in the 100% organic *vs* the 100% conventional scenarios. Cropland production corresponds to the sum of the energy production of the 61 crop species considered.

We found that this large production gap is caused by a massive N deficiencyof 36 Tg N globally corresponding, on average, to ~30 kg ha^{-1} of croplands. This N deficiency varies widely among global regions and is large in several areas of the US, Western Europe, Egypt, East Asia, and Indonesia (Figure 11) that also experience large drop in cropland production (Figure 10). We calculated N deficiency as the amount of N that would be necessary to achieve the maximum organic attainable yields (Equation 2) for each crop species and each grid-cell. This global N deficit is significantly lower (~23 kg ha^{-1}) when non-food crops (e.g. temporary fodders, cotton, rubber, etc.) are excluded from the calculation. Despite this large N deficiency to achieve maximum organic yield, the model also simulates some N surpluses in specific global regions, corresponding to an average amount of ~13 kg N ha^{-1} of cropland. This surplus accumulates in particular in grid-cells with high number of ruminant animals and a predominance of permanent grasslands over croplands (Figure S13). If such N surplus could be fully transportable to cropland areas, it would be sufficient to produce ~2.4e+14 kcal of wheat equivalents (i.e., a potential +8%

increase in food production globally[4]). Note, however, that this surplus is much lower than the one observed currently in conventionally managed cropland soils due to the significant lower N inputs in organic systems (Figure 12), thus potentially leading to lower N losses to the environment from organic croplands.

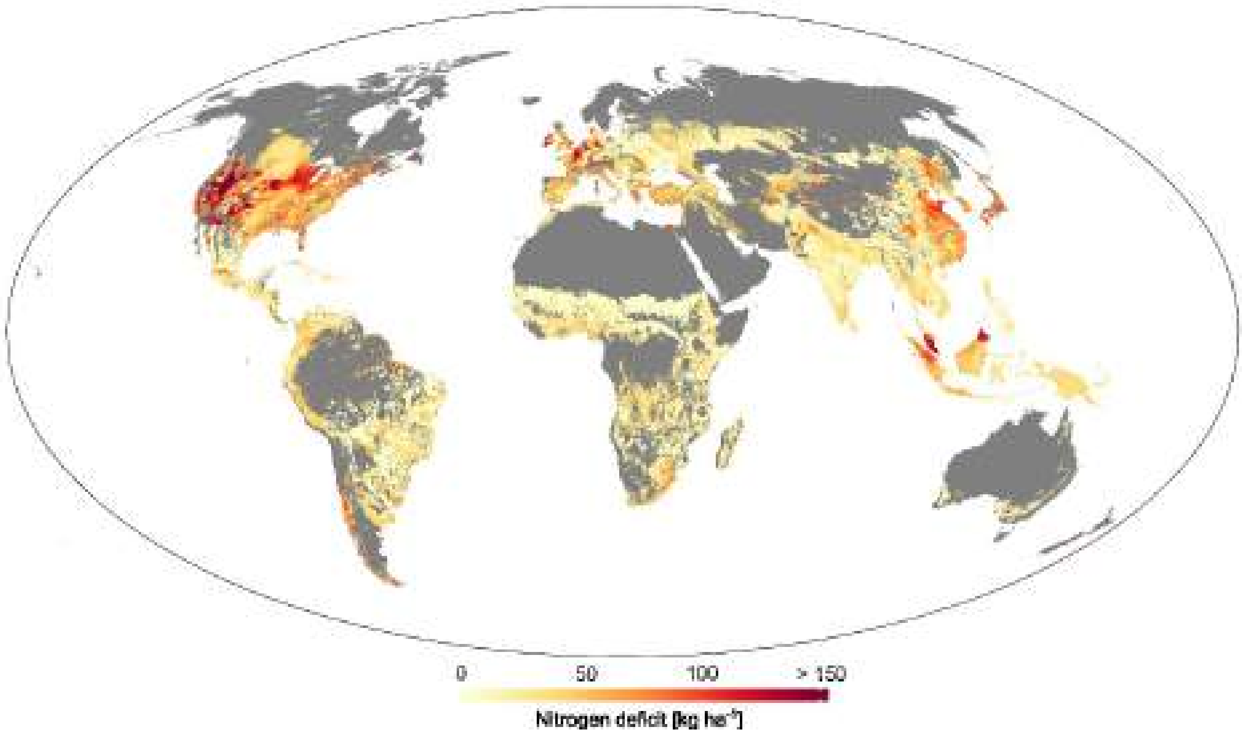

Figure 11. Total N deficit [kg ha^{-1} cropland] for all the 61 considered crop species. The N deficit is calculated at the grid-cell scale as the sum of the N needed to achieve the maximum organic attainable yield for each crop species. Grid-cell size at the equator is ~10 km × 10 km.

[4] We performed this simple calculation after having discounted the total N surplus by an average 10 kg ha^{-1} globally, which is considered as the minimal surplus observed in cropland soils in the literature (Mueller et al. 2014; Good & Beatty 2011).

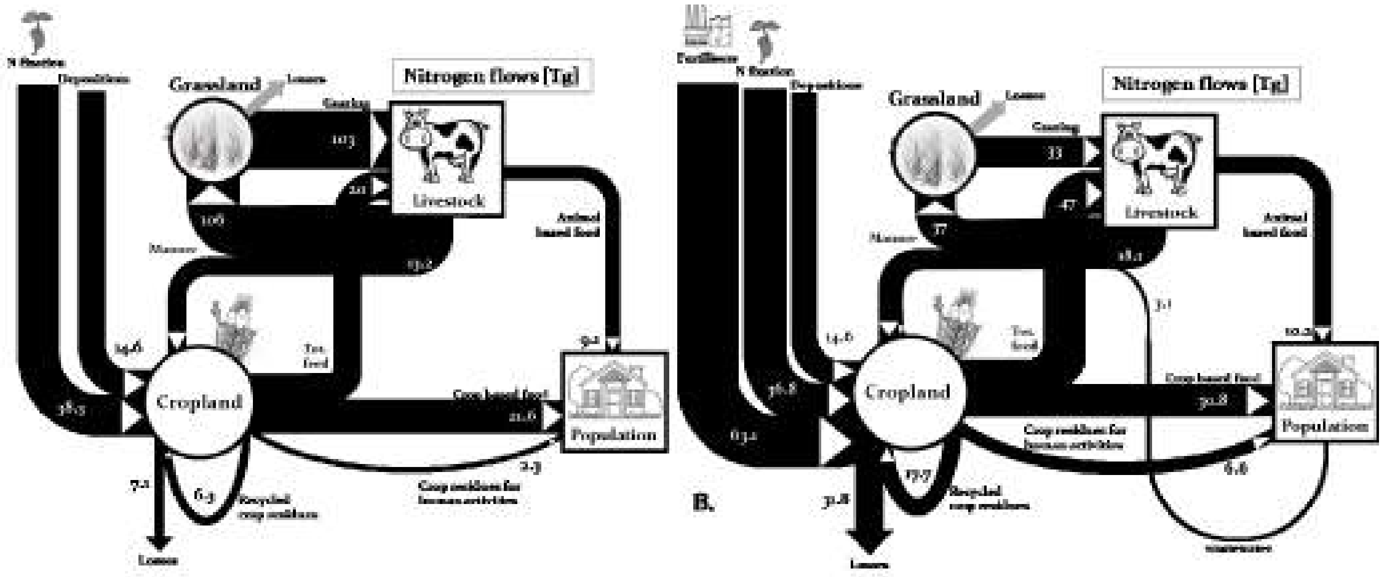

Figure 12. GRAFS-based N flows [Tg N] in the 100% organic (A) and in the 100% conventional farming (B) scenarios. Arrows are indicative but not proportional to the magnitude of the flows. N fixation accounts for both BNF and free-living cyanobacteria fixation. Arrows in grey are not quantified.

Organic livestock limits nitrogen deficiency and sustains global food production

We found that redesigning livestock production is key to sustain crop yields and the overall global food production. The optimisation procedure we used to maximise food availability from organic production systems resulted in (i) a ~10% decrease of total animal populations (calculated in Livestock Units[5]), (ii) a strong shift among animal species in favour of ruminants (that are able to be fed by low food-competing feedstuff such as permanent grasslands) and (iii) changes in animal geographic distribution compared to the current conventional baseline (Figure 13). Altogether, these changes are key to sustain crop production in regions where suitable conditions for animal production are present, in particular for providing manure to cropland soils: crop production in areas where livestock densities is enhanced exhibits null or low yield gaps (Figure S14). The strong shift in favour of ruminant animals is explained by the higher share of temporary fodders in organic crop rotations and by the ability of ruminants to consume and transform fodders and roughage into useful resources such as food and manure. In addition, this increase in ruminant animal densities (especially small dairy ruminants) allows a further N fertility transfer from grasslands to croplands. This redesign of the livestock sector

[5] Livestock Unit (LU) is a reference unit which facilitates the aggregation of livestock from various species and age. One livestock unit correspond to an adult dairy cow.

and, especially, the shifts towards more ruminant livestock species at the expenses of monogastrics plays a fundamental role in making a conversion to organic farming feasible. This is because if current livestock geographic distribution and composition are maintained, then a conversion to organics would be physically impossible since livestock feed requirements would exceed global cropland production (Table S19).

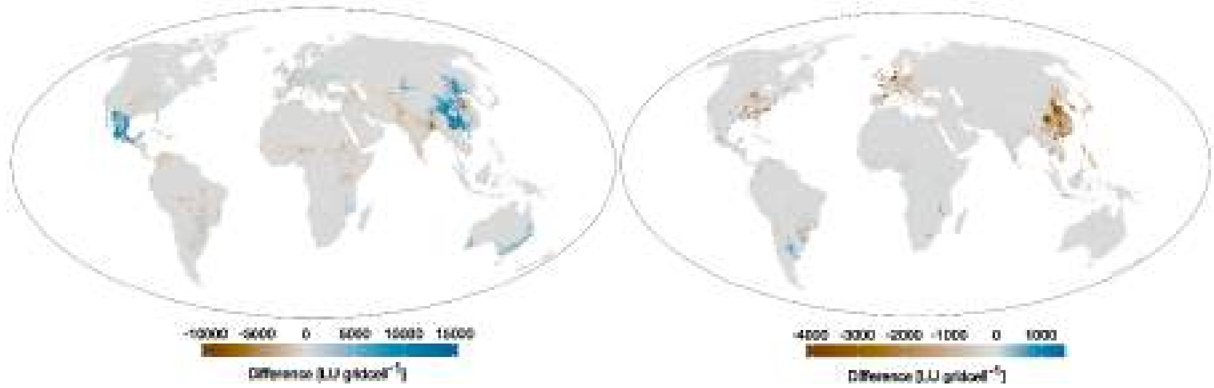

Figure 13. Difference in livestock densities [LU per gridcell] for ruminant (a) and monogastric (b) livestock species between the 100% organic minus the 100% conventional scenarios. Grid-cell size at the equator is ~10 km × 10 km

This shift towards ruminant animal species is also explained by their lower requirements of food-competing feedstuff compared to monogastrics. Indeed, the share of cropland production used as food-competing feedstuff (excluding temporary fodder crop species) drops from 40% currently to 11%, thus drastically increasing food availability from croplands. In addition, energy derived from animal food products increases by +22% compared to the conventional baseline. This is due to the switch towards dairy and small ruminant production, at the cost of a strong decrease of monogastric species (-94%) and meat production (-76%) (Table 2). Finally, combining the reduced feed *vs* food competition with this slight increase in food derived from animal production, global food energy production would finally drop by -37% compared to the current conventional baseline, a value well lower the -58% drop in cropland production mentioned above.

Table 2. Energy production [expressed in e+15 kcal] for food and feed from cropland (in violet), and food from animal commodities (in brown) in the 100% organic *vs* the 100% conventional scenarios. For livestock food commodities, meat energy production is split into energy from ruminant *vs* from monogastric species.

Scenario	Cropland production			Livestock production			
	Total energy [e+15 kcal]	*Food energy [%]*	*Feed energy [%]*	*Total energy [e+15 kcal]*	*Dairy production [%]*	*Meat production [%]*	*Egg production [%]*
100% organic scenario	5.1	72	28	0.9	87	8 [rum 98%, mon 2%]	4
100% conventional scenario	11.9	54	46	0.73	58	34 [rum 41%, mon 59%]	8

Global organic food production remains far lower than global food demand

We found that farming global cropland entirely organically would result in a food production well below the current global food demand (Figure 14) with a 34% production to consumption gap. The production-consumption mismatch would be still considerable – i.e. 28% gap – if per capita energy consumption were reduced in line with physiological dietary recommendation of 2200 kcal cap-1 day-1 (9.20 MJ cap-1 day-1) (Ahmed & Blumberg 2009) globally. Reducing food wastage would help to narrow the production-demand gap by an additional 8%, on average, for both the current and the reduced dietary energy estimates. Furthermore, we found that an organic world would come with significant changes in the global food basket. Indeed, the combined effect of the changes in the types of crop grown (Barbieri et al., submitted for publication), of the nitrogen limitations and of the complex interactions between crop and livestock sectors would modify the relative importance of the different food commodities. Organics would come with a higher share of pulses (+309% compared to the current global consumption) and dairy products (+153%). This higher supply would come at the cost of a decrease of all others food commodities, especially vegetable (-60%), root crops (-60%) and monogastric derived commodities (-90%), with the exception of sugar crops. Indeed, the production of crops unable to efficiently use limited nitrogen resources would be the most affected.

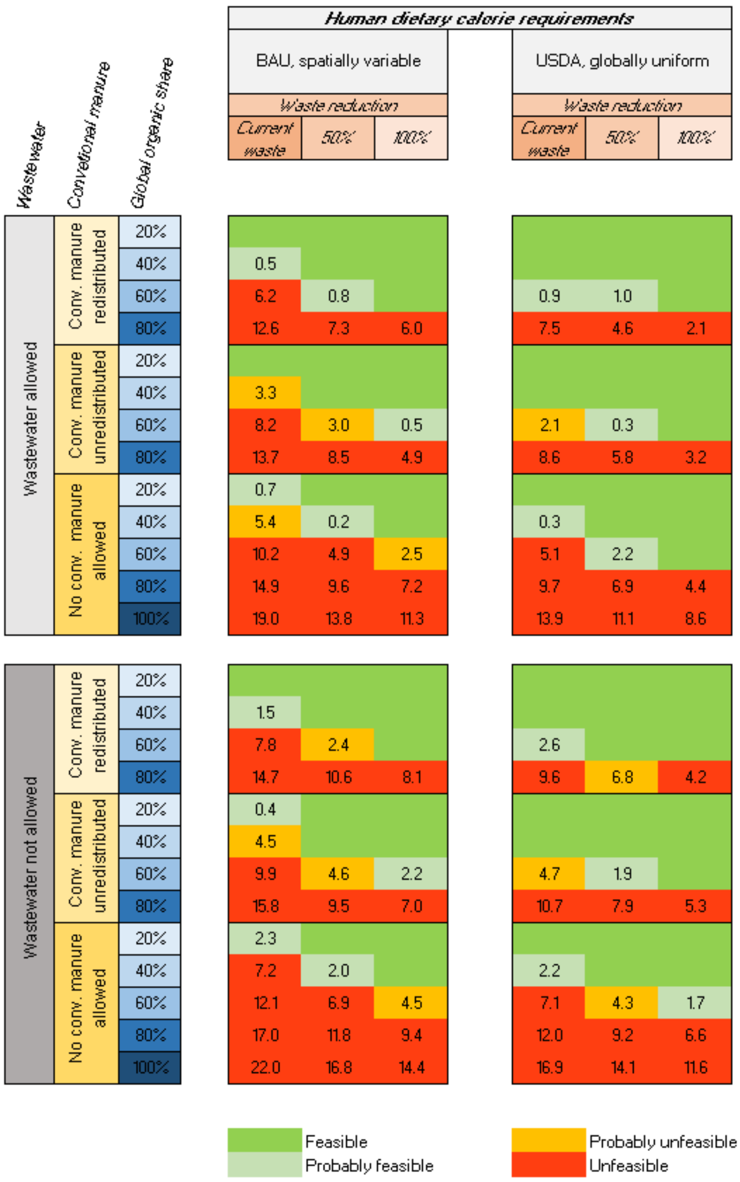

Figure 14. The global production-demand options space, for scenarios involving livestock redesign. The energy production-demand comparison results from the combination of (i) five shares of global conversion to organic farming, (ii) three conventional organic manure management options, and (iii) two recycled wastewater management options for the supply side (lines) together with (a) two human dietary variants, combined with (b) three variants of food waste reduction for the demand side (columns). Each cell represents a scenario. Because in the 100% global organic share scenario there is no conventional livestock, the use of conventional manure in this scenario is not possible. Feasible scenarios represent cases where global food demand is equal or lower than global food supply; probably feasible and probably unfeasible scenarios represent cases where global food demand is 0-5% and 5-8% higher than global food supply, respectively; unfeasible scenarios represent cases where global food demand is more than 8% higher than global food supply. Numbers in each cell (i.e. each scenario) indicate the average amount of N (expressed in kg N ha^{-1} cropland) that would be necessary to sufficiently raise organic yields globally in order to match global food demand.

Reducing the per capita calorie demand to 2200 kcal cap^{-1} day^{-1} as well as food waste have the additional benefit of curtailing the N resources necessary to sufficiently raise crop yields globally in order to match global food demand. Indeed, we found that only 11.6 kg N ha^{-1} of cropland would be sufficient, on average, to produce sufficient calories to feed the current global population if these two demand-side measure are taken up (Figure 14), assuming that all the additional food produced would be used for human consumption. We also tested the contribution that wastewater would have in sustaining global organic food production. Given the current collecting facilities and the N retrieving capacity in every single country, an additional 2.3 Tg N would be available for sustaining crop yields globally, increasing cropland production by 7%. This increase would still not be sufficient to match global food demand for any of the variants considered in this study (Figure 14).

Alternative supply-side solutions are needed to meet the global food demand

We explored several alternative supply-side solutions by (i) testing lower shares of cropland conversion to organic farming and (ii) by allowing the use of additional N resources (i.e. conventional manure and wastewater) to fertilize cropland soils. These additional inputs would significantly improve organic system productivity in several global regions. The use of conventional manure on organically managed croplands rises organic yields by +12% (median across the different cropland conversion shares to organic farming, Figure S15). This effect is even stronger (+23%) when conventional manure is distributed nationally. Wastewater use on organic cropland would lead, instead, to a +7% increase in crop production. Unsurprisingly, these benefits decrease with the increase of the global organic share, due to the dual effect of the progressive decrease of conventional resources and the increase of organically harvested areas.

Therefore, we found that converting 20% of global croplands to organic farming would be feasible for any demand-side scenario (Figure 14), while a conversion up to 60% would possible only by importing N resources both from conventional farming and from recycled wastewater. In contrast, conversion rates of 80% or higher would not make it possible to match food demand according to our calculations. Allowing this additional N input resources further reduces the amount of N necessary to raise crop yields in order to match global food demand to ~8.2 kg N ha^{-1} of cropland (median across scenarios). Given this relatively low amount of N, the production-demand energy gap could be potentially closed, in most cases, by redistributing the global modeled N surplus in locations where N-deficiency occurs (Figure S16, Figure S17).

It is important to note that as for the 100% conversion scenario, the development of organic farming comes necessarily with a global redesign of the livestock sector. If current global livestock populations' densities and geographic distribution are maintained, even a conversion of 20% of cropland areas to organics would be unlikely (Figure S18). In addition, any scenario excluding external (i.e. conventional) N inputs to organic systems would be physically unrealizable because livestock feed energy requirements for food-competing feedstuff would exceed cropland production (Figure S18).

Discussion

The productive capacity of organic farming in a context of global food security is a heated topic. Several studies have developed and assessed agronomic scenarios to investigate the consequences that farming the planet organically could have on the global food production (Erb et al. 2016; Muller et al. 2017; Barbieri et al., submitted for publication). However, none of these studies has considered the N dynamics in the production systems and its potential feedback on crop production. Because the N cycling is a key ecological process with strong implications on agroecosystem functioning, in particular when inorganic fertilizers are banned (Connor 2008), not considering this process is likely to lead to erroneous conclusions about the capacity of organics to feed the planet. All previous studies have used the organic-to-conventional yield ratios of individual crops as direct estimate of organic productivity if organics was to be expanded, whereas those ratios have been reported in contexts of little organic farming expansion, large N availability and strong capacity of organic farms to source N in their surrounding environment (Nowak et al. 2013b; Nowak et al. 2013a). Therefore, because it neglects the consequences that organic farming expansion could play on N fertilizing resource availability, the sole use of these ratios overestimates the global productivity of organic systems (Connor 2018). In contrast, our results show that global cropland production in a full organic world would be much lower than the previously estimated (Badgley et al. 2007; Muller et al. 2017) –e.g. we found energy production from cropland to be 31% lower than estimates by Barbieri et al. (submitted for publication), and would strongly vary across global regions (Figure 10). Beyond overall productivity, the large N deficiency that we found in many croplands around the world is also likely to affect the temporal crop yield stability. Evidence of a negative relationship between soil N availability and organic crop yield has been published recently (Knapp & van der Heijden 2018), suggesting that organic farming expansion may alter the resilience of the global food systems, especially under less predictable climatic events. Further studies are required to explore that important question, in particular, to account for the differences in types of crops grown in organic *vs* conventional systems (Barbieri et al. 2017).

The strong gap in production that we found has major implications for global food security. In particular, the large estimated gap (-34%) between overall food production and food consumption at the global scale in scenarios of large organic farming expansion is likely to limit the development of this way of farming. Indeed, such a decrease in global food availability would likely worsen global food insecurity (Halberg et al. 2006). Nevertheless, solutions exist to narrow that gap, as reported by previous studies. As demand-side solutions, we found that reducing food waste and revising dietary requirements would help to narrow the production to consumption gap to 21%. In addition, supply-side solutions like the allowance of N from waste-water sources –i.e. sewage sludge– would further narrow such gap to 16%, underlining the necessity of overcoming current barriers to the use of such nutrients resources.

Organic farming expansion may also come with some benefits for the global food systems. First, the fact that we found increased cropland productivity in some contexts (in particular in Latin America and some spots in southern Africa) means that enhanced N availability and changes in crop rotations related to conversion to organics are key to improve farming system sustainability and profitability for the farmers. Second, organic farming expansion is likely to bring profound changes in the basket of food delivered by the different crop and livestock commodities. In particular, despite the strong decrease of vegetables and fruits predicted by our model –with potential essential losses in micronutrients–, we found that organic farming expansion would come with a higher share of non-staple crop species compared to the current baseline. Non-Staple Food Energy, which has been often reported as a good proxy for food supply quality (Smith & Haddad 2015; Chaudhary et al. 2018), would be as high as 53% in organic *vs* 39% in the conventional food production. Additionally, the higher diversity in the type of crops grown in organic systems (Barbieri et al. 2017; Barbieri et al., submitted for publication) is likely to lead to a higher dietary diversification (Chinnadurai et al. 2016) and, to improve micronutrients availability (Gibson & Hotz 2001). GOANIM simulations lead to more diversified diets (Global Shannon Diversity of Food Supply (Chaudhary et al. 2018) of 2.76 in organic *vs* 2.53 in the conventional baseline), and, thus, to a higher global nutrient adequacy[6] (Nutritional Balance Score (Chaudhary et al. 2018) of 76 in organic *vs* 64 in the current baseline). All these

[6] Conventional and organic energy production were made comparable by downscaling conventional production relatively to the organic production levels. The proportions between the different food commodities are maintained.

evidence support the claiming that organic farming would provide better diets, despite the overall decrease in energy production. Note that, in our approach, the simulated changes are not driven by dietary shifts exogenous to our model (i.e., externally determined at the consumer level), but are, instead, clear consequences of the production shifts towards organic farming systems. Therefore, some discrepancy between the food production simulated by GOANIM and food consumption might be present.

Importantly, our results show that livestock animals play a much more important and complex role than previously estimated in many scenario-based global food studies. Contrarily to some scenario-based studies associating sustainable farming systems with a vegan dietary option (Erb et al. 2016), livestock animals do not disappear from GOANIM's simulated scenarios. Instead, our results show that global food availability would decrease in a vegan diet world (-38% compared to a scenario of 100% conversion to organic farming at the global scale with animal production), showing that animals are a key structural component of organic farming systems. This result is in line with previous studies showing that the minimum amount of arable land necessary to produce sufficient food does not come together with null livestock populations density (Van Zanten et al. 2018). Because livestock animals –especially monogastrics- are direct competitors with humans for grain crop resources, several studies have proposed the decrease of the pig and poultry production as a strategy to narrow the food production *vs* consumption gap and to make organic systems more viable (Schader et al. 2015; Muller et al. 2017; Mottet et al. 2017). This study converges to similar conclusions – as illustrated by the strong redesign of livestock systems towards ruminant species (Figure 13) – although through a different approach based on an optimization procedure that did not set any a priori constraint on livestock animal population. However, while in previous studies the decrease in monogastrics and in food *vs* feed competition was accompanied by a general decrease in animal food commodities (Schader et al. 2015), our results show an increase in food provisioning from livestock based commodities. In addition, our results show that husbandry management actively sustains food availability for humans in organic systems. Indeed, husbandry is a key component of the N cycle, and so of the GOANIM model, both for supplying manure to fertilise cropland soils and for allowing balanced crop rotations based on hays, temporary grasslands and arable cropping (Schiere et al. 2002; Lemaire et al. 2014; Herrero & Thornton 2013). Ruminants, in particular, are one of the central points of organic systems, by being able to value and transform the commonly used grass/legumes hays into products of primary importance such as manure and rich and nutrient dense food commodities (Lampkin 1990; White & Hall 2017; Van Zanten et al. 2018). This is especially true because the higher share of temporary fodders in organic rotations (Barbieri et al. 2017) contributes to recoupling livestock with cropland production and to transfer fertility from N-fixing temporary fodder crops to cropland soils (Lampkin 1990; Peyraud et al. 2009). This fertilization transfer is further enhanced in our model by the increased density of small ruminants on permanent grasslands, with positive effects on manure production and cropland fertilisation capacity, a finding robust to the moderate quality of the data regarding permanent grassland Net Primary Productivity (a ±15% variation of grassland grazable NPP resources had only ±3%impact on food availability).

Finally, because our results provide the evidence that cropland production would be severely N limited in scenarios of large organic farming expansion, solutions to overcome this N deficiency are strongly required to make organic systems more viable. Cropping system diversification (Waha et al. 2018) with special regards to the abundance of N-fixing crops is one of those solutions with benefits on both organic productivity and resilience (Ponisio et al. 2015). Our simulations are based on global organic land-use maps (Barbieri et al., submitted for publication), thus accounting for the increase in harvested grain pulses and legume lays at the cost of other crops categories – e.g. cereals – when organic crop rotations are adopted. Nevertheless, we did not investigate where and whether there would be the conditions (in terms of space, time, and climate dimensions) for further diversify organic cropping systems by (i) increasing crop intensity or (ii) increasing the share of non-harvested N-fixing crops (e.g. cover crops or green manures). Such strategy is particularly needed in low-producing agricultural areas, such as Sub-Sahara Africa, where small amounts of nitrogen resources, typically as provided by BNF, would fulfil nitrogen deficits and raise crop yields (Figure 11). Nevertheless, up to now, global dataset does not allow properly estimating the contribution of these additional crops at the global scale. Better closing the N cycle within societies by improving and implementing facilities for collecting and recycling human wastewater (especially in developing countries), and allowing the use of such resources on organically managed croplands is another solution to overcome N deficiency in organic farming (Sato et al. 2013). Our results show that these additional inputs, even if currently limited in several global regions, would significantly help to reduce organic N deficits. Therefore, social barriers obstructing the allowance of such resources in organic farming need to be disentangled. To do so, any related issues with contaminants and health risks need to be solved. Additionally, we have shown the important role that conventional manure N resources could play to overcome N deficit in organic systems when global conversion rates to organic farming below 100% are considered. Currently, concerns about the use of such resources exist, and some countries have even banned the use of such resources (McKinnon et al. 2014; Oelofse et al. 2013). Nevertheless, these resources are essential, especially given that such intermediate scenarios (i.e. global conversions shares between 20 and 80%) are the most likely to be successfully achieved (Figure 14). Finally, reducing N losses to the environment is a further key asset to overcome N deficiency. Indeed, in a scenario of 100% conversion to organic farming, N losses to the environment – excluding losses from livestock and manure management practices – represent alone about 20% of the total N deficiency.

Conclusion

In summary, we report the first spatially explicit assessment of a 100% conversion of global cropland to organic management, with full consequences for the N resource availability and global food production. We show that N deficiency limitation would limit a full global conversion to organic farming. However, a coexistence of organic farming with conventional systems is more likely to represent a feasible solution. Under such conditions, up to 60% of the global agricultural area could be shifted to organics if coupled with a reduction in global food consumption and a decrease in global food wastage. Such conversion rate would still bring enormous benefits by reducing several environmental impacts from agriculture (Muller et al. 2017; Reganold & Wachter 2016). Despite a lower production (-32% in a 100% conversion scenario compared to the current baseline), organics would also require a strong shift in global diets for both crops- and livestock-derived food commodities, and would provide a better quality of diets for the global population by diversifying the food baskets. The spatially explicit nature of our study also underlines how different performances are reached in different global regions, suggesting that organic farming might be a promising solution in some regions – e.g. in Brazil, Mexico and the south part of Africa –, while its implementation would be more challenging in others (e.g. North America). Hence, organic farming does not represent a black or white solution, but it stands as a remarkable shade of grey that could indeed play an important role in sustainable food systems.

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Author Contributions

P.B., S.P., and T.N. designed the study; P.B. collected the data, coded the model and performed the calculations; P.B. and L.S. were involved in the model set-up and improvement. All authors were involved in the interpretation of results and contributed to writing and revising the manuscript.

4. General discussion and conclusions

In this chapter, we firstly discuss the research context into which we place our work. We synthesizes and combine the results of the previous chapters, and we compare them with previous studies. We then discuss the GOANIM model, focusing especially on its novelties, limitations, and further implementations and application perspectives. We then discuss the implications of our findings for global food systems and the organic sector. Overall, we show how this dissertation significantly contributes to understanding the role that organic farming could play in feeding the world.

