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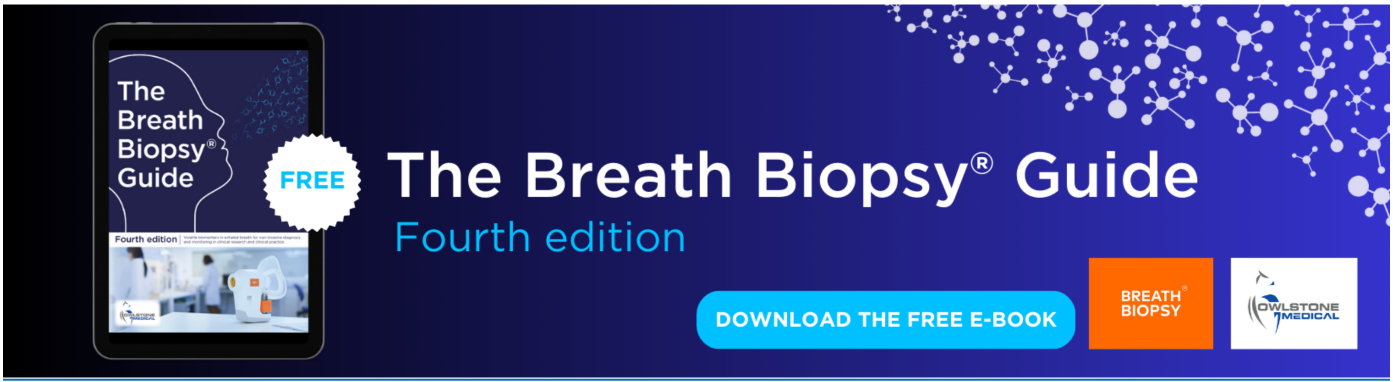

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LETTER

Bioenergy in Europe is unlikely to make a timely contribution to climate change targets

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Supplementary material for this article is available online

Abstract

Increasing bioenergy production is a significant component of European efforts to mitigate climate change, but has contested potential for reducing emissions. We use an integrated land system model to explore the effects of large-scale bioenergy production within the European Union on carbon balances. We find that increased bioenergy crop production is likely to cause substantial deforestation and a commensurate loss of associated carbon stocks largely due to displacement of food production from other areas. Deforestation would occur either within the EU if European forests were not protected, or in other parts of the world arising from indirect land use change if European forests were protected. The net carbon benefit of bioenergy production is largely negative, or uncertain, even under the most optimistic levels of fossil fuel replacement, and will not offset initial carbon losses over the coming 50 yr. The growth of intensive agriculture required to satisfy the demand for bioenergy and food will have negative impacts on crucial ecosystem services. Overall, we identify substantial disadvantages to increasing bioenergy production relative to freeing land for natural succession. At best, large-scale bioenergy production is likely to be irrelevant to time-sensitive climate targets.

1. Introduction

Bioenergy refers to energy content in solid, liquid and gaseous products derived from biomass feedstocks and biogas [1]. Bioenergy is strongly supported by European Union (EU) renewable energy policy in order to reduce fossil fuel use and plays an important role in net-zero emission pathways [2]. For example, modern bioenergy use (i.e. excluding traditional biomass) accounted for 10% of energy consumption in 2022, which will be doubled by 2030 [1]. Domestically-sourced bioenergy alone is planned to supply 14% of the transport sector's energy requirements [3], and to meet almost a third of the EU's renewable energy shares target by 2030 [4–6].

The carbon benefit of this increasing bioenergy usage depends on the energy efficiency per unit area of the biomass used (crop species and yield), on the fossil fuel it offsets (if it does reliably do so), and on carbon stock changes via land use change [7–11]. Land use change emissions include impacts on existing carbon stocks (e.g. timber removal) and on future vegetation growth in cultivated areas (net primary productivity). By adding to human land requirements, bioenergy can also displace agriculture and forestry to other, naturally-vegetated areas [12, 13]. This displacement is global in nature: two-thirds of the cropland required to satisfy the EU's non-food biomass consumption is located in other world regions, mainly in China, the US, and tropical countries in the Global South [14, 15]. The impacts of European bioenergy usage have been estimated to include a 10% increase in European food prices (and a 2.5% increase globally [16]), and substantial negative impacts on biodiversity and ecosystem services worldwide have been suggested in some studies [12, 17–19].

The global footprint of bioenergy for use in the EU may reach 70 Mha in 2030 [20]; an area about twice the size of Germany. Bioenergy production on this scale could have major implications for both European and global land systems, but its overall effect remains uncertain [21]. Numerous studies have explored the specific benefits and costs of bioenergy production (e.g. [7, 22–29]). The largest benefits are found by studies that consider a limited range of criteria, or that assume bioenergy is produced on 'surplus' agricultural land [30–32], or with a significant yield increase [33, 34]. The assumption that carbon capture and storage (CCS) will eventually be able to offset direct emissions of bioenergy production is a crucial, but highly uncertain, component of many studies that find large carbon benefits [21, 35]. Meanwhile, studies that account for a wider range of environmental, social, and economic constraints find substantial drawbacks [24, 36–38]. Many of these relate to bioenergy production exerting additional pressure on limited land resources; resources that already provide insufficient levels of carbon sequestration, biodiversity preservation, and, in some contexts, food [8, 16, 18, 26, 39, 40]. The IPCC also concluded that bioenergy production on 'a limited share of total land' could have a range of positive benefits, but that these were likely to disappear under large-scale production (IPCC special report on land, summary for policymakers B.3.2. [21, 41]). Meanwhile, bioenergy targets are based almost exclusively on its direct potential for fuel provision and emissions reductions, neglecting the negative impacts of using land for production and their indirect environmental and socio-economic impacts [27, 37, 42–44].

Bioenergy production must also occur within the context of increasing prioritisation of carbon and biodiversity in the land system, with potentially limiting effects on the scope for land conversion. In recent years, the development of the EU's Regulation on Land, Land Use Change and Forestry has been particularly challenging, not least because of its implications for forestry and bioenergy [45]. Ambitious, nationally-binding targets for increased carbon removals via the land system, and proposals for the EU's Nature Restoration Law [46], make widespread land use change problematic, and may conflict especially with the Renewable Energy Directive's reliance on bioenergy [47, 48].

The overall benefits or drawbacks of bioenergy production, therefore, remain ambiguous even as policy support grows [26, 36, 49, 50]. To fully assess the potential impacts of large-scale bioenergy production in Europe, we modelled the impacts of bioenergy production using an integrated and cross-sectoral model of the EU land system [51]. This approach allows an examination of the net effects of different levels of bioenergy production while controlling for the displacement of land use change to other countries, by maintaining net food imports at today's levels. We explore results in terms of land use change, the time required to achieve net carbon benefits from bioenergy production, and net changes in the provision of other ecosystem services. We use 'bioenergy' to refer to cultivated land to produce plants used to displace fossil emissions hereafter in this study.

