How will an increase in organic agricultural area affect land use in Germany?

Livia Rasche · Jan Steinhauser

Abstract Organic agriculture is an attractive land use alternative to conventional farming in terms of environmental and biodiversity protection. The official German target is a 30% share of organic agricultural area by 2030, while German stakeholders consider 24% realistic and 44% desirable. It is unclear how such a shift may affect the food and land use system. We use data from a crop/pest model to estimate yield differences between conventional and organic systems, and the FABLE accounting tool to assess changes in indicators like calories available per person and day, and the extent of cropland, pasture and area where natural processes predominate. We investigate how an increase in organic agricultural area may affect these indicators up to 2050, and if adaptation measures may become necessary to ameliorate the potential pressure to expand cropland or raise import rates. The results show that if organic agricultural area is increased, there will be a calorie deficit of 7–80 kcal per person and day, corresponding to 1000–5000 km^2 of missing cropland. The deficit will disappear without any changes to the system by 2045 at the latest due to demographic and technological development. No additional cropland at all would be required if crop productivity increased at a higher rate than observed today, and an additional 600,000 ha could be freed even with a 30% share of organic agriculture. A higher share of organic agriculture is thus a realistic target for Germany, but technological advancements should accompany the transformation to minimize cropland demand.

Keywords Food system · Land use change · Organic agriculture · Socioeconomic change · Stakeholder opinion

Introduction

Organic farming is based on four principles, defined in 2005 by the International Federation of Organic Agriculture Movements (IFOAM) "1): Organic farming should sustain and enhance the health of soil, plants, animals and humans as one and indivisible; 2) Organic farming should be based on the living ecological systems and cycles, work with them, emulate them and help sustain them; 3) Organic agriculture should build on relationships that ensure fairness with regard to common environment and life processes; 4) Organic farming should be managed in a precautionary and responsible manner to protect the health and well being of current and future generations and

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the environment." Similarly, the European Parliament and the Council have codified general principles and specific agricultural production rules for organic farming in the European Union, where the leading principle is "respect for nature's systems and cycles and the sustainment and enhancement of the state of the soil, the water and the air, of the health of plants and animals, and of the balance between them" (European Union, 2018). These higher standards required for the production of certified organic products make it an attractive land use alternative for policy-makers that are concerned with transforming food and land use systems into more sustainable ones. The German government is no exception. In 2002, a target of 20% organic agricultural area was set in the national sustainability strategy, with the explicit goal to enhance soil and water conservation, contribute to animal welfare and preserve natural resources (Bundesregierung 2002). The intention was to reach this target by 2010, but the goal was eventually abandoned, and, today, the share of organic agricultural area is approximately 10% (Statistisches Bundesamt, 2021). Recently, new goals were set, first to reach a share of 20% within the "next few years" (BMEL 2019b), then, more concretely, to reach a share of 20% by 2030 (Bundesregierung 2021). In their coalition agreement,[1] the new government of Germany, elected in 2021, has agreed to set an even more ambitious target: a 30% share of organic agricultural area by 2030. Their argument is that, in addition to the already mentioned benefits, there are considerable market opportunities for local farmers. The German market for organic products is expanding every year — in 2020 by 22%, for example — but not all products which could be produced domestically actually are. In 2019/2020, 15% of organic cereals, 28% of organic milk and 27% of organic pork were imported (BMEL, 2019b). A larger share of organic agricultural area could potentially reduce imports of these products and support domestic farmers, who would benefit from the price premium of on average 36 to 175% (Statista & AMI, 2021).

There are some reservations about this strategy. While organic agriculture has positive impacts on above and below ground biodiversity, soil organic carbon and nitrogen contents, and water pollution (Erhart & Hartl 2009; Forman & Silverstein 2012; Letourneau & van Bruggen 2006; Niggli 2015; Tuck et al. 2014), yields are 19–50% lower in organic system (Aune 2012; de Ponti et al., 2012; Halberg et al. 2006; Ponisio et al. 2015; Seufert et al., 2012). The total area necessary to produce the same amount of product is thus on average higher in organic systems than in conventional ones, causing many of the positive per unit of area effects to disappear when looking at a unit of product, which has been shown for biodiversity, greenhouse gas emissions, and nitrate leaching (Gabriel et al. 2013; Green et al. 2005; Meemken & Qaim 2018; Mondelaers et al. 2009; Schneider et al. 2014).

For a truly integrated assessment of the consequences of a larger share of organic agricultural area, all of these aspects should be considered. However, currently available data and methods are not sufficient for an adequate representation of all of these aspects on a larger scale. Determining belowground biodiversity for example is an elaborate process and large-scale data are missing. Greenhouse gas emissions and nitrate leaching can theoretically be estimated for a larger scale using crop models; however, even under conventional agriculture, the accuracy of the models in estimating such emissions still needs improvement (Izaurralde et al. 2017). Yields can be estimated more reliably, either by reducing conventional yields by average reduction factors determined in meta-studies (e.g. Seufert et al. 2012), or by using advanced crop models capable of simulating systems where pest and disease occurences impact crop yields (e.g. Rasche & Taylor 2017, 2019).

In this study, we therefore focus on yields as the distinguishing factor between organic and conventional agriculture, for which we have large-scale data produced with a crop model with pest and disease submodels. We investigate how an increase in organic agricultural area may impact land use and food supply in Germany up to 2050, and how different adaptation measures may ameliorate the pressure to expand cropland in Germany or raise import rates if yields in organic systems are not sufficient to satisfy consumer demand. As indicators for changes in the food and land use system, we examine changes in cropland, permanent pasture and other natural land area, the share of semi-natural area, and total calories available per person and day. We also consider the impacts

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[1] https://www.bundesregierung.de/breg-de/service/gesetzesvorhaben/koalitionsvertrag-2021-1990800

of socio-economic and demographic change on the future demand for agricultural products.

Material and methods

Models and input data

An increase in agricultural area managed with organic methods will have effects on the food and land use system. We use the FABLE calculator (Mosnier et al. 2020) to estimate some of these effects. FABLE is an accounting tool that focuses on agriculture as the main driver of land use change and depicts changes in the level of agricultural activities, land use, food consumption, trade, and GHG emissions under different policy scenarios. Currently, FABLE runs on a national scale and does not consider regional heterogeneity. FABLE includes 76 agricultural raw and processed products from the crop and livestock sectors and relies extensively on the FAOSTAT database[2] for input data. To start a calculation, the user has to select a combination of 16 different input scenarios. Then, the calculator runs through a list of calculation steps, where all steps after the first are dependent on variables computed in the previous steps. In the first step, the targeted human consumption of different product groups is calculated, in steps 2 and 3, these values form the base for the calculation of the necessary livestock and crop production, taking into account crop requirements for livestock feed. In step 4, the pasture and cropland area required for this production are accounted for. In step 5, it is checked if the targeted pasture and cropland area is higher than the maximum available area. If yes, the targeted area, livestock and crop production (steps 7 and 8, respectively), and human consumption (step 9) are reduced to feasible values based on the maximum available area; if no, the targeted values are accepted as the feasible values. In the last step, indicators for food security, GHG emissions, biodiversity, freshwater use, self-sufficiency, and diversification are calculated based on the feasible consumption, production and land use values, and displayed for each 5-year time step over the time period 2000–2050.

