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LETTER

Land-free bioenergy from circular agroecology—a diverse option space and trade-offs

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Abstract

Bioenergy from energy crops is a source of negative emissions and carbon-neutral fuels in many 1.5/2 °C IPCC pathways. This may compete with other land uses. In contrast, ancillary biomass like by-products and waste is not primarily grown for energy and thus without land/food/feed competition. Here, we examine the availability and environmental impacts of ancillary bioenergy from agricultural sources under 190 circular agroecological strategies using the global food-system model SOLm for the year 2050. We find that there is a diverse option space for the future food and energy system to meet both global warming targets (1.5 °C) and food system sustainability (medium to highly organic) – a similar range of ancillary bioenergy global potential (55–65 EJ)from very different food systems (50%–75% organic agriculture and various levels of waste and concentrate feeding reduction). We find three trade-offs between food system sustainability and ancillary bioenergy provision. First, there is a clear trade-off between nutrient recycling and negative emissions potential. 1.4–2.6 GTCO_2eq of negative emissions supplied through ancillary bioenergy with carbon capture and storage comes at the cost of nutrient deficits and resulting incompatibility with even a medium degree of organic farming. Second, reducing feed from croplands increases the ancillary bioenergy production with low shares of organic agriculture and reduces it for high shares. Third, food waste reduction reduces ancillary bioenergy provision. Hence, the sustainable transformation of the food system towards a less animal-based diet and waste reduction may conflict with a higher ancillary bioenergy provision, especially when the organic share is high as well. The policy implication of our results is that ancillary bioenergy can provide a similar range of future bioenergy as foreseen in IPCC AR6 illustrative pathways (±10%) without additional land use or compromising food availability. However, higher ancillary bioenergy provision or additional negative emissions compete with food system sustainability; hence, we recommend policymakers consider aligning energy system planning with the compatibility of sustainable food systems simultaneously.

1. Introduction

The Paris Agreement set the global warming limit to 2 °C by the end of this century. Many nations envision achieving climate neutrality by 2050, for instance, the European Union Green Deal [1]. As the only renewable energy providing negative emission potential, bioenergy appears to be an attractive option in most future carbon-neutral pathways. Over 95% scenarios in the latest Intergovernmental Panel on Climate Change (IPCC) AR6 (Sixth Assessment Report) deploy BECCS (bioenergy with carbon capture and storage) for reaching the 1.5 or 2 °C target [2]. Yet, the contribution of dedicated and residual bioenergy varies significantly among models and scenarios. On the one hand, residues could meet 7%–50% of bioenergy demand in 2050 and 2%–30% towards 2010, according to the latest IAM (integrated assessment models) comparison [3]. In the case of European models, on the other hand, dedicated bioenergy crops are foreseen to constitute about 70% of the future energy supply [4]). However, dedicated energy crops may compete with food and feed for arable land and water [5]. Recent policies have gradually recognized the pitfalls of dedicated bioenergy. The European Commission, for example, has amended several types of sustainable bioenergy feedstocks in the Renewable Energy Directive, which requires the biomass feedstocks not to be fit for use in the food/feed chain (e.g. oil palms in Annex IX [6]).

The land use or food/feed conflicts caused by sustainable biomass are difficult to quantify and are treated highly inconsistently when comparing policy goals and modeling studies (e.g. inconsistent definitions [7] and differences between models [8]. Therefore, we proposed a land-free type of ancillary bioenergy and defined it as various non-dedicated bioenergy feedstocks recovered from residue and co-/by-products from agriculture, forests, and human settlements, which is sustainable in the sense that it reduces competition for land, food, feed, or water [9]. In our previous study, we found that ancillary bioenergy is important for realizing deep energy system decarbonization; for example, ancillary bioenergy can replace land-intensive dedicated biomass or balance intermittent renewable power in a nuclear-free scenario while achieving a similar total system cost [8]. The concept of ancillary bioenergy is different from previous literature mainly in two ways. First, it includes the embedded by-/co-products with high energy density (e.g. fish oil), which are not included in most residual/waste bioenergy studies/models like [4, 10]. Second, ancillary bioenergy excludes food/feed/land conflicts that were not captured in previous studies (e.g. [11, 12] proposed similar concepts without ruling out food/feed conflicts).

However, we simplified the agricultural bioenergy availability by assuming the business-as-usual case in the future food system. Nevertheless, when the food system evolves towards a more circular one, it is likely to alter the availability of ancillary bioenergy. A circular food system implies the reduction of waste and consumption of cropland-based livestock products, reuse of byproducts and waste, recycling of nutrients, and other circular practices to close mass or nutrient loops [13]. In relation to bioenergy and the energy system, for example, recycling food waste can yield more bioenergy with low opportunity costs [14]. The increased organic farming leads to lower yields and less waste biomass for energy, which can impose a trade-off between bioenergy demand and sustainable agriculture [15, 16]. Dietary changes may help reduce energy-system mitigation costs by 25% through the reduction of ruminant products [17]. It thus remains highly uncertain how much ancillary bioenergy will be available if we have fundamental changes toward a more circular global food system, especially when different and interrelated circular practices are in place.

Given the unsustainable food systems of today, significant changes in global production and consumption structures may be expected. Policy-wise, in the near term, the European Commission has already proposed to increase the share of organic production to 25% by 2030 in the context of its farm-to-fork-strategy and European Green Deal [18]. Organic farming is not the only agroecological strategy toward a circular food system. Due to its generally lower yields, it also risks leading to increased land use, and complementary strategies are required to hedge against this [19]. In the long term, there are other circular practices available such as waste reduction, concentrate feeding reduction, reduced mineral fertilizer use, recycling nutrients in sewage sludge, etc [16, 19]. Such circular changes in the food system may alter ancillary bioenergy potential concurrently and significantly, both in quantities available and in its use as a nutrient source in agroecological production systems. In other words, the future global ancillary bioenergy potential will be well constrained by how we shape our future food system and vice versa, which is an unknown option space. It is hence vital to identify how ancillary bioenergy interacts with the various sustainability strategies for a more circular food system for timely policy advice.

Our research aims to answer the following questions. How do future circular agroecological strategies impact the supply of ancillary bioenergy from the food system, and does the resulting option space show any synergies or trade-offs? To answer these questions, we examine the option space for supplying ancillary bioenergy from agricultural sources under 190 circular agroecological scenarios using SOLmV6 [20]. Based on the FAO BAU 2050 scenario (Food and Agriculture Organization of the United Nations' Business-as-Usual 2050 scenario), we vary three parameters to explore the option space: organic agricultural share, concentrate feed reduction, and waste reduction. However, we do not model socioeconomic parameters or aim to capture the impacts of uncertain future food demand. Instead, we keep agricultural land use constant, i.e. we assume no more land than today is used.

This research contributes to the missing bridge between renewable energy and sustainable food system modeling, where both carbon neutrality and food sustainability are desirable but may have trade-offs between each other. The identified option space and trade-offs help both energy and agriculture policymakers to navigate the interplay between the two systems and make better decisions.

2. Methods and data

2.1. Food system model and datasets

Our food system model SOLm is a mass- and nutrient-flow model of the global food system, which is by default calibrated with Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) data and categories of crops and livestock at the national level [19, 20]. Our baseline is the 2050 BAU scenario as provided by FAO in their Future of Food and Agriculture Report [21], where there is no organic farming, waste reduction, or concentrate feeding reduction. We chose the year 2050 because that is when bioenergy is envisioned to provide massive negative emissions or carbon-neutral fuels in most energy transition pathways [22]. In the 6th version of SOLm (cf the model documentation [20]) that is used by this study here, the average from 2016 to 2020 FAOSTAT data serves as the baseline scenario.

2.2. Ancillary bioenergy potential

Using the definition of land-free ancillary bioenergy as in our previous study, we model the ancillary bioenergy potential from non-dedicated bioenergy feedstocks recovered from agricultural residue and co-/by-products that do not cause competition for land, food, feed, or water [8]). We then aggregate hundreds of crop residues and commodity byproducts into six categories of ancillary bioenergy feedstocks (First column of table A1). Note that the system boundary of this research is the food system, so we do not include forestry and municipal biomass outside the food system. For detailed assumptions of ancillary bioenergy potential, please refer to the appendix A.