2. Materials and methods

2.1. Stylised bioenergy production scenarios

We analysed the impacts of bioenergy production on land use change and emissions across Europe using the Integrated Assessment Platform (IAP2) version 2[7] [51–56]. The IAP is a cross-sectoral model including meta-models for urban development, water resources, coasts, agriculture and forests, and biodiversity, which simulate carbon dynamics, agricultural inputs and ecosystem service provision through these sectors [29, 52, 56]. The model has been used in many European applications to explore cross-sectoral interactions without the very large biases associated with single-sector analyses [51, 53, 54, 57–59]. The model simulates spatially explicit land use and ecosystem service changes over the EU 27 plus the United Kingdom, Norway, and Switzerland, or EU 27+3 (Croatia is not included). The model runs on a 10-arcminute grid (10'; ca. 16 km^2 in Central Europe) and the total number of cells is 23 718. The model uses default input data (demand and capitals) largely based on the year 2010, with a corrected CO$_2$ concentration of 400 ppm. The IAP includes six major land use types: Intensive Arable, Forest, Extensive Grassland, Intensive Dairy, Other (natural vegetation), and Urban [56]. Intensive dairy areas are used for grassland production to support dairy herds and forage-fed intensive beef cattle. Extensive grassland areas are used for grass-fed beef and sheep. 'Other' land, including bare, sparsely vegetated, and scrub areas, has low productivity for trees and is not used

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[7] http://tiamasg.ro/test/IAP2.1.

for either agriculture or forestry. Land use types are assigned in proportions to grid cells and have variable intensities, giving cell-specific mixes at the 10’ scale. We used the baseline model setup except for variations in bioenergy crop demand and a fixed agricultural set-aside percentage of 3%.

To assess the net impact and the implications of increased bioenergy production, we simulated the cost and the benefit through land use change triggered by bioenergy cropping. We did not account for biomass fuels derived from by-products of forests and excluded it from further analyses.

We increased the bioenergy crop area demand from 4% (baseline) to 30% of the intensive arable land use area in steps of 1%. Land use is allocated in the model based on biophysical (water availability, soil condition, climate and potential yields) and economic conditions (relative profitability determined by commodity prices, crop yield, support rules and costs) [55, 56]. Increasing demand affects land use decision-making through the meta-model SFARMOD, a farm-based agricultural land use model using constrained optimisation [58, 60]. Land use allocation is first constrained by non-agricultural land use (urban, protected and flooded areas) and then divided into intensive agriculture, extensive agriculture, forest and other land. The model adjusts prices iteratively to allocate land areas that meet net food demand. Food demand is simulated based on population, net imports (i.e. as a proportion of food demand, fixed at the baseline level of 20% in this study), dietary preferences (for plant and different animal products), and bioenergy crop demand [58]. Where relative profit is > 350 Euro ha^{-1}, land is allocated to intensive agriculture (e.g. crop or intensive dairy) and where between 350 and 150 Euro ha^{-1}, it is allocated to extensive agriculture or managed forest. If relative profit is lower than 150 Euro ha^{-1}, the land is allocated either to unmanaged forest or unmanaged land [56]. Within agricultural classes, the IAP simulates major crops across commodity groups (cereals, oils, roots, protein and fibre) and grass for dairy farming; simulated crops include winter and spring wheat and barley, oilseed rape, potatoes, maize, sunflower, sugar beet, soya, and cotton. The level of food production is calculated based on the total amount of food crops and dairy products [55, 56]. Managed forest areas are profitable forests that are used for timber production, whereas unmanaged forests undergo natural succession. In this study, managed and unmanaged forest areas were combined into a single forest category, but distinct rates of net primary productivity (NPP) and carbon sequestration were retained.

The impact of bioenergy crop expansion was evaluated in terms of land use, carbon, food production, and other ecosystem service indicators in three sectoral indicator groups: climate mitigation (carbon benefit), food production, and environmental quality (agricultural chemicals and water use). To account for the cross-sectoral aspects of the land use competition, we analysed the output indicators against the actual area size of the bioenergy crops (ha) instead of the prescribed bioenergy crop demand (i.e. x% of the intensive arable area). We constrained indirect land use change impacting areas outside the EU 27+3 (or ‘leakage’ of land use) by maintaining net imports of food and other commodities at the baseline level (i.e. 20% of the total food demand). Otherwise, the agricultural production meta-model would resolve the extra demand for crop production by importing more food from outside Europe, making it impossible to assess net impacts on carbon or other criteria, since these impacts would occur in other parts of the world. Urban areas are also fixed to baseline extents.

2.2. Carbon benefit

We implemented an area-based net carbon benefit calculation. Net carbon benefit (B_{net}) over its annual life cycle is

$$B_{\text{net}}\ \left(t\text{C}\,\text{yr}^{-1}\right) = B_{\text{offset}}\ \left(t\text{C}\,\text{yr}^{-1}\right) + \Delta \text{C}_G\ \left(t\text{C}\,\text{yr}^{-1}\right) + \frac{\Delta \text{C}_{\text{stock}}\,(t\text{C})}{D\,(\text{yr})} \tag{1}$$

and the fossil fuel offset of bioenergy crops (B_{offset}) is

$$B_{\text{offset}}\ \left(t\text{C}\,\text{yr}^{-1}\right) = \text{Area}_{\text{bio}}\ (\text{ha}) \times b_{\text{offset}}\ \left(t\text{C}\,\text{ha}^{-1}\,\text{yr}^{-1}\right), \tag{2}$$

where C_G and C_{stock} are annual carbon growth and carbon stock, respectively, D is a time-dependent stock change factor used to amortise carbon stock changes (= 20, 50, 100 yr), Area_{bio} is allocated bioenergy area, and b_{offset} is the carbon benefit coefficient excluding the land use change effects [8]. We used carbon stock (C_{stock}) changes to estimate carbon emissions following the IPCC 2006 guideline (sections 1.2 and 2.3, Vol. 4 [61]). We defined ΔC_{G_i} as a change in annual NPP and $\Delta\ \text{C}_{\text{stock}_i}$ as a change in carbon stock between the scenario and the baseline bioenergy production. b_{offset} is the carbon benefit coefficient excluding the land use change effects [8]. The benefit refers to carbon saving by using a hectare of land for dedicated biofuel production or growing woody biomass on agricultural land. As the benefit is highly dependent on bioenergy pathways (i.e. crop species, sequestration rate, forms of bioenergy, fossil fuel to replace), it is highly variable. To address that, a range of literature-based offset values considering various bioenergy pathways are used, following the work of Searchinger *et al* [8].