How will an increase in area managed with organic agriculture affect the FABLE calculations? Steps 1 to 3, the calculation of human demand and the resulting necessary production of livestock and crop products, will remain unchanged. What will change is the area required for the production of these products (step 4), since yields per hectare are usually lower in organic systems than in conventional ones, which means that the higher the share of organic area, the lower the mean average yields per hectare, and the larger the amount of area needed to produce the same amount of crops. Thus, in order to assess the change in cropland accurately, data on current and projected future yields under organic management are necessary. We used a dataset that was created with the Pest-EPIC crop model (Rasche & Taylor 2017). It covers the European Union for the years 1995–2100 and provides values for pesticide, fertilizer and irrigation water application rates as well as yields for the crops barley, maize, maize silage, durum wheat, flax, oats, peas, potatoes, rape, rice, rye, soyabeans, sugarbeet, sunflower, and wheat (Rasche 2021). For the calculation of the yield modifiers, we focused on the 5146 simulation units covering the agricultural area of Germany. In the simulations, under conventional management, mean annual N, P and K-fertilization rates were 85, 15, and 45 kg/ha, respectively. These data were taken from a land use database originally compiled for the CCTAME project.[3] In the organic scenario, manure was applied instead of elemental N/P/K fertilizers. The application rate was adapted to the nitrogen content of the manure but capped at a maximum of 250 kg/ha. Furthermore, the crop rotation was adapted to include a legume catch crop for N-fixation and green manure fertilization if the field was fallow for more than 60 days between two crops.

For each crop and simulation unit, we retrieved the yields simulated under organic and conventional management in the years 2010–2019, and averaged the yields over this time. We then calculated the relative difference between organic and conventional yields for each crop and simulation unit. In a last step, we estimated a representative yield shifter for each crop by calculating the median of all simulated yield differences (Table 1, Organic yield modifier). We chose the median instead of the average to avoid giving

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Table 1 Average yields recorded in FABLE based on the FAOSTAT database, calculated organic yield modifiers, and current share of organic area for different crops

Crop[a]	FAOSTAT yield [t/ha]	Organic yield modifier [-]	Organic area share [%]
Barley	6.3	0.77	1.39
Linseed[b]	0.7	0.73	43.67
Maize	8.8	0.64	0.95
Oats	4.9	0.75	15.25
Peas	3.0	0.91	15.33
Potatoes	40.0	0.32	3.21
Rapeseed	3.9	0.86	0.15
Rye	4.6	0.72	9.09
Sugarbeet	63.8	0.8	0.33
Sunflower	1.9	0.36	8.01
Wheat	7.3	0.69	1.64

[a] Modifiers for cotton, rice, and soyabeans were also implemented but of no relevance as there are no crop data for Germany (rice, cotton) or the recorded area is negligible and likely faulty (soyabeans)

[b] Oilseeds_other in the FABLE Calculator

too much weight to outliers. In FABLE, the average yields of each crop are based on the FAOSTAT database (Table 1, FAOSTAT Yield), which does not account for different farming systems. To calculate total crop production in Germany under different organic agricultural area shares, average yields are multiplied with the yield modifiers to return values for organic yields. Weighted by area (organic/conventional), total crop production can be estimated.

For other crops considered in FABLE but not included in the simulations, we applied an average modifier of 0.8 (de Ponti et al. 2012; Ponisio et al. 2015). To ensure that the implementation of organic agriculture does not skew overall yields, we also calculated conventional crop modifiers and calibrated them using the initial FAOSTAT-based yields. To do so, organic crop area share for the historic timesteps 2000–2010 was estimated based on organic agriculture area data from the FiBL database[4] and total crop area from FAOSTAT. Using the organic area shares as weight for the calculated organic yield, we calculate conventional yield for the

historic timesteps. Future yields are calculated based of the 2010 yields, taking into account the selected productivity growth scenario as well as climate change modifiers derived from simulations with a global gridded version of the EPIC model (GEPIC, Liu et al. 2007).

Besides changes in crop productivity, the percentage share of organic agricultural area is another essential input. To enable the user to choose a specific target share in FABLE, we added a new item to the scenario selection, in which the user can choose the desired organic area share in 2030 and the rate of implementation. In the calculation, the organic area share will rise linearly over time until the target share is reached in 2030, and remain constant afterwards. The official goal of the German government is that by 2030, 30% of agricultural area should be managed organically (BMEL 2019a; BMU 2020). Stakeholders in the agricultural and food sector may have a different perspective, however. For this reason, we included a question about desirable and realistic shares of organic agricultural area in an online stakeholder survey we conducted recently for a different project (Rasche et al. 2022). Invitations to the survey were sent to 51 institutions working in the food and land use sector: one to the German Federal Environmental Agency (Umweltbundesamt), one to the German Federal Office for Agriculture and Food (Bundesanstalt für Landwirtschaft und Ernährung), thirteen to state departments of agriculture (Landwirtschaftsministerien), seven to state chambers of agriculture (Landwirtschaftskammern), eleven to farmer's associations (Bauernverbände), eleven to organizations of the private sector such as supermarket chains, lobby groups, and other associations, and seven to universities and research institutes. Overall, 25 people responded. Twelve respondents stated that their organization was a scientific institution, seven said it was part of the public sector and six stated that it was a private association. The respondents had a background in agriculture (16), climate (2), animal husbandry (2), environmental protection (2), soil science (1), communication (1), and nutrition and health (1).

The question we asked for this study was:

- Which percentage share of organic agricultural area by 2030 is realistic, which area share would be desirable?

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[4] https://statistics.fibl.org/world/selected-crops-world.html

Table 2 Scenario portfolios. The listed scenarios were selected in the Scenario_definition Table of the FABLE calculator to run the calculation