The scientific context – global agronomy

A body of literature has explored the impacts that different farming systems – i.e. organic, intensive, integrated, etc. – may have on global food security (Waha et al. 2018; Erb et al. 2016; Muller et al. 2017; Pickett 2013). However, recent research on these topics has been mainly left at the mercy of geographers and economists. As a consequence, most of the recent modelling efforts on those topics have represented these farming systems in a rather simplistic way (Badgley et al. 2007; Thieu et al. 2011; Odegard & van der Voet 2014; Erb et al. 2016). As agronomists, we acknowledge the need and the opportunity to deal with global issues about global food security and environmental protection and we aim to become important players within the scientific community working on those fields (Makowski et al. 2013). At this purpose, moving agronomy from the local scales to the global scale is necessary. We place the work presented in this dissertation within this relatively new field of research that is 'global agronomy' (Makowski et al. 2013). We believe that our work significantly contributes to advancing scientific evidence on global agriculture and food security issues, and indicating future pathways for more sustainable food systems.

Summary of our key results: organic crop rotations, yield gaps, nitrogen cycling, livestock animals, and how they influence global food production

In this dissertation, we have estimated global food production for different scenarios of organic farming expansion at the global scale, with a particular focus on N cycling in a 100% organic world. Our aim was to better model organic farming systems in comparison with previous studies by focusing on their structural differences with current –i.e. conventional- systems (Badgley et al. 2007; Seufert et al. 2012; Erb et al. 2016; Muller et al. 2017). To do so, we identified the need for exploring four main aspects related to organic farming systems: crop rotations, organic-to-conventional crop yield gaps, N availability to fertilise cropland soils, and livestock animal management. We provide a summary of our finding related to these four aspects in the following lines.

Crop rotations and types of crops grown

Because synthetic fertilisers and pesticides are banned by organic guidelines, crop rotations are strategic in organic production systems (Lampkin 1990). In particular, it is generally acknowledged that more complex and diversified rotations are adopted in organic systems to provide alternative levers for pest control and nutrient management. However, previous modeling studies have failed to fully consider this higher complexity: most studies have restricted this greater complexity to an increase in the share of N-fixing crops when organic farming is adopted (Badgley et al. 2007; Muller et al. 2017). This rather simplistic approach was due to the absence, up to now, of any study systematically comparing organic *vs* conventional crop rotations at the global scale. In Chapter 1, we carried out a meta-analysis to provide a global-wise comparison of organic *vs* conventional crop rotations. Our study confirmed that, globally, organic crop rotations are more complex and diverse than their conventional counterparts (Chapter 1, Figure 1). It also confirmed that N-fixing crop species are more abundant in organic rotations, especially as temporary fodders and non-harvested catch and cover crops. The abundance of grain pulses, instead, have different behaviours in different global regions, i.e. not always increasing. More importantly, our study reported original evidence that temporary fodder crops are more abundant in organic rotations in all the world regions. Finally and importantly, our study showed that the differences in crop rotations between organic *vs* conventional farming vary across world regions. This analysis provided an answer to our *Research Question #1,* i.e. understanding and quantifying the difference in organic *vs* conventional crop rotations.

We then transformed this information about crop rotations (Chapter 1) into spatially explicit world maps reporting the distribution of the types of crops grown in a scenario of 100% organic management of the global cropland area (Chapter 2). Overall, we found an increase in the areas harvested with pulses and, especially, temporary fodders (+25%, +62% compared to the current baseline, respectively), mainly at the expense of primary cereals (-31%). Based on these maps, we showed that the adoption of organic rotations, along with organic-to-conventional crop yield gaps, would cause a -27% drop in the energy produced from cropland, compared to the current –i.e. conventional– production (Table 3). In particular, we found an important decrease in the energy delivered by primary cereals (-41%, Table 3). We also propose a decomposition of this drop and we show that it is mainly caused by decreased cropland area under primary cereals – i.e. contributing 61% of the total energy gap (Table 3). Note that the organic-to-conventional yield gap used in Chapter 2 does not explicitly account for the N availability for cropland production. Overall, this analysis allowed to investigate how the type of crop grown would change in a full organic world and how they would impact organic food production at the global scale? –i.e. our research questions #2 and #3. Answering those two questions allowed overcoming previous simplistic estimations of cropland use when organics is adopted.

Table 3. Global cropland production in scenarios of 100% conversion to organic farming with or without considering N limitation to crop production.

N effect on crop production	Cropland energy production [10^{15} kcal]	Org. to conv. gap	Livestock energy production [10^{15} kcal]	Org. to conv. gap	Total food energy [10^{15} kcal]	Org. to conv. gap	Prim. cereal energy production [10^{15} kcal]	Org. to conv. gap	Primary cereals org. to conv. production gap due to…		
									Crop rotation	*Yield gap**	*N availability*
N limitation non-modelled	9.4	27%	0.86	-7%	5.6	28%	3.4	41%	25%	16%	0%
N limitation modelled	5.1	58%	0.9	-22%	4.6	37%	1.5	75%	26%	10%	38%

* The yield gap when N limitation is not explicitly modelled accounts for all biotic and abiotic stresses that may affect crop production in current organic systems (Ponisio et al. 2015). The yield gap when N limitation is explicitly modeled accounts for all biotic and abiotic stresses that may affect crop production with the specific exclusion of N stress.

Organic-to-conventional yield gap

Organic-to-conventional yield gaps have been used -and misused (Connor 2018)- to estimate organic yields as a function of conventional yields (Seufert & Ramankutty 2017; De Ponti et al. 2012; Ponisio et al. 2015). These yield gaps have been considered to be indicative of the biotic and abiotic stresses that organically managed crops face in comparison with conventionally managed crops (Seufert et al. 2012; De Ponti et al. 2012). Those stresses are, in general, higher in organic systems due to the ban of synthetic inputs. Since these yield gaps have been estimated under current conditions (Seufert et al. 2012; Ponisio et al. 2015), they do not explicitly account for the stress that could occur when N becomes more limiting compared to the current conditions.

In Chapter 2, similarly to previous studies (Erb et al. 2007; Muller et al. 2017), we used the yield gap data provided by the literature (Ponisio et al. 2015) to calculate organic crop yields when we estimated cropland production in a scenario of large organic farming expansion. Under such conditions, using the response of primary cereals as an example, the organic-to-conventional yield gap contributed to -16% decrease in energy production (Table 3). In Chapter 3, instead, we explicitly accounted for the effect that N limitation can have on crop yields. The organic-to-conventional yield gap due to stresses other than N limitation[7] caused a reduction in the energy produced by primary cereals of only -10%. This indirectly indicates that when applying the organic-to-conventional yield gaps extracted from the literature[8], the effect of N stress on cropland production has an order of magnitude of ~6%. Explicitly modeling N limitations in Chapter 3 causes a further -38% reduction in the energy produced by primary cereals, compared to the current baseline (Table 3) leading to a total yield reduction of -48%. This gap is much higher than the one reported in the literature, thus confirming and quantifying that N supply would represent a limiting factor in scenarios of drastic organic expansion at the global scale.

N availability for croplands

Our approach allowed isolating the effects of N limitation on organic cropland production. Overall, we found that N undersupply causes a -38% reduction in the energy produced by primary cereals compared to the conventional baseline (Table 3). Therefore, our work clearly tests, confirms and quantifies the hypothesis that has been made since long that N availability is a major constraint to the development of a full organic world (Cassman 2007; Connor 2008; Connor 2018). The overall N deficiency, which results in a global food production drop of -37%, is due to the inability of organic systems to counterbalance the ban of synthesized fertilisers. The increased frequency of N-fixing crops in organic rotations has sometimes been reported as sufficient to cover crops' N demand (Badgley et al. 2007). Our study shows that this would not be the case. Indeed, despite an increase in N-fixing crop areas up to 30% in some global regions, organic crop rotations guarantee globally only a +15% BNF compared to the current baseline. This effect may be partially due to the fact that organic pulses yields are lower than in conventional farming due to the high susceptibility to pest and diseases of these crop species (Baldoni & Giardini 2000). Since our modeling approach estimates BNF as a function of crops' yield, BNF increases less than the increase in the harvested areas with N–fixing crops.

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[7] In Chapter 3, we recalculated Ponisio et al.'s (2015) yield gaps in order to account only for crop yield reduction due to stresses other the N, i.e. mainly due to biotic stresses (Oerke 2006), see Materials and Methods in Chapter 3.

[8] i.e. the yield gap when N limitation is not explicitly modelled

The second source of N in organic systems is represented by animal manure. Surprisingly, the ability of organic livestock animals to sustain cropland production through N flows in manure was less significant than expected. Nevertheless, organics would come with a strong increase in ruminant animal densities (especially small dairy ruminants), thus resulting in important N fertility transfer from grasslands to croplands. This is because ruminants consume and transform fodders and roughage into useful resources such as food and manure. Therefore, ruminant livestock species play a key role in regulating N flows between different compartments in organic systems.

We also show that N availability in organic systems can be enhanced by accounting for N from urban sources. The use of such resources, helping to close as much as possible the N cycle within agro-food systems, would be a key leveler towards an expansion of organic farming. Overall, this analysis allowed answering our *research question #4, i.e.* to which degree global food production may be limited by N availability in scenarios of organic agriculture expansion at the global scale

Organic livestock animals

Our modelling approach allowed optimising livestock population density and geographic distribution at the global scale. Our results confirmed that a massive conversion to organic farming would be possible only if the livestock sector is strongly redesigned. Indeed, if current livestock populations' density and distribution are maintained, then cropland production would not be sufficient to cover animals' feed requirements (Chapter 3). Therefore, this redesigning is key to sustain crop yields and to achieve a high level of global food production. Our model results show a strong shift towards ruminant animal species at the detriment of monogastrics and important changes in the animal geographic distribution compared to the current baseline. Such changes are key to sustain organic food production. This is due to (i) lower competition for grains with humans from enhanced ruminant populations and (ii) slight increase in animal-based food production (Chapter 3). In contrast with previous studies, we show here that livestock animals, especially ruminants, are a key component of organic systems, by regulating N flows between grassland and cropland compartments. Therefore, in our simulations, animal population would drop of just ~10% (in Livestock Units) when organic farming is adopted. Previous studies, instead, suggested that livestock population density and production should be drastically reduced in a full organic world (Erb et al. 2016; Muller et al. 2017). Therefore, our results confirmed that a redesign of the livestock sector would be essential to sustain organic food supply at the global scale.

Comparison with previous studies

As shown in our review of the literature, only a few studies have already attempted to explore scenarios of organic expansion at the global scale. Our modeling approach –i.e. optimizing organic food production at the global scale as a function of the N available in organic systems– leads to conclusions that clearly differ from the ones previously reported (Table 4). In particular, per-capita food supply estimated in this dissertation is 30% lower than estimates provided by Muller et al. (Muller et al. 2017), 36% lower than estimations by Erb et al. (Erb et al. 2016) and 41% lower than estimation by Badgley et al. (Badgley et al. 2007). These discrepancies clearly show, as previously stated, the importance of considering explicitly N cycling when exploring scenarios of organic expansion at the global scale. Both Badgley et al. (2012) and Muller et al. (2017) overestimated N resources to fertilise croplands in comparison to our study. Badgley et al.'s estimate of 140 Tg N from N-fixing crops has been reported as simplistic and overoptimistic (Connor 2008). Therefore, the authors' claim that sufficient N resources are available to achieve food supply of 2440 kcal cap^{-1} $year^{-1}$ (Table 4) does not stand. Muller et al. (2017) elaborated a much more appropriate estimation of the amount of N available to fertilise cropland soils. Biological N fixation is in line with our estimates, while N from livestock manure available to fertilise croplands was higher than our estimates (Table 4). The reasons for our lower estimation is probably related to the higher abundance of small ruminants in our study, and to the low availability of small ruminants manure for cropland application. Despite the higher amount of N available to fertilise croplands, Muller et al. found an overall, global negative N budget of cropland soils. This means that they introduced more N into the model calculation then the actual N supply. Therefore, their crop yields and the consequent food production results are overestimated (Connor 2018). In spite of this, our results tend to converge with Muller et al. (2017) when a lower organic expansion is considered, especially below 60% of the global cropland area under organics. More in details, both studies show that conversion below 60% would be feasible when coupled with demand-side solutions. Interestingly, our results are in line with those of Smith et al. (2018), who simulated a scenario of organic conversion of the UK agriculture by using a similar approach to ours (Table 4). Smith et al. (2018) applied linear programming to explore the impacts of a 100% conversion to organic farming in England and Wales by accounting for the feedbacks of N availability on organic production. The authors concluded that such feedback would have severe consequences on food systems. Organics would come with a drastic drop in food production and an increase in food imports from abroad, thus making this scenario likely unfeasible.

The role that N availability plays on cropland production in scenarios of large organic farming expansion has already been considered in a study analyzing Bhutan's ambitious goal to become the first 100% organic world nation. In particular, the absence of Bhutan's strategic actions to prepare the conversion of current farming systems would cause a -22.4% drop in the amount of N available to fertilise cropland soils: average application N rate would fall from 38.4 kg ha^{-1} to 29.8 kg ha^{-1} (Feuerbacher et al. 2018). The cause of this drop in N resources was mainly related to the inability to replace synthetic N fertiliser by manure resources, confirming the critical need to redesign the livestock sector when organic farming is largely adopted. The estimated N deficiency would limit cropland production and would force the country to import more food from abroad, thus confirming the difficulties to achieve full conversion to organic farming (Feuerbacher et al. 2018).

Table 4. Comparison between studies simulating conversion of global cropland area to organic farming. NS: not simulated; NA: value not available.

Organic scenario		Badgley *et al.* (2007)	Erb *et al.* (2016)	Muller *et al.* (2017)	Smith *et al.* (2018)	This study		Comments
						Chapter 2	*Chapter 3*	
100% conversion to organic farming	Simulation year	current	2050	2050	current	current	current	
	Spatial scale	Global	Global	Global	UK	Global	Global	
	Food supply (excluding food wastage)	2640 kcal cap^{-1} day^{-1}	*Equal to food demand*	*Equal to food demand*	~37% production gap	2141 kcal cap^{-1} day^{-1}	1552 kcal cap^{-1} day^{-1}	
	Food demand (excluding food wastage)	NA	2400* kcal cap^{-1} day^{-1}	~2200 kcal cap^{-1} day^{-1}	NS	2200 kcal cap^{-1} day^{-1}	2400 kcal cap^{-1} day^{-1}	* Corresponding to a vegetarian/vegan scenario
	N from BNF	140 Tg	NS	25Tg *	NA	NS	38 Tg	* BNF without N fixation from rice and sugarcane
	N from animal manure applied to cropland soils	NA	NS	20 Tg	NA	NS	13Tg	
	Total N resources applied to cropland soils	140 Tg	NS	79 Tg	NA	NS	57 Tg *	* Excluding N atmospheric depositions
	N surplus or deficit[a]	NS	NS	From -3 to -7 kg N ha^{-1} *	0 kg N ha^{-1}	NS	0 kg N ha^{-1}**	* Considering both croplands and permanent grasslands areas ** Not considering the structural N surplus (see Chapter 3)
	Cropland expansion	0	0	-2%	0	0	0	
	Average org-to-conv yield ratio	1.32	0.6	0.75	NA	0.80	0.52	

	Feasibility (supply meets demand)	Feasible	Feasible for a vegan diet option	Feasible *	Unfeasible	Probably feasible	Unfeasible	* Considering a reduction of 25% in food waste and a 50% reduction in food-competing feedstuff
60% conversion to organic farming	Feasibility (supply meets demand)	NS	NS	Feasible*	NS	NS	Feasible **	* Cropland expansion: +8% ** For a scenario with a food demand of 2200 kcal cap^{-1} day^{-1}

[a] Note that some studies have kept constant organic yields, thus leading to positive or negative N budgets, whereas other studies have simulated crop yields as a function of N supply to cropland soils, thus leading to null budgets.

GOANIM discussion

Model's novelties

Undoubtedly, GOANIM allowed bringing scientific research and global agronomy a step forward towards understanding the role that organic farming can play for global food security.

One of GOANIM's most important strengths lies in its spatially explicit nature. This characteristic is key, because N flows and, thus, organic crop yields and livestock animal densities are simulated and optimised at the local scale. This means that local characteristics, i.e. the local area, the types of crops grown, and the area under permanent grasslands influence all the simulated variables, namely, crop yields, N flows and livestock animal densities. The type of soil and climate is indirectly captured by using spatially explicit data reporting the current average crops' yield as a baseline (Monfreda et al. 2008) because observed yields are directly influenced by the soil and climate characteristics of each location. Our approach is very similar to the one used by Smith et al. (Smith et al. 2018), who explored scenarios of organic expansion in England and Wales agriculture. Indeed, previous studies about effects of organic farming expansion on food production (Erb et al. 2016; Muller et al. 2017) have been based on data at the country, region or global levels, without accounting for the spatial variability characterising agricultural systems. As a consequence, these studies may have overestimated organic productivity in comparison to our work. This is because they considered N resources from manure and BNF as transportable far from the regions where they were generated, thus overestimating local N availability.

Thanks to our spatially explicit approach, we have shown how the conversion to organics would translate in large consequences for food production that vary across world regions (Chapter 2 and 3). In particular, we have shown that organics may lead to similar or higher production outputs in specific global regions (e.g. Brazil, Mexico, Southern African regions and Western Europe). Our approach was based on applying share (from 0 to 100%) conversion to organic farming evenly across grid-cells at the global scale. Alternative approaches exist though. One would be to simulate a 'mosaic' adoption of organic farming (for scenarios with less than 100% conversion to organics). That is, to simulate large conversion in regions where organic farming has comparative advantages compared to conventional systems (or where there are important issues potentially addressed by organic farming) while leaving conventional farming being predominant in regions where adopting organic systems may be less beneficial. A second alternative approach would consist in differentiating the conversion to organic farming among crop species within grid-cells. Although those two approaches would have some interests, they would require a deep transformation of GOANIM to be implemented.

A second core innovation of GOANIM is to take into accounts the systemic changes and feedbacks occurring when organic farming systems are adopted. In this respect, as mentioned before, our work made it possible to account for organics' specific crop rotations characteristics, through global maps detailing the types of crops grown in organic *vs* conventional systems. Crop rotations are complex processes to be consistently retrieved, especially at large spatial scale. Detailed, spatially explicit and global databases about land use by the types of crops grown in organic *vs* conventional farming are missing. Our innovative approach coupling meta-analysis with modeling allowed to partially overcome the lack of such information. Thanks to the global datasets we elaborated, we were able to (i) improve the estimation of N flows in organic systems by providing higher details about N-fixing crop species distribution and (ii) have better estimates of the global and local food baskets that organic farming systems would provide. Note that our estimation of the types of crops grown when organics is adopted is based on agronomic drivers. We are aware, that, under real conditions, changes in cropland use do not only depend on such agronomic drivers, but also on economic and regulation forces. Nevertheless, those drivers were not considered here given that GOANIM is not a socioeconomic model. In addition, the model accounts for the systemic feedbacks rising from the complex interactions between croplands, grasslands and livestock animal. Such interactions have been simulated under the form on N flows between these three compartments. In particular, our model connects cropland and livestock production, as a key systematic change that often occurs during the conversion to organic farming. Such interactions have not been directly accounted for by previous studies.

GOANIM was shown to be useful for a multiple "supply-side" scenario analysis. A multiple scenario analysis is needed to explore the future of organic systems since e.g. different type of regulations may be put in place allowing or not alternative nutrients sources (e.g. sludge from wastewater). In particular, GOANIM was able to take into account different patterns of N flows between organic and conventional farming. Whereas it is known that current organic systems benefit from such flows (Nowak et al. 2013b), our study is the first to include them when modeling N flows in scenarios of organic farming expansion. Our results clearly suggest that organic and conventional farming have to be considered more as complementary farming systems than often do. In addition, GOANIM allowed quantifying the contribution that additional N sources that are currently banned by organic regulations, such as sludge from wastewater, could have in sustaining organic cropland production. Our results may help the organic sector to estimate to what extent these sources represent valuable resources to close the N cycle and to decrease the N deficiency in organic systems.

GOANIM limitations, application, and perspectives

Undoubtedly, the GOANIM model and the linear modeling approach we used open avenues to simulate the consequences of the adoption of alternative farming systems, such as organic farming, for the global food systems. The model structure and its relatively simple technical code make it flexible and easily adaptable to other scenarios. In the following paragraphs, we explore possible GOANIM father applications and improvement perspective, especially as related to the current model limitations.

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Main model limitations

Despite its innovative aspects, our approach has some limitations. They are mainly due to (i) low availability and/or quality of organic farming data at the global scale and (ii) uncertainties in upscaling data retrieved from a global context where organic farming represents only 1% of the global area (Willer & Lernoud 2017) to contexts where it would represent up to 100% of the global area. In addition, whereas meta-analyses have been largely used to synthesize global pieces of information about organic farming, this approach has the drawback of over-representing developed countries, with very few studies from developing countries (Seufert & Ramankutty 2017). Increasing the number of organic farming high-quality research projects in developing countries is, therefore, crucial for generating high-quality data utilizable in large-scale studies. This means that the organic-to-conventional crop rotation data presented in Chapter 1 might not be totally representative of a 100% organic world, especially in developing countries. Consequently, the structural changes in the types of crops grown we carried out in Chapter 2 might underestimate the changes that organic farmers might enforce if organics was adopted at the global scale. In particular, organic farmers may try to compensate the N deficiency we found by further increasing the share of N-fixing crops in rotation. Our simulation of the types of crops grown in organic systems takes into account only harvested crops and temporary fodders. As such, it does not consider any potential intensification in the use of N-fixing (non-harvested) catch and cover crops, a solution to increase N supply to cropland soils, with gained efficiency compared to adding livestock animals to provide manure (Figueiredo et al. 2009). However, in Chapter 1 we have shown that organic rotations exhibit higher share of non-harvested N-fixing crops as a strategy to increase N availability in the system, compared to their conventional counterparts. Unfortunately, we lack global, spatially explicit datasets to estimate properly to what extent additional cover/catch crops could be included in organic rotations. Answering this question would require information on the temporal successions of crops, as well as seeding and harvesting dates, climatic and soil data. This question is highly relevant and represents a noteworthy scientific challenge.

Spatial and temporal scales and datasets

In this study, we applied GOANIM at the global scale. However, the model could be easily used to explore spatially explicit scenarios at any geographical scale, e.g., national or regional scales. This could be interesting for simulating the consequences of large conversion to organic farming at the country scale, especially for countries where better data availability would help to better simulate some specific aspects of the model. The model could also be used at any spatial resolution other than 5 arc-min. Decreasing the spatial resolution may be useful to explore the consequences of larger travel distances for feed and N fertilizing resources (see the additional scenario tested in Chapter 3 as an example). Additional N sources to fertilise organic cropland soils, such as green materials from cities, household compost, industry derived fertilisers (e.g. blood and bones meals), etc. can also be easily implemented in the model, thus increasing the number of hypotheses and scenarios that could be tested. Note, however, that, in this study, we did not include any of the above-mentioned additional resources due to the lack of sufficient data to derive spatially explicit and robust datasets.

In this study, we did not aim at exploring future trajectories of the food system. This could be easily done by feeding the model with consistent datasets (e.g., about future human population, future food demand or climate-impacted yield) to estimate organic food production and demand in the future, as done by other previous studies (Erb et al. 2016; Muller et al. 2017).

GOANIM is a static model. It simulates food production and N flows within a one-year timeframe. Therefore, it does account for conversion timeline that takes place when farms switch to organic farming. For instance, it is well known that i.e. crop yields need several years to stabilise, since farming systems go through important structural changes when organic is adopted. All these adaptation processes would probably cause an even stronger impact in the short term. Nevertheless, accounting for those processes would be challenging, since it would require solid global datasets to estimate the processes that take place in the conversion period. Being static, GOANIM also assumes that its internal compartments such as soils or livestock populations are at steady state. As a result, variation in N pools and stocks are not accounted for. Considering these processes is important, however, especially to add a module about phosphorus cycle and flows in the model (see further on in this Chapter).

Husbandry and livestock feeding regimes

Another compartment that strongly drives our results is the organic livestock sector. As previously presented here and in Chapter 3, the livestock sector would have to be strongly redesigned in case of massive conversion to organic farming, as a function of the local feed resources, and of the animal species ability to provide manure for croplands. In GOANIM, the simulated livestock animal densities can be influenced by (i) imposing upper or lower bounds limiting animal densities at the grid-cell scale, or (ii) modifying animals' dietary requirements. In the current study, we did not impose any constraint on animal densities at the local or the global scale. This choice was driven by the interest of finding the best optimal solution to maximise food production while letting the model exploring all the possible technical solutions. Imposing further constraints based, for instance, on current conditions would move away from the best optimization solution for the organic systems. Regarding animals' diets, we assumed that the dietary requirements are the same for animals grown organically *vs* conventionally (Muller et al. 2017). However, feeding practices are reported to be quite different inorganic *vs* conventional livestock systems (Sossidou et al. 2011; Hansen et al. 2006). In addition, it is possible that future feeding practices of both ruminants and monogastrics would use fewer grains and crop products in a context of enhanced food *vs* feed competition (Edwards 2005; Hansen et al. 2006). Once again, the lack of consistent and detailed database about those changes in animal feeding prevented us from modifying this livestock component of our model. GOANIM could be used, though, to explore the consequences of changes in animal feed diets, notably by decreasing the share of grains commodities used to feed monogastric animal species.

The phosphorus issue

Our work focused on modeling N cycles in organic farming. Nevertheless, as shown in our literature review, it is acknowledged that meeting crop phosphorus (P) demand might be challenging if organic farming expands massively at the global scale (Nesme et al. 2016). Such a challenge is mainly linked to the fact that current organic systems often benefit from soil P legacy due to generous applications of synthetic fertilisers by conventional farms prior to their conversion to organics (Sattari et al. 2012). Such soil P legacy is destined to fade out in the coming decades since negative P soil budgets are often reported in organic farming (Oehl et al. 2002; Ringeval et al. 2017). In addition, soil P stocks are not distributed evenly at the global scale (Ringeval et al. 2014). In particular, organic farms would not benefit from abundant soil P stocks in regions that have not been massively fertilised during the last decades –e.g. in Sub-Saharan Africa (Sattari et al. 2012). In addition to the problematics linked to P availability and P fertilization for organic farming, investigating the interactions between P and N cycling represent an additional research effort. This is because N and P are strongly bound in organic fertilisers. In other words, the stoichiometry of organic fertiliser resources may challenge the ability to provide enough of both nutrients while avoiding imbalanced applications (Nowak et al. 2013a). In addition, addressing the crop response to P supply to soils through specific P-response curves fertilise may be more challenging than for N (Mollier et al. 2008), especially in organic systems for which the amount of data is limited. GOANIM may be a suitable model to be adapted via the implementation of a P add-in to investigate such a question.

Environmental impacts and GHG emissions

GOANIM was developed to maximize organic food production at the global scale. To do so, the model optimizes the use of available N resources to fertilise cropland soils in order to reach the best food output, calculated as the sum of food commodities from both croplands and livestock animals. While modeling N flows between the different compartments, the model takes into account N losses to the environment due to management and application of organic fertiliser sources. In spite of that, the model was not coded to (i) investigate agricultural activity emission –e.g., greenhouse gas and other emissions or to (ii) explore the trade-off between maximum organic food production *vs* minimum N-derived emissions to the environment. Organic farming is often claimed as a production method that leads to decreased environmental losses (Meier et al. 2015; Reganold & Wachter 2016; Tuomisto et al. 2012), even if contrasting results exist at these regards (Seufert & Ramankutty 2017). Estimating the environmental consequences of a full organic world has been estimated by Muller et al. (2017). Nevertheless, given the discrepancies in the results between previous studies and the current study, further evidence on this topic is needed. Our results indirectly show that much larger cropland areas would be required to meet global food demand in a full organic world, thus potentially leading to large negative environmental impacts (Mehrabi et al. 2018). GOANIM could be used to estimate some of those environmental impacts, by parameterizing the model to better simulate e.g. N losses in organic farming systems, or GHGs emissions. This would be extremely important, especially if the recent meta-analysis reporting higher GHGs emission factors for organic than for conventional production is confirmed (Skinner et al. 2014).

Implications for global food systems

Global trade and food flows

GOANIM is clearly not an economic model. Changes in production are not driven by any explicit trade module with price elasticities or transportation costs. The model does not take into account economic restrictions or market effects relating changes in quantities to changes in prices. We are aware that economic aspects are key to the social viability of the scenarios tested in this work. Nevertheless, including such aspects would require many additional assumptions on price and cross-price elasticities, thus considerably increasing the model complexity. The focus of this work was, instead, to test the biophysical and agronomic viability of scenarios, rather than their social viability.

In our model, trade is assumed to balance any regional discrepancy between food demand and supply, assuming no trade barriers prevail. To get an overview of those discrepancies, we calculated, for some selected supply-demand combinations, the balance between food production and demand for six global regions (Europe, Oceania, North America, Latin America, Africa, and Asia, Figure 15). Global regions exhibiting negative balance are likely to import food commodities from regions with positive food balance. The region that would be most impacted by conversion to organic farming would be Asia, which is the only region shifting from positive to negative food balance when organic farming is adopted. Conversion to organic farming would also be likely to aggravate African food issues, regardless of the type of scenario considered (Figure 15). To a lesser extent, we also found that N from conventional manure and wastewater would help to attenuate the food gap, especially in Asia and North America, whereas its contribution would be limited in regions like Oceania. Note also that any socioeconomic barrier or obstacles to biomass trade would strongly modify these flows. Indeed, a better understanding of how global trade would influence the development of organic farming (Müller & Lotze-Campen 2012; Kastner et al. 2012) is an open question and a noteworthy scientific challenge (Erb et al. 2016).