For the forested areas, C_G and C_{stock} are potential values simulated by the meta-model MetaGOTILWA+ [58, 62], which emulates a biophysical vegetation growth model GOTILWA+ using neural networks [56]. The model simulates carbon and water fluxes through forests of different tree species, and evaluates the impacts of climate and forest management [62–64]. The model accounts for climatic conditions (temperature, radiation, precipitation, vapour pressure deficit, and wind speed), stand characteristics (tree structure), tree physiology (photosynthetic and stomatal conductance parameters) and soil and hydrological characteristics.

For the other land use types (i.e. arable, intensive and extensive grasslands, and other), we calculated ΔC_G and ΔC_{stock} using IAP simulated yield (t harvested fresh matter ha^{-1}) and vegetated area (ha) using Tier 2 and 3 methods of the IPCC carbon inventory guidelines [61], with simplification. For a vegetation type j, annual C_G is

$$\begin{aligned} C_{G_j}\ \left(t\text{C}\,\text{yr}^{-1}\right) &= \text{Yield}_j\left(t\,\text{fresh matter}\,\text{ha}^{-1}\,\text{yr}^{-1}\right) \times \text{Area}_j\,(\text{ha}) \\ &\times \text{DMF}_j\left(\text{dry matter fresh matter}^{-1}\right) \\ &\times \text{CF}_j\left(t\text{C}\ t\ \text{dry matter}^{-1}\right), \end{aligned} \tag{3}$$

where Yield and Area are the fresh harvested yield and the area size simulated by the IAP, DMF is the dry matter fraction of the harvested product, and CF is the carbon-to-dry matter ratio. For these types, we assumed changes in carbon in the biomass pools (ΔC_B) and soil organic carbon (ΔSOC) were equal to the change in carbon stock ($\Delta C_{\text{stock}} = \Delta C_B + \Delta\text{SOC}$). ΔC_B is the change in standing carbon stock ($t\text{C ha}^{-1}$). Note that changes in other carbon pools (e.g. litter pool) for non-forest types and non-CO_2 emissions (e.g. denitrification) for all types were not considered in the calculation. The parameter values were taken from IPCC [61, 65] and the FAO publications [66, 67] for Europe (supplementary table ST2).

B_{net} is sensitive to b_{offset}, which is determined by cultivated crop species, the fossil fuel being replaced, crop yield, conversion efficiency, and other transaction costs such as transport. We did not make a fixed assumption about the types of bioenergy crops or fossil fuels they replace because such assumptions are highly uncertain. Instead, we explored the uncertainty in these terms by applying the highest and the lowest offset coefficients derived from the literature [8] summarised in table 1. For simplicity, we assumed no other transaction costs.

Bioenergy production alters the ecosystem by removing existing land cover and introducing a new rate of carbon sequestration, and initial loss in ecosystem carbon stock from land use change (the carbon debt) can only be compensated for by later emissions reductions associated with bioenergy usage. The carbon payback time (CPT), or greenhouse gas payback time, measures the time required to pay off the carbon debt incurred by land-use change emissions; the more carbon emitted initially, the longer the payback time [68–71]. However, note that this is not the same as carbon neutrality in biogenic fuels, although it does indicate a period over which neutrality would be achieved after the establishment of bioenergy crops. Assuming that land conversion happens once at the beginning of bioenergy production on an area of land, then the payback period is defined as the number of years required to accumulate a benefit from fossil fuel replacement equivalent to the initial carbon debt (note that this does not imply a net carbon benefit from bioenergy production, but only a benefit relative to a highly-polluting alternative):

$$\text{CPT}\ (\text{yr}) = \frac{\Delta C_{\text{stock}}\ (t\text{C})}{B_{\text{offset}}\ \left(t\text{C yr}^{-1}\right)}. \tag{4}$$

3. Results

3.1. Land use change caused by bioenergy production

At the European scale, increasing the area of bioenergy crops has strong implications for other land uses and land covers. These implications do not take the form of perfectly proportional relationships because increased production of bioenergy is possible through intensification and reassignment of land within existing agricultural areas (visible in the solid lines in figure 1) as well as through agricultural expansion. Nevertheless, pronounced linear trends do emerge (dashed lines, figure 1). In particular, we found that forest area decreased by approximately 0.80 Mha for each 1 Mha of additional bioenergy area. The area of intensive arable and intensive dairy farming had smaller negative trends (−0.12 and −0.09 Mha per 1 Mha bioenergy area increase, respectively). Together, these trends demonstrate the effects of increased land use competition in driving non-bioenergy agriculture onto sub-optimal land areas that produce less food per unit area. As a consequence, bioenergy production leads to a reduction in food production (figure 4) when areas of land sufficiently large and productive enough to maintain food provision alongside increased bioenergy are not available (figure 2).

We also found an increase in extensive grassland areas of 0.12 Mha per additional 1 Mha of bioenergy as extra grassland is required to satisfy the demands for grass-fed meat products, forcing further conversion of forested and other land (figure 2(c)). The reduction of 'Other land' of −0.11 Mha per additional 1 Mha of bioenergy shows that increasing demand also shifts land use into areas where the production of agricultural or forestry-related goods and services had previously not taken place (figure 2(b)).

These trends highlight a cascading series of indirect impacts as bioenergy expands into productive agricultural and forest areas, forcing the management of larger areas of marginal land to compensate for losses in food production (appendix figure A1).

The impact of bioenergy crop expansion on deforestation was observed across Europe (figure 2), but with clear smaller-scale geographical patterns.