Scenario	Baseline	Organic24	Organic30	Organic44	OrganicA1	OrganicA2	OrganicA3	OrganicAll
GDP projections	SSP2	SSP2	SSP2	SSP2	SSP2	SSP2	SSP2	SSP2
Population projections	SSP2	SSP2	SSP2	SSP2	SSP2	SSP2	SSP2	SSP2
Diets	noChange	noChange	noChange	noChange	noChange	9050101p5[a]	noChange	9050101p5[a]
Food Waste	Current	Current	Current	Current	Rapid50[b]	Current	Current	Rapid50[b]
Import changes	No change	No change	No change	No change	No change	No change	No change	No change
Export changes	No change	No change	No change	No change	No change	No change	No change	No change
Livestock productivity	BAU growth	BAU growth	BAU growth	BAU growth	BAU growth	BAU growth	BAU growth	BAU growth
Crop productivity	BAU growth	BAU growth	BAU growth	BAU growth	BAU growth	BAU growth	High growth[c]	High growth[c]
Agricultural expansion	No	No	No	No	No	No	No	No
Afforestation	No	No	No	No	No	No	No	No
Activity level of pop	Middle	Middle	Middle	Middle	Middle	Middle	Middle	Middle
RCP	RCP6.0-y	RCP6.0-y	RCP6.0-y	RCP6.0-y	RCP6.0-y	RCP6.0-y	RCP6.0-y	RCP6.0-y
Protected Areas	No Change	No Change	No Change	No Change	No Change	No Change	No Change	No Change
Post-harvest loss	No Change	No Change	No Change	No Change	Reduced[d]	No Change	No Change	Reduced[d]
Biofuel demand	OECD AGLINK	OECD AGLINK	OECD AGLINK	OECD AGLINK	OECD AGLINK	OECD AGLINK	OECD AGLINK	OECD AGLINK
Organic area	No change	24by30	30by30	44by30	30by30	30by30	30by30	30by30

[a] 90–50–10–1.5: By 2050, the diet of a German will be reduced to 90% of the total calories consumed in 2010 (FAOSTAT), sugar and fat consumption will be reduced by 50%, 10% of the population will be vegetarians, and 1.5% vegans

[b] Rapid 50%: 50% reduction of food waste reached in 2030

[c] High growth: higher productivity growth than observed in period 2000–2010

[d] Reduced post harvest losses: 50% reduction of crop and livestock products lost during storage and transportation compared to 2010

We received 21 responses for this question. The range of answers was wide, with 12–100% for the realistic share of organic area, and 3–100% for the desirable share. Averaged over all responses, an area share of 24% was deemed realistic, a share of 44% desirable by the stakeholders.

Description of pathways

Baseline pathway

In the baseline pathway, we establish a point of reference for the other pathways. Each pathway in FABLE is defined by a scenario portfolio containing 16 topics (Table 2, first column). For the baseline pathway (Baseline), we chose those scenarios which either denote 'no change', or a continuation of the currently observed trends. For the projection of GDP and population development in Germany, we chose the "Middle of the Road" scenario SSP2, with a medium speed of economic growth for most advanced countries and medium speed of convergence for other countries, medium fertility, medium mortality, medium migration, medium education, and the extension of current trends in urbanization. The percentage of food waste and post-harvest losses, diet composition and caloric content, and import shares as well as export amounts are assumed to remain equal to today's values. Crop and livestock productivity are assumed to increase at the same speed as observed in the period 2000–2010. Based on German land use policies, cropland expansion and reforestation are not permitted and there is no expansion of protected areas. We assume that the population exhibits a middle activity level, meaning a moderately active lifestyle that includes physical activity equivalent to walking about 2.5 to 5 km per day at 5 to 6.5 km/h, in addition to the activities of independent living. The climate and crop productivity change scenario selected is based on RCP 6.0 run with the GCM hadgem2-es and the crop model GEPIC. Projections of future biofuel demand until 2028 are based on the OECD-FAO Agricultural Outlook, and are assumed to stay constant afterwards. The share of organic area is not allowed to change from the share observed in 2010 (Table 2, Baseline).

Pathways with a higher share of organic agricultural area

We defined three pathways with a higher share of organic agricultural area by 2030. The first pathway is based on the German government's official goal of 30% (Organic30), the second on the stakeholders' estimation that constitutes a realistic share by 2030, which is 24% (Organic24), the third on the stakeholders' estimation that constitutes a desirable share by 2030, which is 44% (Organic44) (Table 2).

Adaptation pathways with a higher share of organic agricultural area

The hypothesis is that with an increasing share of organic agricultural area, total cropland area will increase as well due to the lower per unit area yields. For this reason, we defined four additional pathways, in which we examine which adaptation measures in the food and land use system may compensate for this tradeoff most efficiently. In the first pathway (OrganicA1), we assume that food waste and post-harvest losses will be reduced by 50% by 2030 and 2050, respectively. In the second pathway (OrganicA2), we assume that the German population will consume a slightly different diet than today: by 2050, total consumed calories will be reduced by 10% in comparison to 2010, sugar and fat consumption will be reduced by 50%, overall consumption of animal products is reduced, proxied by 10% of the population being vegetarians, and 1.5% vegans.

In the third pathway (OrganicA3), we assume that the growth in crop productivity will proceed at a higher speed than which was observed in the period 2000–2010. In the fourth pathway (OrganicAll), we consider the combined effects of the previously described changes in food waste, diet, and productivity (Table 2). These assumptions have been developed for the 2020 Report of the FABLE consortium (Steinhauser & Schneider 2020), representing both current policy targets and cultural shifts as well as ambitious scenarios beyond the current trends. Since 30% of organic agricultural area by 2030 is the German government's official target, this scenario is used as baseline for the different adaptation pathways.

Land use change analysis

For the analysis of the effects of an expansion of organic agricultural area, we consider the extent of cropland area and the extent of area where natural processes predominate. The latter term is an indicator related to biodiversity conservation and was defined by Jacobson et al. (2019) as "areas where natural processes predominate, but are not necessarily places with intact natural vegetation, ecosystem processes or faunal assemblages". In FABLE, this area is calculated as the sum of forest, low-impact grassland, marginal area and other natural land. We do not consider the other indicators provided by FABLE, such as food security, GHG emissions, biodiversity, and self-sufficiency, since we lack important input data for these indicators. GHG emissions per unit area, for example, are up to 40% lower in organic systems, and species richness and abundance 30–50% higher (Meemken & Qaim 2018), but no dataset is available that provides spatially-explicit, crop-specific values for these factors.

Results

Land use changes with increasing shares of agricultural area

Even in the baseline pathway, where many factors are assumed to remain constant, the extent of cropland, pasture and other land — land that is not urban, forest, cropland, or pasture and may be very heterogeneous, including degrees of wilderness — changes over time. From 2010 to 2050, cropland area decreases by 12%, pasture area by 25%, whereas other land area increases by 70%, and the share of area where natural processes predominate increases from 18 to 25% (Fig. 1a, Baseline). Thus, in the baseline pathway, less cropland and pasture will be necessary in the future to feed the German population their accustomed diet, freeing area that may instead be used for biodiversity conservation. This development is primarily due to the projected population decline, which means a reduction in total caloric demand, and the gradual increases in crop and livestock productivity, which means that caloric density per cropland, livestock, and pasture unit is increased. The population projection does not affect urban areas, which are kept constant on 2010 levels. The impacts of decreasing population and increasing productivity on cropland requirements are visible in all pathways, with all showing a cropland reduction over time, but are less pronounced when the share of organic area is higher.