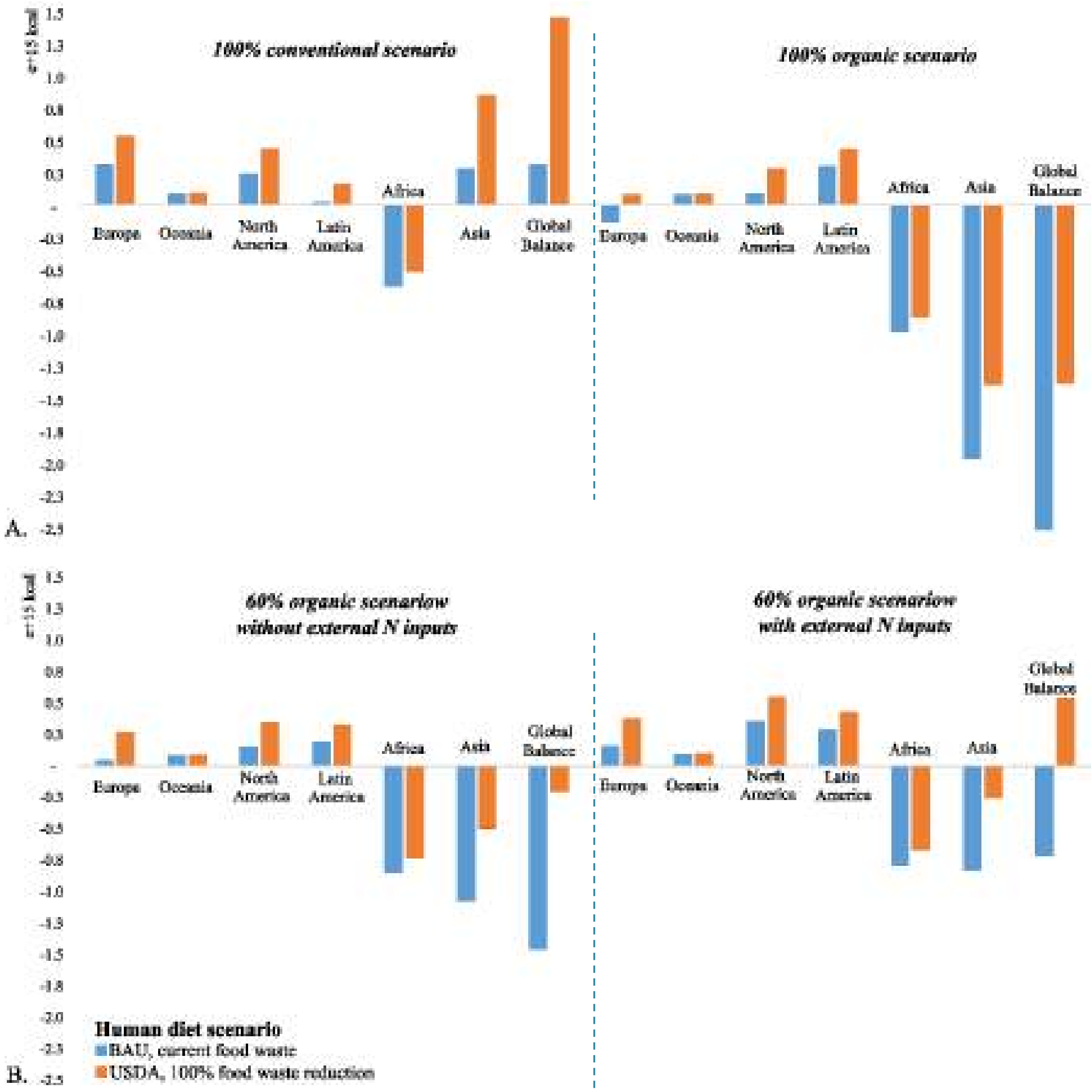


Figure 15. Balance between total food production (form croplands and livestock) minus demand [in 10^{+15} kcal] for six regions and at the global scale for a 100% conventional (top left), 100% organic (top right),

60% conversion to organic farming without (bottom left) or with (bottom right) conventional manure and wastewater. For each scenario, two types of food demand are considered (Business as Usual -BAU- with current food wastage *vs* reduced calorie intake according to USDA guidelines with 100% reduced food wastage). Note that for the 100% conventional scenario (top left), we calculated regional food production from croplands as the difference between total cropland production minus cropland commodities used as feed. To do so, we disaggregated global feed requirements to the regional level based on the contribution of each region to the global cropland production.

Consumers, public policies, and the organic sector

Our work suggests that, given the current knowledge about organic farming systems at the global scale, reaching a full organic world would be most likely impossible due to the major limitation that N fertilising resources represent for global food production. Full conversion of global croplands to organics would be achievable only if large amounts of N can be additionally provided by legumes cover crop and if N losses are drastically reduced. However, we show that organic farming can, still, play an important role in feeding the world and in reaching a sustainable and fair food system. Indeed, conversion up to 60% of global agriculture would be feasible if coupled with a reduction in global food consumption or a decrease in global food wastage. This shows and confirms that changes in both the food supply and the food demand are required to achieve a sustainable food system (Springmann et al. 2018). Such a conversion would have huge impacts on consumers, with strong changes in the global food basked provided by agricultural systems (Chapter 3). Nevertheless, we also showed how this conversion would come with higher diversification and nutritional value of such food basket (Chapter 3), likely to benefit human health (Baudry et al. 2018). In order to drive this dietary change, integrated approaches would be necessary. They include a combination of e.g. education campaigns especially in schools, consumer information and labeling, economic incentives and fiscal measures, and more direct behavior restrictions (Mozzafarian et al. 2012). The definition of new dietary guidelines can also play an important role (Ritchie et al. 2018), even if providing information without additional economic or legislation changes has limited influence on consumer's behaviour (Mozzafarian et al. 2012). Meaningfully, along with driving dietary changes, reducing food loss and waste will require measures across the entire food supply chain (Springmann et al. 2018). Investments in technological skills, food storage, transport, and distribution capacity will be necessary, especially in developing countries (Springmann et al. 2018). On a consumer behavior side, education and awareness campaigns, packaging, food labeling, and policies to drive changes in individual and businesses behaviors are highly needed.

Converting 60% of the global agricultural area to organic farming would still represent a key challenge and an extreme opportunity for the organic sector. To reach such goal, strategies like the so-called "Organic 3.0"[9] are welcome to support the development and the adoption of organic farming systems worldwide. This can be reached only through strong relationships between consumers, producers and public policies (Arbenz et al. 2016). In view of the results presented in this dissertation, organic farming will not represent a "Holy Grail" farming system that would, alone, allow reaching a sustainable food system. Nonetheless, organics may play an essential role in regions where it has a comparative advantage over conventional systems, and the organic sector remains with huge growth margins at the global scale. The increasing adoption of organic systems will play a huge potential to decrease the environmental burdens of conventional farming systems and should thus be supported by public policies. In addition, beyond its adoption, organic farming is extremely useful to increase the sustainability and the diversification of farming systems (Seufert & Ramankutty 2017) (Figure 16). Indeed, in recent years, the adoption of organic farming sustainable practices by conventional systems, such as cover cropping, composting, and others have drastically increased and provided some environmental benefits (Conservation Technology Information Center 2008; Pretty et al. 2018).

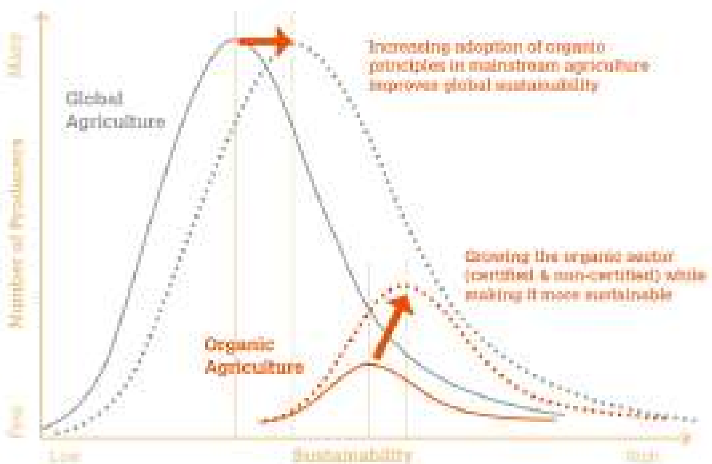


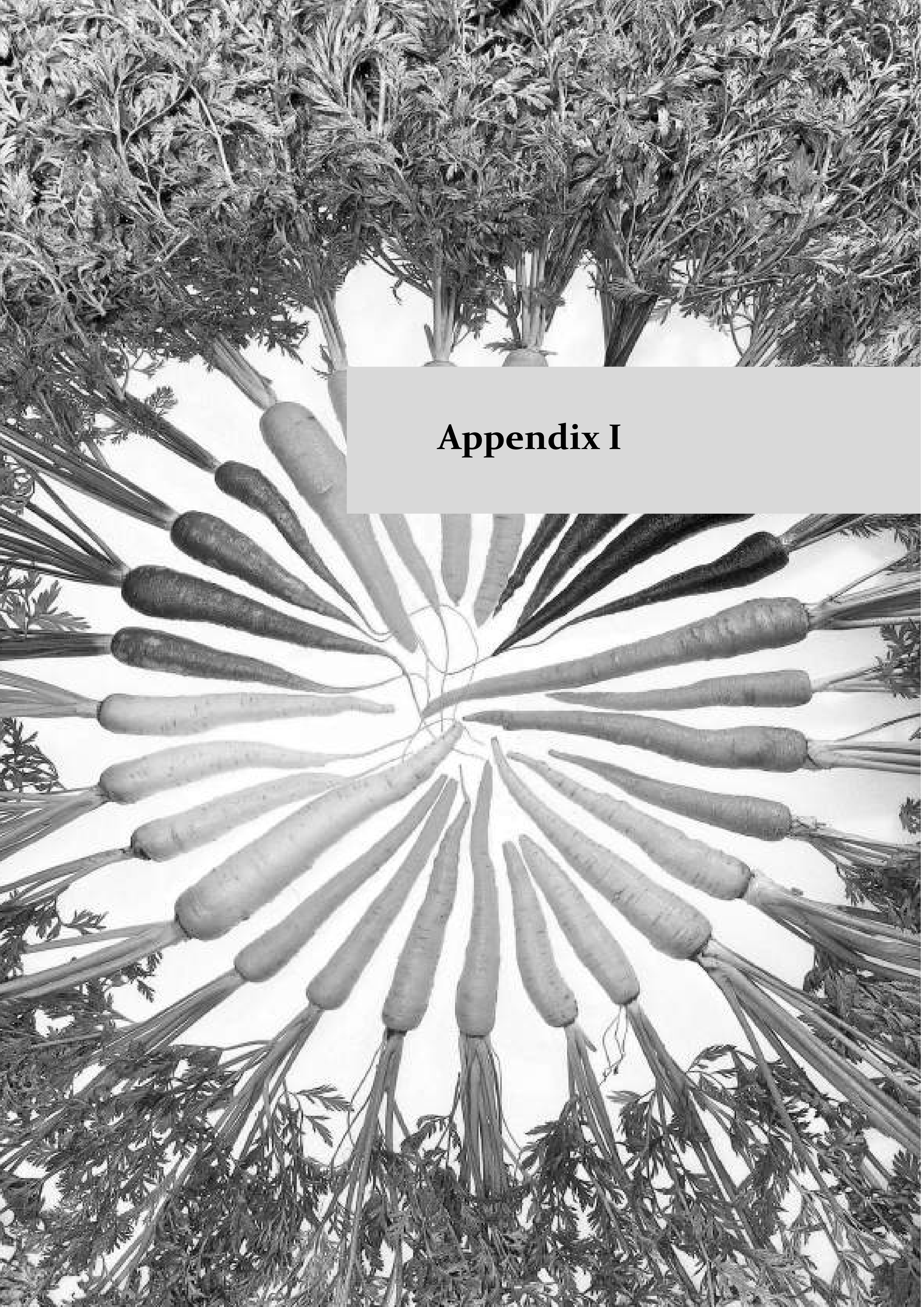
Figure 16. Trends towards more sustainable agricultural production. Source: "*Organic 3.0 – the truly sustainable farming and consumption*" (Arbenz et al. 2016)

[9] Organic 3.0 is an action manifesto for enabling a widespread uptake of sustainable farming systems and markets based on organic principles and imbued with a culture of innovation, of progressive improvement towards best practice, of transparent integrity, of inclusive collaboration, of holistic systems, and of true value pricing (Arbenz et al. 2016).

Conclusions

In this Ph.D., we analyzed the scientific literature focusing on estimating the role that organic farming may have in feeding the planet and leading the transition towards a sustainable, global food security. This analysis highlights the research gaps of previous studies and models, namely (i) having oversimplified certain systemic changes occurring when organic systems are adopted and (ii) having missed a critical ecological phenomenon by not considering the key role that N cycling plays in sustaining crop yields in organic systems. We have, thus, investigated how crop rotations –which systemically differ between organic and conventional systems- change when organic farming is adopted. We have converted this information into global maps of the harvested areas of crops under organic management, and we have investigated the consequences of such changes on global organic food production. In order to take into account N availability and flows, we designed the GOANIM, a linear optimization model, developed in R Open 3.3.2, to estimate N cycling and its consequences on organic global food production in scenarios of drastic organic spatial expansion at the global scale. We have used this model to simulate several (52) supply-side scenarios, including growing conversion shares of global agricultural systems to organic farming up to a full organic world. Finally, we have compared each of there scenarios to different estimates of the food demand, including different dietary and food wastage reduction patterns, for a total of 312 supply-demand combinations. Only 107 of these combinations resulted to be feasible (34%), showing that N limitation may represent a major constraint to organic farming development at the global scale. In conclusion, the GOANIM model allowed bringing the understanding of the role that organic farming could play in feeding the world a significant step forward. This work and the GOANIM model also opens new research questions and avenues for further understanding how sustainable farming system may develop and for reaching a fair and sustainable global food system.

Appendix I



Supplementary Tables

Table S1. Rotation summary data and results of the non-parametric ANOVA (Kruskal-Wallis) showing the effect of the system (organic *vs* conventional farming), region (Europe, North America *vs* Others) and system × region interactions, and their significance levels on the percentage of the timeshare under each crop category (rotation dataset).

Model			Rotation length	Number of crop categories	Primary cereal	Secondary cereal	Cereal/ Pulse	Pulse	Oilseed	Root	Industrial	Vegetable	Fodder	Number of catch crops	Number of undersown cover crops
	Organic rotation		4.5	3.5	32%	15%	4%	16%	2%	5%	1%	4%	21%	0.78	0.61
	Conventional rotation		3.8	2.9	44%	13%	1%	15%	4%	7%	2%	7%	7%	0.32	0.07
	Fixed effects	*DF*	*ChiSq*	*ChiSq*										*ChiSq*	*ChiSq*
Poisson GLM	System	1	3.6 *	6.3 *										15.6 ***	15.9 ***
	Region	2	9.0 *	11.6 **										13.6 **	12.6 **
	System × Region	2	0.6	1.6										6.87 *	7.5 *
	Group	*DF*			*ChiSq*	*ChiSq*	*ChiSq*	*ChiSq*	*ChiSq*	*ChiSq*	*ChiSq*	*ChiSq*	*ChiSq*		
Kruskal-Wallis	System	1			12.5 ***	3.7	8.5 **	0.6	2.2	1.6	0.1	1.6	31.4 ***		
	Region	2			41.2 ***	39.3 ***	39.3 ***	24.6 ***	3.9	51.1 ***	5.4 †	9.33 **	8.5 *		
	Interaction (S × R)	5			54.6 ***	46.1 ***	46.2 ***	26.7 ***	6.6	55.0 ***	6.1	10.9 †	42.3 ***		

DF degrees of freedom; *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$; † $P < 0.1$

Table S2. Land-use summary data and results of the non-parametric ANOVA (Kruskal-Wallis) showing the effect of the system (organic *vs* conventional farming), region (Europe, North America *vs* Others) and system × region interactions, and their significance levels on the percentage of the area under each crop category (land-use dataset).

Model			Cereal	Pulse	Oilseed	Root	Industrial	Vegetable
	Organic land use		61%	11%	9%	2%	3%	14%
	Conventional land use		69%	8%	10%	6%	1%	5%
	Group	*DF*	*ChiSq*	*ChiSq*	*ChiSq*	*ChiSq*	*ChiSq*	*ChiSq*
Kruskal-Wallis	System	1	0.43 †	0.01	7.79 **	21.2 ***	0.53	3.80 †
	Region	4	13.2 **	6.33 *	5.10 †	3.48	6.85 *	5.52 †
	Interaction (S × R)	9	16.9 **	36.5 ***	20.3 **	26.1 ***	12.1 *	10.9 †

DF degrees of freedom; *** P < 0.001; ** P < 0.01; * P < 0.05; † P < 0.10;

Table S3. Results of the permutational analysis of variance (ADONIS) on the rotation and on the land-use datasets showing the significance of the effects of system (organic *vs* conventional farming), region (Europe, North America *vs* Others) and of the interaction system × region, and their share of explained variance (R^2).

	Rotation dataset				Land-use dataset			
Effect	*DF*	*Sum of squares*	*P-value*	*R^2*	*DF*	*Sum of squares*	*P-value*	*R^2*
System	1	2.42	0.001 ***	0.051	1	0.38	0.001 ***	0.051
Region	2	5.51	0.001 ***	0.114	2	0.85	0.002 **	0.090
System × Region	2	0.31	0.487	0.006	2	0.61	0.007 **	0.065

DF degrees of freedom; *** P < 0.001; ** P < 0.01; * P < 0.05; † P < 0.10;

Table S4. List of studies included in the rotation database (author, year, journal and title) and the country in which the studies were conducted.

Study	Author	Year	Journal	Title	Country
1	Acs et al.	2007	Biological Agriculture & Horticulture	Comparison of conventional and organic arable farming systems in the Netherlands by means of bio-economic modeling	Netherlands
2	Andrist-Rangel et al.	2007	Agriculture, Ecosystems & Environment	Long-term K dynamics in organic and conventional mixed cropping systems as related to management and soil properties	Sweden
3	Benoit et al.	2015	Agriculture, Ecosystems & Environment	Nitrous oxide emissions and nitrate leaching in an organic and a conventional cropping system (Seine basin, France)	France
4	Chirinda et al.	2010	Agriculture, Ecosystems & Environment	Soil properties, crop production and greenhouse gas emissions from organic and inorganic fertilizer-based arable cropping systems	Denmark
5	Garnier et al.	2016	Environmental Science & Policy	Reconnecting crop and cattle farming to reduce nitrogen losses to river water of an intensive agricultural catchment (Seine basin, France): past, present and future	France
6	Küstermann et al.	2008	Renewable Agriculture and Food Systems	Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems	Germany

7	Lazzerini et al.	2014	Italian Journal of Agronomy	A simplified method for the assessment of carbon balance in agriculture: An application in organic and conventional micro-agroecosystems in a long-term experiment in Tuscany, Italy	Italy
8	Lee et al.	2014	The Journal of Horticultural Science and Biotechnology	Effects of hairy vetch, rye, and alternating cultivation of rye-vetch cover crops on soil nutrient concentrations and the production of red pepper (Capsicum annuum L.)	South Korea
9	Mancinelli et al.	2010	Applied Soil Ecology	Soil carbon dioxide emission and carbon content as affected by conventional and organic cropping systems in Mediterranean environment	Italy
10	Osler et al.	2008	Applied Soil Ecology	Soil micro arthropod assemblages under different arable crop rotations in Alberta, Canada	Canada
11	Pardo et al.	2014	Outlook on Agriculture	Economic profitability analysis of rainfed organic farming in SW Spain	Spain
12	Smith et al.	2004	Renewable Agriculture and Food Systems	Profitability and risk of organic production systems in the northern Great Plains	Canada
13	Wortman et al.	2012	Renewable Agriculture and Food Systems	Soil fertility and crop yields in long-term organic and conventional cropping systems in Eastern Nebraska	USA
14	Zentner et al.	2011	Renewable Agriculture and Food Systems	Effects of input management and crop diversity on economic returns and riskiness of cropping systems in the semi-arid Canadian Prairie	Canada
15	Acher et al.	2007	Agronomy Journal	Leaching and crop uptake of N, P and K from organic and conventional cropping systems on a clay soil	USA
16	Aronsson et al.	2007	American Society of Agronomy	Soil Use and Management	Sweden
17	Auerswald et al.	2006	Soil and Tillage Research	Influence of cropping system on harvest erosion under potato	Germany
18	Baeckström et al.	2006	Communications in Soil Science and Plant Analysis	Nitrogen Use Efficiency in an 11-Year Study of Conventional and Organic Wheat Cultivation	Sweden
19	Cavigelli et al.	2009	Renewable Agriculture and Food Systems	Long-term economic performance of organic and conventional field crops in the mid-Atlantic region	USA
20	Chirinda *et al.*	2008	16th IFOAM Organic World Congress	Effects of organic matter input on soil microbial properties and crop yields in conventional and organic cropping systems	Denmark
21	Clark et al.	1999	Agriculture, Ecosystems and Environment	Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems	USA
22	Delmotte et al.	2011	European Journal of Agronomy	On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate	France
23	Deria et al.	2014	Organic Wheat Production and Soil Nutrient Status in a Mediterranean Climatic Zone		Australia
24	Doltra	2010	ICROFS News	A better nitrogen use to improve organic wheat production	Denmark
25	Eltun et al.	2002	Agriculture, Ecosystems and Environment	A comparison of environmental, soil fertility, yield, and economical effects in six cropping systems based on an 8-year experiment in Norway	Norway
26	Entz et al.	2005	Proceedings of the First Scientific Conference of the International Society of Organic Agriculture Research	Influence of organic management with different crop rotations on selected productivity parameters in a long-term Canadian field study	Canada
27	Fjelkner-Modig et al.	2000	Acta Agriculturae Scandinavica, Section B - Soil & Plant Science	The Influence of Organic and Integrated Production on Nutritional, Sensory and Agricultural Aspects of Vegetable Raw Materials for Food Production	Norway
28	Gelfand et al.	2010	Environmental Science and Technology	Energy efficiency of conventional, organic, and alternative cropping systems for food and fuel at a site in the U.S. Midwest	USA
29	Kirchmann	2007	Agronomy Journal	Comparison of Long-Term Organic and Conventional Crop–Livestock Systems on a Previously Nutrient-Depleted Soil in Sweden	Sweden
30	Kitchen et al.	2003	Australian Journal of Agricultural Research	Comparing wheat grown in South Australian organic and conventional farming systems. 1. Growth and grain yield	Australia
31	Mazzoncini	2006	Aspects of Applied Biology 79, What will organic farming deliver? COR 2006	Sunflower under conventional and organic farming systems: results from a long term experiment in Central Italy	Italy
32	Murphy	2007	Field Crops Research	Evidence of varietal adaptation to organic farming systems	USA
33	Nguyen	1995	Agriculture, Ecosystems and Environment	Energy and labour efficiency for three pairs of conventional and alternative mixed cropping (pasture-arable) farms in Canterbury, New Zealand	New Zealand
34	Peck et al.	2006	HortScience	Apple Orchard Productivity and Food Quality under Organic, Conventional, and Integrated Management	USA
35	Pimentel	2005	BioScience	Environmental, Energetic, and Economic Comparisons of Organic and Conventional Farming Systems	USA
36	Porter et al.	2003	Agronomy Journal	Organic and Other Management Strategies with Two- and Four-Year Crop Rotations in Minnesota	USA

37	Posner et al.	2008	Agronomy Journal	Organic and conventional production systems in the Wisconsin integrated cropping systems trials: I. Productivity 1990-2002	USA
38	Ryan et al.	2004	Journal of the Science of Food and Agriculture	Grain mineral concentrations and yield of wheat grown under organic and conventional management	Australia
39	Sermenli et al.	2007	Journal of Sustainable Agriculture	Effect of Strip intercropping and organic farming systems on quantity and quality of maize yield in a Mediterranean region of Turkey	Turkey
40	Smith et Gross	2006	Weed Science	Weed community and corn yield variability in diverse management systems	USA
41	Smolik et al.	1995	American Journal of Alternative Agriculture	The relative sustainability of alternative, conventional, and reduced-till farming systems	USA
42	Tamm et al.	2009	Agronomy Research	Spring cereals performance in organic and conventional cultivation	Estonia
43	Teasdale	2007	Agronomy Journal	Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement	USA
44	Thorup-Kristensen	1999	Organic eprints	An organic crop rotation aimed at self-sufficiency in nitrogen	Denmark
45	Treadwell et al.	2008	HortScience	Nutrient management with cover crops and compost affects development and yield in organically managed sweet potato systems	USA
46	Welsh et al.	2009	Agronomy Journal	High yielding organic crop management decreases plant-available but not recalcitrant soil phosphorus	Canada
47	Delate et Cambardella	2004	Agronomy Journal	Agroecosystem performance during transition to certified organic grain production	USA
48	Korsaeth et al.	2012	Applied and Environmental Soil Science	N, P, and K budgets and changes in selected topsoil nutrients over 10 years in a long-term experiment with conventional and organic crop rotations	Norway
49	Martini et al.	2004	Field Crops Research	Yield increases during the organic transition: Improving soil quality or increasing experience?	USA
50	Posner et al.	2005	WICST 10th Technical Report (http://wicst.wisc.edu/wp-content/uploads/wicst-yields-yield-variability-and-yield-trends-1990-20021.pdf)	The Wisconsin Integrated Cropping Systems Trials: yields, yield variability, and yield trends 1990-2002	USA
51	Thorup-Kristensen et al.	2012	European Journal of Agronomy	Crop yield, root growth, and nutrient dynamics in a conventional and three organic cropping systems with different levels of external inputs and N re-cycling through fertility building crops	Denmark
52	Torstensson	2006	Agronomy Journal	Nutrient use efficiencies and leaching of organic and conventional cropping systems in Sweden	Sweden
53	Campanelli et al..	2012	Journal of Sustainable Agriculture	Crop Production and Environmental Effects in Conventional and Organic Vegetable Farming Systems: The Case of a Long-Term Experiment in Mediterranean Conditions (Central Italy)	Italy
54	Coulter et al.	2011	Agronomy Journal	Agronomic performance of cropping systems with contrasting crop rotations and external inputs	USA
55	Drinkwater et al.	2000	Plant and Soil	Effects of tillage intensity on nitrogen dynamics and productivity in legume-based grain systems	USA
56	Liebhardt et al.	1989	Agronomy Journal	Crop production during conversion from conventional to low-input methods	USA
57	Lotter et al.	2003	American Journal of Alternative Agriculture	The performance of organic and conventional cropping systems in an extreme climate year	USA
58	Mahoney et al.	2004	Renewable Agriculture and Food Systems	Profitability of organic cropping systems in southwestern Minnesota	USA
59	Reganold et al.	1987	Nature	Long-term effects of organic and convention farming on soil erosion	USA
60	Temple et al.	1994	American Journal of Alternative Agriculture	An interdisciplinary, experiment station-based participatory comparison of alternative crop management systems for California's Sacramento valley	USA
61	Gallaher et al.	2015	Renewable Agriculture and Food Systems	Organic management and legume presence maintained phosphorus bioavailability in a 17-year field crop experiment	USA
62	Knudsen et al.	2014	Journal of Cleaner Production	Carbon footprints of crops from organic and conventional arable crop rotations - Using a life cycle assessment approach	Denmark
63	Moreno et al.	2011	Soil and Tillage Research	Rainfed crop energy balance of different farming systems and crop rotations in a semi-arid environment: Results of a long-term trial	Spain
64	Sánchez de Cima et al.	2015	International Agrophysics	Organic farming and cover crops as an alternative to mineral fertilizers to improve soil physical properties	Estonia

65	Eltun and Nordheim	1999	Designing and testing crop rotations for organic farming Danish Research Centre for Organic Farming DARCOF Report no. 1	Yield results during the first eight years crop rotation of the Apelsvoll cropping system experiment	Norway
66	Melero et al.	2006	Soil and Tillage Research	Chemical and biochemical properties in a silty loam soil under conventional and organic management	Spain
67	Stalenga	2007	Journal of Plant Nutrition	Applicability of different indices to evaluate nutrient status of winter wheat in the organic system	Poland
68	Benoit et al.	2016	Agricultural Systems	A participative network of organic and conventional crop farms in the Seine Basin (France) for evaluating nitrate leaching and yield performance	France
69	Cooper et al.	2011	Journal of Agricultural and Food Chemistry	Effect of Organic and Conventional Crop Rotation, Fertilization, and Crop Protection Practices on Metal Contents in Wheat (Triticum aestivum)	USA
70	Jaradat et al.	2011	Agronomy Journal	Statistical modeling of yield and variance instability in conventional and organic cropping systems	USA
71	Wander et al.	1994	Soil Science Society of America Journal	Organic and Conventional Management Effects on Biologically Active Soil Organic Matter Pools	USA
72	Wu et al.	2003	Geoderma	Soil management effects on the non-limiting water range	USA
73	Ryan et al.	2009	Weed Research	Weed-crop competition relationships differ between organic and conventional cropping systems	USA
74	Wortman	2010	Renewable Agriculture and Food Systems	Increased weed diversity, density and above-ground biomass in long-term organic crop rotations	USA
75	Adamtey et al.	2016	Agriculture, Ecosystems & Environment	Productivity, profitability and partial nutrient balance in maize-based conventional and organic farming systems in Kenya	Kenya
76	Korsaeth et al.	2008	Relations between nitrogen leaching and food productivity in organic and conventional cropping systems in a long-term field study	Agriculture, Ecosystems and Environment	Norway
77	Lien et al.	2006	Comparison of risk in organic, integrated and conventional cropping systems in eastern Norway	Journal of Farm Management	Norway

Supplementary Figures

Figure S1. Map showing the 77 study sites that were included in the rotation dataset. The map was generated using R: A Language and Environment for Statistical Computing 3.3.2 (R Core Team, Vienna, Austria, 2016, https://www.R-project.org) and the "rworldmap" package (South A. Package 'rworldmap. *CRAN Repos.*, 2016).

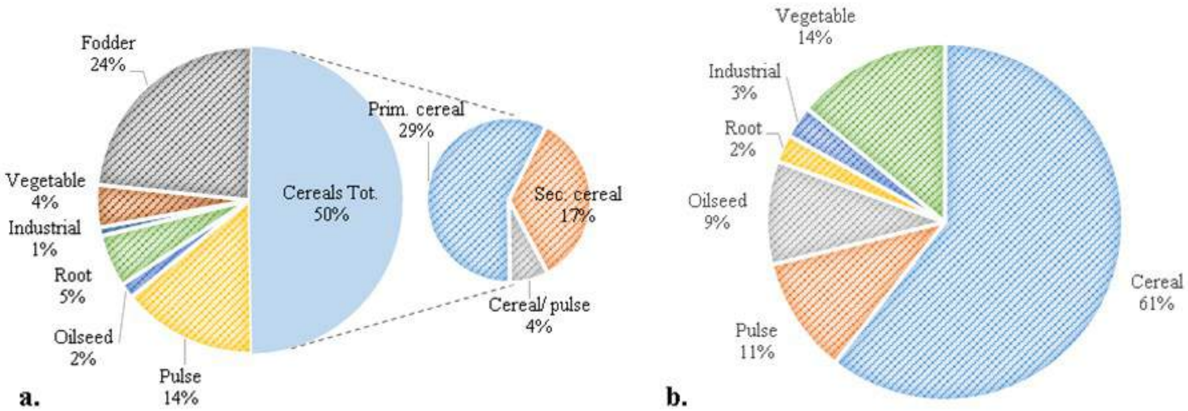


Figure S2. Average composition of organic (a) rotations and (b) land use by crop category. Shares are calculated as the percentage of total crop rotation length occupied by each crop category and the share of the area occupied by each crop category, respectively.