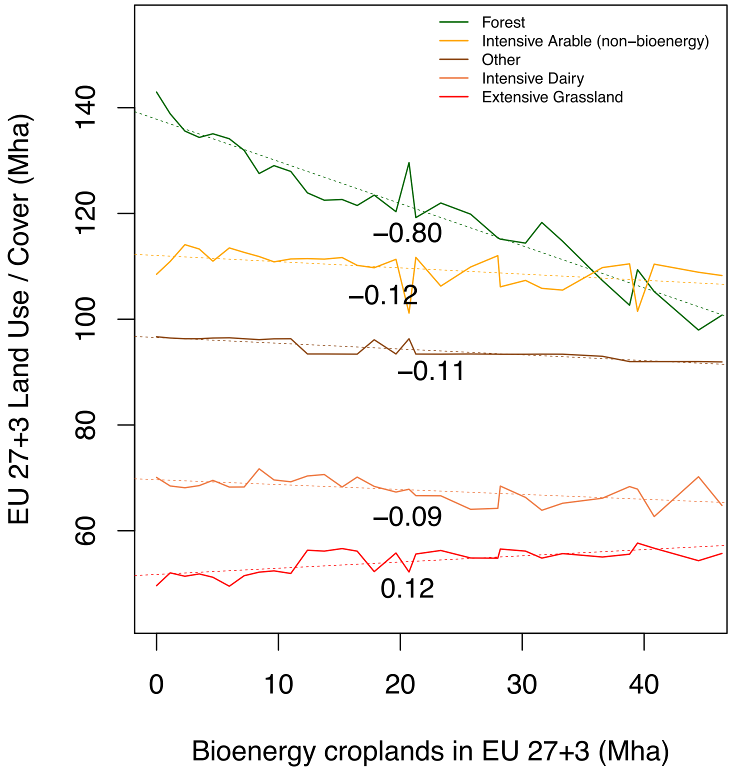

Figure 1. Modelled changes in land use and land cover with respect to increasing bioenergy crop production. Coloured lines show absolute areas produced by the model, and dotted lines show fitted slopes, all statistically significant with 1% confidence level. 'Other' (brown) includes bare, sparsely vegetated, scrub and low-productivity forest land covers. Extensive Grassland (red) includes extensive and very extensive grazed vegetation. Urban land is excluded in the plot as it covers a fixed, small proportion (3.96%) of the land area.

These patterns of deforestation are largely determined by land availability and productivity. To meet bioenergy demands, arable land expands most into Eastern European forests (e.g. in Latvia), with indirect land conversion following in northern Europe (figure 2(b)), where crop and timber yields were previously below profitability thresholds.

As intensive arable land (both bioenergy and non-bioenergy) expands into forests and previously extensively-managed grasslands (figure 2), environmental stress, in terms of irrigation water use and agricultural chemical inputs, consequently increases (figure 3). Irrigation water usage is particularly sensitive to large scale bioenergy production as irrigated crops are relocated to drier areas previously unused for agriculture without irrigation.

3.2. Net carbon benefit

The substantial land use and land cover changes associated with large-scale bioenergy production in Europe have important implications for carbon stocks (figure 4). Results show that the overall changes in annual NPP associated with increasing bioenergy crop production are sufficiently great to produce an increase in atmospheric carbon in most cases (figure 4(a) and appendix table A1). Whether or not bioenergy usage can compensate for this increase depends also on the size of the associated fossil fuel offset, with low values from the literature giving net carbon costs (increasing emissions) and high values giving net carbon benefits (reducing emissions). As the bioenergy expansion causes deforestation and relocation of grassland to less productive areas [72], overall NPP declines (supplementary figure SF1), reducing the annual amount of carbon stored by European ecosystems.

When changes in existing carbon stocks are also taken into account (figures 4(b)–(d)), the net effect of bioenergy crop production is almost always negative. This is true even when carbon stock changes are amortised over a 100 yr time horizon (figure 4(d)), revealing that bioenergy crops are unlikely to make a positive contribution to emissions reductions in Europe in the 21st Century, with small carbon benefits occurring only if bioenergy crops are high-yielding per unit area (e.g. short rotation coppice) and if they consistently replace the highest-emitting forms of fossil fuel (e.g. hard coal). Even then, the associated offset of 6.6 tC ha^{-1} assumes high water and chemical inputs and favourable climate conditions. Furthermore, these unlikely gains are dependent on substantial reductions in European food and timber production necessary to allow increases in the bioenergy cropping area (figure 4).