2.3. Scenario assumptions

We model the three following agroecological practices. By combining the different shares of practices, we then have 95 circular strategies. Further driven by two bioenergy conversion pathways, we finally have 190 scenarios in total, as described below.

Agroecological practices. Changing agroecological strategies can significantly alter the availability of ancillary bioenergy and the corresponding environmental impacts. We depict different mixes of circular agroecological strategies by varying the three most central aspects of those in our model, namely (1) organic agriculture: how food is produced, (2) concentrate feeding: how animals are fed, and (3) waste management: how much is wasted, and in consequence, which role animal source products play in human diets ('practices' hereafter). Another reason we choose these three agroecology practices is that they are supposed to change the food system, and thus bioenergy potential, in different ways that may compensate for each other.

Circular strategies. Strategies are correspondingly captured by varying and combining the following three agroecological practices. We explain in detail how they are captured in the model and how they alter ancillary bioenergy provision as follows:

1. **Organic agriculture share**(captured by 'Organic share': 0%–100% that directly reduces the availability of primary crop residues and indirectly reduces the other residual, by-/co-product biomass potential). This is because a higher organic share is assumed to have lower yields and less residue available for energy. We adopt a conservative and broadly accepted assumption on organic yields, assuming a yield gap between the organic and conventional systems, where organic yields are considerably lower in reference to the large meta-studies [23]. This then results in the corresponding decreasing effects on ancillary biomass availability. We admit there are cases when organic yields may improve gradually and surpass conventional yields in the long run [24]. However, one may expect conventional agriculture to develop further and thus keep up with the yield gap.
2. **Food-competing feeding reduction**, as in the concentrate and other feed from cropland, such as forage maize (captured by 'Concentrate feeding reduction': 0%–100% that directly changes manure potential and frees-up land that is proportionally assigned to conventional/organic farming based on the organic share). Therefore, this practice can reduce manure biomass provision in response to the lower livestock numbers and increase the land used to cultivate crops, thus increasing/decreasing the crop production/residues based on the organic agriculture share changes.
3. **Waste reduction** (captured by 'Waste reduction': 0%–75% including the end waste and the waste for food/feed purposes that directly reduces the secondary residues and byproducts for bioenergy provision). The combination of different practices hence creates an option space of possibly supplying similar ranges of ancillary bioenergy. Note that we keep the total land use constant and allocate all the freed-up land from concentrate feeding reduction to cropland. For detailed information on how we model organic agriculture, concentrate feeding reduction, and waste reduction, please refer to the previous paper using SOLm [19] and the SOLm documentation [20].

All three agroecological practices contribute to a more circular food system in terms of (1) reduced mineral fertilizer inputs, (2) less dedicated land for growing feed that frees up cropland for food, and (3) less waste. The intervals in which each strategy is implemented is 25% (i.e. 0%, 25%, 50%, etc organic, etc), which results in 95 strategies with different combinations of these agroecological practices. Note that the highest waste reduction we assume is 75%, as there will always remain some unavoidable share of waste from production to consumption (while the conversion to 100% organic production and 100% reduction of feed from cropland is possible in principle).

Bioenergy conversion pathways. We further model two different bioenergy conversion pathways driving the aforementioned circular strategies to depict how the energy system impacts the food system in return.

(1) ***NutrientFirst*** is the default bioenergy conversion pathway that preserves as many nutrients as possible by producing biogas via distributed anaerobic digestors. We optimistically assume that all nitrogen in digestible biomass can be recycled in this pathway to maximize nutrient circularity. However, we assume this pathway has the drawback of providing no negative emission potential since it deploys distributed digestors instead of centralized BECCS.

(2) ***NegativeFirst*** is another plausible bioenergy conversion pathway, assuming all viable biomass (excluding manure) is used for stationary BECCS to maximize negative emissions but feeds no nutrients back to the food system. This pathway is also the prevailing use of dedicated biomass in most 1.5 °C AR6 scenarios [2]. To estimate the negative emissions potential that could be achieved through BECCS, we adopt the same method as in our previous study [8]. We assume the use of stationary power plants or Fischer-Tropsch diesel plants based on the viable biomass feedstocks. For BECCS technology cost and efficiency, we use data from the 2050 projection of biomass for electricity/liquids with CCS (carbon capture and storage) used in TIAM-Grantham [25]. We base the emissions factors of different biomass feedstocks on their default GHG emissions values [4], and multiply the emissions by carbon capture rate (ranging from 90% to 99.5% for different BECCS technology chains [10].

2.4. Indicators for environmental impacts

Changing agroecological strategies inherently changes the environmental impacts of the food system. SOLm captures various environmental impacts as detailed in a previous study [19] and the SOLm documentation [20]. The environmental impacts modeled in this study include (1) irrigation water (scarcity adjusted according to [26]; (2) soil erosion; (3) food availability (Calories per capita per day); (4) food system GHG emissions based on Tier 1 and 2 methods (GWP100) from the IPCC 2019 (where applicable; otherwise IPCC 2006); (5) nutrient balances (Nitrogen inputs, outputs, surplus, etc). There are other impacts provided by SOLm but are not sensitive to different strategies, and they are all available in our open-access data repository for each scenario [27]. In addition to the environmental impacts modeled by SOLm, we also examine the negative emissions of ancillary bioenergy per scenario using the same emission factors and methods as in our previous study [8].

2.5. Consistency check

We conduct a consistency check by comparing the model results for the baseline scenario to the same parameters from the established literature—i.e. FAOSTAT livestock numbers and production volumes, national UNFCCC (United Nations Framework Convention on Climate Change) GHG inventories [28] and OECD (Organization for Economic Cooperation and Development) nutrient balances [29]. Overall, there is no significant inconsistency between our baseline scenario and literature values (livestock numbers and production volumes are replicated, and there is no deviation of magnitude of total GHG emissions or Nitrogen balance). The consistency check consists of eight countries covering different world regions (South Africa, Brazil, Australia, Indonesia, China, the Netherlands, the United Kingdom, and the United States of America). Specifically, we compare the direct and indirect CH_4 and N_2O emissions (e.g. from dairy cattle enteric fermentation, managed soil, etc) to the latest UNFCCC GHG inventories, and the Nitrogen flows to the OECD nutrient balance (i.e. total manure Nitrogen production per livestock, N in different harvested crops, etc) whenever possible. One exception is for Brazil that the CH_4 emissions are unavailable from UNFCCC, so we use the Brazilian SEEG (Greenhouse Gas Emission and Removal Estimating System) database instead [30].