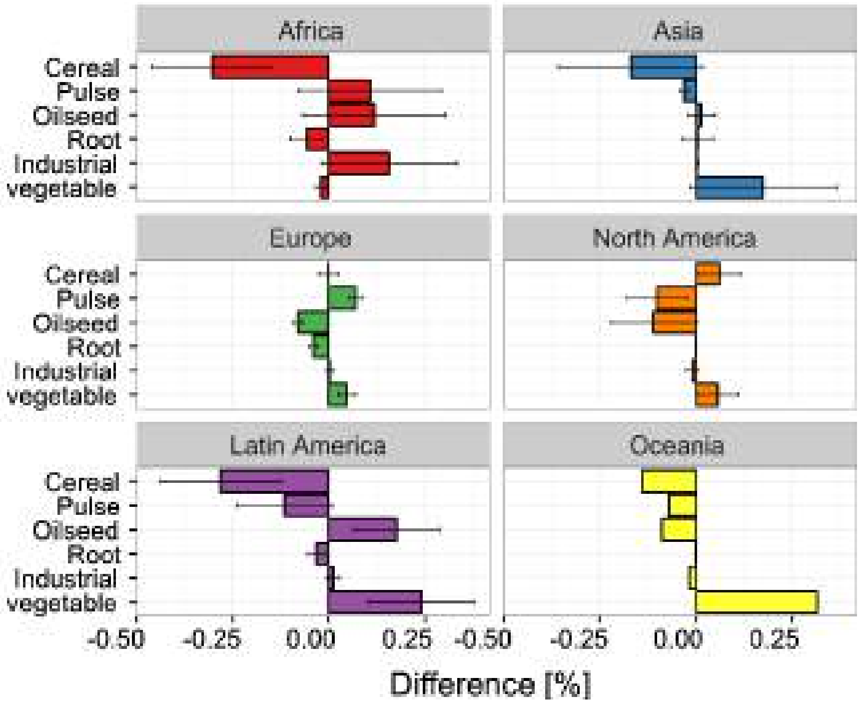


Figure S3. Difference (organic minus conventional, ±standard error of the mean) in crop categories between organic and conventional land use for the extended global regions (in % of harvested area of each crop in relation to the total cropland area under organic *vs* conventional farming) based on the land-use dataset. Number of countries: Africa (7), Asia (6), Europe (29), North America (2), Latin America (9), Oceania (2).

Appendix II

Supplementary Methods

Cropland-use simulations

We estimated the harvested areas in the 100% organic farming scenario at a 5-min resolution according to the following four steps:

(i) We first calculated the timeshare (in %) of the seven crop categories considered (i.e., primary and secondary cereals, pulses, oilseed crops, root crops, temporary fodders and industrial crops) in both organic and conventional rotations and for each global region (i.e., Europe, North and South America, Africa, Asia and Oceania) using the data from Barbieri et al. (2017). We then calculated the organic-to-conventional ratio of those timeshares for each crop category and each global region. Finally, for each global region, we selected the crop categories for which the corresponding ratio was below one (Table S6), i.e., those crop categories for which the cropland-use share is likely to be lower in organic than in conventional farming;

(ii) We multiplied the maps of harvested areas for the years circa 2000 (Monfreda et al. 2008) – assumed to be a proxy for the conventional harvested cropland areas – of these selected crop categories by the above-mentioned ratios below one (hereafter referred to as the 'tightening coefficient'), according to Equation S1. This multiplication yielded the amount of land that is freed up by those crop categories that are less frequent in organic than in conventional rotations;

(iii) We allocated such freed-up land to the remaining crop categories, i.e., to the crop categories for which the timeshare is higher in organic than in conventional rotations. The allocation was performed according to the timeshare of these categories in the organic rotations (i.e., using the coefficients reported in Table S6) (Equation S2). These coefficient were calculated from Barbieri et al. (2017) as in this example: assume that the freed-up land has to be allocated to pulses and temporary fodders, and that these two crop categories represent respectively the 15 % and the 30 % of the original crop rotation. Given the example, the coefficient reported in Table S6 would have been calculating as follows:

$$p\ (pulses) = \frac{15}{(30+15)}; p\ (fodders) = \frac{30}{(30+15)}$$

(iv) Finally, for each global region, we disaggregated the resulting cropland use into the seven crop categories considered for the 38 crop species (Table S5), as explained in the core of the manuscript.

All of those estimations were performed at the grid-cell scale.

Equation S1 $$FL_k = \sum_{i=1}^{7} CL_{i,k} \times r_{i,k}$$

where: FL_k is the total harvested area that is freed up in the global region k, $CL_{i,k}$ is the current (i.e., conventional) harvested area of crop category i in the region k, and $r_{i,k}$ is the ratio between the organic and conventional rotation timeshare of the crop category i in the region k obtained from Barbieri *et al.* (Barbieri et al. 2017), with $r_{i,k} < 1$.

Equation S2 $$\boldsymbol{AL_{j,k}} = \sum_{i=1}^{7} \boldsymbol{FL_k} \times \boldsymbol{p_{j,k}}$$

where: $AL_{j,k}$ is the land allocated to crop j in the global region k, $p_{j,k}$ is the 'expanding coefficient' used to redistribute the freed-up land to the crop categories that exhibit higher timeshares in organic than in conventional rotations in the region k, also obtained from Barbieri et al. (2017).

We also took the possibility of applying an alternative method to simulate the organic cropland use in a 100% organic scenario into consideration. Such an alternative would consist of starting from the crop categories that would 'expand' in a full organic scenario, i.e., those crop categories for which the ratio between the timeshare in organic *vs* conventional rotations is greater than one (Table S6), and of then computing the symmetrical calculation rather than the one applied in this study. However, this alternative led to inconsistent results for the following reasons: (i) this approach did not make it possible to introduce new crop categories (e.g., temporary fodders) in grid cells where they are currently absent (as is clearly allowed by our method; Table S7); (ii) several crop categories would disappear in a considerable number of grid cells to leave enough area for the 'expanding crop categories' that are more frequent in organic rotations; (iii) using the 'expanding coefficients' provided in Table S6 to estimate the land occupied by those crop categories that are more frequent in organic rotations resulted in total amounts of cropland that exceeded the current total harvested land in many grid cells, which was in contradiction with our assumption of a constant total harvested area. We thus discarded this alternative method even though the method we finally applied was somewhat conservative (i.e., it resulted in moderate changes in harvested cropland area).

Organic yield estimation

We estimated species-based crop yields in organic farming based on the conventional yield maps developed by Monfreda *et al.* (2008). Organic yields were estimated by applying organic-to-conventional yield gap coefficients (Ponisio et al. 2015) at the crop category level. Yield gap was assumed to be inexistent in the regions where the current conventional yield is lower than 55% of the corresponding potential attainable yield (Erb et al. 2016; Kilcher 2007). The spatially-explicit database of potential attainable yields was taken as a reference (Mueller et al. 2012).

Sensitivity analysis

We performed a sensitivity analysis on both (i) the coefficients used to estimate the cropland-use changes (i.e., the organic-to-conventional ratios of timeshares in rotations; and (ii) the 'expanding' coefficients to redistribute the freed-up land) and the coefficients used to disaggregate the crop categories to the crop species level. For the first analysis, we tested four different sets of coefficients by increasing the organic-to-conventional ratio of timeshares in rotations of primary cereals and pulses by ±25% in each grid cell. To do this, we increased the $r_{i,k}$ ratio in Equation S1 by ±25% for these two crop categories and consequently decreased the abundance of the other six crop categories. Based on these 'new' rotation timeshares, we re-calculated the allocation coefficients $p_{j,k}$ in Equation S2. Results showed that although the variation of the coefficients $r_{i,k}$ had a bigger impact than the variation of the coefficient $p_{j,k}$, variation in one crop category induced only limited variation in the total crop production (Table S15).

For the second analysis, we tested different disaggregation combinations for the primary cereal crop category (maize, rice and wheat). By starting from the share among crop species within the primary cereal crop category that is observed in conventional farming (Table S5), we tested three sets of disaggregation coefficients. To do so, we increased the share of each crop species by 25% and, consequently, we decreased the share of the remaining crop species by an equal amount. Hence, we tested three possible combinations: (i) Maize share +25%, rice and wheat share -12.5%; (ii) rice +25%, maize and wheat -12.5%; and (iii) wheat +25%, maize and rice -12.5%. Results show that, overall, the total protein and energy produced by primary cereals depend little on the share of crop species within that crop category (Table S15). Therefore, the use of the current conventional shares to disaggregate the crop categories to the crop species does not significantly influence the final aggregated production results of the 100% organic scenario.

Repartitioning of the total energy production into use categories

We tested an alternative approach to calculate the repartition between feed, food and other uses in the 100% organic scenario, compared to the one described in the main text. In this alternative approach we also keep fix the total amount of feed calculated for conventional farming also for the organic counterpart, and we recalculate the share of food for each crop category as the difference between total production, feed and other uses. This alternative approach did not result is any significant difference in terms of number of people fed by organic farming (Table S13).

Supplementary Tables

Table S5. List of the 38 arable crop species considered (grouped into seven crop categories), and their coefficients for the disaggregation of the organic simulated cropland use to the crop species level. Within a given crop category, the sum of the disaggregation coefficients across the crop species is equal to 100%. n.e.s.: not elsewhere specified.

Crop category	Crop species	Crop species disaggregation coefficient			
		Europe	North America	Africa	South America, Asia, Oceania
Primary cereals	Maize	27.37%	45.40%	58.84%	19.62%
	Rice	0.89%	1.78%	17.65%	37.91%
	Wheat	71.74%	52.82%	23.52%	42.48%
Secondary cereals	Barley	60.81%	53.57%	9.82%	38.91%
	Buckwheat	1.78%	0.62%	0.00%	3.10%
	Millet	0.80%	1.24%	42.30%	19.66%
	Oat	13.59%	19.98%	0.42%	10.86%
	Rye	16.09%	2.16%	0.11%	7.50%
	Sorghum	0.37%	22.19%	47.34%	19.24%
	Triticale	6.55%	0.24%	0.01%	0.73%
Pulses	Bean	12.61%	2.64%	22.53%	22.14%
	Broadbean	5.52%	0.02%	4.78%	1.91%
	Chickpea	2.75%	0.58%	2.74%	11.17%
	Cowpea	0.25%	0.02%	50.64%	0.20%
	Lentil	1.07%	2.04%	0.77%	3.37%
	Pea	48.19%	4.32%	2.55%	3.95%
	Pigeon pea	0.00%	0.00%	2.34%	4.15%

	Pulse n.e.s.	8.78%	0.00%	8.19%	3.02%
	Soybean	20.82%	90.40%	5.45%	50.08%
Oil crops	Groundnut	0.09%	5.46%	69.90%	27.62%
	Linseed	3.51%	11.48%	1.02%	3.18%
	Rapeseed	37.94%	68.83%	0.32%	32.74%
	Sesame	0.00%	0.00%	20.60%	8.45%
	Sunflower	58.46%	14.23%	8.16%	28.01%
Root crops	Cassava	0.00%	0.00%	59.35%	20.17%
	Potato	99.92%	95.86%	6.21%	52.68%
	Sweet potato	0.08%	4.14%	12.93%	26.64%
	Yam	0.00%	0.00%	21.51%	0.51%
Temporary fodders	Alfalfa	14.26%	47.05%	5.89%	9.16%
	Clover	10.44%	5.34%	29.40%	4.72%
	Forage n.e.s.	0.00%	0.00%	27.02%	17.24%
	Grass n.e.s.	0.52%	0.00%	0.00%	2.41%
	Legume n.e.s.	13.45%	5.34%	0.07%	5.00%
	Maize	13.83%	0.17%	0.10%	4.60%
	Mixed grass	45.99%	42.11%	37.52%	56.88%
	Oilseed forage	1.51%	0.00%	0.00%	0.00%
Industrial crops	Sugar beet	99.97%	63.59%	9.14%	12.59%
	Sugarcane	0.03%	36.41%	90.86%	87.41%

Table S6. Coefficients used to calculate the organic cropland-use distribution (see Equations 1 and 2 in the Supplementary Methods) for each arable crop category and each global region.

Crop category	Global region	Organic-to-conventional ratio of timeshare (r) in rotations. Only values for 'tightening crops' (r<1) are reported	Expanding coefficient (p) to redistribute freed-up land. Only values for 'expanding crops' (r>1) are reported
Primary cereals	Europe	0.705	
Secondary cereals		0.838	
Pulses			39.81%
Oil crops		0.266	
Root crops		0.617	
Temporary fodders			60.19%
Industrial crops		0.651	
Primary cereals	North America	0.739	
Secondary cereals			35.16%
Pulses		0.888	
Oil crops		0.613	
Root crops			4.67%
Temporary fodders			60.17%

Industrial crops		0.677	
Primary cereals	Africa	0.677	
Secondary cereals			53.58%
Pulses			36.89%
Oil crops		1.000	
Root crops			9.53%
Temporary fodders		1.000	
Industrial crops		1.000	
Primary cereals	South America, Asia, Oceania	0.680	
Secondary cereals			29.11%
Pulses			20.04%
Oil crops		1.000	
Root crops			5.17%
Temporary fodders			45.68%
Industrial crops		1.000	

Table S7. Total number of grid cells with a positive cropland use by the different crop categories in the 100% conventional and in the 100% organic scenarios, as well as the number of grid cells for which new crop categories were introduced in the 100% organic scenario.

Crop category	**No. grid cells with non-null values for the given crop category in the conventional scenario**	**No. grid cells with non-null values for the given crop category in the organic scenario**	**No. and % of grid cells for which new crop categories were introduced in the organic scenario**		**No. and % of grid cells for which new crop categories were introduced on more than 5% of the total harvested grid cell area in the organic scenario**	
			[No.]	*[%]*	*[No.]*	*[%]*
Primary cereals	902826	902868	0	0	0	0
Sec. cereals	861772	921152	61149	6.6	39567	4.3
Pulses	889300	893991	7327	0.8	2942	0.3
Oilseeds	844588	844588	0	0	0	0
Root crops	868578	920925	55103	6	0	0
Industrial crops	587335	587335	0	0	0	0
Fodders	637093	784912	149130	19	103345	13.2

Table S8. List of the 164 countries considered, their corresponding global region, and the observed average yield gap defined as the difference between the current conventional crop yield and the potential attainable yield at the same location (Mueller et al. 2012)

Country	**Global region**	**Yield gap**	**Country**	**Global region**	**Yield gap**
Afghanistan	Africa	53%	Latvia	Europe	46%
Albania	Europe	47%	Lebanon	Asia	64%
Algeria	Africa	45%	Lesotho	Africa	35%
Angola	Africa	46%	Liberia	Africa	56%

Argentina	South America	74%	Libya	Africa	63%
Armenia	Asia	47%	Lithuania	Europe	49%
Australia	Oceania	68%	Luxembourg	Europe	50%
Austria	Europe	80%	Macedonia	Europe	56%
Azerbaijan	Asia	47%	Madagascar	Africa	51%
Bangladesh	Asia	78%	Malawi	Africa	45%
Belarus	Europe	42%	Malaysia	Asia	89%
Belgium	Europe	56%	Mali	Africa	56%
Belize	South America	68%	Mauritania	Africa	81%
Benin	Africa	51%	Mexico	South America	67%
Bhutan	Asia	83%	Mongolia	Asia	41%
Bolivia	South America	61%	Montenegro	Europe	54%
Bosnia and Herzegovina	Europe	45%	Morocco	Africa	55%
Botswana	Africa	43%	Mozambique	Africa	36%
Brazil	South America	66%	Myanmar	Asia	69%
Brunei Darussalam	Asia	85%	Namibia	Africa	68%
Bulgaria	Europe	45%	Nepal	Asia	71%
Burkina Faso	Africa	63%	Netherlands	Europe	79%
Burundi	Africa	48%	New Zeeland	Oceania	81%
Cambodia	Asia	69%	Nicaragua	South America	77%
Cameroon	Africa	53%	Niger	Africa	72%
Canada	North America	72%	Nigeria	Africa	50%
Central African Republic	Africa	29%	Norway	Europe	84%
Chad	Africa	63%	Oman	Asia	91%
Chile	South America	92%	Pakistan	Asia	73%
China	Asia	77%	Panama	South America	70%
Colombia	South America	83%	Papua New Guinea	Asia	85%
Congo	Africa	41%	Paraguay	South America	62%
Costa Rica	South America	87%	Peru	South America	77%
Cote d'Ivoire	Africa	45%	Philippines	Asia	81%
Croatia	Europe	63%	Poland	Europe	58%
Cuba	South America	52%	Portugal	Europe	63%
Cyprus	Africa	60%	Puerto Rico	South America	42%
Czech Republic	Europe	71%	Qatar	Asia	40%
Democratic People's Republic of Korea	Asia	56%	Republic of Korea	Asia	76%
Democratic Republic of the Congo	Africa	43%	Republic of Moldova	Europe	40%
Denmark	Europe	80%	Romania	Europe	46%
Djibouti	Africa	88%	Russian Federation	Asia	54%
Dominican Republic	South America	58%	Rwanda	Africa	42%
Ecuador	South America	75%	Saudi Arabia	Asia	88%
Egypt	Africa	99%	Senegal	Africa	60%

El Salvador	South America	71%	Serbia	Europe	54%
Equatorial Guinea	Africa	37%	Sierra Leone	Africa	59%
Eritrea	Africa	45%	Slovakia	Europe	58%
Estonia	Europe	48%	Slovenia	Europe	67%
Ethiopia	Africa	56%	Somalia	Africa	69%
Finland	Europe	68%	South Africa	Africa	74%
France	Europe	84%	South Sudan	Africa	42%
French Guiana	South America	54%	Spain	Europe	73%
Gabon	Africa	45%	Sri Lanka	Asia	63%
Gambia	Africa	57%	Sudan	Africa	58%
Georgia	Asia	54%	Suriname	South America	48%
Germany	Europe	78%	Swaziland	Africa	52%
Ghana	Africa	53%	Sweden	Europe	72%
Greece	Europe	66%	Switzerland	Europe	89%
Guatemala	South America	74%	Syrian Arab Republic	Asia	68%
Guinea	Africa	46%	Tajikistan	Asia	57%
Guinea-Bissau	Africa	51%	Thailand	Asia	75%
Guyana	South America	59%	Timor-Leste	Asia	69%
Haiti	South America	46%	Togo	Africa	40%
Honduras	South America	61%	Trinidad and Tobago	South America	70%
Hungary	Europe	60%	Tunisia	Africa	43%
Iceland	Europe	80%	Turkey	Africa	57%
India	Asia	64%	Turkmenistan	Asia	34%
Indonesia	Asia	88%	Uganda	Africa	52%
Iran (Islamic Republic of)	Asia	66%	Ukraine	Europe	48%
Iraq	Asia	80%	United Arab Emirates	Asia	99%
Ireland	Europe	72%	United Kingdom	Europe	82%
Israel	Asia	79%	United Republic of Tanzania	Africa	55%
Italy	Europe	71%	United States of America	North America	70%
Jamaica	South America	59%	Uruguay	South America	58%
Japan	Asia	86%	Uzbekistan	Asia	59%
Jordan	Asia	58%	Venezuela	South America	78%
Kazakhstan	Asia	49%	Vietnam	Asia	74%
Kenya	Africa	62%	Western Sahara	Africa	40%
Kuwait	Asia	98%	Yemen	Africa	70%
Kyrgyzstan	Asia	76%	Zambia	Africa	47%
Lao People's Democratic Republic	Asia	69%	Zimbabwe	Africa	58%

Table S9. List of the 61 crop species considered, their respective protein and energy density, and their use repartition between food, feed and other uses (retrieved from the FAOSTAT Balance Sheets).

Crop Species	Crop category	Protein [% DM]	Source	Metabolisable energy [kcal (kg DM)$^{-1}$]	Source	Food share [%]	Feed share [%]	Other share [%]
Corn	Primary cereals	9.51	INRA et al. (2016)	3977	Food Standards Agency (2002)	78	14	8
Rice		8.75	INRA et al. (2016)	4056	Food Standards Agency (2002)	88	4	8
Wheat		15.31	Food Standards Agency (2002)	3483	Food Standards Agency (2002)	48	30	8
Barley	Secondary cereals	11.75	INRA et al. (2016)	2957	INRA (2007)	14	3	56
Buckwheat		13.10	INRA (2007)	2609	INRA (2007)	78	14	8
Millet		13.10	INRA (2007)	2747	INRA (2007)	37	60	3
Oat		11.10	INRA (2007)	2501	INRA (2007)	57	39	4
Rye		10.30	INRA et al. (2016)	3114	INRA (2007)	57	38	5
Sorghum		10.85	INRA (2007)	3233	INRA (2007)	33	61	6
Triticale		11.35	INRA (2007)	3088	INRA (2007)	2	75	5
Bean	Pulses	24.80	INRA et al. (2016)	3026	INRA (2007)	83	13	4
Broadbean		29.63	INRA et al. (2016)	3000	Food Standards Agency (2002)	65	3	5
Chickpea		23.75	INRA et al. (2016)	3555	Food Standards Agency (2002)	65	3	5
Cowpea		27.00	INRA et al. (2016)	3455	Food Standards Agency (2002)	65	3	5
Lentil		27.50	INRA et al. (2016)	3300	Food Standards Agency (2002)	65	3	5
Pea		23.90	INRA et al. (2016)	3320	Food Standards Agency (2002)	77	18	5
Pigeon pea		20.35	Food Standards Agency (2002)	3455	Food Standards Agency (2002)	65	3	5
Pulse n.e.s.		16.26	Pulses average	3391	Pulses average	65	3	5
Soybean		39.60	INRA et al. (2016)	4021	Food Standards Agency (2002)	43	36	21
Coconut	Oil crops	7.31	Food Standards Agency (2002)	6861	Food Standards Agency (2002)	76	0	24
Groundnut		31.45	Food Standards Agency (2002)	5989	Food Standards Agency (2002)	59	26	15
Linseed		25.00	INRA (2007)	4281	INRA tables	43	36	21
Oil palm		9.50	INRA et al. (2016)	4681	Food Standards Agency (2002)	25	33	42
Olive		3.63	Food Standards Agency (2002)	4291	Food Standards Agency (2002)	92	0	8
Rapeseed		20.90	INRA et al. (2016)	5445	INRA et al. (2016)	45	26	29
Sesame		22.63	Food Standards Agency (2002)	6294	Food Standards Agency (2002)	57	28	15
Sunflower		24.61	Food Standards Agency (2002)	6115	Food Standards Agency (2002)	43	30	24

Cassava	Root crops	2.60	INRA et al. (2016)	3678	INRA (2007)	54	18	28
Potato		10.80	INRA et al. (2016)	3571	Food Standards Agency (2002)	81	5	14
Sweet potato		5.50	INRA et al. (2016)	3222	Food Standards Agency (2002)	83	14	3
Yam		7.94	INRA et al. (2016)	3454	Food Standards Agency (2002)	87	7	6
Sugar beet	Industrial crops	8.40	INRA et al. (2016)	2769	Food Standards Agency (2002)	64	13	23
Sugarcane		3.91	INRA et al. (2016)	3698	INRA et al. (2016)	7	22	71
Alfalfa	Fodders	20.60	INRA et al. (2016)	2245	INRA (2007)	0	100	0
Clover		21.90	INRA (2007)	2567	INRA (2007)	0	100	0
Forage n.e.s.		20.60	Alfalfa	2245	INRA (2007)	0	100	0
Grass n.e.s.		13.75	INRA et al. (2016)	2245	INRA (2007)	0	100	0
Legume n.e.s.		20.25	INRA (2007)	2340	INRA (2007)	0	100	0
Maize		10.50	INRA (2007)	2507	INRA (2007)	0	100	0
Mixed grass		14.69	INRA (2007)	2245	INRA (2007)	0	100	0
Oilseed forage		10.50	Maize	2507	Maize	0	100	0
Vetch		21.40	INRA et al. (2016)	2340	INRA (2007)	0	100	0
Apple	Other crops	2.34	Food Standards Agency (2002)	2937	Food Standards Agency (2002)	91	4	5
Banana		4.75	Food Standards Agency (2002)	3800	Food Standards Agency (2002)	94	4	2
Cashew		24.63	Food Standards Agency (2002)	6298	Food Standards Agency (2002)	1	0	0
Cocoa		24.06	Food Standards Agency (2002)	3250	Food Standards Agency (2002)	94	0	6
Coffee		16.00	Food Standards Agency (2002)	781	Food Standards Agency (2002)	96	0	4
Cotton		21.75	INRA et al. (2016)	2866	INRA et al. (2016)	17	35	48
Fruit n.e.s.		12.00	Average fruits	3472	Average fruits	1	0	0
Grape		1.88	Food Standards Agency (2002)	3000	Food Standards Agency (2002)	88	0	12
Mango		4.69	INRA et al. (2016)	3166	Food Standards Agency (2002)	1	0	0
Orange		7.03	Food Standards Agency (2002)	2642	Food Standards Agency (2002)	1	0	0
Plantain		4.00	INRA et al. (2016)	5303	Food Standards Agency (2002)	94	4	2
Rubber		13.75	INRA et al. (2016)	0	Food Standards Agency (2002)	0	0	1
Tea		30.69	http://www.o-cha.net/english/cup/pdf/38.pdf	0	Food Standards Agency (2002)	1	0	0
Tobacco		11.25	Leffingwell, Basic Chemical Constituents of Tobacco Leaf and	0	Food Standards Agency (2002)	0	0	1

			Differences among Tobacco Types (1999)					
Cabbage		17.19	INRA (2007)	2600	Food Standards Agency (2002)	1	0	0
Onion		11.36	Food Standards Agency (2002)	3272	Food Standards Agency (2002)	1	0	0
Tomato	Vegetables	9.82	Food Standards Agency (2002)	2428	Food Standards Agency (2002)	98	0	2
Vegetable n.e.s.		9.82	Tomato	2428	Tomato	98	0	2
Watermelon		10.00	INRA et al. (2016)	3875	Food Standards Agency (2002)	1	0	0

Table S10. Total protein production estimations [in millions of tons] at the global scale for each global region and by the different crop categories, and the relative organic-to-conventional production gap. Food crops refer to all crop categories that could potentially be used as food sources.

Global Region	System	All crops	Food Crops	Primary cereals	Secondary cereals	Pulses	Oil crops	Root crops	Fodders	Industrial crops	Other
Global	Organic	391.994	260.774	100.083	29.362	72.347	23.589	12.830	118.149	14.702	20.719
	Conventional	428.767	339.281	170.554	27.662	68.331	33.530	13.591	75.537	15.632	23.929
	Org-to-Conv gap	*8.6%*	*23.1%*	*41.3%*	*-6.2%*	*-5.9%*	*29.6%*	*5.6%*	*-56.41%*	*5.9%*	*13.4%*
Europe	Organic	66.837	34.456	14.713	7.201	7.558	0.856	1.525	33.133	1.851	1.065
	Conventional	71.019	47.227	24.610	10.101	1.907	3.912	2.973	23.456	2.807	1.252
	Org-to-Conv gap	*5.9%*	*27.0%*	*40.2%*	*28.7%*	*-296.3%*	*73.19%*	*48.7%*	*-41.3%*	*34.1%*	*14.9%*
Oceania	Organic	5.367	4.145	1.843	1.147	0.400	0.231	0.182	1.237	0.326	0.308
	Conventional	6.116	5.168	3.049	1.180	0.251	0.276	0.054	0.635	0.326	0.345
	Org--to-Conv gap	*12.2%*	*19.6%*	*39.6%*	*2.8%*	*-59.4%*	*16.3%*	*-237.0%*	*-94.8%*	*0%*	*10.7%*
South America	Organic	48.290	37.712	6.443	1.785	21.111	1.743	0.815	11.383	5.001	1.971
	Conventional	51.988	43.880	11.037	1.404	22.425	2.281	0.785	6.839	4.911	2.304
	Org-to-Conv gap	*7.1%*	*14.0%*	*41.6%*	*-27.1%*	*10.0%*	*35.4%*	*-3.8%*	*-66.4%*	*-1.8%*	*14.5%*
North America	Organic	80.030	50.203	20.108	5.005	22.034	1.042	1.112	30.163	0.564	2.186
	Conventional	95.801	69.393	33.460	3.752	27.878	2.256	0.796	24.397	0.816	2.446
	Org-to-Conv gap	*16.5%*	*27.6%*	*39.9%*	*-33.4%*	*31.0%*	*53.8%*	*-39.7%*	*-23.6%*	*30.9%*	*10.6%*
Africa	Organic	25.829	22.103	6.021	4.486	3.413	3.243	2.354	5.203	1.108	3.224
	Conventional	27.739	25.187	9.904	4.255	2.355	3.731	2.242	4.157	1.095	3.467
	Org-to-Conv gap	*6.9%*	*12.2%*	*39.2%*	*-5.4%*	*-44.9%*	*12.8%*	*-5.0%*	*-25.6%*	*-1.1%*	*7.1%*
Asia	Organic	144.483	112.144	50.805	9.738	17.830	16.473	6.842	37.029	5.764	11.959
	Conventional	172.028	147.996	88.268	6.965	13.441	21.042	6.734	15.882	5.648	14.048
	Org-to-Conv gap	*16%*	*24.2%*	*43.4%*	*-39.8%*	*-32.7%*	*21.7%*	*-1.6%*	*-133.2%*	*-2.0%*	*14.8%*

Table S11. Total metabolisable energy production estimations [in kcal] at the global scale for each global region and by the different crop categories, and the relative organic-to-conventional production gap. Food crops refer to all crop categories that could potentially be used as food sources.