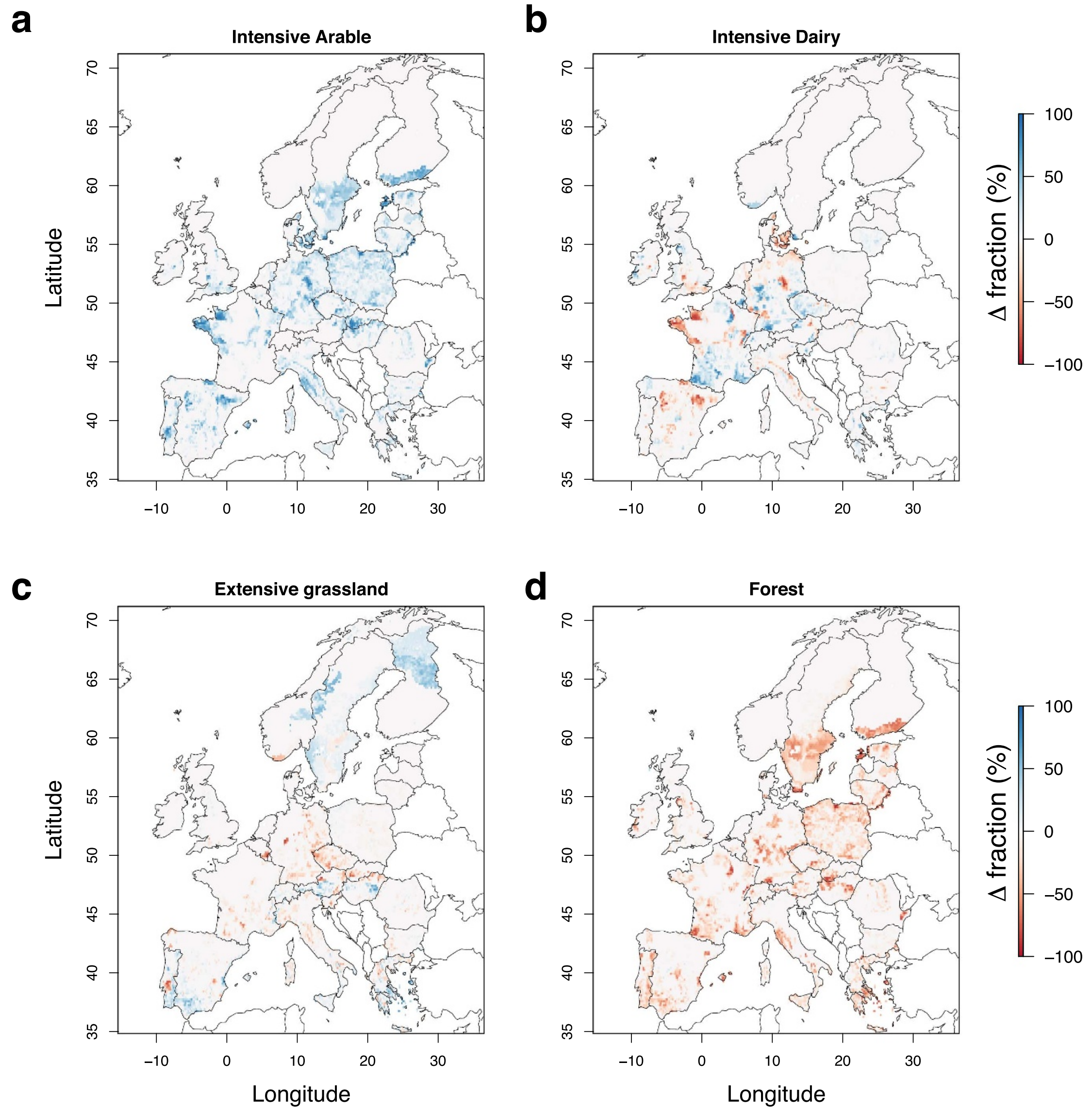

Figure 2. Modelled changes (%) in land use and covers with increasing bioenergy cropland area (from the baseline of 4.62 Mha to 45 Mha). (a), Bioenergy expansion increases land use pressure of 'Intensive Arable' (including both bioenergy and non-bioenergy crops) all over Europe. (b) and (c), as new intensive arable land is allocated, 'Intensive Dairy' (b) and 'Extensive Grassland' (c) are forced to less productive land parcels in mountainous regions or in the higher latitudes. (d), Deforestation occurs all over Europe with particular impacts in Eastern European countries. Note that 'Urban' area is fixed, and thus remains unchanged in the model runs.

If bioenergy crops are less productive (e.g. 0.54 tC ha^{-1} of Maize for ethanol) and replace less carbon-intensive fossil fuels (e.g. natural gas, which comprises 21.4% of the EU 28 energy mix as of 2018 [73]), annual carbon impacts can actually be negative (figure 5). Such carbon costs of bioenergy production accumulate through time whether or not an initial loss in carbon stocks occurs (i.e. wherever bioenergy crops are grown). Note that in figures 4 and 5, the observed variability across bioenergy areas is an emergent property of the model that arises from different land use configurations, rather than being a stochastic input to the model. For example, the high forest area at 21 Mha of bioenergy area arises from different configurations in food production (e.g. more meat and dairy products produced than cereals and root crops) meeting the food demand.

4. Discussion

Increasing the production of bioenergy is a key component of European and global targets to mitigate climate change, even though the scientific literature is unclear about the relative benefits and negative impacts that might result [21]. The IPCC's Special Report on Climate Change and Land summarised this uncertainty by identifying the benefits of bioenergy production on a strictly 'limited share' of global land [21, 41]. Our results suggest that any additional large-scale (of the order of millions of hectares)

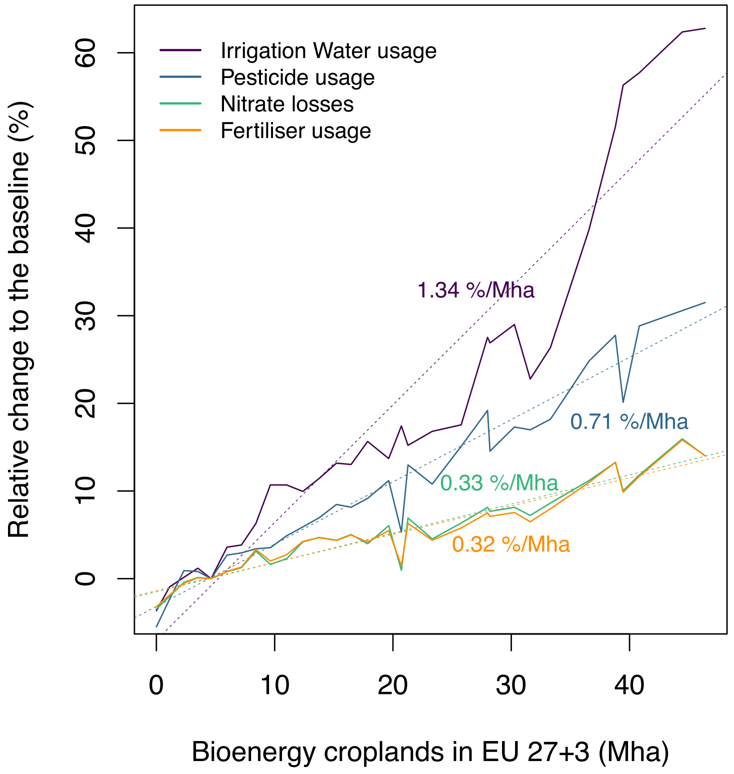

Figure 3. Relative average change in the modelled environmental indicators with increasing bioenergy production across the EU 27+3, showing modelled changes (solid lines) and trends (dotted lines and slope coefficients from linear regression models).

bioenergy production in Europe is likely to either have no benefits for emissions reductions and negative environmental impacts, or small positive benefits for emissions that will materialise too late to contribute to existing climate targets. Below we discuss these impacts across direct and indirect land use changes, alterations of NPP, and fossil fuel offset levels.

4.1. Land use change and intensification

Increasing the land area of bioenergy crop production requires either additional cropland or intensification of production on existing cropland. Our results show that intensification is likely to occur as bioenergy is produced over increasingly large areas in Europe, but that areal expansion of crop production is also inevitable as food production shifts onto less productive land with lower climatic and topographic suitability [14, 15]. Intensification and areal expansion of cropland both lead to environmental impacts through the loss of other (particularly forest) land covers, and the additional use of irrigation water, pesticides, and nitrogen fertilisers [74].

Our results highlight particularly strong competition between bioenergy production and managed forests. The IAP model prioritises food production over timber production (and other forest products), and so removes forests on agriculturally productive land as bioenergy demand grows. European forests do exist, to a considerable extent, on relatively fertile agricultural land, particularly in Eastern Europe where large areas of agricultural land were abandoned after the collapse of the USSR [75, 76]. This reforestation has been supported by a more-than doubling of food imports to the European Union in the intervening period [73]. It is in these areas that the greatest increase in bioenergy production occurs in our results (figure 2(b)) with each additional ha of bioenergy producing an average of 0.8 ha of deforestation. These areas of abandoned farmland [77, 78] are also frequently identified as suitable for bioenergy production, erroneously described as ‘surplus’ land [79].

Nevertheless, other studies suggest that bioenergy could be grown on grasslands or other kinds of ‘surplus’ agricultural land, with impacts on food production that are relatively small or that can be compensated for by intensification [23, 31, 80, 81]. As shown in figure 4(a), large bioenergy production (>27 Mha) was unachievable in the model as the demand for food and other commodities was unmet (represented by crosses). This indicates that when cross-sectoral land system impacts are accounted for, producing bioenergy with little impact on food production is highly unlikely [82]. Moreover, reduced food production may cause substantial rises in agricultural imports, which effectively exports unsustainable impacts to other parts of the world (primarily the tropics, under current trade arrangements [83, 84]).