Stakeholders determined that a share of 24% by 2030 would be realistic for agricultural area managed organically in Germany. If this goal was reached, cropland area would decrease by 8% over the period 2010 to 2050, about 33% less than the baseline decrease. Pasture area would decrease by 25%, other land area would increase by 58%, and the share of area where natural processes predominate would increase from 18 to 24% (Fig. 1a, Organic24). Whereas there is a continuous decrease in the baseline pathway, cropland area remains unchanged in the organic24 pathway until after 2030, where it starts to gradually decline. The absolute difference in cropland area between the baseline and organic24 pathway amounts to around 500,000 ha (Fig. 1b, Cropland), a value that remains nearly unchanged from 2030 to 2050. We can conclude that this additional cropland area will be needed if the organic agricultural area share is increased to 24% in Germany. The difference in the share of area where natural processes predominate is negligible (Fig. 1b, Area where natural processes predominate). One important factor to consider in this land use analysis is that we did not allow cropland expansion beyond the area occupied in 2010, since competition with other land uses is high and there are strict guidelines in Germany for which land use changes are allowed. This means that if more cropland area than available would be needed to satisfy the caloric demand of the population, a shortage of provided calories would occur. This is the case for the years 2020–2030 in the organic24 pathway, where there is a deficit of 7–19 kcal per person and day (Fig. 2). If agricultural area expansion was allowed, this deficit would translate to an increase in agricultural area of 42,000–115,000 ha.

The goal of the current German government is to have a share of 30% of organic agricultural area by 2030. If this goal was reached, the consequence would be that from 2010 to 2050, cropland area decreases by 7%, pasture area by 25%, other land area increases by 54%, and the share of area where natural processes predominate increases from 18 to 24% (Fig. 1a, Organic30). Cropland area remains almost constant until 2040, in which year a slow decrease begins. The absolute difference in cropland area between the baseline and organic30 pathway rises up to around 650,000 ha in 2035 (Fig. 1b, Cropland). The difference between the organic30 and the baseline pathway in the share of area where natural processes predominate is almost as small as in the organic24
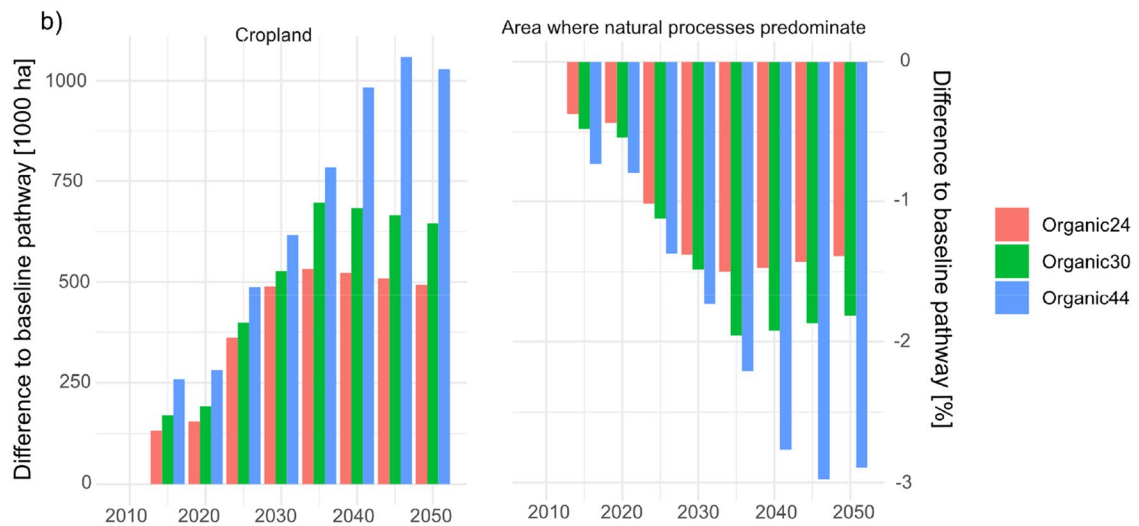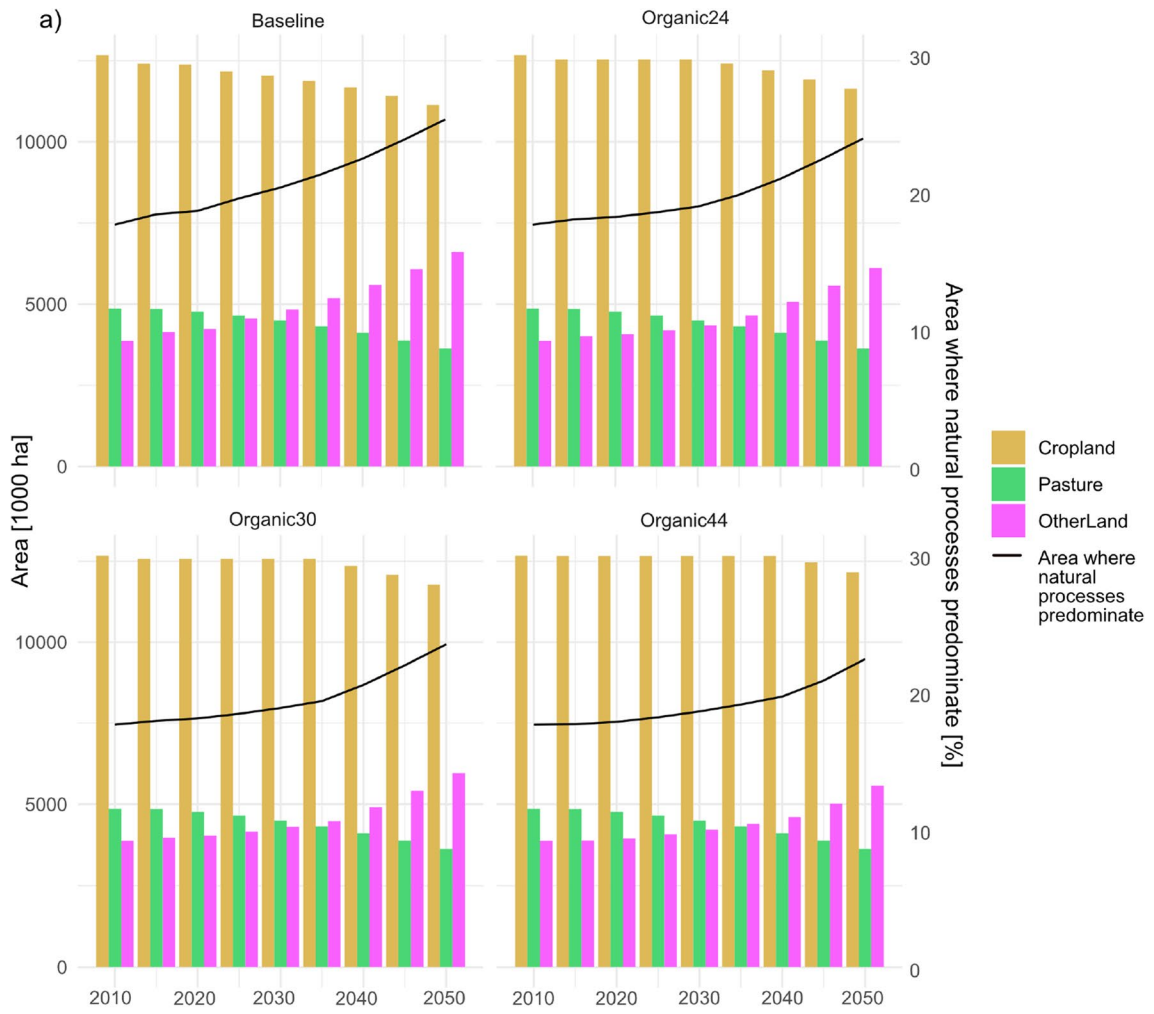
◄**Fig. 1** Development of cropland, permanent pasture and other land area as well as share of area where natural processes predominate in the pathways baseline, organic24, organic30 and organic44 (a). Absolute differences between the baseline pathway and the pathways organic24, organic30 and organic44 in cropland area and the share of area where natural processes predominate (b)