Global Region	System	All crops	Food Crops	Primary cereals	Secondary cereals	Pulse	Oilcrops	Root crops	Fodders	Industrial crops	Other
Global	Organic	9.39e+15	7.53e+15	3.44e+15	7.52e+14	7.86e+14	8.77e+14	6.34e+14	1.70e+15	7.54e+14	4.40e+14
	Conventional	1.16e+16	1.03e+16	5.87e+15	7.09e+14	7.29e+14	1.21e+15	6.82e+14	1.14e+15	7.81e+14	5.25e+14
	Org-to-Conv gap	*19.1%*	*27.2%*	*41.4%*	*-6.1%*	*-7.8%*	*27.5%*	*7.1%*	*-49.1%*	*3.5%*	*16.3%*
Europe	Organic	1.42e+15	8.55+13	4.05e+14	1.84e+14	9.48e+13	2.76e+13	5.04e+13	5.64e+14	6.10e+13	3.56e+13
	Conventional	1.71e+15	1.29+14	6.76e+14	2.58e+14	2.41e+13	1.07e+14	9.83e+13	4.05e+14	9.26e+13	4.46e+13
	Org-to-Conv gap	*16.9%*	*34.1%*	*40.1%*	*28.7%*	*-293.3%*	*74.2%*	*48.7%*	*-39.3%*	*34.2%*	*20.1%*
Oceania	Organic	1.32e+14	1.09e+14	4.36e+13	2.94e+13	4.93e+12	5.92e+12	6.03e+12	1.78e+13	1.86e+13	5.30e+12
	Conventional	1.49e+14	1.32e+14	7.25e+13	3.02e+13	3.15e+12	7.06e+12	1.78e+12	9.24e+12	1.86e+13	6.18e+12
	Org-to-Conv gap	*11.5%*	*18.7%*	*39.8%*	*2.6%*	*-56.5%*	*16.1%*	*-238.7%*	*-92.6%*	*0%*	*14.2%*
South America	Organic	1.12e+15	9.49e+14	2.38e+14	4.98e+13	2.17e+14	6.24e+13	5.63e+13	1.60e+14	2.83e+14	5.21e+13
	Conventional	1.26e+15	1.15e+15	4.11e+14	3.99e+13	2.30e+14	8.16e+13	5.80e+13	9.50e+13	2.78e+14	6.63e+13
	Org-to-Conv gap	*11.2%*	*17.6%*	*42.1%*	*-24.8%*	*5.7%*	*23.5%*	*2.9%*	*-68.4%*	*-1.7%*	*21.4%*
North America	Organic	1.62e+15	1.16e+15	7.08e+14	1.31e+14	2.26e+14	2.44e+13	3.73e+13	4.31e+14	2.33e+13	3.63e+13
	Conventional	2.07e+15	1.69e+15	1.19e+15	9.86e+13	2.86e+14	5.27e+13	2.66e+13	3.49e+14	3.35e+13	4.26e+13
	Org-to-Conv gap	*21.8%*	*31.6%*	*40.2%*	*-32.8%*	*31.0%*	*53.7%*	*-40.9%*	*-23.5%*	*31.5%*	*14.6%*
Africa	Organic	8.20e+14	7.36e+14	1.93e+14	1.15e+14	4.09e+13	1.00e+14	1.65e+14	6.27e+13	5.23e+13	8.87e+13
	Conventional	9.37e+14	8.64e+14	3.16e+14	1.09e+14	2.97e+13	1.12e+14	1.72e+14	5.05e+13	5.17e+13	9.47e+13
	Org-to-Conv gap	*12.5%*	*14.8%*	*39.9%*	*-5.5%*	*-37.7%*	*10.7%*	*4.1%*	*-24.2%*	*-1.3%*	*6.3%*
Asia	Organic	4.27e+15	3.74e+15	1.84e+15	2.42e+14	2.02e+14	6.55e+14	3.19e+14	4.71e+14	3.11e+14	2.22e+14
	Conventional	5.50e+15	5.19e+15	3.20e+15	1.73e+14	1.55e+14	8.46e+14	3.24e+14	2.27e+14	3.05e+14	2.69e+14
	Org-to-Conv gap	*22.4%*	*28.4%*	*42.5%*	*-39.8%*	*-30.3%*	*22.6%*	*1.5%*	*-107.4%*	*-1.9%*	*17.69%*

Table S12. Cropland energy production (broken down into food, feed, and other uses) and total number of people fed, based on a 2700 kcal per capita per day diet. The grey shade indicates a crop category whose production is higher in the 100% organic scenario compared to the conventional counterpart.

Crop type	Scenario	Food [e+14 kcal]	Feed [e+14 kcal]	Other uses [e+14 kcal]
Primary Cereals	*100% organic*	28.0	3.7	2.6
	Conventional	48.0	6.2	4.7
Secondary Cereals	*100% organic*	2.2	3.2	2.1
	Conventional	2.0	3.0	2.1
Pulses	*100% organic*	4.1	2.5	1.3
	Conventional	3.6	2.4	1.3

Oilcrops	*100% organic*	4.5	1.7	2.6
	Conventional	6.1	2.4	3.6
Roots	*100% organic*	4.7	0.7	1.0
	Conventional	5.0	0.75	1.1
Industrial	*100% organic*	1.2	1.6	4.8
	Conventional	1.4	1.6	4.8
Others	*100% organic*	3.3	0.4	0.7
	Conventional	4.1	0.45	0.76
Fodders	*100% organic*		17.0	
	Conventional		11.0	

Table S13. Repartitioning of the total energy and protein produced within food, feed, and other use categories, for both the conventional baseline and the 100% organic farming scenario, and keeping the current feed production as constant.

	System	Organic	Conventional	*Org-to-conv gap*	*Organic (constant feed)*	*Org-to-conv gap (constant feed)*
Energy	Food	4.79e+15	6.99e+15	*32%*	*5.05e+15*	*28%*
	Feed	3.08e+15	2.82e+15	*-9%*	2.82e+15	*0%*
	Others	1.53e+15	1.84e+15	*17%*	1.53e+15	*17%*
Protein	Food	1.62e+8	2.23e+8	*27%*	*1.95e+8*	*12 %*
	Feed	1.78e+8	1.45e+8	*-23%*	*1.45e+8*	*0 %*
	Others	5.15e+7	6.11e+7	*16%*	*5.15e+7*	*16%*

Table S14. Sensitivity analysis of the coefficients used to simulate cropland-use changes in the 100% organic farming scenario. In Sensitivity 1 and 2, the organic-to-conventional ratios of timeshares in rotations of primary cereals have been reduced and increased by ±25%, respectively. In Sensitivity 3 and 4, the pulses 'expanding' coefficients to redistribute the freed-up land have been reduced and increased by ±25%, respectively.

		Baseline scenario	**Sensitivity 1**	**Sensitivity 2**	**Sensitivity 3**	**Sensitivity 4**
All crops	Proteins	391.99	401.82	382.19	392.84	391.20
	Difference [%]		*2.51%*	*-2.50%*	*0.22%*	*-0.20%*
	Energy	9.39E+15	9.05E+15	9.73E+15	9.43E+15	9.37E+15
	Difference [%]		*-3.65%*	*3.64%*	*0.38%*	*-0.21%*
Food crops	Proteins	252.68	238.42	266.95	250.24	254.92
	Difference [%]		*-5.65%*	*5.65%*	*-0.97%*	*0.89%*
	Energy	7.23E+15	6.59E+15	7.87E+15	7.21E+15	7.25E+15
	Difference [%]		*-8.86%*	*8.91%*	*-0.25%*	*0.27%*
Primary cereals	Proteins	100.08	75.06	125.10	100.08	100.08
	Difference [%]		*-25.00%*	*25.00%*	*0.00%*	*0.00%*

	Energy	3.44E+15	2.58E+15	4.30E+15	3.44E+15	3.44E+15
	Difference [%]		*-25.03%*	*24.96%*	*0.00%*	*0.00%*
Secondary cereals	Proteins	29.36	33.07	25.65	29.70	29.03
	Difference [%]		*12.65%*	*-12.64%*	*1.17%*	*-1.11%*
	Energy	7.52E+14	8.47E+14	6.58E+14	7.61E+14	7.44E+14
	Difference [%]		*12.62%*	*-12.56%*	*1.19%*	*-1.07%*
Pulses	Proteins	72.347	78.05	66.64	69.42	75.03
	Difference [%]		*7.88%*	*-7.88%*	*-4.03%*	*3.72%*
	Energy	7.86E+14	8.52E+14	7.20E+14	7.52E+14	8.18E+14
	Difference [%]		*8.42%*	*-8.39%*	*-4.35%*	*4.03%*
Oilseed crops	Proteins	23.589	23.58	23.58	23.58	23.58
	Difference [%]		*0.00%*	*0.00%*	*0.00%*	*0.00%*
	Energy	8.77E+14	8.77E+14	8.77E+14	8.77E+14	8.77E+14
	Difference [%]		*0.00%*	*0.00%*	*0.00%*	*0.00%*
Root crops	Proteins	12.83	14.13	11.52	12.96	12.70
	Difference [%]		*10.14%*	*-10.14%*	*1.04%*	*-0.98%*
	Energy	6.34E+14	6.89E+14	5.80E+14	6.40E+14	6.29E+14
	Difference [%]		*8.67%*	*-8.56%*	*0.99%*	*-0.82%*
Fodders	Proteins	118.149	141.73	94.56	121.44	115.12
	Difference [%]		*19.96%*	*-19.96%*	*2.79%*	*-2.56%*
	Energy	1.7E+15	2.02E+15	1.40E+15	1.76E+15	1.67E+15
	Difference [%]		*18.75%*	*-17.78%*	*3.24%*	*-2.02%*
Industrial crops	Proteins	14.702	14.70	14.70	14.70	14.70
	Difference [%]		*0.00%*	*0.00%*	*0.00%*	*0.00%*
	Energy	7.54E+14	7.54E+14	7.54E+14	7.54E+14	7.54E+14
	Difference [%]		*0.00%*	*0.00%*	*0.00%*	*0.00%*

Table S15. Sensitivity analysis of the coefficients used to disaggregate the primary cereal organic areas to the crop species level. In Sensitivity 5, 6 and 7, we tested the following 'disaggregation coefficients': maize share +25%; rice and wheat share -12.5%, respectively (Sensitivity 5); rice share +25%, maize and wheat share -12.5%, respectively (Sensitivity 6); and wheat +25%, maize and rice share -12.5% (Sensitivity 7).

Crop		**Baseline scenario**	**Sensitivity 5**	**Sensitivity 6**	**Sensitivity 7**
Maize	Proteins	29.85	22.39	33.58	33.58
	Energy	1.25E+12	9.3589E+11	1.4038E+12	1.4038E+12
Rice	Proteins	25.11	28.25	18.83	28.25
	Energy	1.16E+12	1.31E+12	8.7312E+11	1.3097E+12
Wheat	Proteins	45.12	56.40	56.40	33.84
	Energy	1.03E+12	1.2835E+11	1.2835E+11	7.7007E+11
Total	Proteins	100.08	101.40	103.17	95.67

Difference [%]		*+1.32%*	*+3.09%*	*-4.41%*
Energy	3.44E+12	3.40E+12	3.43E+12	3.48E+12
Difference [%]		*-1.11%*	*-0.20%*	*+1.30%*

Supplementary Figures

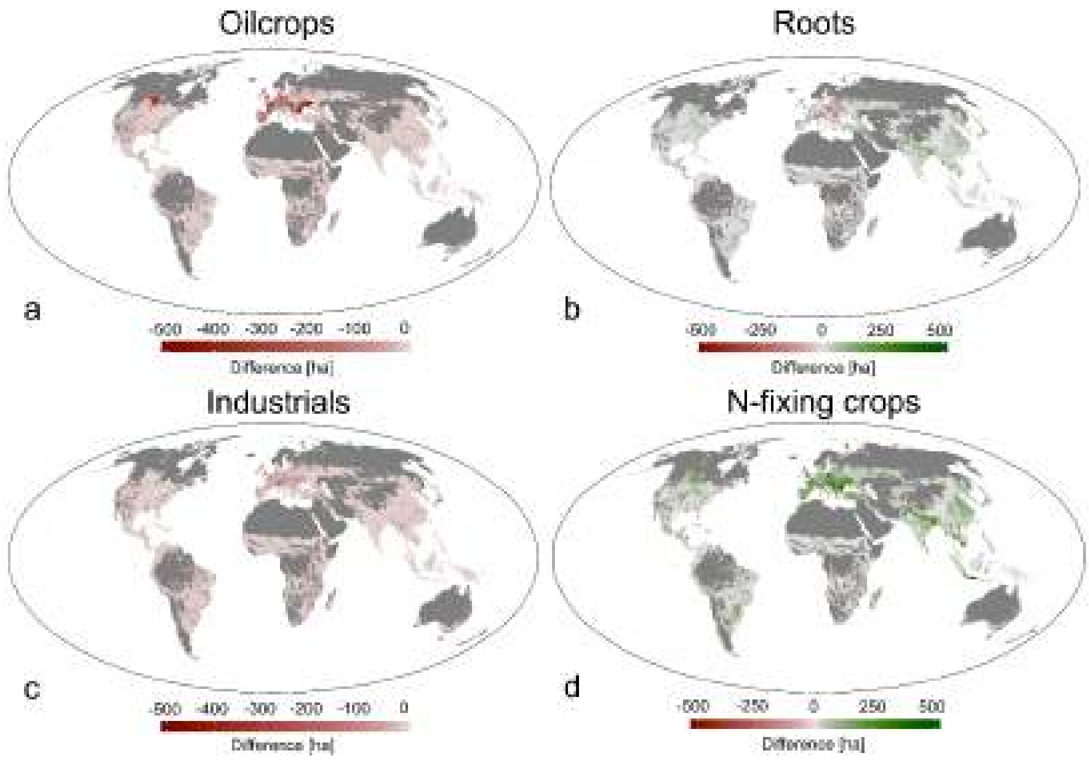


Figure S4. Difference in harvested cropland areas [ha] for major crop categories – including oil crops (a), Root crops (b), industrial crops (c) and total N-fixing crops (d) - between the 100% organic minus the 100% conventional scenario.

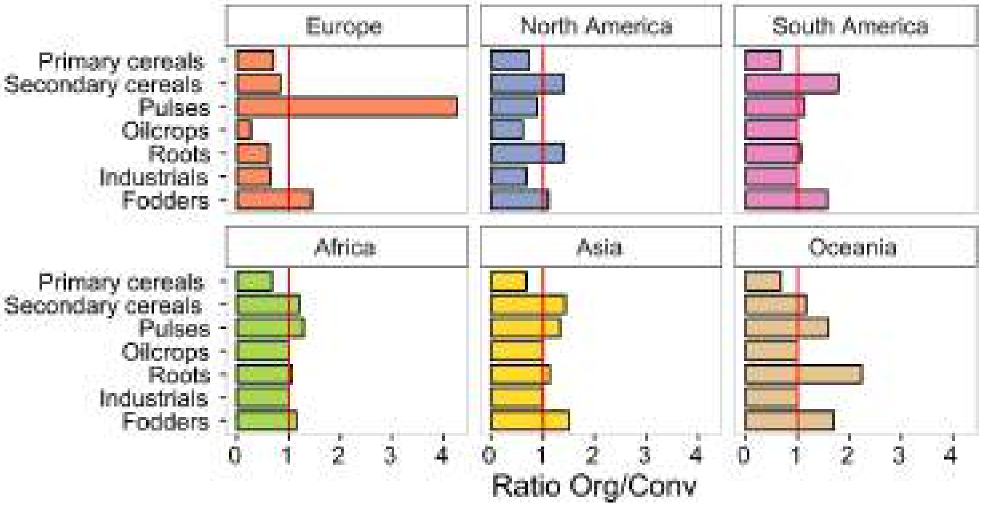


Figure S5. Average organic-to-conventional ratios between the land-use shares [%] of the different crop categories (primary cereals, secondary cereals, pulses, oil crops, root crops, industrial crops and fodders) between 100% organic minus 100% conventional scenarios for different global regions. The shares are calculated as the total fraction under each crop category divided by the total harvested area of the considered species. Values above one indicate a higher share in the organic scenario compared to the conventional baseline.

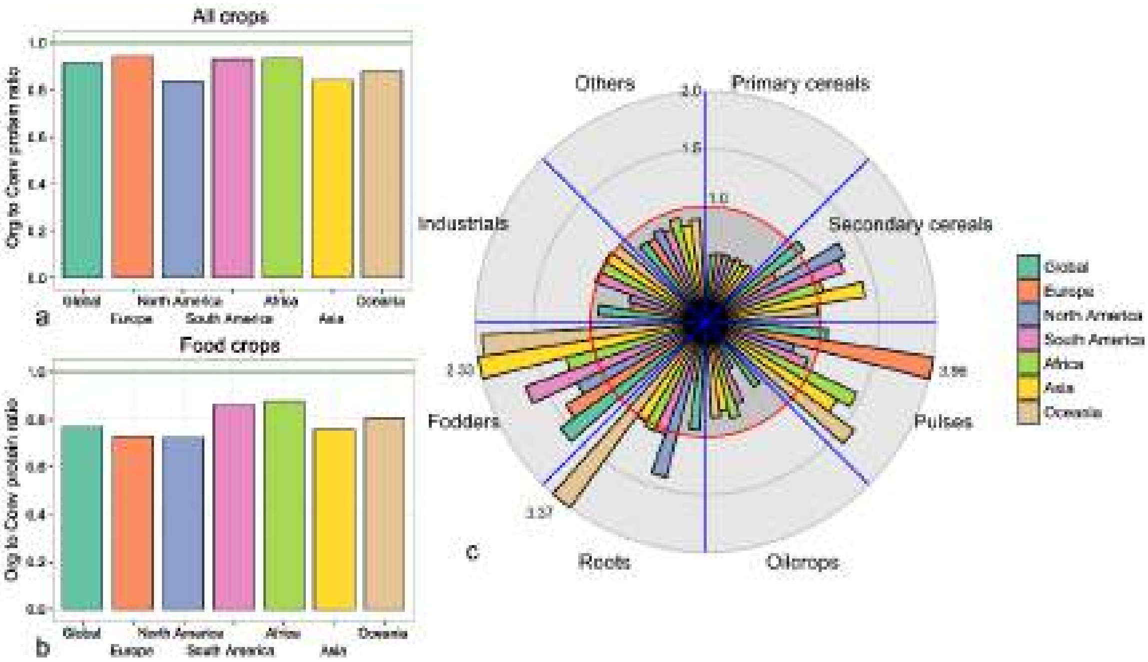


Figure S6. Organic-to-conventional protein production ratios at the global scale and for each global region and the different crop categories (considering all 61 crop species); (a) organic-to-conventional protein production ratios of all crop categories; (b) organic-to-conventional protein production ratios of food crops (i.e., all crops that could potentially be directly used for human food); (c) organic-to-conventional ratios for each global region and each crop category. Values exceeding a ratio of 2 are indicated. Precise estimated values are reported in Table S10.

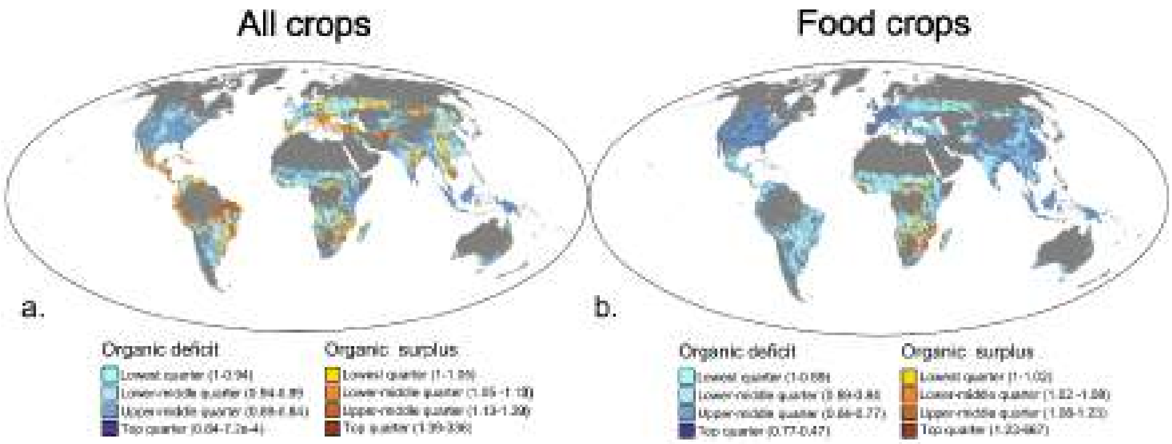


Figure S7. Organic-to-conventional production ratios (expressed in quartiles) between the 100% organic and the 100% conventional scenarios for (a) total protein production, and (b) protein production by food crop category (considering all 61 crop species). Numbers in brackets refer to the organic-to-conventional production ratio values of the corresponding quartiles.

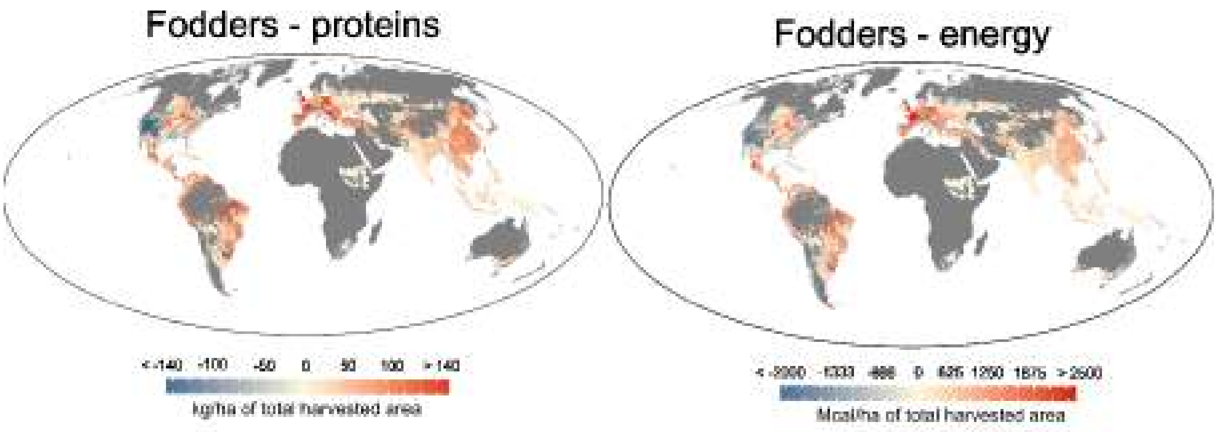


Figure S8. Difference in the protein [in kg protein year^{-1} per ha of total harvested area] and energy [in thousands kcal year^{-1} per ha of total harvested area] produced by temporary fodder crops between the organic minus the conventional scenarios.

Appendix III

Supplementary figures

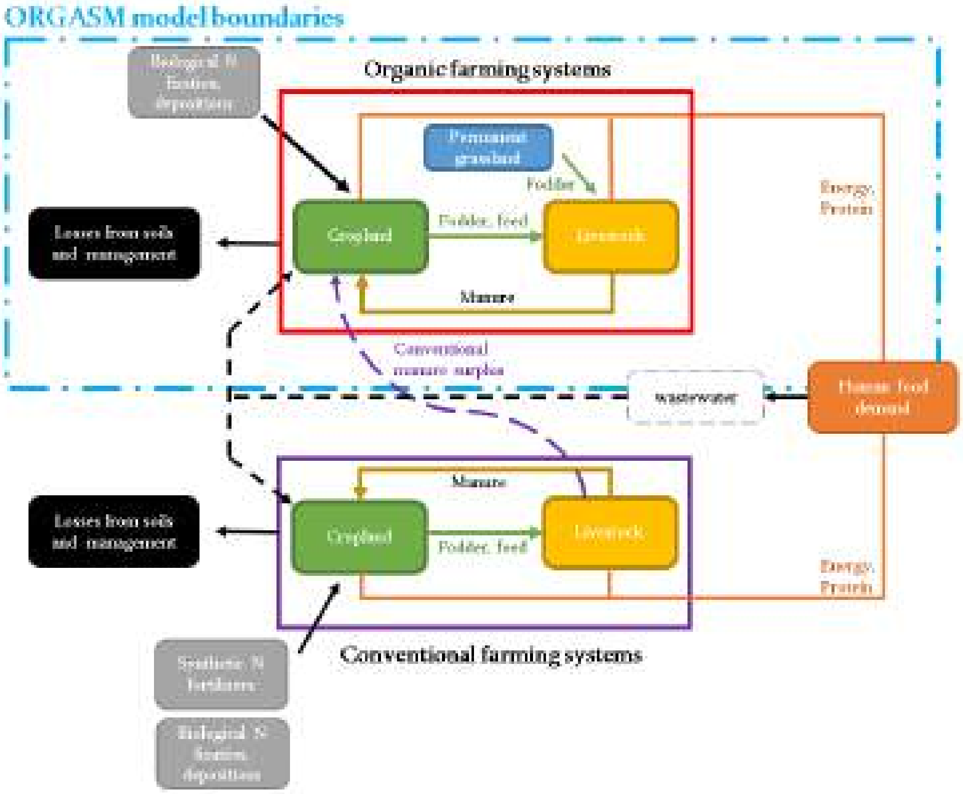


Figure S9. System definition of the ORGASM model represented by its boundaries, biomass and N flows. Note that conventional farming systems and wastewater management are also represented because they can provide some N to the organic soils (as conventional manure and sewage sludge).

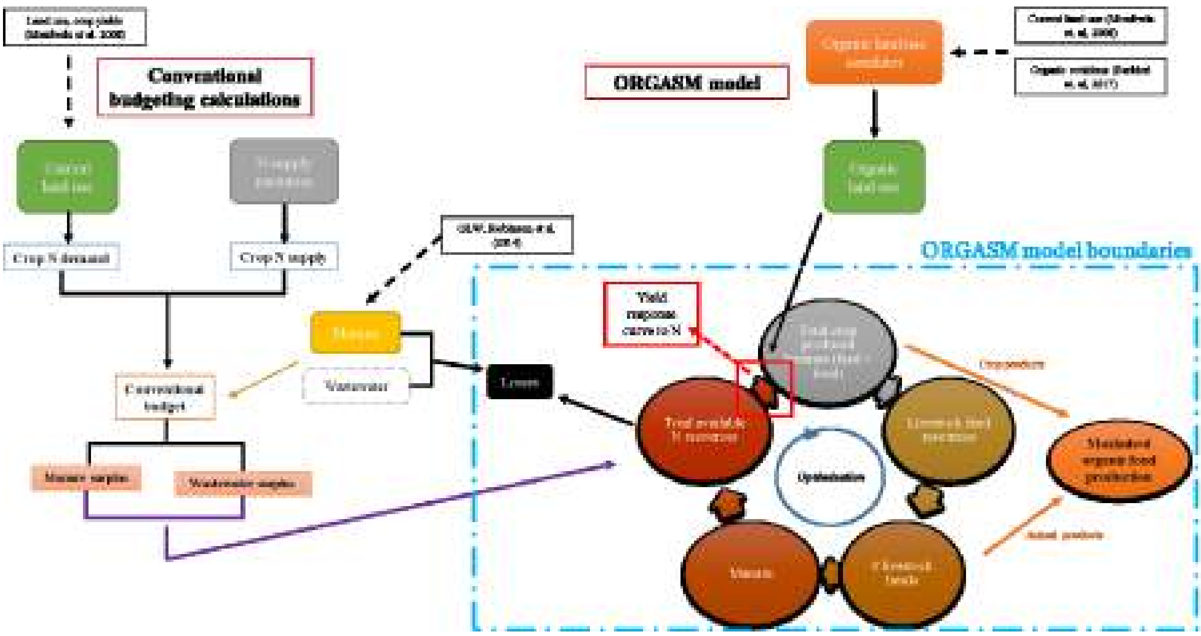


Figure S10. Schematisation of the budget calculation for the conventional farming systems, of the ORGASM model, and their interactions. The most important input datasets are also specified.

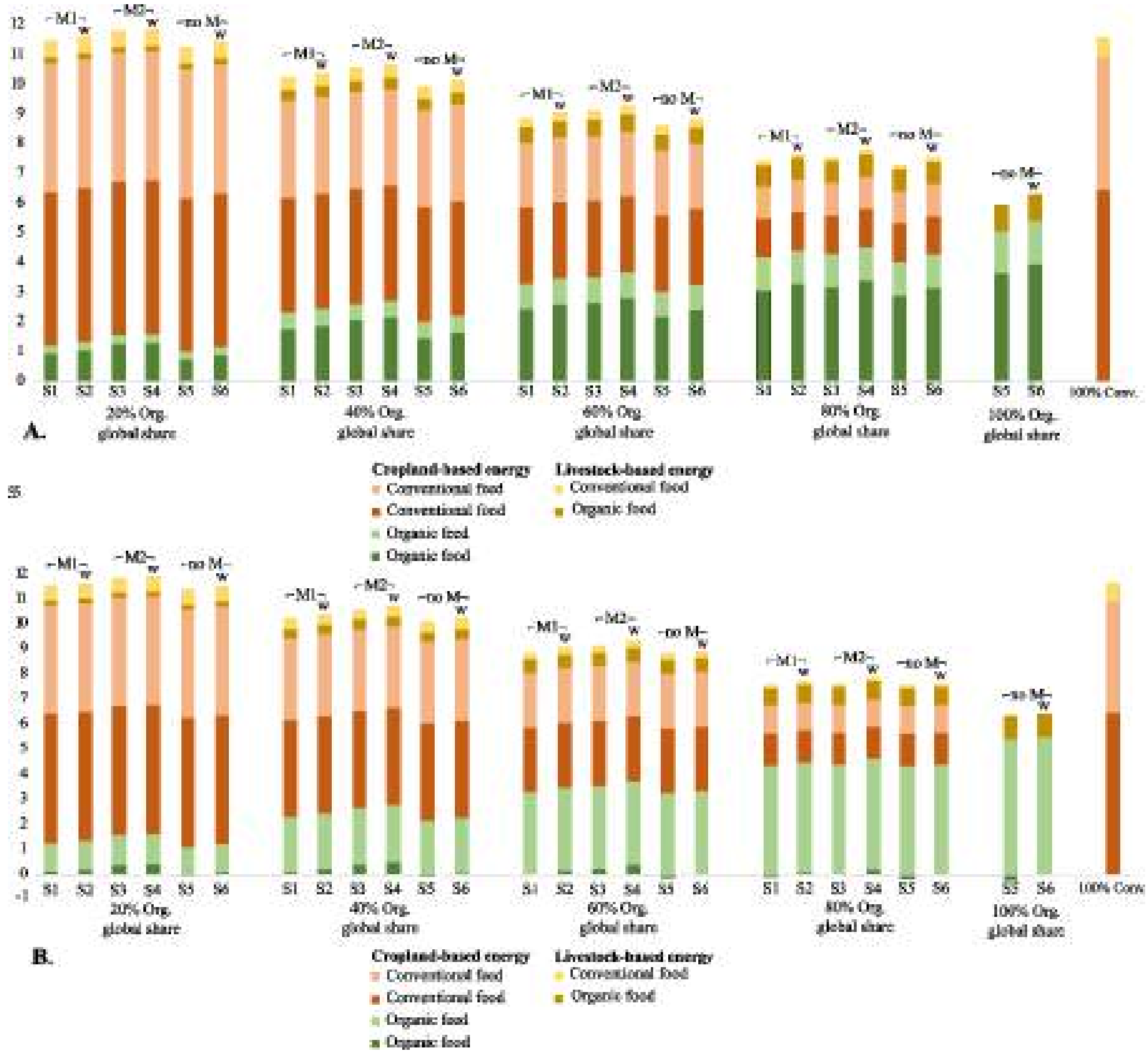


Figure S11. Total energy production [in e+15 kcal] in scenarios involving livestock redesign (A.) and in scenarios where we assume no changes in livestock densities and distribution compared to the current, conventional livestock production (B.). Scenarios allowing the use of N from conventional manure sources assuming that conventional livestock densities and spatial distribution are left unchanged (M1) and conventional livestock is re-located with cropland production (M2) are indicated. Scenarios allowing the use of N from wastewater sources (w) are also indicated. No-M indicated scenarios without conventional manure inputs. Note that some of the scenarios where we assume no changes in livestock densities and distribution (B.) are physically impossible –i.e. organic food energy production has a negative value–.