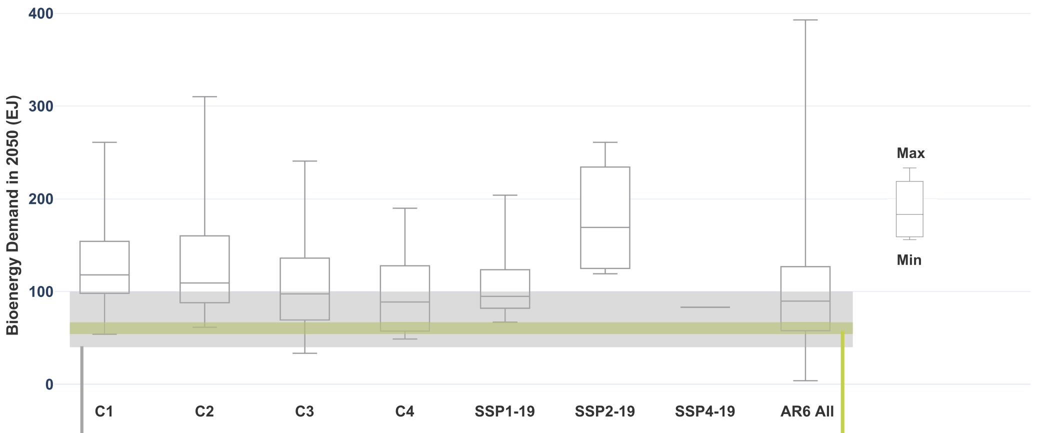
3. Results

3.1. Similar bioenergy potential from diverse agroecological strategies

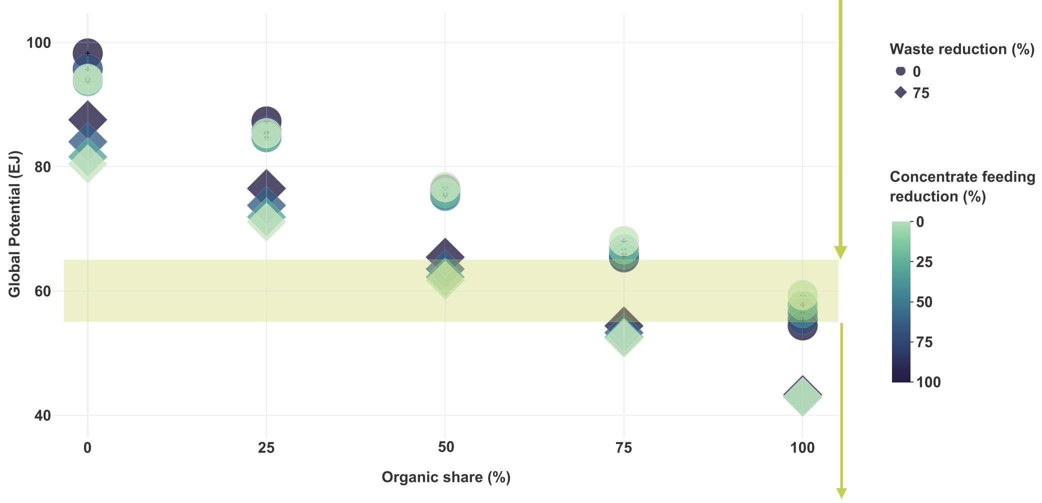
We find that ancillary bioenergy from agricultural sources can provide a total range of around 40–100 EJ in 2050 (figure 1(a)). Within the total range, there is an option space of a similar range of ancillary bioenergy potential (around 55–65 EJ) from a diverse combination of agroecological strategies (50%–75% organic farming, figure 1).

This similar range of 2050 agricultural ancillary bioenergy potential is around the current global production of total renewable biofuels and waste (57 EJ; 9% of the 2020 global energy supply) [31]. Compared to the 2050 bioenergy demand in the latest IPCC AR6 scenarios, this range of similar ancillary bioenergy potential can meet the lower range of 1.5 °C scenario

(a) Comparing ancillary bioenergy supply to bioenergy demand from AR6 scenarios



(b) Range of ancillary bioenergy supply potential from 95 strategies



(c) Example strategies decomposed by feedstocks within the "Option Space"

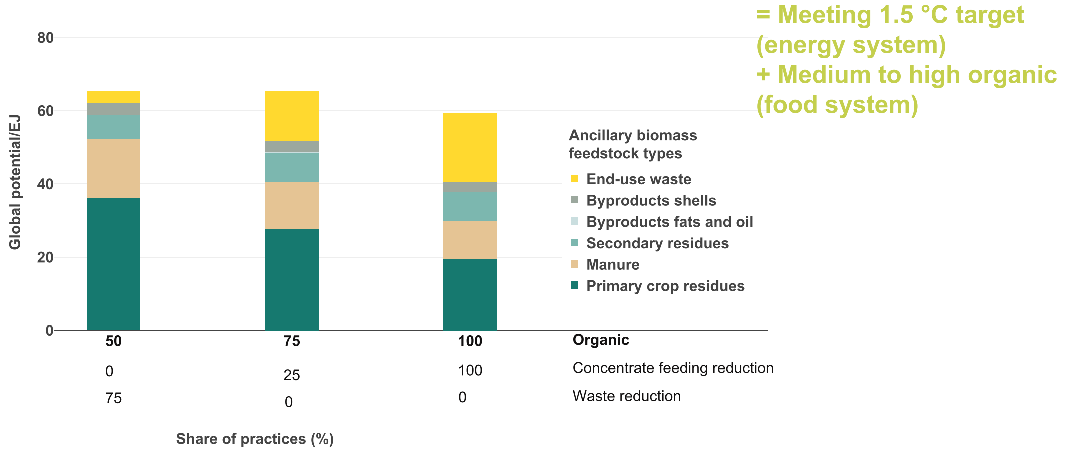


Figure 1. Global supply potential ranges of ancillary bioenergy in 2050. (a) Compared to the bioenergy demand range from IPCC AR6 scenarios, climate categories (C1–C4), and SSPs. (b) Decomposed by strategies. (c) Decomposed by feedstock types. (See table B2 for the detailed numeric results.)

categories ('C1': below 1.5 °C with no or limited overshoot, 'C2': below 1.5 °C with high overshoot, 'SSP1-19': net zero around 2050)[2]. We thus use the term 'option space' throughout the paper and figures to imply a similar range of ancillary bioenergy potential that can both meet the 1.5 °C targets (energy system) and medium to high organic shares (food system).

The reason behind this diverse option space is that the three agroecological practices are different in controlling the availability of various ancillary biomass feedstocks, which compensate for each other and result in a similar global potential (figure 1). Here we analyze the trade-offs among different agroecological strategies—organic share, waste reduction, and concentrate feeding reduction, namely how they change the availability of various ancillary biomass feedstocks in different ways. In the following, we present results for the default biomass conversion pathway *NutrientFirst*. We subsequently discuss the results for the other pathway *NegativeFirst* in section 3.3. For detailed explanations of the two pathways, please refer to section 2.

First of all, the organic share is the driving factor in altering the total ancillary bioenergy potential because of its impact on agricultural productivity. The global ancillary bioenergy potential drops from around 100 EJ to 40 EJ when the organic share increases from 0% to 100% (figure 1), regardless of the other agroecological aspects. Higher organic share reduces all crop yields and, hence, primary crop residues, which constitute the most ancillary bioenergy potential. Moreover, lower yields from organic farming also indirectly reduce the commodities available to produce secondary residuals and byproducts.

Second, waste reduction has a negative correlation with the total ancillary bioenergy potential by directly reducing the post-harvest feedstocks (i.e. end-use waste, secondary residues, and byproducts). Therefore, in combinations of high organic share with low waste reduction, the reduced primary crop residues can be compensated by the increased secondary residues and byproducts, which then barely changes the total ancillary bioenergy potential (e.g. figure 1).

Third, concentrate feeding reduction directly reduces manure due to lower animal numbers and also frees up land for growing crops, indirectly increasing primary and secondary crop residues. Since the amount of freed-up land is fixed when the concentrate feeding share is constant, the same freed-up land provides less biomass when the organic share increases (i.e. more freed-up land is assigned to organic farming with lower yields). That explains why the concentrate feeding reduction has the highest impact on increasing the total ancillary bioenergy potential when there is 0% organic farming (i.e. all freed-up land is for conventional farming with the highest yields) and the impact reverses when the organic share increases (i.e. the same area of land is to organic agriculture with low yields plus the reduced number of livestock produce less manure).

Therefore, the three practices/central parts of circular agroecology alter ancillary biomass feedstocks in compensatory ways, which forms a diverse option space for sourcing similar bioenergy potential (figure 1). Even within a similar range of global ancillary bioenergy potential, their feedstock compositions can be quite different due to the various agroecological strategies (figure 1).

However, from a sustainability perspective, waste reduction clearly is a primary goal, and as in earlier assessments (e.g. on organic agriculture and global food security [19], combinations of intermediate levels in all practices allow to meet potentially conflicting targets (e.g. bioenergy provision and sustainable food systems) to decent extents.

3.2. Varying environmental impacts from similar ancillary bioenergy potential

Focusing now on the option space of ancillary bioenergy potential (i.e. meeting both 1.5 °C climate targets and medium to high organic shares; the green shades in figure 1), we can see that different strategies to provide this potential come with varying environmental impacts (figure 2). On the one hand, we have a flexible option space to enhance certain environmental impacts for agroecology while providing a similar amount of bioenergy—a supposedly win-win situation for both the energy and food systems. On the other hand, one cannot improve all environmental impacts simultaneously; there are trade-offs between agroecological strategies and environmental impacts. For example, we find that the nitrogen deficit is the key challenge to a more organic and circular food system.