pathway (Fig. 1b, Area where natural processes predominate). Since cropland area remains constant until after 2030, we can assume that there is a shortage of produced calories in this pathway as well. Figure 2 shows that this shortage is slightly higher than in the organic24 pathway, with 21–30 kcal missing per person and day, translating to 125,000–180,000 ha missing cropland (Fig. 2).

A desirable share of organic agricultural area would be 44% by 2030, according to the stakeholders. If this goal was reached, the consequence would be that from 2010 to 2050, cropland area decreases by 4%, pasture area by 25%, other land area increases by 44%, and the share of area where natural processes predominate increases from 18 to 22% (Fig. 1a, Organic44). As in the other organic pathways, cropland area remains almost unchanged in the first time steps, and only starts to decline in 2045. The absolute difference in cropland area between the baseline and organic44 pathway rises up to a maximum of over 1,000,000 ha in 2045 (Fig. 1b, Cropland). The difference decreases again in 2050, and we can assume that it will slowly decrease further, corresponding to the trends observed for the pathways organic24 and organic30. The difference in the share of area where natural processes predominate is higher than in the other scenarios, but still negligible (Fig. 1b, Area where natural processes predominate). In this pathway, the deficit in supplied calories rises to 81 kcal per person and day in 2030, translating to over 500,000 ha missing cropland (Fig. 2).

Cropland area development under adaptation pathways

In the following section, we focus on the pathway organic30, since 30% organic agricultural area by 2030 is the German government's official target. Cropland area in the organic30 pathway decreases from 12,674,000 ha in 2010 to 12,573,000 ha in 2030 and 11,783,000 ha in 2050. This decrease is due to the SSP2-projected population decline combined with increasing crop and livestock productivity. Even so, this is a smaller decrease than in the baseline pathway, where the same population and productivity assumptions are made but without any organic

area increase. There, cropland decreases to 12,046,000 ha in 2030 and 11,137,000 ha in 2050 (Fig. 3a). This means that in 2030, 527,258 ha or 4.3% more cropland are needed in the organic30 pathway to produce the same amount of crop products as in the baseline pathway, and 645,861 ha or 5.8% more in 2050 (Fig. 1b). Can this difference be compensated with other adaptation measures in the food and land use system? To answer this question, we defined four adaptation pathways.

In the first adaptation pathway (organicA1), we assume that food waste will be reduced by 50% until 2030 and post-harvest loss until 2050. The results show that this change has a positive effect on cropland area in comparison to the organic30 pathway, but the effect is not strong enough to bridge the entire distance to the baseline pathway (Fig. 3a). This positive effect also only becomes apparent after 2030, when about 230,000 ha less cropland area is needed in the organicA1 pathway than in the organic30 pathway to meet demand (Fig. 3b). Furthermore, the caloric deficit is reduced to 18 kcal from 30 kcal per person and day (Fig. 3c), which means that the missing cropland area is also smaller and occurs only early on in the transition to a larger share of organic agricultural area (Fig. 3a).

In adaptation pathway organicA2, we assume that there will be a change in diet of the average German citizen. Total calorie as well as fat and sugar consumption is reduced, and more plant-based products are consumed. It is interesting to see that in this pathway, roughly 200,000 ha more cropland area will be needed to meet the demand than in the organic30 scenario (Fig. 3b), even though total calorie consumption is reduced by 10%. This is primarily due to the 50% reduction of highly calorie-dense fats and sugars. These calories need to be substituted by a relative increase in other products, leading to a 16% increase in crop products and a 13% increase in egg and milk production, while meat consumption only declines by 1%. This effect only becomes pronounced after 2035 because until 2035, more cropland would be needed than available to fill the calorie deficit in both pathways (Fig. 3a, dashed lines). The forced status quo of cropland area prevents these differences from showing when looking at cropland areas, but the calorie deficit in this period is higher in the organicA2 pathway than in the organic30 pathway, with a maximum of just under 40 kcal per person and day in the organicA2 pathway, and under 30 kcal in the organic30 pathway (Fig. 2, Fig. 3c).

In the third adaptation pathway, organicA3, we assume that crop productivity will increase at higher

Fig. 2 Average daily per capita calorie deficit that is accumulated in each time step if organic area share is increased but cropland expansion is prohibited (left y-axis), and cropland area that would be necessary to avoid the deficit (right y-axis)
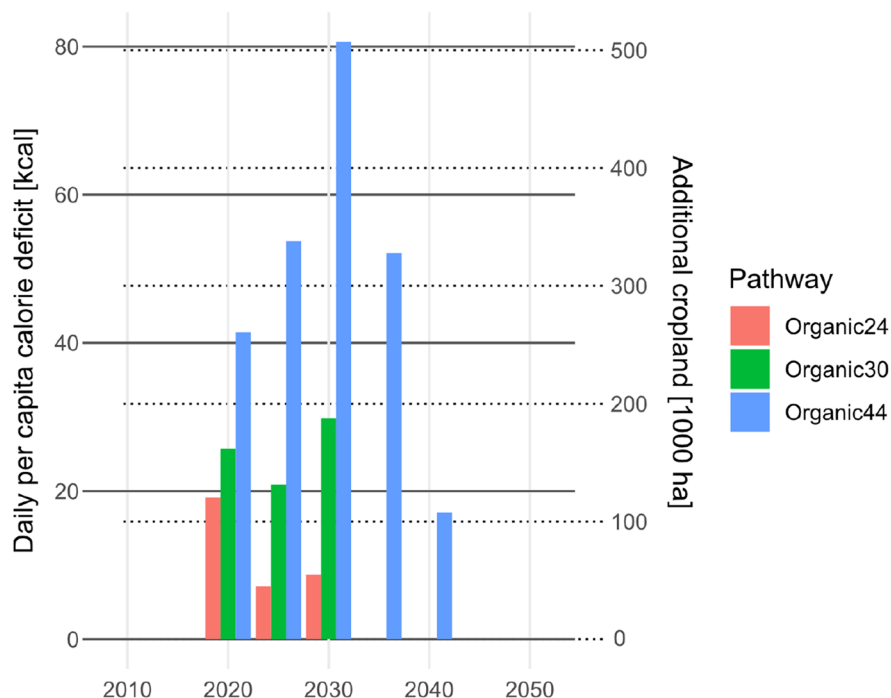
rates than observed in 2000–2010. This change has a profound effect on cropland areas. In 2030, 380,000 ha less cropland area is needed in the organicA3 pathway than in the organic30 pathway, by 2050, this number increases to 1,257,062 ha (Fig. 3b). After 2035, the necessary cropland area in the organicA3 adaptation pathway is even lower than in the baseline pathway, with cropland area savings of 611,201 ha in 2050 (Fig. 3a). There is a slight calorie deficit of 8 kcal in 2030, when the share of organic agricultural area reaches its maximum of 30%, but this deficit disappears quickly again (Fig. 3c).