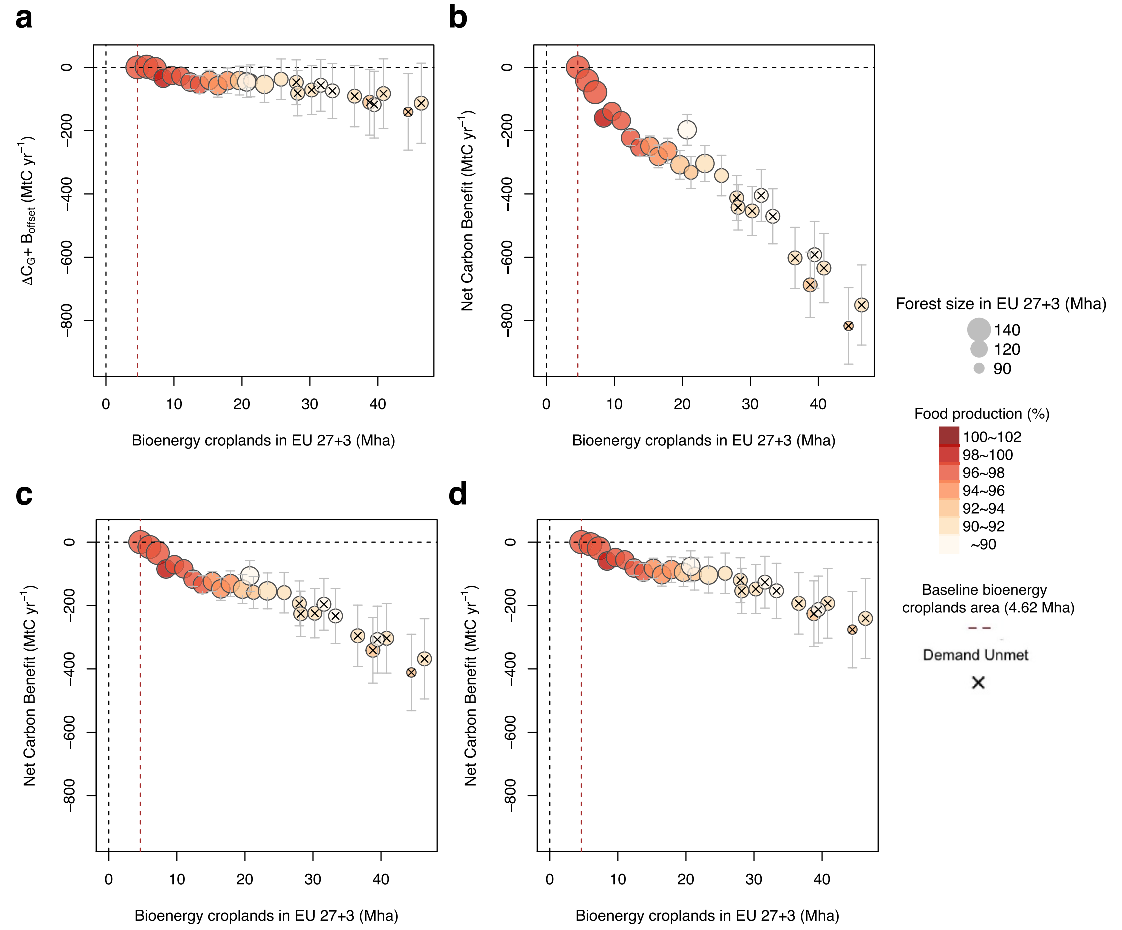

Figure 4. Carbon benefit of bioenergy crops across a range of cropping areas (current production of 4.62 Mha to max. 46.4 Mha) considering fossil fuel offset (B_{offset}), changes in annual carbon accumulation (ΔC_G) and carbon stock ($\Delta\ C_{stock}$) in the EU 27+3. (a), with no consideration of initial C_{stock} changes, showing annual carbon gain and loss (first and second terms in equation 1) and (b)–(d) with C_{stock} changes amortised over 20 yr (b), 50 yr (c), and 100 yr (d). Where net carbon benefits are negative over a particular timescale, carbon payback is not achieved (figure 5). The colours of the symbols reflect modelled changes in food production to the baseline (%) and the size reflects the remaining forest area in Europe (Mha). The circles based on the midpoint fossil fuel offsets and the error bars are the minimum and maximum offsets assumed (see table 1). The crosses mean that the demand for food and other commodities was unmet in the model simulations.

Here, we fixed food imports at today's levels in order to avoid this displacement effect and to make the impacts of bioenergy production assessable; quantifying global impacts would otherwise require a global model with strong assumptions about trade patterns and consequent displacement or leakage locations. In consequence, increased crop production either forces livestock farming into European forest land (a zero-sum game) or requires huge decreases in meat and milk production (appendix figure A1). Grasslands also contain high stocks of carbon, substantial portions of which would be emitted on conversion to cropland [9]. As a result, negative impacts on carbon emissions are unavoidable by acting purely on the supply-side of production, implying the need for systemic changes on the demand-side of the food system [55].

From a management and policy perspective, even if bioenergy could be produced with little or no net increase in the agricultural area because of intensification, it is not a given that bioenergy is the best use of that extra land capacity. It might instead be better to release land for carbon sequestration through forest regrowth [8]. For example, it has been suggested that bioenergy crops may be useful for mitigation within the context of reduced demand for meat, which would free-up pasture and cropland for bioenergy production. However, aside from debates about whether reducing meat consumption is feasible in practice, our results suggest that the freed-up land would sequester more carbon if left under natural cover than if used for bioenergy. This conclusion is not always reached by other studies, which find variable effects or greater benefits of bioenergy production than natural forest growth in some contexts (e.g. Ter–Mikaelian *et al* 2015 [85]), but most agree that bioenergy cannot be assumed to offer the best option for net carbon balance. Somewhat clearer is