More specifically, the two most varying impacts include the drastically different nitrogen balance (over −50% maximum) and a moderate variation of GHG emissions (±30%). The other environmental impacts do not vary significantly (within 20%). We also display the most varying environmental impacts of all scenarios in the appendix (table B1). Note that figure 2 and table B1 do not cover all the modeled environmental indicators, but the most varying ones. For the detailed results of all environmental indicators per scenario, please refer to our open-access data repository [27].

Comparing the similar ancillary bioenergy potential from medium- and high-organic scenarios (figure 2), most environmental aspects improve with higher organic share (e.g. GHG emissions). Therefore, sourcing similar bioenergy potential from a more organic food system is generally more beneficial for the environment, albeit with reduced food availability and potential nutrient deficit as the trade-off. Meanwhile, waste reduction and concentrate feeding reduction can significantly increase food availability regardless of organic share, thus mitigating the trade-off between high organic share and food supply (e.g. an average of 20% higher calories per capita in (See table B1). Hence, waste and concentrate feeding reduction strategies are necessary for a highly organic system if one prioritizes future food supply.

Nevertheless, the nitrogen deficit is the most challenging impact in a highly organic system because it is the only impact that cannot be sufficiently remedied by the other two practices (either waste or

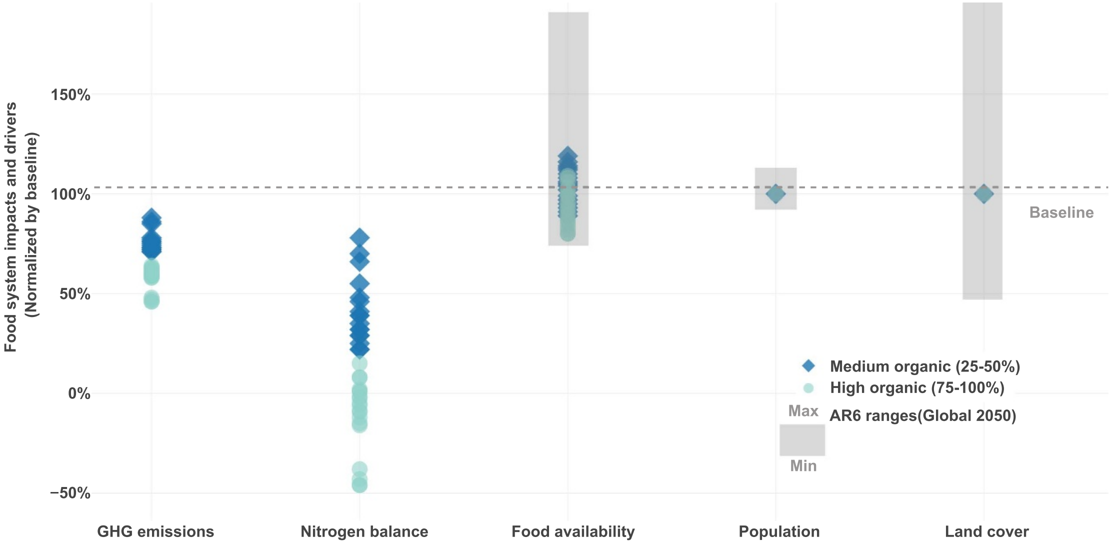


Figure 2. Example impacts and drivers compared to the IPCC AR6 scenario ranges (if their global 2050 values are available; nitrogen balance and food-system GHG emissions are unavailable).

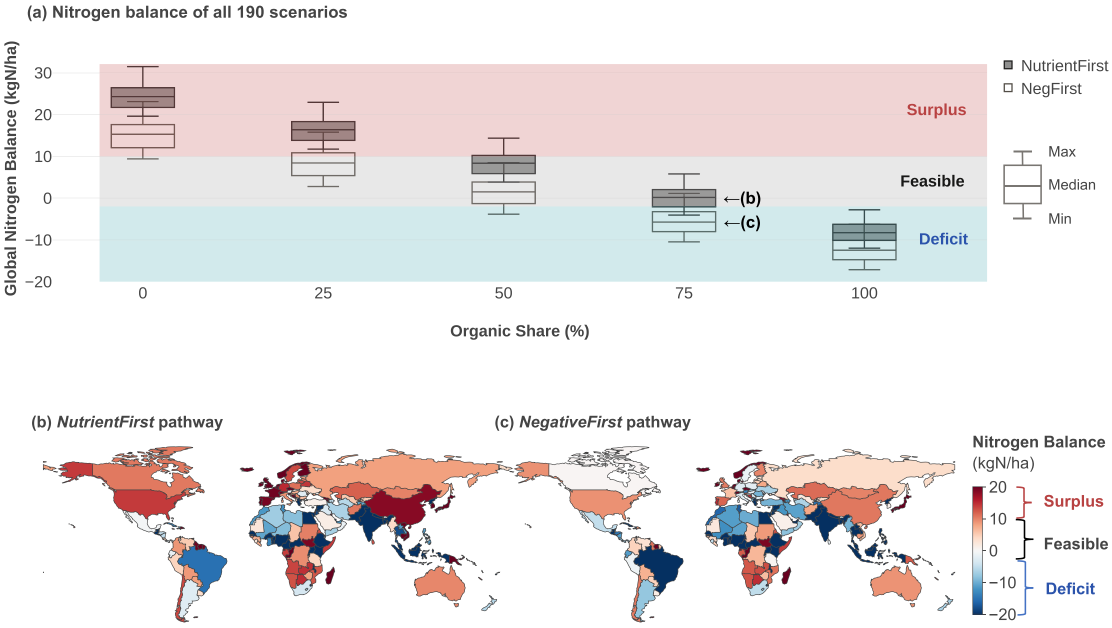


Figure 3. Changing bioenergy conversion pathways alters global and regional nitrogen balance. (a) is the global nitrogen balance of all scenarios comparing two bioenergy conversion pathways. (b) and (c) are the national distribution of nitrogen balance when the same example strategy switches from (b) *NutrientFirst* to (c) *NegativeFirst* pathway. (The example strategy has organic share: 75%, concentrate feeding reduction: 25%, waste reduction: 0% as annotated in (a).)

concentrate feeding reduction). Actually, the nitrogen deficit makes a fully organic system infeasible even when nutrients are all recycled back from bioenergy. I.e. when it is 100% organic, all options fall into the nitrogen deficit category (see the blue shades in figure 3). Therefore, the nitrogen deficit is a key environmental impact constraining the food system from becoming fully organic while providing land-free ancillary bioenergy.

To benchmark our food system impacts and assumptions, we further compare those with the complete range of IPCC AR6 scenario results (i.e. the food availability, population, and land cover in figure 2; the rest is unavailable). Overall, our assumed population in 2050 (9.1 billion according to the FAO 2050 projection [21]), is in the middle of the AR6 range), and so is the total land cover (4900 million ha of cropland and pastures, which is consistent with FAO

[21] and fits into the AR6 range as well). The resulting food availability range is also within the AR6 demand range. Therefore, when our modeled land cover is constant, our lowest food availability from the highest organic scenario can still meet the lower range of AR6 scenario ranges, although not covering the whole range.

3.3. Changing bioenergy conversion pathways constrains the circularity of agroecology

In the previous sections, we assume anaerobic digestors convert all ancillary bioenergy to biogas that maximizes the nutrients preserved for the food system (i.e. Pathway *NutrientFirst*; see detailed explanations of pathways in section 2). Now we compare *NutrientFirst* to another plausible bioenergy conversion pathway maximizing the negative emission potential via stationary BECCS (i.e. Pathway *NegativeFirst*). How we design future bioenergy conversion pathways in the energy system alters the agroecological circularity. When massive nutrients are lost at BECCS, it can hinder the food system from being more circular and organic. Besides nutrient loss, we also find its trade-off with negative emission potential when choosing from different bioenergy conversion pathways.