Given the trends described for the pathways A1 to A3, it is not surprising that the last adaptation pathway, consisting of all adaptation measures taken together (organicAll), exhibits a strong resemblance to the pathway with the highest impact, organicA3. Since the differences in cropland area under these two pathways are so small, it can be assumed that the effects of a reduction of food loss and a change in diet more or less neutralize each other (cf. Figure 3b).

The differences in the share of area where natural processes predominate between the pathways are small, especially in the year 2030, where they range between 19 and 20% (Table 3). The differences grow slightly more pronounced up to 2050, where the share varies between 23% in the organic30 and organicA2 pathways

and 27% in the organicA3 and organicAll pathways. The share is thus the highest in the pathways where there is an increased crop productivity, and, as a consequence thereof, a smaller cropland area and a stronger increase in other natural land, where natural processes predominate. Organic24, organic30, and organic44 all have a slightly lower share than the Baseline pathway due to the lower average crop productivity in organic production systems and hence a higher cropland demand, allowing for less additional other natural land. However, the productivity increases in the organicA3 and organicAll pathways counter this organic yield gap and allow for a stronger increase in area where natural processes predominate than the Baseline.

A table with all the data presented here is provided in the Appendix (Table 4).

Discussion

The German government has the goal to direct the German food and land use system onto a more sustainable path. As one step in this direction, it is planned to increase the share of agricultural area that is managed organically from currently 10 to 30%. Due to the on average lower per unit area yields in organic systems,

Fig. 3 Total cropland area
per time step (a), difference
in cropland area between
adaptation pathways A1,
A2, A3, All and organic30
pathway (b), daily per
capita calorie deficit that is
accumulated in the adapta-
tion pathways organicA1,
organicA2 and organicA3
if cropland expansion is
prohibited (c)
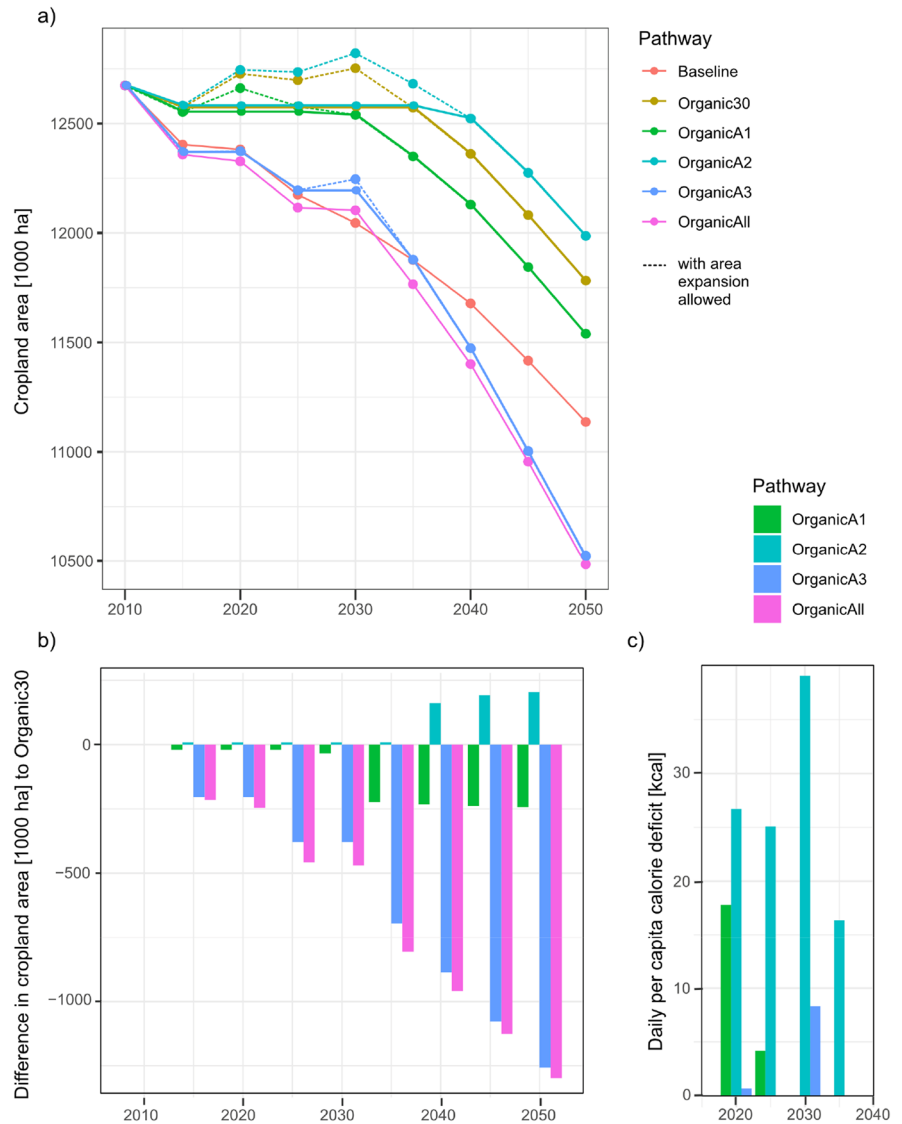
Table 3 Percentage share of area where natural processes predominate

	Baseline	Organic24	Organic30	Organic44	OrganicA1	OrganicA2	OrganicA3	OrganicAll
2010	18%	18%	18%	18%	18%	18%	18%	18%
2030	20%	19%	19%	19%	19%	19%	20%	20%
2050	25%	24%	23%	22%	24%	23%	27%	27%

there are concerns that, in doing this, a larger area will
be needed to produce the same amount of products. A
study showed that the average organic diet in Germany
requires 40% more land than the average conventional
diet (Treu et al. 2017). A larger agricultural area would

effectively offset the benefits associated with organic
agriculture (cf. Meemken & Qaim 2018). Our analysis
shows that this is true to some extent. When the share
of organic agriculture is expanded to 24%, 30% or 44%
of cropland area, there is either a calorie deficit, i.e.

not enough food is produced to satisfy the demand of the population as well as current export levels, or the cropland area needs to be expanded beyond the current area. However, the deficits only occur in the early years of the considered time horizon; until 2030 with a share of 24% and 30%, and 2040 with a share of 44%. This means that if the demographic and technological development in Germany will continue as projected, the current cropland will suffice to feed the population their accustomed diet by 2045 at the latest, even with a share of 44% organic agriculture. In the meantime, a virtual import of agricultural area between 1000 and 5000 km^2 will be necessary to close the calorie gap, which can be reduced through respective export reductions, shifting the caloric deficit to other countries.