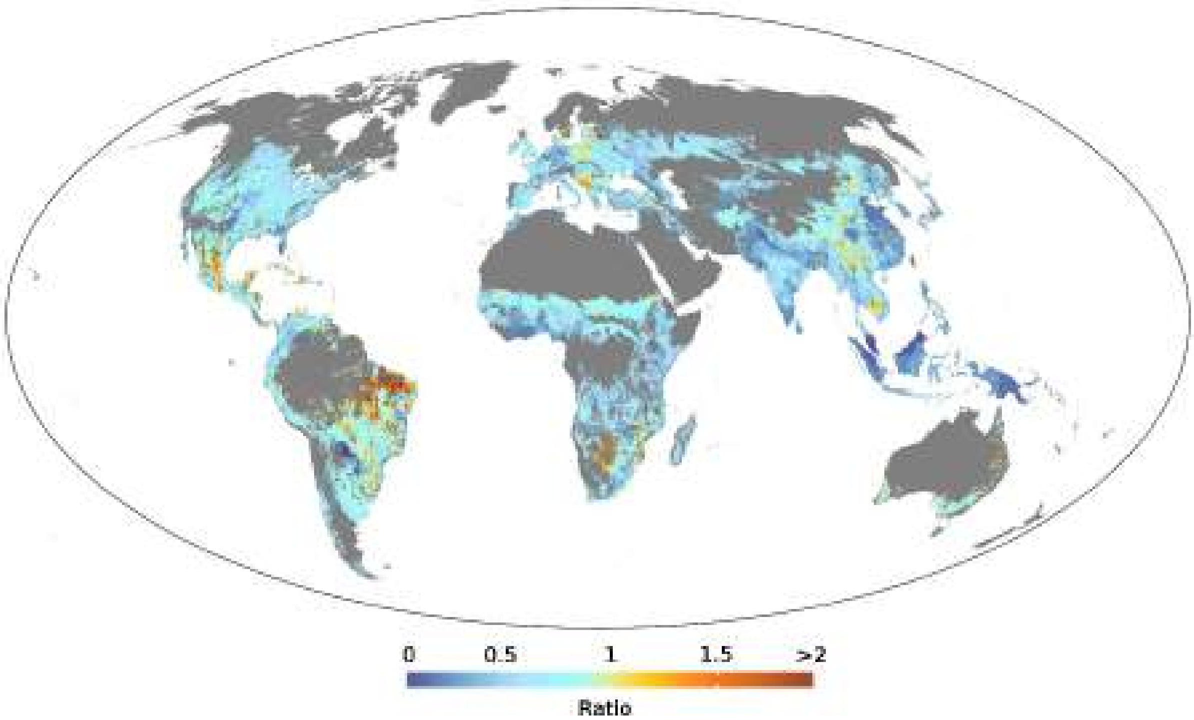


Figure S12. Ratios between cropland protein production in the 100% organic vs the 100% conventional scenarios. Cropland production corresponds to the sum of the protein production of the 61 crop species considered.

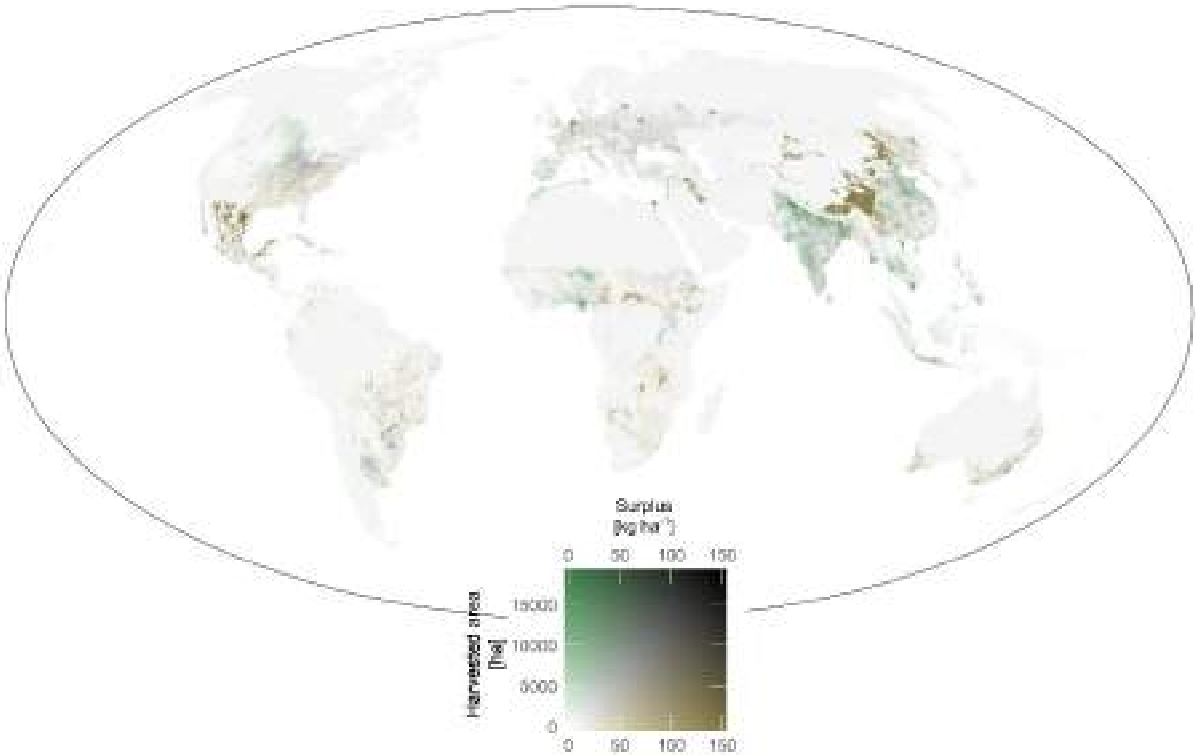


Figure S13. Biplot of N surplus [kg ha^{-1}] (cumin colour) vs harvested cropland areas [ha] (green colour) in each grid-cell in a scenario of 100% conversion to organic farming globally. Grid-cell size at the equator is ~10 km × 10 km.

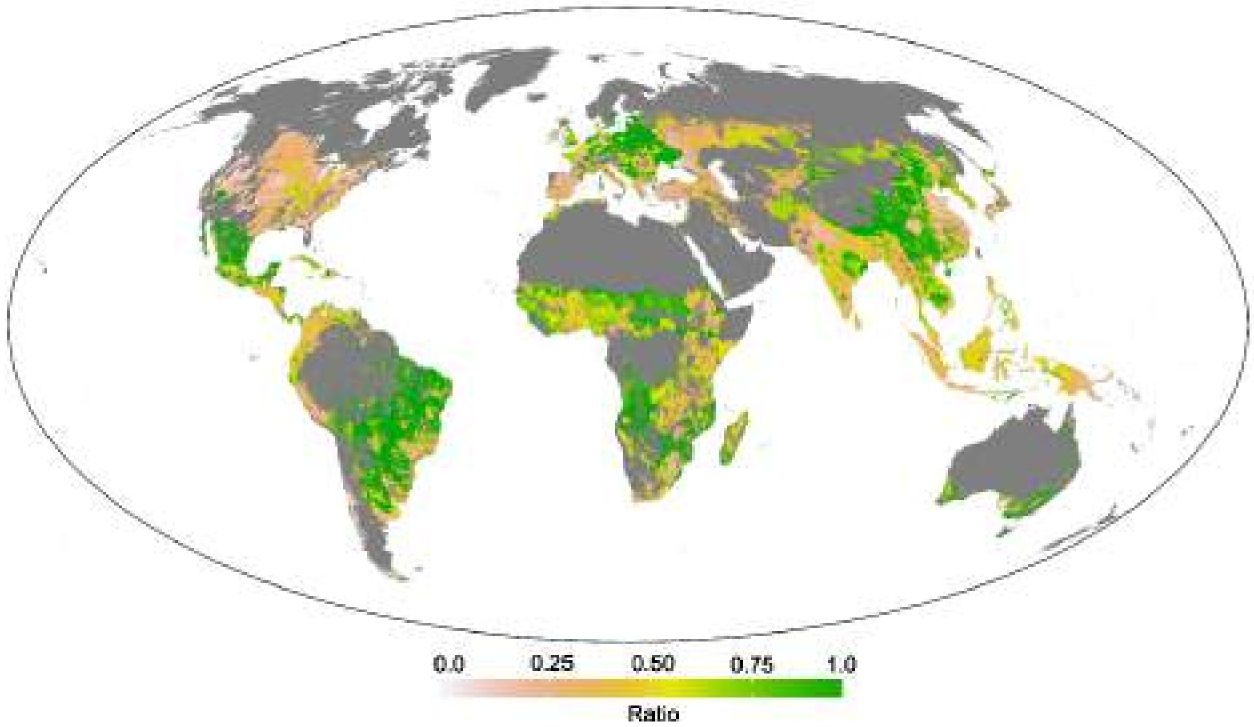


Figure S14. Yield gap for primary cereals (maize, wheat, and rice), expressed as the ratio between the N-limited and the maximum organic attainable crop yields for these three species in a scenario of 100% conversion to organic farming globally. Yield ratio in each grid-cell is calculated as an area-weighted sum across the crop species. Grid-cell size at the equator is ~10 km × 10 km

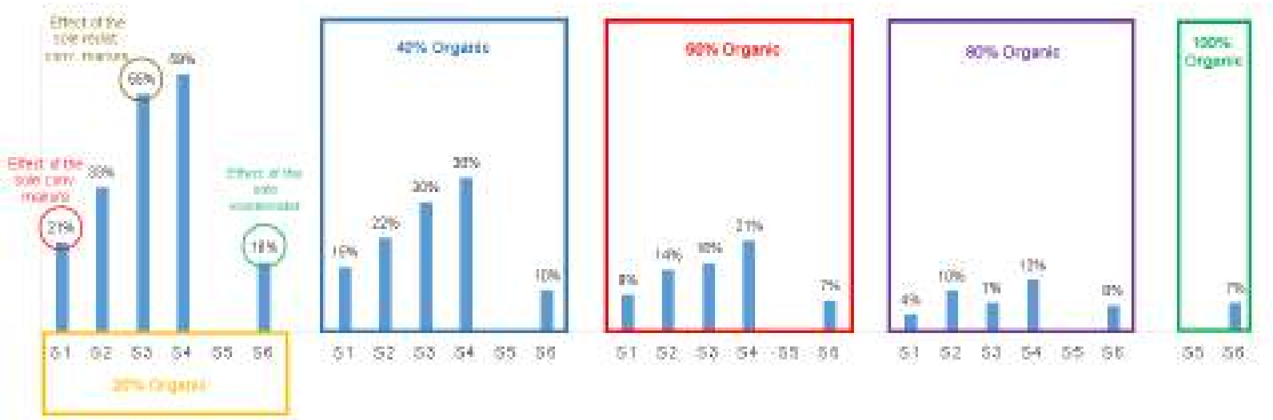


Figure S15. Variation (in percentage) of the total energy production from croplands in organic systems as a function of the different external N resources to fertilize cropland soils. Energy production of each scenario with external inputs (S1-S4 and S6) is compared, within each scenario of cropland conversion to organics, with scenario S5 (no external inputs). Scenarios are described in Table S18.

Wastewater	Convetional manure	global organic share	N surplus [kg ha^{-1}]	N limitation [kg ha^{-1}] *All crops*	N limitation [kg ha^{-1}] *Food crops*
Wastewater allowed	Conv. manure redistributed	20%	27.7	12.3	8.0
		40%	16.0	20.0	14.2
		60%	14.1	24.1	17.8
		80%	13.6	26.4	20.0
	Conv. manure unredistributed	20%	31.8	19.7	14.9
		40%	18.3	23.4	17.6
		60%	15.0	25.6	19.4
		80%	13.8	27.0	20.6
	No conv. manure allowed	20%	14.5	25.1	19.0
		40%	13.6	26.9	20.5
		60%	13.6	27.6	21.1
		80%	13.5	27.9	21.4
		100%	13.6	27.7	21.3
Wastewater not allowed	Conv. manure redistributed	20%	23.2	13.8	8.9
		40%	15.2	21.7	15.5
		60%	13.9	25.6	19.2
		80%	13.5	28.0	21.5
	Conv. manure unredistributed	20%	30.2	23.4	17.8
		40%	17.5	25.4	19.3
		60%	14.8	27.3	20.9
		80%	13.7	28.5	22.1
	No conv. manure allowed	20%	13.6	29.5	23.0
		40%	13.6	29.5	23.0
		60%	13.6	29.5	23.0
		80%	13.6	29.5	23.0
		100%	13.6	29.5	23.0

Figure S16. N surplus and N limitation, expressed in [kg N ha^{-1} cropland] in any simulated scenario involving a readaptation of the livestock sector. N surplus is calculated both considering (i) all the 61 crop species and (ii) only food crop species. Green colour indicates low values, while red colour indicates high values.

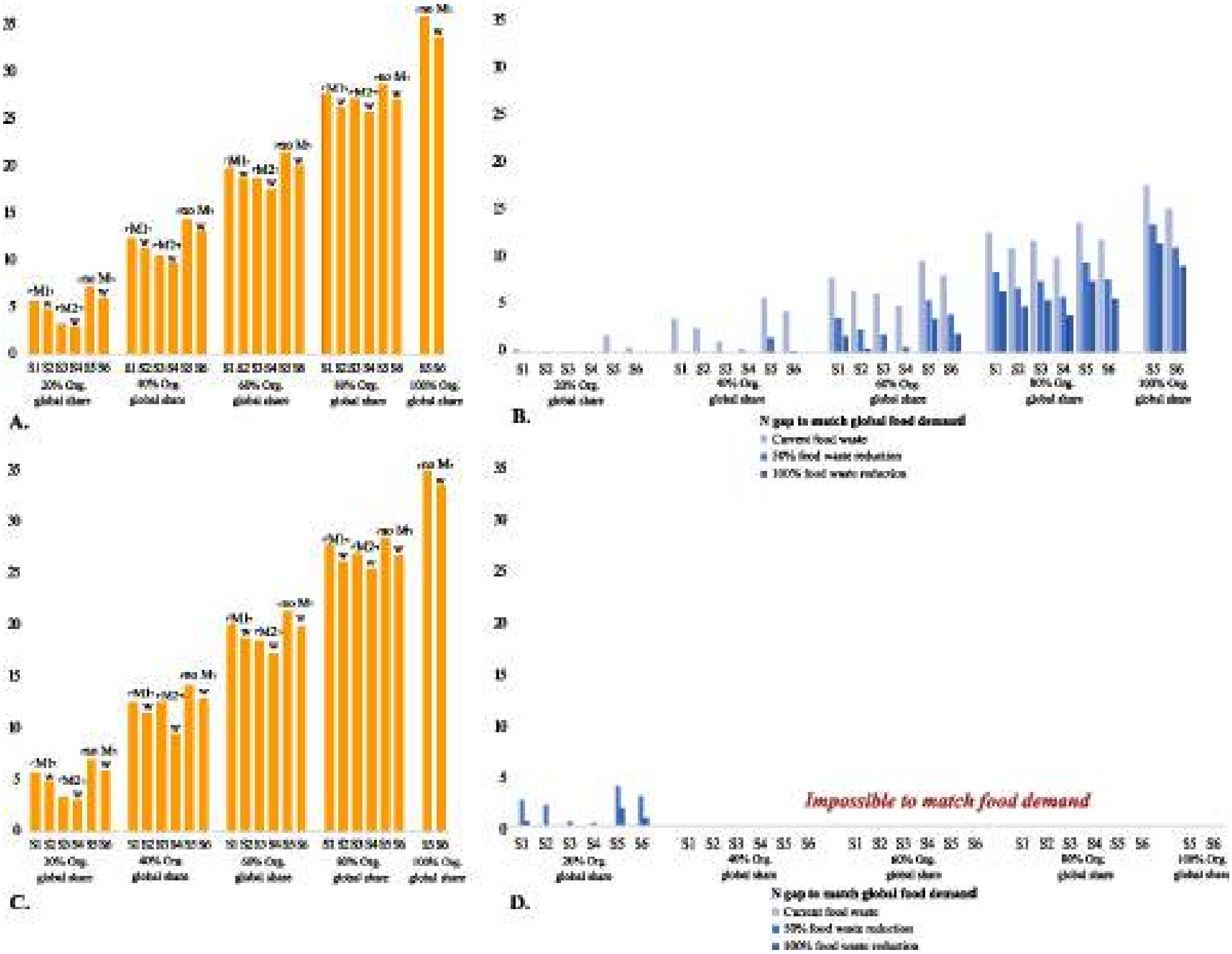


Figure S17. N surplus and N gap necessary to raise crop yields to match global food demand [in Tg] respectively in scenarios involving livestock redesign (A. and B.) and in scenarios where we assume no changes in livestock densities and distribution compared to the current, conventional livestock production (C., D.). Scenarios allowing the use of N from conventional manure sources assuming that conventional livestock densities and spatial distribution are left unchanged (M1) and that conventional livestock is re-located with cropland production (M2) are indicated. Scenarios allowing the use of N from wastewater sources (w) are also indicated. No-M indicated scenarios without conventional manure inputs. Note that most scenarios where we assume no changes in livestock densities and distribution (C. and D.) global food demand cannot meet even by raising organic crop yields up to the maximum achievable organic yields.

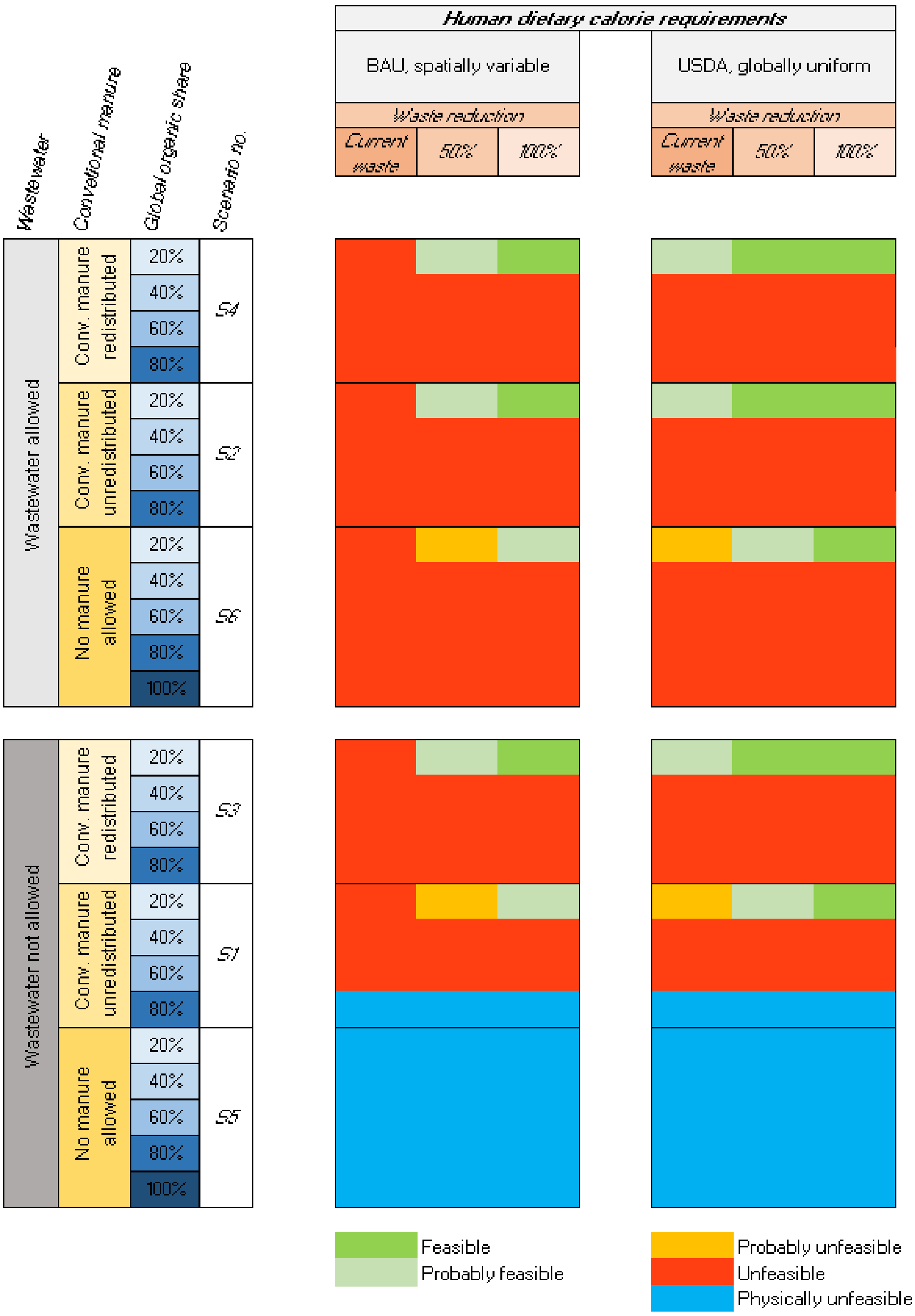


Figure S18. The global production-demand options space, for scenarios where we assume no changes in livestock densities and distribution. The energy production-demand comparison results from the combination of (i) five shares of conversion to organic farming, (ii) three conventional organic manure management options, and (iii) two recycled wastewater management options for the supply side (lines) together with (a) two human dietary variants, combined with (b) three variants of food waste reduction for the demand side (columns). Each cell represents a scenario. Because in the 100% global organic share scenario there is no conventional livestock, the use of conventional manure in this scenario is not possible. Feasible scenarios represent cases where global food demand is equal or lower than global food supply; probably feasible and probably unfeasible scenarios represent cases where global food demand is 0-5% and 5-8% higher than global food supply, respectively; unfeasible scenarios represent cases where global food demand is more than 8% higher than global food supply. Physically unfeasible scenarios represent cases where the global livestock energy demand grains exceed global cropland energy production.

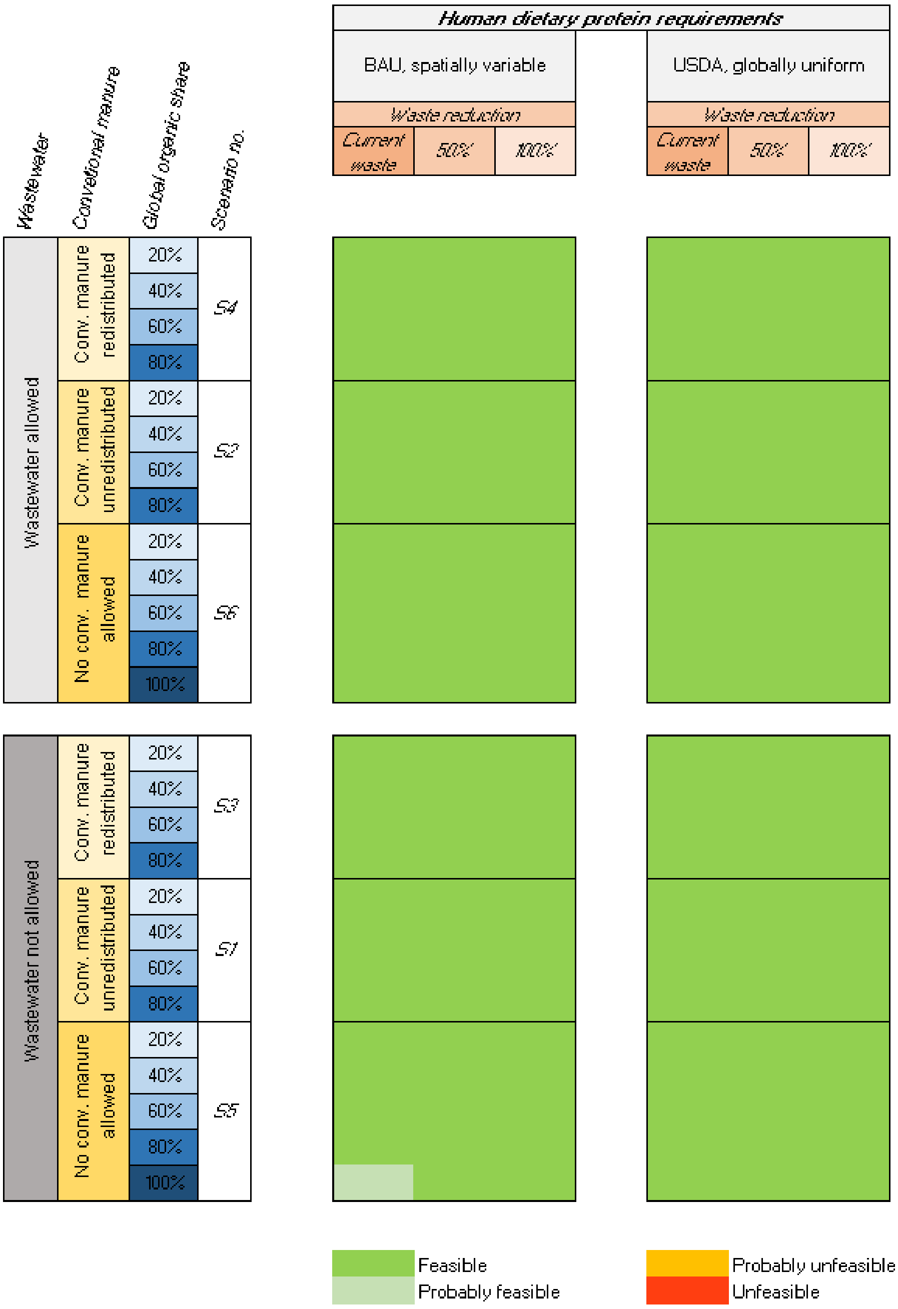


Figure S19. The global protein production-demand options space, for scenarios involving livestock redesign. The protein production-demand comparison results from the combination of (i) five shares of conversion to organic farming, (ii) three conventional organic manure management options, and (iii) two recycled wastewater management options for the supply side (lines) together with (a) two human dietary variants, combined with (b) three variants of food waste reduction for the demand side (columns). Each cell represents a scenario. Because in the 100% global organic share scenario there is no conventional livestock, the use of conventional manure in this scenario is not possible. Feasible scenarios represent cases where global food demand is equal or lower than global food supply; probably feasible and probably unfeasible scenarios represent cases where global food demand is 0-5% and 5-8% higher than global food supply, respectively; unfeasible scenarios represent cases where global food demand is more than 8% higher than global food supply.

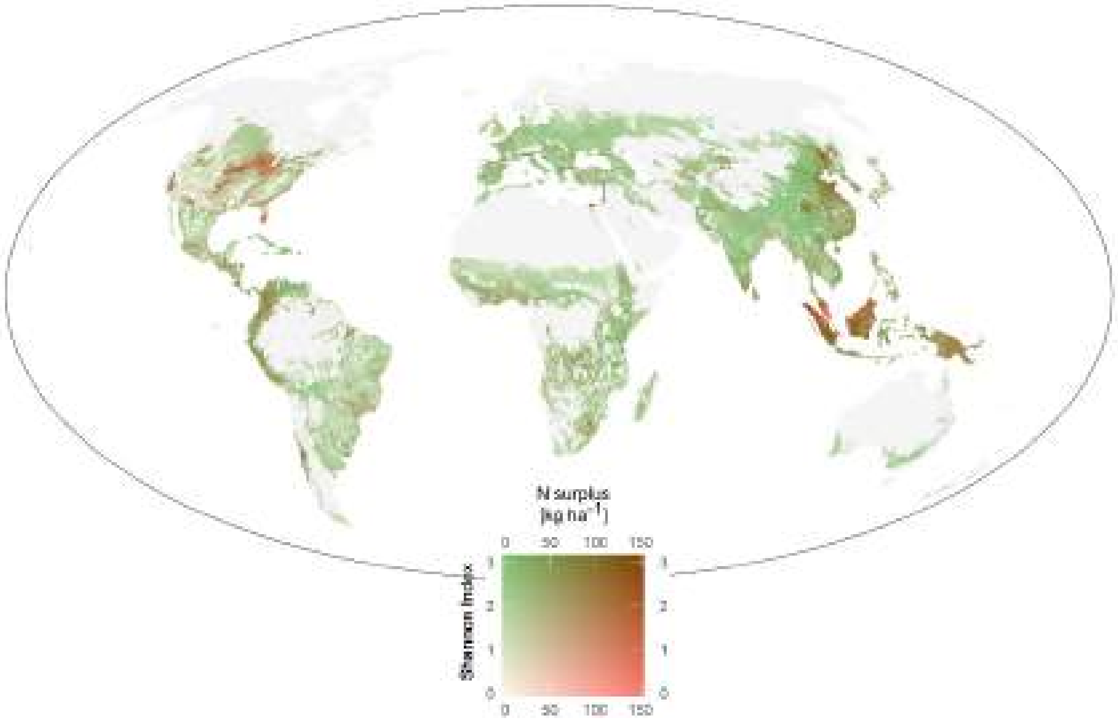


Figure S20. Biplot of N surplus [kg N ha^{-1} cropland] (red colour) vs the Shannon Diversity Index calculated on the organic land use (green colour) in each grid-cell. Areas in grey are grid-cells without harvested area. Grid-cell size at the equator is ~10 km × 10 km.