Nutrient-wise, converting from *NutrientFirst* to *NegativeFirst* significantly reduces the nitrogen inputs that can be recycled from ancillary biomass and drags the nitrogen balance down by around 50% maximum (See figure 3). To compare when nitrogen balance is surplus, feasible, or deficit, we adopt the same classification as in the previous study [19], and plot the nitrogen balance with corresponding color codes in (a) figure 3. When nitrogen balance surpasses 10 $\mathrm{kgN\,ha^{-1}}$ (red), it is ‘Surplus’ (nitrogen is unsustainably high), between 10 $\mathrm{kgN\,ha^{-1}}$ and ‘-’2 $\mathrm{kgN\,ha^{-1}}$ is ‘Feasible’ (grey), below ‘-’2 $\mathrm{kgN\,ha^{-1}}$ is ‘Deficit’ (blue). It has to be emphasized that these numbers are very aggregate global average indicators of total nutrient surplus or deficit on agricultural land, which show considerable regional differences. Therefore, these indicators provide a risk measure for running into related problems of nitrogen surplus or deficit in the scenarios rather than displaying the actual number observed on a field.

Nitrogen deficit makes deploying organic farming in such energy scenarios infeasible, as fewer chemical fertilizers are allowed when the organic share is higher. In the case of the *NegativeFirst* pathway, most 75% (and partially 50%) organic scenarios are no longer feasible due to the nitrogen deficit. However, they could work in the *NutrientFirst* pathway. In addition to the global scale, *NegativeFirst* also alters the national distribution of nitrogen balance. We identify what regions are more prone to nitrogen deficit when converting to *NegativeFirst*, such as Canada, the Latin American continent, Nordic regions, and central Europe (See the example in (b) and (c), figure 3).

Emission-wise, *NegativeFirst* mitigates biogenic $\mathrm{CO_2}$ emissions (i.e. emissions from biologically based materials like biomass, but not from fossil-based resources) both in energy and food systems that *NutrientFirst* does not. First, BECCS plants can provide additional negative emission potential for the energy system (1.4–2.6 $\mathrm{GTCO_2eq}$, which is around 10%–20% of the total food system GHG emission), while localized biogas digestors do not. Second, *NegativeFirst* also prevents a small proportion of emissions from processing and digesting ancillary biomass in the food system (about 2%–5% of the total food system GHG emissions).

Compared to the default *NutrientFirst* pathway, where all nutrients can be recycled yet without negative emissions, we identify the trade-offs between worse nutrient deficit and additional negative emissions in the *NegativeFirst* pathway. For the detailed results of nutrient balance, negative emissions, and bioenergy potential in both pathways, please refer to tables B2 and B3 in appendix.

4. Discussion

4.1. Trade-offs and policy implications

Compiling the aforementioned results, we find that there are trade-offs between two different goals: increasing the sustainability of the food system and increasing the ancillary bioenergy potential (for energy provision or for negative emissions). We use three example strategies and their corresponding pathways to illustrate the trade-offs when sourcing a similar range of ancillary bioenergy potential (figure 4). All three examples lie within the option space, and the green and blue scenarios have the same ancillary bioenergy potential (65 EJ).

First, there is a clear trade-off regarding nutrient recycling and negative emissions (the middle bar charts from two pathways in figure 4). This trade-off can be particularly challenging for carbon-neutral scenarios with massive deployment of BECCS. For now, most 1.5/2 °C pathways rely on biomass conversion technologies that barely preserve any nutrients. For instance, over 95% of the latest IPCC AR6 scenarios deploy BECCS for negative emissions [2], in which case all nutrients are lost during the conversion process. Only two mature bioenergy conversion technologies can preserve nitrogen–(1) bioethanol that can recycle only 3% of the nitrogen from its stillage byproduct [32] and (2) biogas via anaerobic digestors that preserve most nitrogen. Unfortunately, these two technologies are unfavorable (biogas is not even viable) in most large-scale carbon-neutral scenarios [2].

Policy-wise, there is so far no regulation on how to convert bioenergy strategically that recycles sufficient

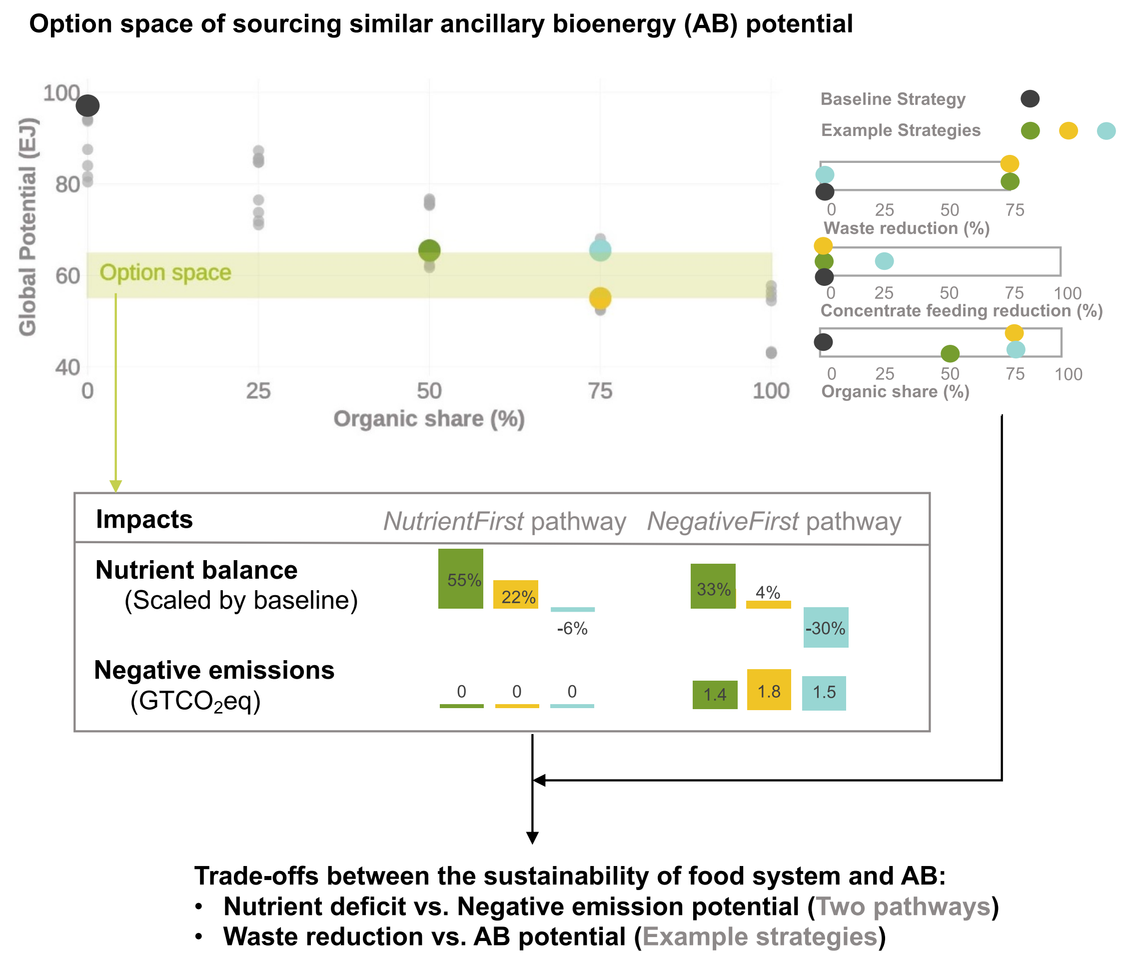


Figure 4. Option space and trade-offs between the sustainable food system and ancillary bioenergy illustrated by three example strategies. Strategy Green (waste reduction: 75%, concentrate feeding reduction: 0%, organic share: 50%); Strategy Yellow (waste reduction: 75%, concentrate feeding reduction: 0%, organic share: 75%); Strategy Blue (waste reduction: 0%, concentrate feeding reduction: 25%, organic share: 75%).

nutrients back to agroecology. This could potentially threaten a medium-to-high organic food system in the future, where fewer chemical fertilizers are available. Therefore, such a trade-off implies policy suggestions that bioenergy conversion pathways that allow for maximal nutrient recycling are important not to compromise sustainable agricultural production. We thus urge energy policymakers to consider nutrient deficit when designing the future carbon-neutral energy system, which is subtly connected to the food system via the nutrient cycle. Otherwise, we might achieve carbon neutrality, yet at the cost of deteriorating the food system's sustainability.