While it is encouraging to see that the existing cropland area in Germany will suffice to realize a 44% share of organic agriculture in the future, the differences between the organic agriculture and the baseline pathways are not insignificant. If conventional intensive agriculture continues to be practiced on 90% of the cropland area, the total cropland area required declines faster and to a greater degree than with a lower share. In 2050, the difference between a 10 and a 30% share of organic agricultural area thus would lead to a difference in total cropland area roughly the size of the agricultural area of the German state of Rhineland-Palatinate; and roughly the size of the agricultural area of Schleswig–Holstein for a share of 44%. This area could be used for other purposes instead, e.g. the production of more bioenergy products or for biodiversity conservation.

Can a higher share of organic agricultural area be realized without requiring additional cropland? Our analysis of different adaptation pathways shows that investing in the development of higher-yielding crops may be the most efficient strategy in this regard. Even with a 30% share of organic agricultural area, cropland area declines at the rate of the baseline pathway or even faster if crop productivity increases can be augmented. In the past, improving the availability of nitrogen and water resources and breeding focused on higher yields were both responsible for crop productivity increases of conventional crops, which amounted to approximately 1% per annum for cereals (Duvick 2005; Fischer et al. 2012). In the last decade, optimal plant nutrition has been an integral part of modern intensive agriculture, and annual crop productivity increases have decreased to 0.5% (Fischer et al. 2012). To achieve the adaptation potential shown in our analysis, yield gains

of 0.75–2% per annum would be necessary. For conventional crops, such productivity increases might be feasible if resource limitations are avoided, especially water limitations in systems with optimal plant nutrition (Sinclair & Rufty 2012), and if the breeding of high-yielding varieties is accelerated by using advanced technologies such as speed breeding, genome selection or CRISPR gene editing (Voss-Fels et al. 2019). Even then, yield gains of up to 2% may be hard to achieve in situations where breeders have to simultaneously select for more stress-tolerant varieties to counter the negative impacts of climate change (Challinor et al. 2014). Yield gains in the range of 0.75–2% will be even more difficult to reach in organic systems, where nutrient limitations are the major yield-limiting factor (Barbieri et al., 2021). Options to increase yields could be to change current policies that ban a recycling of nutrients from human wastes to agricultural systems and to allow the use of mineral fertilizers from renewable sources (Röös et al. 2018). Others suggest reintroducing beneficial properties from wild relatives into crop varieties used in organic agriculture as a means to increase yields, but concede that this would entail using biotechnology not generally accepted in organic farming (Andersen et al. 2015). More traditional breeding for higher-yielding crops in organic systems could focus on strengthening traits such as weed competitiveness, resistance to seed-borne pathogens, and the ability to establish symbiont relations with soil organisms to enhance the uptake of resources (Crespo-Herrera & Ortiz, 2015). Considering all of these factors, yield increases of 0.75–2% may not be out of reach for conventional crops, but may be difficult to achieve for crops grown in organic systems, where nutrient availability may limit productivity despite advances in crop breeding. For simplicity and due to lack of data, in this study, relative productivity increases per crop were assumed to be equal for organic and non-organic farming. As discussed above, a productivity growth differentiation between both systems may show a bigger crop area gap than the current results.

In the previous sections, we have described what trends may be expected in the German food and land use system with an increase of organic agricultural area. The additional cropland area of 1000 to 5000 km^2, which is necessary to fill the calorie gap, is not particularly large, but importing more products could nevertheless have a negative effect on other countries (Huang et al. 2017). This increased need for imports could be lowered by

reducing exports from Germany. However, this would only shift the calorie deficit and the related burden to increase imports from other countries to those that cannot import as much as before from Germany. Either way, an enhanced agricultural production in exporting countries may, e.g. lead to non-sustainable consumption of land and other resources, and environmental pollution may increase (Sun et al. 2018). Halberg et al. (2006) estimate that a conversion of 50% of cropland area in Europe and North America to organic agriculture would cause to a global price increase for agricultural commodities of at least 6–10%, leading to higher levels of food insecurity especially among the urban poor (Ecker & Qaim 2011; Tscharntke et al. 2012). If other European countries expand their organic agricultural area as well, this problem may become more prevalent. In 2020, the organic area was 14.7 million hectares in the EU, corresponding to a share of 9.1% of total agricultural area (EUROSTAT 2022). In the Green Deal, a target of at least 25% by 2030 was set for the EU (European Comission, 2019), which means that further conversion of conventional to organic area is to be expected in the near future.

Even though these potential drawbacks may appear if the organic agricultural area in Germany (and other countries) is expanded, there are also benefits. If we set aside the controversial benefits of organic agriculture in terms of per unit/per area biodiversity conservation, greenhouse gas emissions and nitrate leaching (Gabriel et al. 2013; Green et al. 2005; Meemken & Qaim 2018; Mondelaers et al. 2009; Schneider et al. 2014), benefits in terms of greater profitability, enhanced soil quality, and reduced pesticide use remain (Crowder & Illan 2021). Especially pesticides impose high external costs on society, most of which are currently ignored. In India, external damages caused by conventional cotton amount to USD 2,245 million (Rasche et al. 2016), and Pimentel (2005) estimated that annual environmental and social costs from pesticides in the US amount to USD 9,645 million, of which USD 1,140 million were due to public health impacts. Even though these costs will be lower in smaller countries like Germany, it can be assumed that they are still considerable, especially since the main source of human pesticide exposure are residues on conventional fruits and vegetables (Mie et al. 2017).

While we assume that all of the targets in the pathways are potentially achievable (based on expert and stakeholder opinions), there are uncertainties attached

to the analysis that cannot be considered explicitly in the framework we used for this study. FABLE is an Excel-based accounting tool that was specifically developed to be transparent, easy to use, and approachable. This entails that there is no automatization of pathway calculations; each pathway analysis requires its own calculator in which one specific set of scenarios defining the pathway is combined. It is thus necessary to accept input data as representative for a given pathway, even though there often is considerable uncertainty attached to it. The calculated yield modifiers for example have a high uncertainty (discussed in Rasche, 2021), as well as the magnitude of productivity increases, consumption changes, or food waste reduction. Even data from databases such as FAOSTAT have their own uncertainty. A pathway analysis with FABLE should thus be considered as a carefully selected set of possible pathways in a wide option space, where only the factors of interest are varied between pathways to highlight the relationships between those factors and the indicators calculated in FABLE.