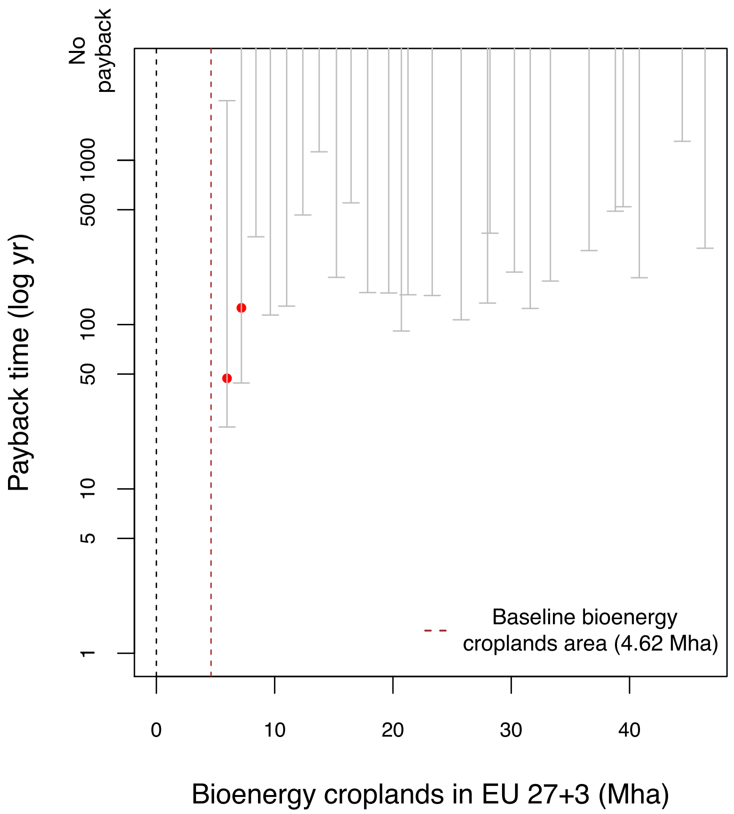

Figure 5. The time required to compensate for the initial carbon debt from land clearance as bioenergy cropland area expands in the EU 27+3. Red dots show the payback time using the midpoint fossil fuel offset from the literature (3.57 *t*C ha^{-1} yr^{-1}) and the upper and lower bars show the minimum offset (0.54 *t*C ha^{-1} yr^{-1}) and the maximum offset (6.6 *t*C ha^{-1} yr^{-1}), respectively (see table 1). The dots and the upper bars are not visible where low fossil fuel offsets and small or negative reductions in NPP mean that bioenergy has an annual disbenefit and therefore never compensates for any level of initial carbon stock loss.

Table 1. Assumed area-based fossil fuel offset coefficients (b_{offset}) of bioenergy in Europe covering various possible energy sources and bioenergy pathways. Values are based on multiple reference sources cited in Searchinger *et al* 2017 [8].

Name	Benefit	Description
Maximum offset	6.6 *t*C ha^{-1}yr^{-1}	Combined heat and power using short rotation coppice replacing hard coal (EU-average). Hard coal is used to reflect the most inefficient fossil fuel energy source. For this assumption to hold across the results, energy derived from hard-coal would have to exist in sufficient quantities within the EU energy mix, which is not the case[a].
Minimum offset	0.54 *t*C ha^{-1}yr^{-1}	Bioethanol from Maize, which offsets 25% CO_2 emissions relative to gasoline. Maize yield of 10*t* ha^{-1} yr^{-1}, and ethanol yield of 417 l *t*DM maize^{-1}.
Midpoint offset	3.57 *t*C ha^{-1}yr^{-1}	Midpoint of the maximum and the minimum offset found in the literature.

[a] Solid fossil fuels occupy 2.28% in final energy consumption in EU 28 as of 2018 [73].

that natural land covers are in most cases likely to be more beneficial for biodiversity [84, 86, 87].

Also, the results presented here demonstrate that large-scale bioenergy implementation in Europe would directly contradict the aims of current EU environmental policy. The EU Biodiversity Strategy has a target of planting 3 billion trees by 2030, which would require an area of land of between 0.81 and 1.37 Mha [88]. Although this target is not especially ambitious, representing only about 40% of recent reforestation trends in the EU [88], increasing the area of bioenergy production would be a barrier to the achievement of the 3 billion tree target. Likewise, the EU has recently introduced a new Nature Restoration Law and a Forest strategy that aims to not only enhance biodiversity and ecosystem functioning, but also to contribute to climate change mitigation. However, deforestation arising from large-scale bioenergy would directly contradict the goals of these policy initiatives by negatively affecting the conservation and restoration of the EU's forests, or forests elsewhere in the world.

4.2. Carbon offsets and payback times

We find that the direct annual carbon benefit of bioenergy crops could be positive or negative depending on the crops grown and the fossil fuels replaced. An annual carbon cost (1.8 MtC emissions per one Mha additional bioenergy production in the EU 27+3) is identified using the midpoint offset assumption derived from the literature ($b_{\text{offset}} = 3.57\ t\text{C ha}^{-1}\text{yr}^{-1}$) (represented by the circles in figure 4(a); appendix table A1). With the maximum supported offset ($b_{\text{offset}} = 6.6\ t\text{C ha}^{-1}\text{yr}^{-1}$, assuming short-rotation coppice replacing coal [8]), the annual carbon benefit can actually be positive (0.2 $\text{M}t\text{C Mha}^{-1}$). However, with the lowest supported offset (0.54 $t\text{C ha}^{-1}$), the annual carbon cost is considerably higher ($-5.8\ \text{M}t\text{C Mha}^{-1}$). It is difficult to determine which of these figures would apply to any given level of bioenergy production in Europe. For instance, using short rotation coppice to replace hard coal would have major overall benefits for carbon emissions, but there is only a limited amount of coal use left within the EU energy system (solid fossil fuels represent only 2.28% of final energy consumption in the EU 28 as of 2018 [73]). Precise knowledge of bioenergy impacts, energy substitution and leakage effects would in principle allow for the extent and location of European bioenergy crops to be 'optimised', but such precise knowledge is improbable, and our results suggest that the optimal extent would inevitably be small in any case (figure 4(a)). A similar implication is earned in the comparison of the carbon benefit of bioenergy crops and the simulated forest loss (Supplementary figure SF2), indicating that the window is very narrow.

Direct carbon benefits must also be put into the context of carbon stock changes. When these changes are considered (figures 4(b)–(d)), even the most optimistic direct benefits are totally negated by massive losses in ecosystem carbon stocks from land conversion. We estimate that each hectare of additional bioenergy causes increases in emissions of 5.2 tC with the highest assumed fossil fuel offset, and 11.3 tC with the lowest, if we amortise the initial carbon stock change over 50 yr (appendix table A1). Additional bioenergy produces a cost even with the highest offset assumption and a payback period of 100 yr (with 2.4 tC emissions) (see also [9, 70]). Considering the usual time horizon for accounting land use change impacts for land-based products (e.g. 20 yr in the IPCC guidelines [61] and 30 yr by the US EPA [89]) [90], it is unlikely that bioenergy in Europe would effectively mitigate carbon over the timescale of climate change targets. Globally it is often noted that the initial carbon debt caused by land use change for bioenergy production is only compensated for over extremely long timescales, and calculated payback times increase along the latitudinal gradient as primary productivity reduces. The reported average payback time in central Europe is 145 yr (reference the meta-analysis in [71]), and up to 1000 yr in temperate regions [69]. We find that under some (perfectly reasonable) assumptions, bioenergy production in Europe would never provide a carbon benefit at all, but would instead accumulate disbenefit as bioenergy crops sequester less carbon than the natural or managed forests they replace. Even under far more optimistic assumptions, net benefits are unlikely to be realised this century. Considering the time available to achieve climate targets [41, 91], large-scale bioenergy production is therefore likely to be irrelevant at best.