Moreover, the sustainable transformation of the food system towards a less animal-based diet and waste reduction may conflict with large-scale ancillary bioenergy provision. Reducing feed from croplands can increase the ancillary bioenergy potential in combination with a low organic food system, yet it reduces ancillary bioenergy production when there is a higher share of organic farming (See the blue and green example scenarios in figures 1 and 4). Such a trade-off can be more prominent between waste reduction and ancillary bioenergy provision where there is a negative correlation—less waste reduction is required to ensure a similar ancillary bioenergy availability when the organic share is high (See the yellow and green example scenarios in figure 4 and section 2.2). From a sustainable food system perspective, it is inefficient to keep waste levels or cropland-based livestock numbers high for a higher ancillary bioenergy provision. Importantly, it has to be kept in mind that a change towards less cropland-based livestock results in considerable dietary change [19], which necessitates corresponding consumer-focused strategies for implementation.

Hence, it is crucial for policymakers to avoid one-sided solutions and consider balanced food and energy policy strategies. For instance, the combinations of intermediate levels in all practices allow to meet potentially conflicting targets while providing a similar range of ancillary bioenergy close to the median supply in AR6 illustrative pathways (figure 1). This provides timely policy guidance, especially for the European Union, where both the targets of carbon neutrality (by 2050) and organic farming (25% by 2030) are to be met simultaneously [18].

Lastly, we briefly discuss and summarize the reasons behind the option space and trade-offs. This diverse option space is because the three agroecological practices differ in driving the availability of various ancillary biomass feedstocks (section 2.3), which compensate for each other and result in a similar global potential (figure 1). The same reason holds for the trade-off between the ancillary bioenergy provision and food system transition. As for the other trade-off of nutrients and negative emissions, the essential reason is more straightforward. With the same amount of bioenergy, food and energy systems tend to prefer different bioenergy conversion technologies—one to prioritize nutrient balance and the other to negative emissions—without considering the other system.

4.2. Comparingancillary bioenergy potential to other studies

Compared to previous studies on the global potential of sustainable bioenergy in 2050, our agricultural ancillary bioenergy availability fits into their average estimated range of 40–160 EJ [33–35]. Even under medium-high organic scenarios, our 2050 ancillary bioenergy potential can still reach around 60–70 EJ (See figure 1). This range of ancillary bioenergy potential is very close (±10%) to the median value of the 2050 primary bioenergy supply in the latest IPCC AR6 illustrative pathways (67 EJ) [2], where no organic farming is considered and dedicated bioenergy is included.

Nevertheless, unlike the dedicated energy crops predominantly deployed in these studies, our ancillary bioenergy requires no additional land use. In other words, we find that ancillary bioenergy may have the potential to provide a similar range of renewable energy as estimated in the existing literature, albeit with no land expansion when additional organic farming is in place.

4.3. Limitations and future directions

Our research has the following limitations that can be advanced in future studies. Assumption-wise, we model the three central practices of circular agroecology in a simplified way. However, other sustainable food strategies may also indirectly alter the bioenergy potential, nutrient cycle, and emission. For instance, the shift towards more agroforestry practices [36] and plant-based diets [37] (although our concentrate feeding reduction strategy also leads to fewer animal source products and the corresponding dietary changes).

Moreover, we also assume the total land use in the food system to be constant, and we do not consider any marginal land for cultivating dedicated energy crops in order to avoid additional land expansion and to align with the 'land-free' principle of ancillary bioenergy. The assumption of constant land use is intended for capturing how much ancillary bioenergy is available from sustainable (e.g. also organic) production systems that, in particular, do not use more land than today and less on food security in organic systems (that then may use more land), as e.g. in [19]. This simplification does not consider the land-use heterogeneity or local land conditions that are beyond our modeling scope. However, the net land-use expansion might benefit certain regions (e.g. for improving biodiversity [38]). We encourage future research to explore the land-use expansion or contraction cases with higher-resolution spatial data to better comprehend the trade-offs between land and bioenergy.

The challenge regarding nitrogen deficits in high-organic-share scenarios also relates to how we modeled organic agriculture. We used crop rotations as collected in Barbieri *et al* [39], which could be further optimized by adding off-season legume crops, etc that would reduce the potential nitrogen deficiency. Due to the lack of data, for instance, regarding their yields and water requirements, this was not included, adopting a rather conservative view regarding organic agriculture.

For the *NegativeFirst* bioenergy conversion pathway, we do not consider the transportation or collection of biomass feedstocks to BECCS plants, as well as the transportation, storage, and injection loss of CO_2 as they are beyond our system boundary. We encourage future research to incorporate this biomass supply chain that may cause additional emissions, labor, and energy consumption. Another future research direction could be looking beyond ancillary bioenergy and investigating the nitrogen cycle and the role of organic farming in scenarios with massive BECCS deployment or bioenergy land-use expansion.

5. Conclusion

Our results show that there is a diverse option space between the future food and energy systems to supply land-free ancillary bioenergy. By varying the food system from 0% to 100% organic, we can source 40 to 100 EJ ancillary bioenergy (figure 1), albeit nutrient deficiency or food security identified in (figure 2). Compared to the future supply of bioenergy in IPCC AR6, it is possible to source a similar range of ancillary bioenergy from very different food systems (i.e. 55–65 EJ of ancillary bioenergy when it is 50% to 75% organic and various shares of waste and concentrate feed reduction). This range of agricultural ancillary bioenergy can meet the lower range of 1.5 °C targets, although they include other dedicated from additional land uses and from forestry. The negative emission potential ranges from 1.4 to 2.6 $GTCO_2$eq across this option space. Thus, ancillary bioenergy has considerable potential to contribute to bioenergy futures while not compromising sustainable food systems.

For this, it is however important to hedge against the most challenging trade-offs, and balanced policy strategies for ancillary bioenergy provision and sustainable agriculture are needed, avoiding one-sided solutions. The following key messages can help to support this, as illustrated also in figure 4.

First, there is a trade-off between sustainable agricultural production and ancillary bioenergy production regarding nutrient recycling and supply (both national and global, as depicted in figure 3). Bioenergy pathways that allow for maximal nutrient recycling are important not to compromise sustainable agricultural production. This is a particular challenge for bioenergy scenarios with negative emissions, as these energy conversion pathways go along with low or absent nutrient recycling.

Second, reducing feed from croplands increases the potential for ancillary bioenergy production in combination with low organic agriculture and reduces it for high shares of organic agriculture. Hence, the thorough transformation of the food system and dietary patterns towards animal source food reduction as required for sustainable food systems may conflict with large-scale ancillary bioenergy provision. Third, waste reduction, another key strategy in circular sustainable food systems, negatively correlates with ancillary bioenergy provision.

Finally, from a sustainable food systems perspective, it is inefficient to keep waste levels and cropland-based livestock numbers high for higher ancillary bioenergy provision. Given the sustainability impact of current food systems and the envisaged role of ancillary bioenergy in future energy systems, it is thus important to align ancillary bioenergy provision with what is compatible with sustainable food systems and not to maximize ancillary bioenergy supply to only then adjust food system sustainability.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.8246394.

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Appendix A. Ancillary biomass feedstock and management assumptions

We refine the agricultural residue management assumptions in addition to our previous study [8] in two ways, as shown below.

First, we differentiate how organic and conventional agriculture systems treat the primary residue and manure to supply enough organic fertilizer (by allocating around half of the primary residues and manure to compost in organic systems).

Second, we subtract the possible losses (from collection, storage, and transportation) and cascading uses (biochemicals and materials) to more conservatively estimate sustainable ancillary biomass potential without competing uses.

Compared to the existing literature, our assumption of loss, cascading uses, compost, and the left-on-cropland ratio is close to their average sustainable removal rates (around 50%) [4, 40]. Sustainable removal rates are the only common management assumption among studies, as most energy system models do not consider food/feed competition per feedstock or other cascading uses of biomass. For the detailed ancillary bioenergy potential and management assumptions, please refer to table A1.