We have shown that a higher share of organic agricultural area in Germany is feasible, especially if accompanied by technological advancements towards higher crop productivities. Yet, it remains to be seen if an increase of organic area to 30% by 2030 is realistic. In some German states, the share of organic agricultural area is already high, such as in Hesse, where it is at 18%. Here, an increase to 30% by 2030 is not impossible. In other states, e.g., Lower Saxony, the current share is 5%, and some experts think that an increase to 30% by 2030 is unrealistic (Meyer 2021). The question has also been raised if organic production can even be expanded to a much larger share without running into nitrogen shortages, since the only acceptable fertilizers in such systems are animal and green manure as well as composts. A recent study showed that organic agriculture can be expanded to 20% of global cropland without major issues, but a higher share would require major shifts in the food and land use system, including the creation of sophisticated coupled livestock-crop production systems, a reduction of food waste, and potentially sourcing nitrogen from sewage (Barbieri et al. 2021). Considering these issues, the share of organic agriculture of 24% by 2030 that was determined by the stakeholders to be a realistic value may be a more viable and tangible target than the German 30% target.

Appendix

Table 4 Indicator values for each pathway in 5-year time steps. AWNPP: Share of area where natural processes predominate; Cropland_Ex: cropland area when expansion of agricultural area is allowed

Pathway	Year	Cropland [1000 ha]	Pasture [1000 ha]	OtherLand [1000 ha]	AWNPP [%]	Calories [kcal]	Cropland_Ex [1000 ha]
Baseline	2010	12,674	4861	3876	18%	3145	12,674
Baseline	2015	12,404	4854	4144	18%	3145	12,404
Baseline	2020	12,381	4765	4230	19%	3145	12,381
Baseline	2025	12,175	4646	4556	20%	3145	12,175
Baseline	2030	12,046	4497	4834	20%	3145	12,046
Baseline	2035	11,877	4316	5183	21%	3145	11,877
Baseline	2040	11,678	4109	5589	22%	3145	11,678
Baseline	2045	11,417	3881	6078	24%	3145	11,417
Baseline	2050	11,137	3635	6604	25%	3145	11,137
Organic30	2010	12,674	4861	3876	18%	3145	12,674
Organic30	2015	12,573	4854	3974	18%	3145	12,573
Organic30	2020	12,573	4765	4038	18%	3119	12,727
Organic30	2025	12,573	4646	4158	18%	3124	12,698
Organic30	2030	12,573	4497	4307	19%	3115	12,753
Organic30	2035	12,573	4316	4487	19%	3145	12,573
Organic30	2040	12,361	4109	4906	21%	3145	12,361
Organic30	2045	12,082	3881	5413	22%	3145	12,082
Organic30	2050	11,783	3635	5959	23%	3145	11,783
Organic24	2010	12,674	4861	3876	18%	3145	12,674
Organic24	2015	12,535	4854	4012	18%	3145	12,535
Organic24	2020	12,535	4765	4076	18%	3126	12,649
Organic24	2025	12,535	4646	4195	19%	3138	12,578
Organic24	2030	12,535	4497	4344	19%	3136	12,587
Organic24	2035	12,409	4316	4651	20%	3145	12,409
Organic24	2040	12,201	4109	5066	21%	3145	12,201
Organic24	2045	11,926	3881	5570	22%	3145	11,926
Organic24	2050	11,630	3635	6111	24%	3145	11,630
Organic44	2010	12,674	4861	3876	18%	3145	12,674
Organic44	2015	12,662	4854	3885	18%	3145	12,662
Organic44	2020	12,662	4765	3949	18%	3103	12,916
Organic44	2025	12,662	4646	4069	18%	3091	12,994
Organic44	2030	12,662	4497	4218	19%	3064	13,169
Organic44	2035	12,662	4316	4398	19%	3093	12,984
Organic44	2040	12,662	4109	4605	20%	3128	12,765
Organic44	2045	12,476	3881	5019	21%	3145	12,476
Organic44	2050	12,166	3635	5575	22%	3145	12,166
OrganicA1	2010	12,674	4861	3876	18%	3145	12,674
OrganicA1	2015	12,553	4847	4001	18%	3145	12,553
OrganicA1	2020	12,553	4736	4088	18%	3127	12,662
OrganicA1	2025	12,553	4589	4234	19%	3141	12,578
OrganicA1	2030	12,539	4391	4447	19%	3146	12,539
OrganicA1	2035	12,350	4214	4813	20%	3146	12,350
OrganicA1	2040	12,130	4012	5235	21%	3146	12,130

Table 4 (continued)

Pathway	Year	Cropland [1000 ha]	Pasture [1000 ha]	OtherLand [1000 ha]	AWNPP [%]	Calories [kcal]	Cropland_Ex [1000 ha]
OrganicA1	2045	11,844	3788	5744	23%	3146	11,844
OrganicA1	2050	11,540	3548	6289	24%	3147	11,540
OrganicA2	2010	12,674	4861	3876	18%	3145	12,674
OrganicA2	2015	12,582	4860	3959	18%	3129	12,582
OrganicA2	2020	12,582	4777	4018	18%	3086	12,745
OrganicA2	2025	12,582	4669	4126	18%	3056	12,735
OrganicA2	2030	12,582	4536	4258	19%	2995	12,821
OrganicA2	2035	12,582	4376	4418	19%	2953	12,682
OrganicA2	2040	12,523	4192	4661	20%	2889	12,523
OrganicA2	2045	12,275	3974	5128	21%	2841	12,275
OrganicA2	2050	11,987	3727	5663	23%	2825	11,987
OrganicA3	2010	12,674	4861	3876	18%	3145	12,674
OrganicA3	2015	12,370	4854	4177	18%	3145	12,370
OrganicA3	2020	12,370	4765	4242	19%	3144	12,374
OrganicA3	2025	12,195	4646	4536	19%	3145	12,195
OrganicA3	2030	12,195	4497	4685	20%	3136	12,246
OrganicA3	2035	11,878	4316	5182	21%	3145	11,878
OrganicA3	2040	11,474	4109	5793	23%	3145	11,474
OrganicA3	2045	11,004	3881	6491	25%	3145	11,004
OrganicA3	2050	10,526	3635	7216	27%	3145	10,526
OrganicAll	2010	12,674	4861	3876	18%	3145	12,674
OrganicAll	2015	12,358	4853	4189	19%	3129	12,358
OrganicAll	2020	12,328	4748	4301	19%	3113	12,328
OrganicAll	2025	12,116	4613	4648	20%	3082	12,116
OrganicAll	2030	12,104	4430	4843	20%	3034	12,104
OrganicAll	2035	11,766	4273	5337	22%	2970	11,766
OrganicAll	2040	11,401	4093	5881	23%	2890	11,401
OrganicAll	2045	10,956	3880	6541	25%	2843	10,956
OrganicAll	2050	10,485	3638	7254	27%	2827	10,485

Data availability All data generated and analysed during this study are included in this published article and its supplementary information files; the data can also be requested from the corresponding author. The base version of the FABLE calculator can be downloaded at https://www.abstract-landscapes. com/fable-calculator. The organic/conventional yield dataset can be downloaded at https://doi.org/10.25592/uhhfdm.9213.

Declarations

Competing interests The authors declare no competing interests.

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