Supplementary tables

Table S16. Overview of the ORGASM model variables and assumption (supply-side of food systems)

Variable	Production system (organic vs conventional)	Reference year	Assumptions for the organic scenarios	Source
Harvested areas	Organic	~2000	Global harvested area varies as a function of the specific characteristics of organic crop rotations. Total arable land is kept at the same value than in the conventional scenario	(Barbieri et al. 2017; Barbieri et al., submetted for publication)
	Conventional			Monfreda et al. (Monfreda et al. 2008)
Permanent grassland areas	Organic	~2000	Net grassland area is kept at the same value than in the conventional scenario	Ramankutty at al. (Ramankutty et al. 2008)
	Conventional			Ramankutty at al. (Ramankutty et al. 2008)
Crop yields	Organic	~2000	Model endogenous calculation based on soil N supply. Organic maximum achievable yields equal to conventional yields scaled down by an organic-to-conventional yield gap accounted only for the reduction due to pest and diseases (see Materials and Methods for further details)	(Barbieri et al. 2017; Barbieri et al., submetted for publication)

	Conventional			Monfreda et al. (Monfreda et al. 2008)
Ruminant numbers	Organic	~2006	Model-endogenous calculation of the number of animals that can be locally fed on available feed. Numbers and distribution are considered at the same value than in conventional in the scenario variant assuming no changes in livestock densities	
	Conventional			Robinson et al. (Robinson et al. 2014)
Monogastric numbers	Organic	~ 2006	Model-endogenous calculation of the number of animals that can be locally fed on available feed. Numbers and distribution are considered at the same value than in conventional in the scenario variant assuming no changes in livestock densities	
	Conventional			Robinson et al. (Robinson et al. 2014)
Nitrogen atmospheric depositions	Organic	~2000	N deposition is assumed to be at the same value than in the conventional scenario	Dentener et al. (Dentener et al. 2006)
	Conventional			Dentener et al. (Dentener et al. 2006)
Nitrogen from wastewater	Organic	~2015	N excretion from humans is assumed to be at the same value than in the conventional scenario	Personally developed dataset
	Conventional			Personally developed dataset
Nitrogen from conventional manure surplus	Organic	~2006	Conventional budgeting model endogenous calculation. The surplus is then used (i) in locations where produced or (ii) nationally redistributed proportionally to the organic harvested area (depending on the variant scenario considered)	Personal estimation
Maximum share of production used for feed	Organic	~2015	Each crop species competing with human food can be used as feed up to its current (i.e. 2015) maximum use as feed in conventional agricultural systems	FAOSTAT (Food and Agriculture Organization of the United Nations 2016)

Table S17. Overview of the food demand variables and assumptions (demand-side of food systems).

Variable	Reference year	Assumptions	Source
Human population	~2015		FAOSTAT
Calorie and protein demand	~2015	Equal to the current per capita demand. Demand includes she share of food lost due to food wastage. Calorie and protein demand reduction was based on physiological dietary recommendations for an average adult. With food waste reduction, calorie/protein demand is reduced accordingly	Erb et al. (Erb et al. 2016), USDA (Ahmed & Blumberg 2009)
Food wastage	~2015	Relative reduction (50% or 100%) according to the scenarios	Food wastage footprint (Alexander et al. 2017)

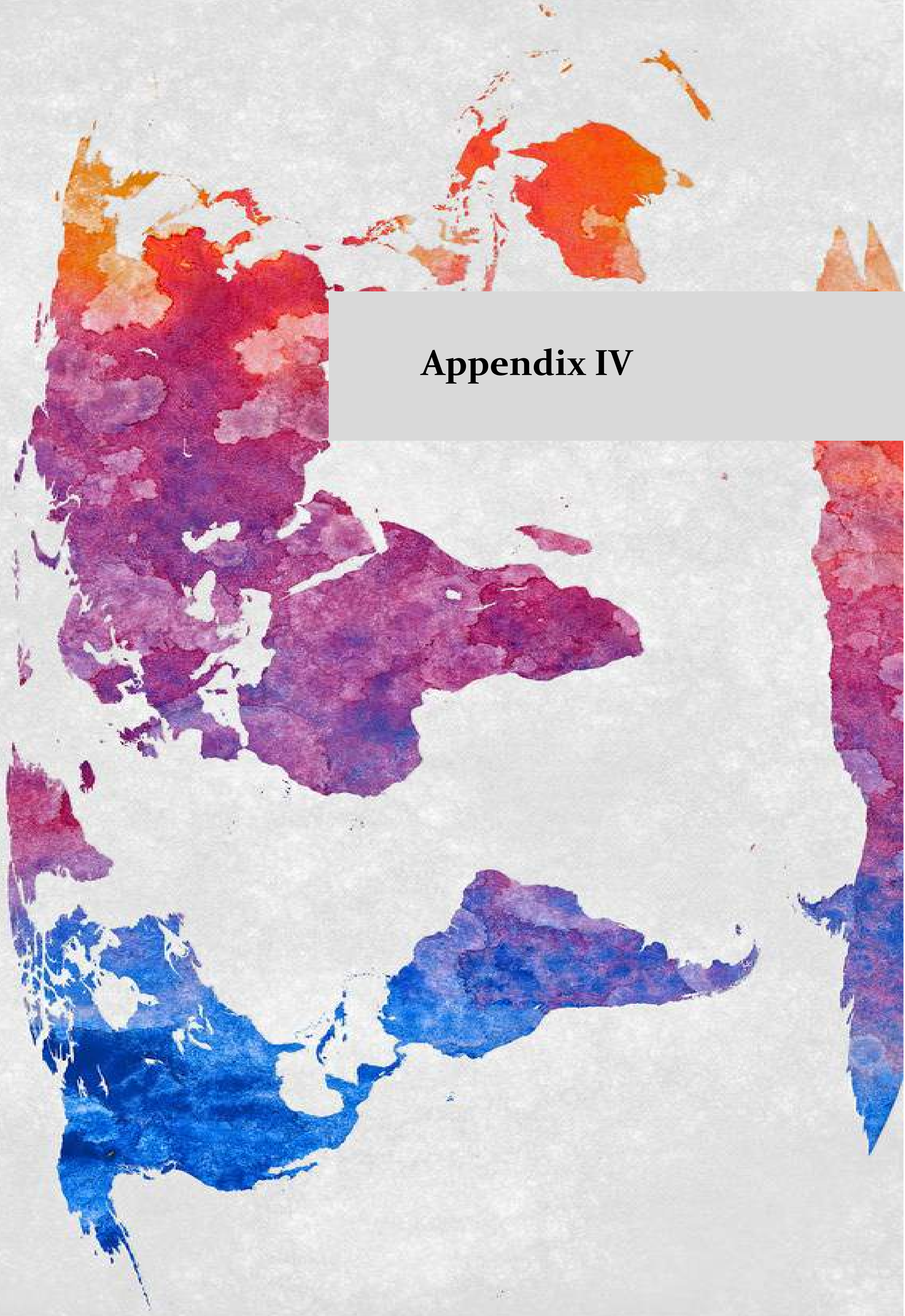
Table S18. External nitrogen inputs allowed to fertilize cropland soils in scenarios S1-S6.

Scenario	Conventional manure	Nationally distributed conventional manure	Wastewater
S1			
S2			
S3			
S4			
S5			
S6			

Table S19. Total cropland production, temporary fodder energy production, livestock energy requirements for food competing feed-stuff and food energy available in a scenario of 100% organic conversion at the global scale for two sub-scenarios: (i) global livestock redesign, and (ii) current livestock density and geographical distribution.

Scenario	**Total Cropland production** [e+15 kcal]	**Temporary fodder production** [e+15 kcal]	**Food competing feed-stuff energy production** [e+15 kcal]	**Total food competing feed-stuff energy requirements** [e+15 kcal]	**Food energy available** [e+15 kcal]
Global Livestock redesign	5.1	0.9	4.1	0.5	3.6
Current livestock density and spatial distribution	5.2	0.9	4.2	4.5	-0.3

Appendix IV



1. Introduction

The GOANIM (Global Organic Agriculture NItrogen Model) model is a spatially explicit, biophysical and linear optimization model simulating cropland soil nitrogen (N) cycling in organic farming systems and its feedback effects on food production at the global scale. It is based on the overall assumption that the global harvested cropland area remains constant at current levels (Tayleur & Phalan 2016). GOANIM includes different compartments (organically managed croplands, livestock animals and permanent grasslands) and accounts the biomass and N flows among these compartments (as feedstuff, grazed biomass and animal manure) as well as the N flows between cropland soils and the environment as represented in Figure S21. System definition of the ORGASM model represented by its boundaries, biomass and N flows. Note that conventional farming systems and wastewater management are also represented because they can provide some N to the organic soils (as conventional manure and sewage sludge).. GOANIM uses high resolution (5 arc-min) spatially explicit databases for the year ~2000, providing consistent data on agricultural biomass flows, encompassing the 61 most important crop species (see the Supplementary Dataset) by global acreage and 5 livestock animal species (cattle, sheep, goats, pigs, and poultry). The model respects the thermodynamic law of conservation of mass and energy it embraces all countries and geographic territories (164) covered by FAOSTAT. ORGASM simulates the supply side of the global food system –i.e. food production–, by maximizing organic production from both cropland and livestock food commodities. Cropland production is maximized in each grid-cell as a function of N supply to cropland soils from different sources, including organic manure from livestock animals, biological N fixation, atmospheric depositions, and additional external inputs. The floating variables in the optimization model correspond to the local livestock animal population and the allocation of animal manure to the different crop species; both floating variables are optimized at the grid-cell scale (Figure S22. Schematisation of the budget calculation for the conventional farming systems, of the ORGASM model, and their interactions. The most important input datasets are also specified.). Any use of cropland resources other than food and feed is not directly considered here, apart for crops like rubber and cotton, whose production is being used for industrial purposes. All model compartments are assumed to be at steady-state –i.e. all state variables are constant in spite of ongoing processes that strive to change them– and all flows are simulated considering a timeframe of one year. The model assumes that each raster's grid-cells is independent, i.e. resources are not transportable or exchangeable outside grid-cell boundaries. This choice is in line with organic farming principles aiming at a local sourcing for both feed and fertilizers (IFOAM 2014; European Commission 2008). Additionally, the resolution of our datasets (10×10 km at the equator) represents a feasible distance for livestock manure sustainable transportability (Bartelt & Bland 2007).

First, a pre-modeling module (*conventional add-in module*) calculates the total nitrogen input and outputs to soils in conventional farming systems, computes N budgets in each grid-cell and calculates the N in livestock animal manure and in wastewater that is not needed to balance the N crop demand. This N surplus embed in conventional manure and wastewater resources, can then be made available by the model user as additional N inputs to organic systems for any given scenario where organic farming production has a global share inferior to 100% - i.e. between 0 and 100% -. Then, the GOANIM optimization model maximizes organic food production in every single grid-cell as a function to N available resources. For each chosen global organic farming production share, GOANIM assumes the conventional farming production share to be equal to *(1-organic$_{global_share}$)*. The conventional add-in module and ORGASM-model are interlinked by allowing, or not, the import of conventional N surplus resources (manure and wastewater) into organic systems.

The model is coded using the R software (R Open 3.3.2 - MRAN 2016, https://mran.microsoft.com/) and the optimization problem is solved using the COIN-OR clp solver.

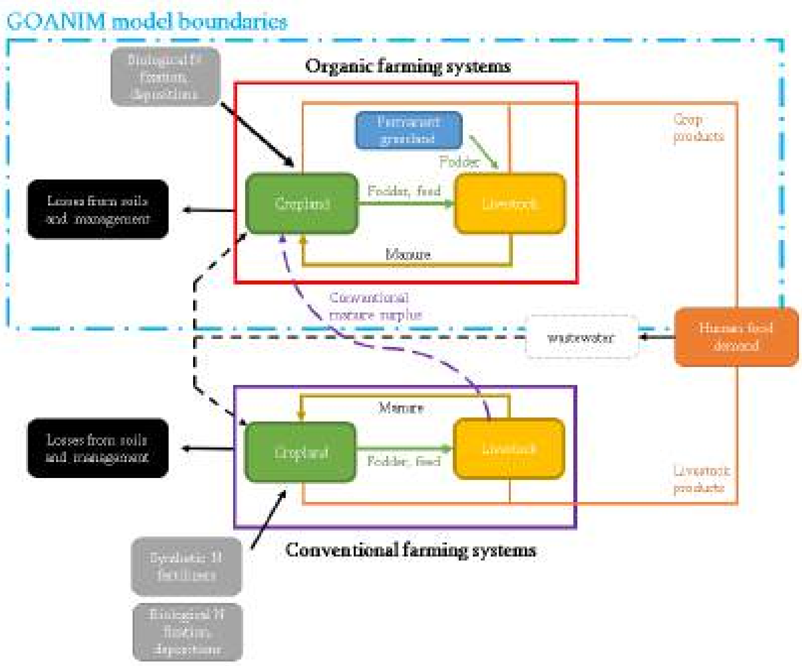


Figure S21. System definition of the ORGASM model represented by its boundaries, biomass and N flows. Note that conventional farming systems and wastewater management are also represented because they can provide some N to the organic soils (as conventional manure and sewage sludge).

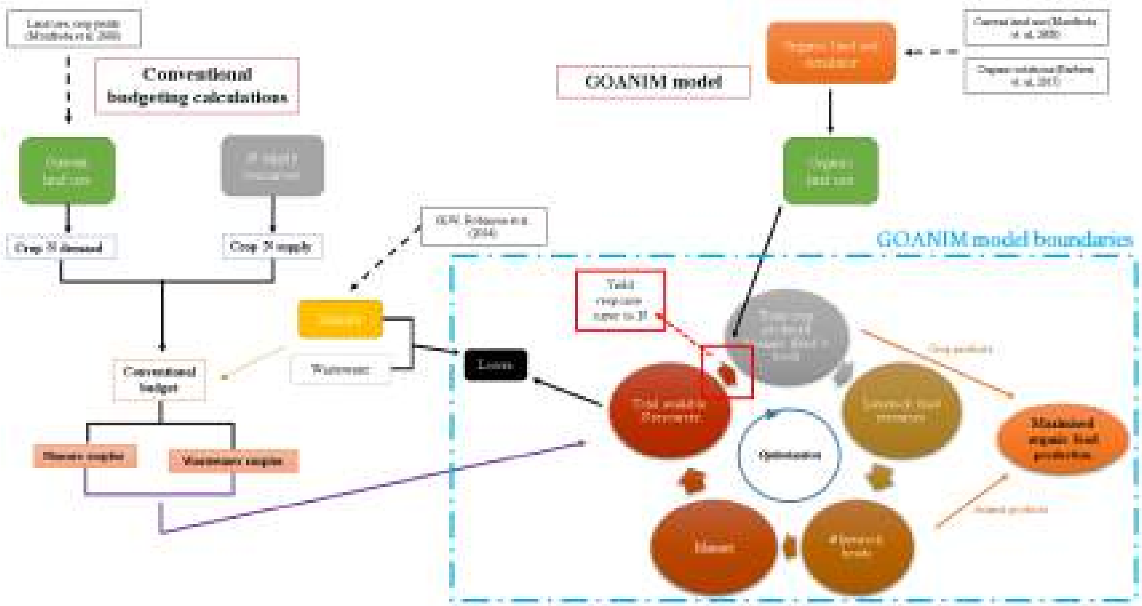


Figure S22. Schematisation of the budget calculation for the conventional farming systems, of the ORGASM model, and their interactions. The most important input datasets are also specified.

1.1 Main model Hypothesis

GOANIM is grounded on a few hypotheses:

1. Global hypothesis valid for all model add-ins:
    a. Nitrogen inputs include: (i) synthetic and (ii) organic fertilizers, N fixation by (iii) symbiotic biological nitrogen fixation (BNF) and (iv) non-symbiotic free-living cyanobacteria, (v) N dry and wet atmospheric depositions, and (vi) N from crop residues recycled to soils;
    b. Nitrogen outputs include: (i) crops N demand (harvested products and crop residues), (ii) losses -i.e. N leaching (NH_3), volatilization (N_2O, N_2, and NO_x) due to manure management/storage and after the application to the soil of any organic or inorganic input;
    c. Grid-cells are independent, i.e. resources are not transportable outside grid-cells, and cannot be exchanged between grid-cells. Grid-cells have a size of about 100 km² at the equator, which well represents the maximum distance to which manure can be transported in an economic rentable way;

   d. The nitrogen density of crops and livestock products does not differ between farming systems;
   e. Livestock diets - calculate in terms of calories and proteins - do not differ between farming systems;
   f. Livestock yields do not differ between farming systems.
2. Hypothesis applicable only to organic farming systems:
   a. Organic maximum attainable yields are estimated by multiplying the current - i.e. conventional - by an organic-to-conventional yield gap (Ponisio et al. 2015). We corrected this organic-to-conventional yield gap in order to account for a yield reduction due only to pest and diseases, i.e. not accounting for the yield reduction due to N deficiency;
   b. Organic yields are calculated as a linear function of nitrogen supply, up to the maximum attainable yield (representing the plateau of the N response curve);
   c. Conversion to organic farming is considered to take place equally in every single grid-cell. This share directly affects the share of cropland and pasture area farmed organically or conventionally -i.e. for a 20% conversion to organic farming, 20% of total cropland and pasture areas in each grid-cell is considered to be converted to organic farming-, as well as the share of livestock animal populations managed organically.

2. Conventional add-in module

2.1 Nitrogen flows

Nitrogen flows from and to cropland soils are estimated by calculating different nitrogen inputs (*IN)* and outputs (*OUT)* elements (Liu et al. 2010). In this study, *IN* is divided into six elements, whereas *OUT* is divided into five elements (Equations 1 and 2):

$$IN = IN_{fert} + IN_{man} + IN_{dep} + IN_{fix} + IN_{res} + IN_{ww} \quad (1)$$

$$OUT = OUT_{crop} + OUT_{res} + OUT_{lea} + OUT_{gas} \quad (2)$$

where *IN* and *OUT* are the total nitrogen input and output, respectively; IN_{fert} is the N in synthetic fertilizers; IN_{man} is the N in manures; IN_{dep} is the N input from wet and dry atmospheric deposition; IN_{fix} is N fixation (symbiotic and non-symbiotic); IN_{res} is the N from the fraction of crop residue recycled to soils; IN_{ww} is the N from wastewater; OUT_{crop}, OUT_{res}, OUT_{lea}, OUT_{gas} are the N output of the harvested crops, crop residues, leaching, and gaseous losses, respectively. All flows variables are calculated in [*tons N* ha^{-1} y^{-1}]. A full reference to the input data is reported in Table S20.

IN_{fert} is calculated using a global spatial explicit database on synthetic N fertilizers application rates [*tons N* ha^{-1}] for every of the 61 crop species considered in this study (Mueller et al. 2012).

IN_{man} is calculated by multiplying livestock populations with animal species-specific N excretion rates. Livestock populations density data for the year 2007 were obtained from the Gridded Livestock of the World (GLW) from the FAO (Robinson et al. 2014). The GLW describes the spatial distribution of cattle, sheep, goats, pigs, and poultry at a resolution of 1 arc-min. Data were aggregated to a 5 arc-mi resolution. Others livestock species were not considered in this study since they have a minor contribution to global livestock production and a little influence in the manure estimates (Liu et al. 2010).

The GLW maps report the livestock populations' density as harmonized with FAOSTAT data and include animal raised for both draft and production purposes. More in details, these maps report the number of animals standing at the moment of enumeration. Since the GOANIM model only simulates producing animals (section 4.1.8), we corrected the GLW density maps to account only for producing animals (no draft-raised animals). To do so, we (i) retrieved from FAOSTAT the number of both standing and producing animals in one year for every of the 164 considered countries (average of the years 2005-2009), (ii) corrected, when appropriate, the number of producing animals by the respective number of batches per year (personal estimation), and (iii) we used the ratio *producing animals/standing animals*, for every given country, to correct the GLW maps and estimate the fraction of producing animals only.

We calculate the N excretion rates of each livestock animal species for every individual country following Sheldrick et al. (2003) and Liu et al. (2010) -i.e. by assuming that the excretion rate of each livestock species is proportional to its slaughter weight. Sheldrick et al. (2003) provide reference data on livestock live body weight and N excretion rates for cattle, pigs, sheep, goats, and poultry (Table S21). We calculated the live weights of each livestock species in every one of the 162 individual countries multiplying the carcass weight (from Food and Agriculture Organization of the United Nations, 2016) by species-specific factors converting the carcass yield into live weight (Table S21). Finally, N excreta was estimated proportionally to the reference body weight reported in Table S21.

In order to estimate the collectible fraction of the excreta (i.e. the fraction of excreta produced in stables or in confined management systems), we retrieved and applied housing system statistics, for different global regions, following the IPCC Tier 1 procedure (Dong et al. 2006). Excreta produced in meadows were not accounted as available for cropland application. We estimate all N losses (volatilization, leaching and run off) happening during manure collection and storage and management following the Chapter 10 of the IPCC procedure (Dong et al. 2006). No manure is considered to be used for permanent grasslands fertilization in addition to the share of excreta directly deposited on permanent grasslands. Instead, fertilisation of temporary fodder crops (< 5 years) is accounted; since these crops are part of the 61 arable crop species covered in this study[10].

IN_{dep} is calculated from Dentener's spatially explicit modeled dry and wet (NO_y + NH_x) N atmospheric depositions (Dentener et al. 2006). Here we applied the estimation for the year 1993, after conversion to a 5 arc-min resolution.

IN_{fix} is the estimate N input from the fixation of atmospheric N, including both symbiotic N fixation via legumes crop species (BNF) and non-symbiotic N fixation by free-living cyanobacteria. BNF was estimating applying the model developed by Hogh-Jensen et al. (Hogh-Jensen et al. 2004) reported in equation (3). Free-living cyanobacteria were estimated using data from Liu et al. (2010).

$$BNF_i = Y_i \times NiC_i \times \frac{1}{NHI_i} \times (1 + PRoot_i) \times Ndfa_i \tag{3}$$

where: BNF_i is the total N fixed [*tons N ha^{-1}*], Y_i is the crop yield [*tons DM ha^{-1}*], NiC_i is the N content of the above-ground biomass [*tons tons^{-1}*], NHI_i is the N Harvest Index [*tons tons^{-1}*], i.e. the ratio between the N content in the harvested biomass and the total N amount in the above-ground biomass, $PRoot_i$ is the amount of N fixed in the roots as proportion of the N fixed in the shoots [*tons tons^{-1}*], and $Ndfa_i$ is the ratio between the amount if symbiotically fixed N and the total N content in the crop biomass [*tons tons^{-1}*], for each given leguminous crop species *i*. BNF from sugarcane was accounted using the average coefficient of 100 *kg N ha^{-1}*. Free-living cyanobacteria N fixation was estimated following Liu et al. (2010). Cyanobacteria fixation coefficients were taken from Liu et al. (2010) and (Smil 1999). More in details we considered a fixation of 20 *kg N ha^{-1}*for rice and 12 *kg N ha^{-1}* for cereal (except rice), tuber, and oil crop species.

[10] Note that the N excreta coefficient were further adjusted as explained in paragraph 4.1.12 to match the same coefficients used in the GOANIM-model

IN_{res} is calculated by multiplying OUT_{res} with a removal factor (β) that accounts for the share of the crop residues removed from the soil, as in equation (4). The removal factor (β) was retrieved from different sources (Liu et al. 2010; Smil 1999; Sheldrick et al. 2003). According to these sources, we considered a removal factor of 35% and 50% in developed and developing countries, respectively.

$$IN_{res} = (1 - \beta) \times OUT_{res} \tag{4}$$

IN_{ww} is estimated as described in section 3.4.

OUT_{crop} is estimated by multiplying the crop production (*yield* × *area*) by the N density of each harvested product as in equation (5):

$$OUT_{crop} = \sum_{i=1}^{61} Y_i \times A_i \times [N_i] \tag{5}$$

where Y_i is the current conventional yield [*tons DM ha*$^{-1}$] for each given crop *i*, A_i is the current area [*ha*] under cultivated under each crop *i*, and $[N]_i$ is the nitrogen density [*tons tons*$^{-1}$] of each crop species *i* harvested product (see Supplementary Dataset). The spatial explicit crop fresh yield for the 61 considered crop species was obtained from Monfreda et al. (2008). Moisture and nitrogen content of various crops was obtained from various sources (Monfreda et al. 2008; INRA 2007; INRA et al. 2016).

OUT_{res} is calculated multiplying the crop residues dry yield by their nitrogen content. The crop residues dry yield was calculated as a function of the harvested yield, as in equation (6):

$$Y_{res_i} = Y_i \times RPR_i \tag{6}$$

Where $Y_{res\ i}$ is the crop residue dry yield, Y_i is the dry matter yield, and RPR_i is the residue-to-product ratio, respectively for each crop species *i*. The *RPR* values were obtained from Liu et al. (2010), or calculated from the harvest index (*HI*) as *(1-HI)/HI* (Liu et al. 2010). *HI* values were obtained from various sources (INRA et al. 2016; Smil 2002).

OUT_{lea} is estimated following the IPCC Tier 1 procedure (De Klein et al. 2006). A loss coefficient of 30% was applied in areas where the annual average rainfalls are higher than the annual average evapotranspiration. Rainfalls and evapotranspiration data where obtained respectively from the NASA and Zomer (Zomer et al. 2007; Zomer et al. 2008). Our leaching estimation was in line with the estimations performed by Liu et al. (2010).

OUT_{gas} estimates the direct (N_2O) and indirect (NH_3 and N oxides -NO_x-) gas losses from soils due to nitrification, denitrification, and volatilization following the IPCC Tier 1 procedure (De Klein et al. 2006). We also accounted for N_2 emissions, calculated using experimental estimation of the $N_2O/(N_2+N_2O)$ ratio, retrieved through personal communication and the literature (Eichner 1990; Ruser et al. 2006). All emissions were estimated for all inputs, i.e. synthetic fertilizers, organic N fertilizers and N in crop residues including N fixed.

Table S20. Model inputs and data sources

Variable/Dataset	System	Unit	Source
Crop harvested areas	Conventional	*ha*	Monfreda et al. (2008)
Crop harvested areas	Organic	*ha*	Barbieri et al. (submitted for publication)
Crop yields	Conventional	*tons DM* ha^{-1}	Monfreda et al. (2008)
Crop yields	Organic	*tons DM* ha^{-1}	Barbieri et al. (submitted for publication)
Synthetic fertilisers	Conventional	*tons* ha^{-1}	Mueller et al. (2012)
Livestock densities	Conventional	*heads* $grid\text{-}cell^{-1}$	Robinson et al. (2014)
Livestock densities	Organic (VII)	*heads* $grid\text{-}cell^{-1}$	Robinson et al. (2014)
N atmospheric deposition	Organic and conventional	*tons* ha^{-1}	Dentener et al. (2006)
N from wastewater	Organic and conventional	*tons* $grid\text{-}cell^{-1}$	Personal dataset

Table S21. Livestock excretion rates (from Sheldrick et al., 2003) and carcass to live weight conversion coefficient

Livestock species	Live weight [kg]	N [kg $year^{-1}$]	Carcass yield over live weight [%]
Cattle	250	50	50.8
Sheep	15	10	50
Goats	12	10	50
Pigs	80	12	77.4
Poultry	2	0.6	70

2.2 Nitrogen budgets

Conventional nitrogen budgets are computed in each grid-cell following a three-step procedure. First, budgets are calculated without considering the N inputs from organic fertilizers - i.e. manure and wastewater - as in equation (7). Then N available in manure is used to balance, when possible, all grid-cells where the budget is negative (equation 8). Finally, N available in wastewater is used to balance to zero all grid-cells that still have a negative budget (equation 9). Overall, an over-fertilization up to 20% of OUT_{crop} is allowed, as commonly over-fertilization practices take place. Budgets can be computed assuming any share of conventional farming at the global scale, ranging from 100% to 0%.

$$\Delta_1 = [(IN_{fert} + IN_{dep} + IN_{fix} + IN_{res}) - (1.2 \times OUT_{crop} + OUT_{res} + OUT_{gaz})] \times global\ share\ conventional \tag{7}$$

$$\forall \Delta_1 < 0, \Delta_2 = \Delta_1 + IN_{man}, until\ \Delta_2 = 0 \tag{8}$$

$$\forall \Delta_2 < 0, \Delta_3 = \Delta_2 + IN_{wwr}, until\ \Delta_3 = 0 \tag{9}$$

The N from manure and wastewater that is not used to balance the conventional budgets to zero (including the allowed over-fertilization) (δIN_{man}, and δIN_{water}) represent the N surplus which can be eventually imported in the GOANIM model as an additional N input.

2.3 Conventional harvested areas

We retrieved spatial explicit conventional harvested areas [ha] for the year circa 2000 from Monfreda et al. (2008).

2.4 Nitrogen from wastewater resources

We estimated the current N available from wastewater resources following the procedure described by Van Drecht et al. (2009). N in wastewater was estimated considering the global population density of 2015 (Doxsey-Whitfield et al. 2015), and the current per-capita N excreta, estimated based on the protein consumption for every of the 164 considered countries. We then spatially allocated the per-capita N available in wastewater at a 5-min resolution proportionally to the harvested area of every single country.

3. The GOANIM model

The GOANIM model is a spatially explicit, biophysical and linear optimization model simulating cropland soil N cycling in organic farming systems and its feedback effects on food production at the global scale (supply-side of the food systems). GOANIM was coded in two versions:

- Version I (*GOANIM V1*) is a linear optimization model that estimates (i) organic crops yields in each geographic location (i.e. grid-cell) as a linear function of the N supply to organic cropland soils and (ii) organic livestock animal population densities in each location as a function of the locally available feed resources. The model objective is to maximize total food production (from crops and livestock food commodities). This version of the model actively estimates livestock numbers for each grid-cell, thus redesigning the organic livestock sector across the globe. The GOANIM (V1) estimates organic crop yields and livestock densities for any global conversion share to organic farming set by the user, from 0% to 100%.