For the energy and carbon content of ancillary biomass feedstocks, we adopt the same estimation method from our previous study [8] (See its appendix). Generally, all of our low heating values are from the Phyllis2 database [41], and the default GHG (greenhouse gas) emissions values are from [4].

Table A1. Ancillary bioenergy potential and management assumptions.

AB feedstock	Production system	Management assumptions	Nitrogen recyclable?
Primary crop residues	Conventional	5% Left on croplands 42.5% Bioenergy 42.5% Loss and cascading uses[a]	Y Y N
	Organic	5% Left on croplands 50% Compost 22.5% Bioenergy 22.5% Loss and cascading uses	Y Y Y N
Manure[b]	Conventional	100% Bioenergy	Y
	Organic	50% Bioenergy 50% Compost	Y Y
Secondary residues, byproducts fats, & end-use waste	Conventional & organic	All non-feed/food uses plus 80% of remaining waste for energy	Y
Byproduct shells	Conventional & organic	All used for bioenergy	Y

[a] A conservative estimation including a post-harvest loss at 20% (handling, storage and transportation) and cascading uses 30% (bio-chemicals and materials) of the remaining 95% primary crop residues not left on the field, i.e. (20+30)%*95% = 42.5% of the total primary crop residues

[b] We use only the manure not left on grassland for local/on-site use, thus no loss. We leave those on grassland as it as (i.e. for pasture, range, orpaddock).

Appendix B. Scenario assumptions and results

Table B1. Environmental impacts scaled by Baseline in all scenarios (*NutrientFirst* pathway). For scenario names, OrgX = Organic farming share; ConcRedX = Concentrate feeding reduction share; WasteRedX = Waste reduction share. Baseline is Org0_ConcRed0_WasteRed0.

Scenarios	Food availability	GHG emissions	Nitrogen balance
Org0_ConcRed0_WasteRed0	100%	100%	100%
Org0_ConcRed0_WasteRed25	102%	101%	107%
Org0_ConcRed0_WasteRed50	104%	102%	114%
Org0_ConcRed0_WasteRed75	107%	103%	121%
Org0_ConcRed25_WasteRed0	107%	97%	88%
Org0_ConcRed25_WasteRed25	109%	98%	95%
Org0_ConcRed25_WasteRed50	111%	99%	102%
Org0_ConcRed25_WasteRed75	114%	100%	109%
Org0_ConcRed50_WasteRed0	113%	95%	80%
Org0_ConcRed50_WasteRed25	116%	96%	87%
Org0_ConcRed50_WasteRed50	118%	97%	94%
Org0_ConcRed50_WasteRed75	120%	97%	100%
Org0_ConcRed75_WasteRed0	119%	94%	76%
Org0_ConcRed75_WasteRed25	121%	95%	82%
Org0_ConcRed75_WasteRed50	124%	96%	89%
Org0_ConcRed75_WasteRed75	126%	97%	96%
Org0_ConcRed100_WasteRed0	125%	94%	76%
Org0_ConcRed100_WasteRed25	127%	95%	83%
Org0_ConcRed100_WasteRed50	129%	96%	89%
Org25_ConcRed0_WasteRed0	93%	87%	67%
Org25_ConcRed0_WasteRed25	96%	88%	74%
Org25_ConcRed0_WasteRed50	98%	89%	81%
Org25_ConcRed0_WasteRed75	100%	90%	88%
Org25_ConcRed25_WasteRed0	100%	85%	56%
Org25_ConcRed25_WasteRed25	102%	86%	64%
Org25_ConcRed25_WasteRed50	104%	87%	71%
Org25_ConcRed25_WasteRed75	106%	88%	78%
Org25_ConcRed50_WasteRed0	107%	83%	49%
Org25_ConcRed50_WasteRed25	109%	84%	56%
Org25_ConcRed50_WasteRed50	111%	85%	63%
Org25_ConcRed50_WasteRed75	113%	86%	70%
Org25_ConcRed75_WasteRed0	113%	82%	45%
Org25_ConcRed75_WasteRed25	115%	83%	52%
Org25_ConcRed75_WasteRed50	117%	84%	59%
Org25_ConcRed75_WasteRed75	119%	85%	66%
Org25_ConcRed100_WasteRed0	119%	82%	45%
Org25_ConcRed100_WasteRed25	121%	83%	52%
Org25_ConcRed100_WasteRed50	123%	84%	59%
Org50_ConcRed0_WasteRed0	87%	74%	34%
Org50_ConcRed0_WasteRed25	89%	76%	41%
Org50_ConcRed0_WasteRed50	91%	77%	48%
Org50_ConcRed0_WasteRed75	93%	78%	55%
Org50_ConcRed25_WasteRed0	94%	72%	25%
Org50_ConcRed25_WasteRed25	95%	73%	32%
Org50_ConcRed25_WasteRed50	97%	75%	39%
Org50_ConcRed25_WasteRed75	99%	76%	46%
Org50_ConcRed50_WasteRed0	100%	71%	18%
Org50_ConcRed50_WasteRed25	102%	72%	25%
Org50_ConcRed50_WasteRed50	104%	73%	32%
Org50_ConcRed50_WasteRed75	105%	74%	39%
Org50_ConcRed75_WasteRed0	106%	70%	15%
Org50_ConcRed75_WasteRed25	108%	71%	22%
Org50_ConcRed75_WasteRed50	110%	72%	29%
Org50_ConcRed75_WasteRed75	112%	73%	35%
Org50_ConcRed100_WasteRed0	112%	70%	15%

(Continued.)

Table B1. (Continued.)

Scenarios	Food availability	GHG emissions	Nitrogen balance
Org50_ConcRed100_WasteRed25	114%	71%	22%
Org50_ConcRed100_WasteRed50	116%	72%	29%
Org75_ConcRed0_WasteRed0	80%	62%	1%
Org75_ConcRed0_WasteRed25	82%	63%	8%
Org75_ConcRed0_WasteRed50	84%	64%	15%
Org75_ConcRed0_WasteRed75	86%	66%	22%
Org75_ConcRed25_WasteRed0	87%	60%	−6%
Org75_ConcRed25_WasteRed25	89%	61%	1%
Org75_ConcRed25_WasteRed50	90%	63%	8%
Org75_ConcRed25_WasteRed75	92%	64%	15%
Org75_ConcRed50_WasteRed0	93%	59%	−12%
Org75_ConcRed50_WasteRed25	95%	60%	−5%
Org75_ConcRed50_WasteRed50	96%	61%	2%
Org75_ConcRed50_WasteRed75	98%	62%	9%
Org75_ConcRed75_WasteRed0	99%	58%	−16%
Org75_ConcRed75_WasteRed25	101%	59%	−9%
Org75_ConcRed75_WasteRed50	103%	60%	−2%
Org75_ConcRed75_WasteRed75	104%	62%	5%
Org75_ConcRed100_WasteRed0	106%	58%	−15%
Org75_ConcRed100_WasteRed25	108%	59%	−9%
Org75_ConcRed100_WasteRed50	109%	60%	−2%
Org100_ConcRed0_WasteRed0	74%	49%	−32%
Org100_ConcRed0_WasteRed25	76%	50%	−25%
Org100_ConcRed0_WasteRed50	77%	52%	−18%
Org100_ConcRed0_WasteRed75	79%	53%	−11%
Org100_ConcRed25_WasteRed0	80%	48%	−38%
Org100_ConcRed25_WasteRed25	82%	49%	−31%
Org100_ConcRed25_WasteRed50	83%	51%	−24%
Org100_ConcRed25_WasteRed75	85%	52%	−17%
Org100_ConcRed50_WasteRed0	86%	47%	−43%
Org100_ConcRed50_WasteRed25	88%	48%	−36%
Org100_ConcRed50_WasteRed50	89%	49%	−29%
Org100_ConcRed50_WasteRed75	91%	51%	−22%
Org100_ConcRed75_WasteRed0	92%	46%	−46%
Org100_ConcRed75_WasteRed25	94%	47%	−39%
Org100_ConcRed75_WasteRed50	96%	49%	−32%
Org100_ConcRed75_WasteRed75	97%	50%	−25%
Org100_ConcRed100_WasteRed0	99%	46%	−46%
Org100_ConcRed100_WasteRed25	101%	47%	−39%
Org100_ConcRed100_WasteRed50	103%	49%	−32%

Table B2. Global ancillary bioenergy potential and nitrogen balance in all scenarios (*NutrientFirst* pathway).