A crucial assumption in these results is that bioenergy is used without CCS. CCS technology is still under development [26, 44] and dependent on technological advances and market conditions as well as social perceptions that cannot reliably be anticipated (e.g. securing high capture rates at low cost) [92]. This requires further research.

5. Conclusions

Our regional, model-based experiments highlight that bioenergy production in Europe has largely negative carbon and environmental impacts once direct and indirect effects are accounted for. Large-scale expansion of bioenergy would offset fossil-fuel usage, but would sacrifice long-term carbon stores in forests and (to a lesser extent) grasslands and replace the natural regeneration of vegetation in these areas, which could be more effective for carbon sequestration. Bioenergy has additional negative environmental impacts associated with agricultural intensification. While results vary with the type and management of bioenergy crops, the fossil fuels they replace and the alternative land uses they preclude, even our most optimistic scenarios with a maximum offset are negated by losses of ecosystem carbon from land conversion. Promoting dedicated bioenergy production in Europe, or in regions from which Europe imports food and timber, would risk major damage to ecosystem carbon stocks and other important ecosystem services. We find very little marginal or spare land for bioenergy production in Europe unless food imports are increased (as has happened since the 1990s), which in itself displaces deforestation to other parts of the world. Given the limited time frame for meeting climate targets, large-scale bioenergy production is likely to be a damaging distraction from the more efficient and strategic use of land in the fight against climate change.

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

B.S. drafted the manuscript, all authors designed the model experiments, B.S. performed the model runs, all authors analysed the results, wrote and reviewed the manuscript, and finalised it.

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Appendix

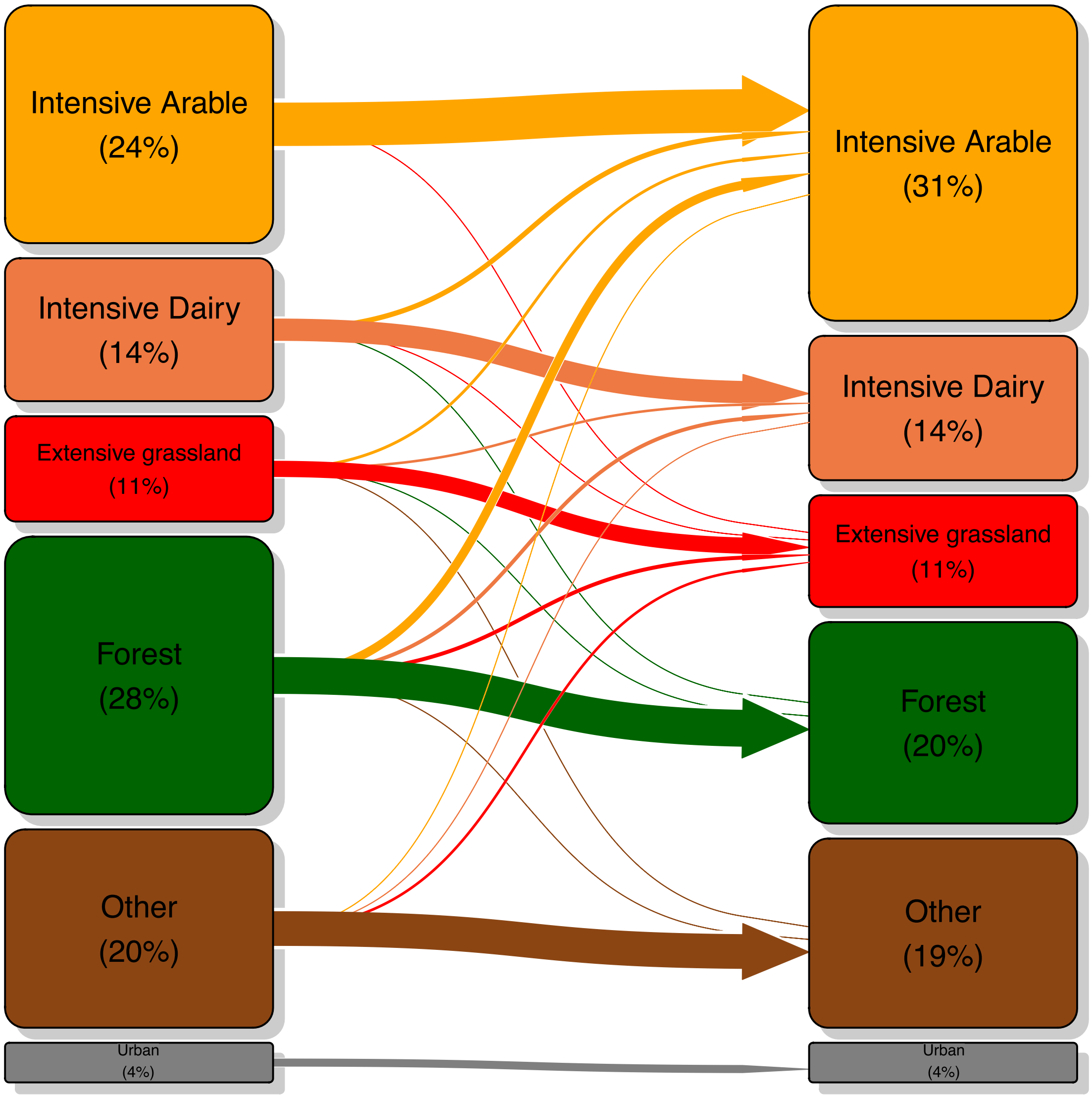

Figure A1. Land use transitions (%) as bioenergy cropping area increases from the baseline (4.62 Mha) to large scale (45 Mha) in the EU 27+3 while keeping imports and exports at today's levels. Intensive arable land includes both non-bioenergy crops and bioenergy crops.

Table A1. Impact of one million ha additional bioenergy in carbon emissions (MtC) based on linear regression models of the net carbon benefit (MtC) against bioenergy area (Mha) in EU 27+3 (Supplementary table ST1). D is time used to amortise carbon stock changes to obtain an annual rate of change. Positive values mean decrease and negative mean increase in emission. All regression models were statistically significant ($p < 0.05$).

		Time dependence of stock change factors (D)		
Assumed offset (b_{offset})	Stock change neglected	20 yr	50 yr	100 yr
Minimum (0.54 tC ha^{-1} yr^{-1})	−5.8	−19.8	−11.3	−8.5
Midpoint(3.57 tC ha^{-1} yr^{-1})	−2.6	−16.8	−8.3	−5.4
Highest (6.6 tC ha^{-1} yr^{-1})	0.2	−13.8	−5.2	−2.4

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