- Version II (*GOANIM V2*) is a linear optimization model that maximizes organic crop yields as a linear function of the N supply to organic cropland soils. Livestock animal population densities are kept as the current -i.e. conventional- ones and the total food output is calculated as the difference between the total cropland production minus the fraction of the cropland production used to feed current livestock animal populations worldwide. The GOANIM (V2) estimates organic crop yields for any global conversion share to organic farming set by the user, from 0% to 100%.

3.1 GOANIM model – Version I

3.1.1 Objective function

The model objective function is to maximise the total food energy produced from organic food commodities, considering both cropland and livestock production, as indicated in equation (11):

$$Max: \sum_{i=1}^{61} A_i \times Y_{food_i} \times [E]_i + \sum_{k=1}^{8} LIV_k \times Y_{food_k} \times [E]_{livestock-products_k} \qquad (10)$$

where A_i is the area cultivated under each crop species i [*ha*], Y_{foodi} is the food sub-yield of any crop species i [*tons ha*$^{-1}$], $[E]_i$ is the energy density of any crop species i [*MJ tons*$^{-1}$], LIV_k is the livestock density of any livestock species k, Y_{foodk} is the food yield of any livestock species k, and $[E]_{livestock-products-k}$ is the energy density of any k livestock type food product [*MJ tons*$^{-1}$].

A few crop species out of the 61 covered in this study do not provide any energy for food (e.g. tea, coffee). Therefore, the model would automatically set to zero the yield of such crops -i.e. no N would be allocated to these crops, even in the case of plenty available N resources. This is because such crops do not contribute to the objective function. To avoid this unrealistic effect, these crops were assigned a very low energy density (e.g. 1e^{-6} *MJ kg*$^{-1}$). In this way, their contribution to the objective function is almost null, but still positive. The model will then allocate N to these crops, if available after allocation to all the other crops species.

3.1.2 Crop yield response curve to N supply

Organic crop and crop residues yields are simulated as a function of the total N supplied to cropland soils via a crop species-specific linear N-response curve (Equation 11). The plateau of each yield curve is estimated as the current -i.e. conventional- dry matter yield corrected by an organic-to-conventional yield gap (referred onwards as organic maximum yield). Current conventional yields are indirectly a function of local pedo-climatic conditions.

$$IF\ N_i \leq N_{max_i},\ THEN\ Y_i = \frac{N_i}{N_{max_i}} \times Y_{max_i}\ ELSE\ Y_i = Y_{max_i} \tag{11}$$

Where Y_i is the simulated organic yield [*tons DM ha^-1*], N_i is the N input to cropland soils [*tons N*], N_{max_i} is the N input to cropland soils that allows Y_{max_i} [*tons N*], and Y_{max_i} is the maximum attainable yield in organic farming [*tons DM ha^-1*] for any crop species *i*.

We estimate the organic maximum attainable yield in equation (11) by multiplying the current –i.e. conventional- yields (Monfreda et al. 2008) by crop species-specific organic-to-conventional yield gaps from recent literature (Ponisio et al. 2015). We corrected these organic-to-conventional yield gaps in order to account for a yield reduction due only to pest and diseases, i.e. not accounting for the yield reduction due to N deficiency. This is because the GOANIM model itself simulates the yield reduction due to N limitation. As in a previous study (Erb et al. 2016), we applied the organic-to-conventional yield gaps (Ponisio et al. 2015) only to industrialized agriculture with high conventional yields, which we define as regions where conventional yields are higher than 55% of their potential attainable value (based on the conventional yield gap analysis by Licker et al. (2010) and Mueller et al. (2012). We made this assumption because the data collected by Ponisio et al. (2015) are largely restricted to developed countries and high-yielding conventional systems and we currently do not have sufficient scientific data on relative organic yields in developing countries with low-input conventional agriculture (Seufert & Ramankutty 2017). Total dry matter production is then calculated by multiplying the simulated crop yields by the corresponding area (organic land use, from Barbieri et al., submitted for publication), see section 4.1.7).

Crop residues yield is estimated as a function of the harvested yield, as in equation (6). The fraction of N inputs derived from crop residues recycled to soil (IN_{res}) is accounted by considering only the crop residues N requirements of the fraction exported from soils, plus the losses occurring after incorporating the fraction of crop residues recycled to soils (violet boxes in Figure S23. Diagram for estimating the N demand from crop residues. The model directly accounts only for the N fractions in the violet boxes.), resulting in the linear equation (12).

$$Y_i \times RPR_i = N_{res-exported_i} \times \frac{1}{[N]_{res}} \times \frac{1}{[\beta + ((1-\beta) \times \gamma)]} \tag{12}$$

where Y_i is the simulated organic yield [$tons\ DM\ ha^{-1}$], RPR_i is the residue-to-product ratio, $N_{res-exported_i}$ is the N content of the exported fraction of the crop residues, N_{res_i} is the N density of the crop residues, β is the crop residues removal factor, and γ is the coefficient estimating losses after the soil incorporation of the N contained the recycled fraction of the crop residues, for each crop specie i. γ is estimated based on the IPCC procedure (Dong et al. 2006), as explained for the conventional sub-model, at section 2.

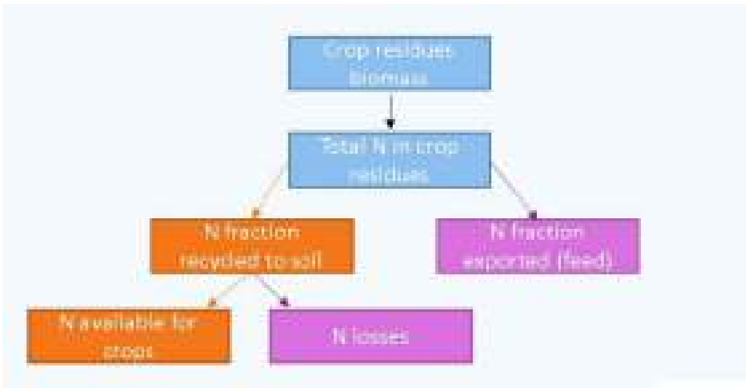


Figure S23. Diagram for estimating the N demand from crop residues. The model directly accounts only for the N fractions in the violet boxes.

3.1.3 Biological N fixation

Biological symbiotic N fixation is calculated as in equation (3). Non-symbiotic N fixation by free-living cyanobacteria is calculated using the coefficient reported in paragraph 2. The non-symbiotic N fixation is considered to be independent of the crop dry matter yield and it is therefore added the right-hand side of the model equations.

3.1.4 N from organically managed livestock manure

Organic livestock provides cropland soils with manure (IN_{man}). IN_{man} for each livestock species and country is calculated as the product of the yearly standing livestock heads and livestock species-specific excretion coefficients. Excretion coefficients are calculated as reported in section 2, -i.e. no differences in manure excretion are considered between organic and conventional farming systems-. The total produced manure is then corrected for losses (leaching, volatilization and runoff) due to storage and management, applying a modified version of the IPCC coefficients reported in section 2. In details, we used the same procedure and coefficient as in section 2, but we corrected the share of ruminant livestock species that are held on permanent pastures. This is because organic farming land use has higher shares of temporary fodders compared to conventional systems (Barbieri et al., submitted for publication). Therefore, we hypothesize that organic farmers would tend to prioritize the use of such temporary fodders, holding livestock proportionally less on permanent pastures. Hence, we decrease the share of livestock held on permanent pasture provided by IPCC proportionally to the increased proportion of temporary fodders in every single grid-cell. For instance, consider a share of a grid-cell with 100 *ha* of permanent pastures, 40 *ha* and 80 *ha* of temporary fodders in the conventional and organic land use, respectively, and a 40% of ruminants kept on permanent pastures. In the organic land use, the ratio of organic temporary fodders on permanent pastures is 0.8, while in conventional in 0.4. Therefore, temporary fodders increase by 50% in organic land use compared to the conventional counterpart. Hence, the share of organic livestock kept on permanent pastures is decreased by 50%, leading to a share of 20% of ruminants kept on permanent pastures.

3.1.5 N budgets

Crops N demand and N supply are balanced via the budgeting equation (13):

$$OUT_{crop} + OUT_{res} + OUT_{pool} = IN_{fix} + IN_{man} + IN_{dep} \tag{13}$$

Where: OUT_{crop} is sum of each N_i inputs necessary to obtain the yield Y_i in equation (10), OUT_{res} is the sum of each $N_{res-exported_i}$ in equation (11), IN_{fix} is the sum of the BNF fixed by each legume crop species, IN_{man} is the N in manure provided by organic livestock and IN_{dep} is the total dry and wet N atmospheric deposition, as described in Section 2. OUT_{pool} represent eventual additional losses to the environment, in the event that $OUT_{crop} + OUT_{res} < IN_{fix} + IN_{man} + IN_{dep}$. This implies that an eventual N surplus for a given crop cannot be transfer to others crop species in the same grid-cell. All variables are in [$tons\ ha^{-1}$] and are then multiplied by respective crop species areas, described at paragraph 4.1.7.

3.1.6 Additional N resources

GOANIM is able to selectively add additional N input resources (Figure S22. Schematisation of the budget calculation for the conventional farming systems, of the ORGASM model, and their interactions. The most important input datasets are also specified.). These resources are the N surplus outputs of the conventional budgeting model add-in described in section 2 (i.e. δIN_{man} and δIN_{water}). These surpluses can be selectively added by the user to the available N resources for cropland application by activating binary variables according to equation (14):

$$IN_{man_{tot}} = IN_{man} + s \times \delta IN_{man} + t \times \delta IN_{water} \quad (14)$$

Where s and t are dummy binary variables activating or deactivating the accounting of additional N resources.

3.1.7 Food and feed production from croplands

The total crops' dry matter yield calculated as in paragraph 4.1.2 is then repartitioned into a food and a feed yield pools, in a way that, for any given crop species i, $Y_i = Y_{food_i} + Y_{feed_i}$. The model is set free to allocate the total dry matter yield either to food or to feed, up to a maximum allowed threshold for feed allocation (Supplementary dataset I). This threshold corresponds to the current global use of each crop species as a feed resource, according to FAOSTAT statistics (Food and Agriculture Organization of the United Nations 2016); temporary fodder crop species are completely allocated to feed.

3.1.8 Organic crop harvested areas

Organic crop harvested areas (land use) for any given crop species has been taken from Barbieri et al. (submitted for publication). Organic areas are then multiplied by the conversion share to organic farming (from 100% to 0%) chosen by the user. This conversion coefficient is equal to (*1 - global share conventional*), where *global share conventional* is the conventional global share defined in Section 2.

3.1.9 Organically managed livestock densities estimations

The model estimates livestock (adult producing animals) population densities in each given grid-cell as a function of (i) the locally available feed resources and (ii) the ability of each livestock species to provide N for application to cropland soils. The model does not simulate any livestock structure, i.e. animals of different ages and non-productive animals.

Livestock diets. We define livestock dietary requirements as the metabolisable energy (ME) and crude protein (CP) necessary to cover the dietary needs of any adult animal[11] over one full

[11] We subdivided the five considered livestock species into 9 sub-categories (livestock types) -respectively dairy cows, beef, dairy and meat goats, dairy and meat sheep, pigs, broilers and hens.

year. Reference data are reported in Table S22. We calculated the ratio between each of the reference ME and CP requirements and the reference live weights, obtaining the feed requirement per kg of live weight for any livestock type (expressed respectively in [*MJ kg-live-weight*$^{-1}$] and [*kg CP kg-live-weight*$^{-1}$]). We used these values to regionalize livestock dietary requirement based on the live weights of the various livestock types in each of the 162 considered countries. We collected data on live weight from FAOSTAT, as for the IN_{man} calculations. For dairy cows, we also separately considered the energy and protein requirements for each liter of produced milk (respectively 5 *MJ ME* l^{-1} and 0.1 *kg CP* l^{-1}). We regionalized this additional requirement using FAOSTAT country data about milk yields.

The total ME and CP dietary requirements were then split into three feed categories, i.e. grains, fodders, and crop residues, using data from Herrero et al. (2013)[12] . In order to be consistent with organic principles, we verified that the share of feed from fodders was above 50% (European Commission 2008). Note that our estimation of livestock feeding requirements is conservative, since based on the current practices. An increased share of organic farming at the global scale could come with a modification of such practices, for example increasing the share of fodders to the detriment of grains. Nevertheless, our approach, even if conservative, allows to keep calculation transparent and consistent with each other.

The modelled animal populations densities accounts for the standing producing animals at the end of the simulated one-year time-frame. Nonetheless, some livestock types have a production turnover lower than one year. For those types (meat goats and sheep, pigs and broilers) we estimated the total annual population in order to correctly assess the total food production from livestock food commodities. To do so, we calculated the number of animals produced in one year by dividing, for each livestock species, the average slaughter weight by an average daily weight gain. For pigs and broilers, we used the average daily weight reported in Table S22, for meat goats and sheep we used regionalize average daily weight gain estimates from Herrero et al. (2013); Broilers' number of heads per year were calculated considering 40 unproductive days per year to allow for sanitation procedures (Lohmann Tierzucht 2016). For pigs, we differentiated between intensive and extensive production systems, following the data reported by Herrero et al. (2013).

[12] Herrero et al. distinguished four feed categories: grains, crop residues, fodders and occasional (cut and carried fodders, legumes, and other planted forage). Our fodder category is the sum of Herrero's fodder and occasional original categories.

Table S22. Reference livestock feed requirements and production parameters expressed in metabolisable energy (ME) and crude protein (CP).

Livestock type	Ref. live weight [*kg*]	Energy [*MJ ME day*$^{-1}$]	Protein [*kg CP day*$^{-1}$]	Ref. daily weight gain [*g*]	Ref. production [*l/no.*]	Sources
Dairy cows	400	42.8	0.43		13.7	Food and Agriculture Organization of the United Nations (2016)
Beef cows	325	32.8	0.94	1500		Adapted from National Research Council (2000)
Dairy goats	27.5	10.85	0.26		1	Langston University
Meat goats	15	6.25	0.10	77		Langston University
Dairy sheep	40	19.37	0.40		21	Lendin (2004)
Meat sheep	17.5	8.87	0.14	77		Lendin (2004)
Pigs	50	12.22	0.13	275*, 617**		Herrero et al. (2013); Carter et al. (2013); Tybirk et al. (2013)
Broilers	2	1.31	0.02			Lohmann Tierzucht (2016)
Laying hens	2	1.17	0.08		1	Cobb-Vantress (2015); Ross Aviagen (2014)

Livestock population densities simulation. Standing livestock population densities are simulated by GOANIM by matching the dietary ME and CP feed requirement of each livestock standing unit with the available feed resources in any given grid-cell (equations 15-17 and 18-20). Livestock numbers are calculated in number of heads and then transformed in Livestock Units by applying the appropriate FAO's Tropical Livestock Unit conversion factor.

$$\sum_{i=1}^{s} LIV_i \times E_{grain-req_i} \leq \sum_{k=1}^{z} A_k \times Y_k \times [E]_k \tag{15}$$

$$\sum_{i=1}^{s} LIV_i \times E_{fodder-req_i} \leq \sum_{k=1}^{z} A_k \times Y_k \times [E]_k \tag{16}$$

$$\sum_{i=1}^{s} LIV_i \times E_{stover-req_i} \leq \sum_{k=1}^{z} A_k \times Y_k \times RPR_k \times \beta \times [E]_k \tag{17}$$

where: LIV_i is the number of heads for animal species i and $E_{grain-req_i}$, $E_{fodder-req_i}$, and $E_{stover-req_i}$ are the ME feed requirements from grain, fodder, and crop residues, respectively for any animal species i; A_k is the harvested area under crop species k, Y_k is the dry matter yield of any crop species k, RPR_k is the residue-to-product ratio (described in section 2), β is the removal factor for crop residues (described in section 2), and $[E]_k$ is the energy density of feed category k.

$$\sum_{i=1}^{s} LIV_i \times P_{grain-req_i} \leq \sum_{k=1}^{z} A_k \times Y_k \times [P]_k \tag{18}$$

$$\sum_{i=1}^{s} LIV_i \times P_{fodder-req_i} \leq \sum_{k=1}^{z} A_k \times Y_k \times [P]_k \tag{19}$$

$$\sum_{i=1}^{s} LIV_i \times P_{stover-req_i} \leq \sum_{k=1}^{z} A_k \times Y_k \times RPR_k \times \beta \times [P]_k \tag{20}$$

where: $P_{grain-req_i}$, $P_{fodder-req_i}$, and $P_{stover-req_i}$ are the feed CP requirements from grain, fodder, and crop residues requirements for any livestock type i (as described in paragraph 3.2.6.1); $[P]_k$ is the protein density of any given harvested crop product or crop residues, for any crop species k.

3.1.10 Permanent grasslands

Livestock fodder dietary requirement can be satisfied by temporary fodder crop species, whose yield is simulated as described at paragraph 3.1.2, or by permanent grassland fodder production. We calculated the energy and protein production by permanent grasslands following the procedure proposed by Fetzel et al. (2017). In details, we estimated the permanent grassland fodder biomass production by combining the MODIS-based (derived using remote sensing techniques) Net Primary Productivity (NPP) (Zhao et al. 2011) maps with a global dataset reporting the distribution of permanent grasslands worldwide (Ramankutty et al. 2008). We considered only the above ground fraction of the total NPP (aNPP), by assuming an aboveground to total NPP proportion of 60% (Fetzel et al. 2017). The resulting aNPP was converted to dry matter biomass considering a carbon content factor of 50% (Haberl et al. 2007). We then transformed the dry matter biomass in total available energy and protein by applying a ME density coefficient of 10.02 and 9.85 $MJ\ ha^{-1}$ and crude protein density of 0.2269 and 0.1251 $kg\ kg\ DM^{-1}$ for temperate and tropical regions, respectively.

3.1.11 Additional constraints

GOANIM comes with a set of additional agronomic constraints, which can be activated/deactivated by the user.

1. **Minimum crop yield.** The user can force the minimum yield of any give crop category[13], as in equation (21):

$$\sum_{i=1,k=1}^{n,10} Y_{i,k} \geq P \times \sum_{i=1,k=1}^{n,10} Yield_{potential_{i,k}} \tag{21}$$

where: $Y_{i,k}$ is the dry matter yield of any crop i within any crop category k, and P a coefficient in between 0 and 1.

In the present study, we only force the crop yield of non-food crops. This is because the model would assign nitrogen to non-food crops only at last, whereas these crops would simultaneously compete for N resources since they still have an important role for e.g. industrial purposes.

2. **Minimum livestock no. of heads.** We include a set of constraints that allow the user to constraint the minimum livestock number of heads (or LU). This set of constraints does not apply to each single livestock type simulated by the model, but either to a certain livestock category (e.g. ruminant *vs* monogastric, bovine *vs* sheep *vs* goats, etc.) or to a livestock products category (e.g. milk-producing animals *vs* meat-producing animals, *vs* eggs-producing animals). The constraint allows to set the minimum share of producing heads (or LU) of any category of choice in comparison to the total number of livestock heads (considering all the 9 livestock types) as in equation (22):

$$\forall k, \sum_{i=1}^{n} LIV_{i,k} \geq P \times \sum_{i=1}^{9} LIV_i \tag{22}$$

where $LIV_{i,k}$ is the livestock density of each livestock type i belonging to any defined category k (e.g. milk, meat or eggs), and P a coefficient in between 0 and 1.

3. **Maximum livestock no. of heads.** We include another set of constraints that allow the user to set the maximum number of heads for any given livestock type, as a percent of the total number of livestock types, as in equation (23):

$$\forall i, LIV_i \leq P \times \sum_{i=1}^{9} LIV_i \tag{23}$$

[13] The 61 covered crop species are grouped in crop categories, according to Barbieri et al. (submitted for publication), namely primary cereals, secondary cereals, pulses, root crops, oil crops, industrial crops, fodder crops, vegetables, fruits, and non-food crops.

where LIV_i is the livestock density of each livestock type *i* and *P* a coefficient in between 0 and 1.

3.1.12 Outputs and statistics

The model output is represented by all the model defined variables. It is up to the user to decide which information to save. In the current version, the model is set to save the following output variables:

- the total simulated dry yields of each single crop species;
- the simulated food sub-yields of each single crop species;
- the simulated feed sub-yields of each single crop species;
- the nitrogen fixed by biological nitrogen fixation (BNF) for leguminous crop species;
- the nitrogen from organic manures provided to each crop species;
- the livestock producing heads of each single livestock type;
- the livestock standing producing heads in LU;
- the total nitrogen available for crop uptake in organic manure;
- a set of in-model calculated statistics including:
    - the total energy and protein in food from crops;
    - the total energy and protein in animal products;
    - the total energy and protein from temporary fodders crops;
    - the total livestock fodder requirements (energy and proteins).

3.1.13 Thermodynamic principles

The model respects the thermodynamic principles (low of the conservation of mass and energy). We checked for the total N input in livestock production (N in feed) to be equal to the total output in livestock production (*N in excreta + N in livestock food products + N in livestock animal body*). N outputs were overall higher than N inputs. We corrected the livestock excreta coefficient for each of the 164 considered countries in order to perfectly match the N input vs N output in the livestock sector to avoid any artificial creation of Nitrogen. We applied this corrected N excreta coefficient to both the Organic optimization sub-model (version I and II), as well as to the conventional sub-model, in order to harmonize the coefficient used throughout the full model.

Table S23. Simplified model structure as coded, reporting a simplified version of all equations' coefficients. Colour boxes represent the different structural matrices as coded in R

	Crop yield (61)	**N crop (61)**	**N stovers (61)**	**N pool (61)**	**N BNF (61)**	**N fert. (61)**	**Food sub-yield (61)**	**Feed sub-yield (61)**	**Stand liv. heads (9)**	**Total N avail. (1)**	**Live. heads (9)**	**Live. LU (9)**	**Stat. (11)**	**DIR**	**RHS**
Yield curve slope (61)	1	$-1/[N_i]$												=	0
Yield curve plateau (61)	1													$\leq$	Y_{max}
Stovers yield (61)	RPR		$-K_{stover}$											=	0
NBF (61)	K_{fix}				-1									=	0
N budget (61)		A_i	A_i	A_i	$-A_i$	$-A_i$								=	IN_{dep} + IN_{cyano}
Avail. N fert. (1)						A_i				-1				$\leq$	$conv\text{-}manure+ww.$
Tot. crop yield (61)	-1						1	1						=	0
Max. feed share (61)	$k_{feed-grain}$							-1						$\geq$	0
Liv. grain req. (2)								$A_i \times K_{grain}$	$-Req_{grain}$					$\geq$	0
Liv. fodder req. (2)								$A_i \times K_{fodder}$	$-Req_{fodder}$					$\geq$	0
Liv. stover req. (2)								$A_i \times K_{stover}$	$-Req_{stover}$					$\geq$	0
Manure (1)									k_{head}	-1				=	0
Liv. head (9)									k_{head}		-1			=	0
Liv. LU (9)									k_{LU}			-1		=	0
Min. liv. density (5)									$K_{head}/(K_{LU})$		$-C_{head_1}$	$(-C_{LU_1})$		$\geq$	0
Max. liv. density (9)									$K_{head}/(K_{LU})$		$-C_{head_2}$	$(-C_{LU_2})$		$\leq$	0
Min. crop yield (10)	C_{crop}													$\geq$	$K_{constr.}$
Stat. (11)													$K_{stat.}$	=	0

Table S 24. Simplified model structure as coded, reporting each single sparse sub-matrix (SM). Colour boxes represent the different structural matrices as coded in R

	Crop yield (61)	N crop (61)	N stovers (61)	N pool (61)	N BNF (61)	N fert. (61)	Food sub-yield (61)	Feed sub-yield (61)	Stand liv. heads (9)	Total N avail. (1)	Live. heads (9)	Live. LU (9)	Stat. (11)	DIR	RHS
Yield curve slope (61)	SM1	SM2	SM3	SM4	SM5	SM6	SM7	SM8							
Yield curve plateau (61)	SM9	SM10	SM11	SM12	SM13	SM14	SM15	SM16							
Stovers yield (61)	SM17	SM18	SM19	SM20	SM21	SM22	SM23	SM24							
NBF (61)	SM25	SM26	SM27	SM28	SM29	SM30	SM31	SM32							
N budget (61)	SM33	SM34	SM35	SM36	SM37	SM38	SM39	SM40							
Avail. N fert. (1)	SM41	SM42	SM43	SM44	SM45	SM46	SM47	SM48							
Tot. crop yield (61)	SM49	SM50	SM51	SM52	SM53	SM54	SM55	SM56							
Max. feed share (61)	SM57	SM58	SM59	SM60	SM61	SM62	SM63	SM64							
Liv. grain req. (2)				SM65 SM71				SM66 SM72							
Liv. fodder req. (2)				SM67 SM73				SM68 SM74		SM92			SM104	DIR	RHS
Liv. stover req. (2)				SM69 SM75				SM70 SM76							
Manure (1)					SM77										
Liv. head (9)					SM78										
Liv. LU (9)					SM79										
Min. liv. density (5)					SM80										
Max. liv. density (9)					SM81										
Min. crop yield (10)					SM2 to SM91										
Stat. (11)							SM93 to SM103, SM105								

3.2 GOANIM model – Version II

The GOANIM-model (V2) works in the same way as version I and use the same data sources. Here we present a detailed explanation of the main differences in comparison to the Version I of the model.

3.2.1 Objective function

The GOANIM-model (V2) simulates only the crop yield response to N supply to soils. Therefore, the optimization procedure is set to maximize only the total energy produced by croplands, as in equation (24):

$$Max : \sum_{i=1}^{61} A_i \times Y_i \times [E]_i \tag{24}$$

Where A_i is the harvested area under each crop species i [*ha*], Y_i is the yield of crop species i [*tons* ha^{-1}], and $[E]_i$ is the energy density of crop species i [*MJ* $tons^{-1}$].

3.2.1 Livestock population densities

The GOANIM-model (V2) does not actively simulated livestock animal densities, but it is based on the hypothesis that livestock densities and distribution will not change in comparison to the current situation. Therefore, livestock organic densities are represented by the current conventional livestock densities maps multiplied by the global share of organic farming set by the user.

3.2.2 Livestock feed requirements

Organic livestock feed requirements are calculated considering the livestock densities as described in the previous paragraph and the ME and CP dietary requirements described at paragraph 3.1.7.1.

In order to consistently calculate the total ME and CP livestock requirements, we considered that the ratio of the across-crop species average energy and protein density (i.e. $\sum_{i=1}^{61}[E]_i \Big/ \sum_{i=1}^{61}[P]_i$ stays constant. Yet, resources to satisfy these requirements come from "pools" where the energy and protein produced by every crop species are pulled together. Energy and protein content of each unit of feed are defined by the stoichiometry of each feed commodity, and hence they are not separable. As instance, consider a dietary requirement for one cow of

1000 *MJ* and 5 *kg protein*. To satisfy these requirements, 10 *kg* of wheat and maize grains are available, containing respectively 400 *MJ* and 3 *kg protein*, and 600 *MJ* and 4 *kg protein*. The total available energy and protein "pool" would then be *400 + 600 = 1000 MJ* and *3 + 4 = 7 kg protein*. Therefore, the available energy is just enough to feed one cow, while the available protein exceed the wow's requirements. Then, possible approach is to use all the energy available and just 5 out of the 7 *kg* of protein; nevertheless, this approach is not correct since the two quantities -i.e. energy and protein- are not separable and if all the energy is fed to the cow (i.e. the whole original biomass), necessary all the proteins are used as feed. Therefore, the protein 'excess' of 7 kg is not any more available for other purposes. Therefore, according to this example, we have to correct the amount of protein fed to the cow to match the energy one (which is the limiting factor). Yet, we do not know any more the original composition of crop products (all crops are pooled together). Therefore, we can just apply a more approximate correction as follows:

- For any grid-cell where protein is the limiting factor, i.e. where:

$$\frac{P_{livestock-requirements}}{P_{pool-crop-products}} > \frac{E_{livestock-requirements}}{E_{pool-crop-products}}$$

$$\text{then: } E_{consumed-by-livestock} = E_{pool-crop-products} \times \frac{P_{livestock-requirements}}{P_{pool-crop-products}}$$

- For any grid-cell where energy is the limiting factor, i.e. where:.

$$\frac{P_{livestock-requirements}}{P_{pool-crop-products}} < \frac{E_{livestock-requirements}}{E_{pool-crop-products}}$$

$$\text{then: } P_{consumed-by-livestock} = P_{pool-crop-products} \times \frac{E_{livestock-requirements}}{E_{pool-crop-products}}$$

3.2.3 Crop production budgets and total food production

Food budgets are calculated as the difference between total crop production minus the crop production needed for feeding livestock animal populations. For any given grid-cell, food budgets can be either positive (meaning that crop production is sufficient to feed livestock in that particular grid-cell), or negative, meaning that crop production is not sufficient to feed livestock in that particular grid-cell. Total global food production is then calculated as the sum between food budgets and the energy into livestock food commodities.

Table S25. Simplified model structure as coded, reporting a simplified version of all equations' coefficients. Colour boxes represent the different structural matrices as coded in R

	Crop yield (61)	**N crop (61)**	**N stovers (61)**	**N pool (61)**	**N BNF (61)**	**N fertil-isation (61)**	**Direction**	**RHS**
Yield curve slope (61)	1						=	0
Yield curve plateau (61)		1/[N]					$\leq$	Y_{max}
Stovers yield (61)	RPR		$-K_{stover}$				=	0
NBF (61)	k_{fix}				-1		=	0
N budget (61)		A_i	A_i	A_i	$-A_i$	$-A_i$	=	$IN_{dep} + N_{cyano}$ $Org\text{-}manure$ +
Avail. N fertiliser (1)						A_i	$\leq$	$conv\text{-}manure$ + $wastewater$

Table S26. Simplified model structure as coded, reporting each single sparse sub-matrix (SM). Colour boxes represent the different structural matrices as coded in R

	Crop yield (61)	**N crop (61)**	**N stovers (61)**	**N pool (61)**	**N BNF (61)**	**N fertil-isation (61)**	**Direction**	**RHS**
Yield curve slope (61)	SM1	SM2	SM3	SM4	SM5	SM6		
Yield curve plateau (61)	SM7	SM8	SM9	SM10	SM11	SM12		
Stovers yield (61)	SM13	SM14	SM15	SM16	SM17	SM18	DIR	RHS
NBF (61)	SM19	SM20	SM21	SM22	SM23	SM24		
N budget (61)	SM25	SM26	SM27	SM28	SM29	SM30		
Avail. N fertiliser (1)	SM31	SM32	SM33	SM34	SM35	SM36		

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