Organic share (%)	Concentrate feeding reduction (%)	Waste reduction (%)	Global potential (EJ)	N balance per ha (kgN/ha)
0	0	0	98.2	26.0
0	0	25	94.8	27.7
0	0	50	91.3	29.6
0	0	75	87.6	31.5
0	25	0	95.7	22.8
0	25	25	92.0	24.7
0	25	50	88.1	26.5
0	25	75	84.0	28.4
0	50	0	94.2	20.7
0	50	25	90.1	22.5
0	50	50	85.9	24.3
0	50	75	81.6	26.1
0	75	0	93.8	19.6
0	75	25	89.5	21.4
0	75	50	85.0	23.2
0	75	75	80.4	25.0
0	100	0	94.1	19.7
0	100	25	89.6	21.4
0	100	50	85.0	23.2
25	0	0	87.3	17.4
25	0	25	83.8	19.2
25	0	50	80.2	21.1
25	0	75	76.5	22.9
25	25	0	85.6	14.7
25	25	25	81.8	16.5
25	25	50	77.9	18.4
25	25	75	73.8	20.2
25	50	0	84.7	12.7
25	50	25	80.6	14.6
25	50	50	76.4	16.4
25	50	75	71.9	18.2
25	75	0	84.8	11.7
25	75	25	80.3	13.5
25	75	50	75.8	15.3
25	75	75	71.1	17.1
25	100	0	85.4	11.8
25	100	25	80.8	13.6
25	100	50	76.0	15.3
50	0	0	76.3	8.9
50	0	25	72.9	10.6
50	0	50	69.2	12.5
50	0	75	65.4	14.4
50	25	0	75.6	6.5
50	25	25	71.7	8.3
50	25	50	67.7	10.2
50	25	75	63.5	12.0
50	50	0	75.3	4.8
50	50	25	71.1	6.6
50	50	50	66.8	8.4
50	50	75	62.3	10.2
50	75	0	75.7	3.8
50	75	25	71.2	5.6
50	75	50	66.6	7.4
50	75	75	61.7	9.2
50	100	0	76.7	3.9
50	100	25	71.9	5.7
50	100	50	66.9	7.4
75	0	0	65.4	0.3
75	0	25	61.9	2.1

(Continued.)

Table B2. (Continued.)

Organic share (%)	Concentrate feeding reduction (%)	Waste reduction (%)	Global potential (EJ)	N balance per ha (kgN/ha)
75	0	50	58.2	3.9
75	0	75	54.4	5.8
75	25	0	65.5	−1.7
75	25	25	61.6	0.2
75	25	50	57.5	2.0
75	25	75	53.3	3.8
75	50	0	65.9	−3.2
75	50	25	61.6	−1.3
75	50	50	57.2	0.5
75	50	75	52.6	2.3
75	75	0	66.7	−4.1
75	75	25	62.1	−2.3
75	75	50	57.3	−0.5
75	75	75	52.4	1.3
75	100	0	68.0	−4.0
75	100	25	63.1	−2.2
75	100	50	57.9	−0.5
100	0	0	54.5	−8.3
100	0	25	50.9	−6.5
100	0	50	47.2	−4.7
100	0	75	43.3	−2.8
100	25	0	55.4	−9.9
100	25	25	51.5	−8.0
100	25	50	47.4	−6.2
100	25	75	43.1	−4.4
100	50	0	56.5	−11.1
100	50	25	52.1	−9.3
100	50	50	47.6	−7.5
100	50	75	42.9	−5.7
100	75	0	57.7	−12.0
100	75	25	53.0	−10.2
100	75	50	48.1	−8.4
100	75	75	43.0	−6.6
100	100	0	59.3	−11.9
100	100	25	54.2	−10.2
100	100	50	48.9	−8.4

Table B3. Global negative emission potential and nitrogen balance in all scenarios (*NegativeFirst* pathway). The ancillary bioenergy potential is the same as in table B2.

Organic share (%)	Concentrate feeding reduction (%)	Waste reduction (%)	N balance per ha (kgN ha^{-1})	Negative emission (GTCO$_2$eq)
0	0	0	16.2	2.6
0	0	25	18.5	2.5
0	0	50	20.8	2.5
0	0	75	23.1	2.5
0	25	0	13.0	2.5
0	25	25	15.3	2.5
0	25	50	17.6	2.5
0	25	75	19.9	2.4
0	50	0	10.7	2.5
0	50	25	13.0	2.5
0	50	50	15.3	2.4
0	50	75	17.6	2.4
0	75	0	9.5	2.5
0	75	25	11.8	2.4
0	75	50	14.0	2.4
0	75	75	16.3	2.4
0	100	0	9.4	2.5
0	100	25	11.7	2.4
0	100	50	14.0	2.4
25	0	0	8.9	2.2
25	0	25	11.2	2.2
25	0	50	13.5	2.1
25	0	75	15.8	2.1
25	25	0	6.1	2.2
25	25	25	8.4	2.1
25	25	50	10.7	2.1
25	25	75	13.0	2.1
25	50	0	4.0	2.2
25	50	25	6.3	2.1
25	50	50	8.6	2.1
25	50	75	10.9	2.1
25	75	0	2.9	2.1
25	75	25	5.2	2.1
25	75	50	7.4	2.1
25	75	75	9.7	2.0
25	100	0	2.8	2.1
25	100	25	5.1	2.1
25	100	50	7.3	2.1
50	0	0	1.6	1.9
50	0	25	3.9	1.8
50	0	50	6.2	1.8
50	0	75	8.5	1.8
50	25	0	−0.8	1.8
50	25	25	1.5	1.8
50	25	50	3.8	1.8
50	25	75	6.1	1.7
50	50	0	−2.7	1.8
50	50	25	−0.4	1.8
50	50	50	1.9	1.8
50	50	75	4.2	1.7
50	75	0	−3.8	1.8
50	75	25	−1.5	1.8
50	75	50	0.8	1.8
50	75	75	3.1	1.7
50	100	0	−3.8	1.8
50	100	25	−1.6	1.8
50	100	50	0.7	1.7

(Continued.)

Table B3. (Continued.)

Organic share (%)	Concentrate feeding reduction (%)	Waste reduction (%)	N balance per ha (kgN ha^{-1})	Negative emission ($GTCO_2eq$)
75	0	0	−5.7	1.5
75	0	25	−3.4	1.5
75	0	50	−1.2	1.5
75	0	75	1.1	1.4
75	25	0	−7.7	1.5
75	25	25	−5.4	1.5
75	25	50	−3.2	1.4
75	25	75	−0.9	1.4
75	50	0	−9.3	1.5
75	50	25	−7.1	1.5
75	50	50	−4.8	1.4
75	50	75	−2.5	1.4
75	75	0	−10.4	1.5
75	75	25	−8.1	1.5
75	75	50	−5.8	1.4
75	75	75	−3.5	1.4
75	100	0	−10.5	1.5
75	100	25	−8.2	1.5
75	100	50	−5.9	1.4
100	0	0	−13.1	1.2
100	0	25	−10.8	1.1
100	0	50	−8.5	1.1
100	0	75	−6.2	1.1
100	25	0	−14.7	1.2
100	25	25	−12.4	1.1
100	25	50	−10.1	1.1
100	25	75	−7.8	1.1
100	50	0	−16.1	1.2
100	50	25	−13.8	1.1
100	50	50	−11.5	1.1
100	50	75	−9.2	1.1
100	75	0	−17.0	1.2
100	75	25	−14.8	1.1
100	75	50	−12.5	1.1
100	75	75	−10.2	1.1
100	100	0	−17.1	1.2
100	100	25	−14.8	1.1
100	100	50	−12.6	1.1

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