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LETTER

Implementing land-based mitigation to achieve the Paris Agreement in Europe requires food system transformation

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Supplementary material for this article is available online

Abstract

Land-based mitigation, particularly through afforestation, reforestation and avoided deforestation, is an important component of the Paris Agreement to limit average global temperature increases to between 1.5 °C and 2 °C. However, the specific actions that would ensure sufficient carbon sequestration in forests remain unclear, as do their trade-offs against other land-based objectives. We use a regional integrated assessment model to identify the conditions under which European forests reach the extent required by mitigation targets. We compare stylised scenarios of changes in meat demand, bioenergy crop production, irrigation efficiency, and crop yield improvement. Only 42 out of 972 model simulations achieved minimum levels of food provision and forest extent without the need to change dietary preferences, but relied on crop yield improvements within Europe of at least 30%. Maintaining food imports at today's levels to avoid the potential displacement of food production and deforestation required at least a 15% yield improvement, or a drastic reduction in meat consumption (avg. 57%). The results suggest that the large-scale afforestation/reforestation planned in European targets is virtually impossible to achieve without transformation of the food system, making it unlikely that Europe will play its required role in global efforts to limit climate change without utilising land beyond its borders.

1. Introduction

Human-induced global CO_2 emissions reached 36.2 Gt CO_2 in 2016 [1] and global temperature averaged more than 1 °C above pre-industrial levels. At the present rate of increase of 0.1 °C–0.2 °C per decade [2], temperatures will likely exceed 1.5 °C above pre-industrial levels around 2050 [3]. Limiting temperature increases to between 1.5 °C and 2 °C as planned in the 'Paris Agreement' [4], is therefore an enormous challenge, and one that requires immediate and substantial global emissions reductions as well as adaptation and mitigation in a wide range of human systems [5–7].

The Paris Agreement was established on the basis of fair, voluntary contributions to climate change mitigation, outlined in (Intended) Nationally Determined Contributions (NDCs). The NDCs recognise the possibility of internationally transferable mitigation actions [4]. Land-based mitigation is among the most prominent strategies, being included in 148 of 160 NDCs [8], and accounting for up to 30% of planned emissions reductions [9–11]. Within these, efforts to maximise the areal extent of forests through afforestation, reforestation or avoided deforestation are central [12].

Increasing forest extent is challenging because it involves competition for land with food production not only locally but also remotely [13, 14], and requires a reversal of long-term trends of forest loss arising from agricultural expansion [15, 16]. In the absence of institutional interventions, forest clearance for agriculture is expected to continue in the near future, as population growth and dietary change steadily increase global food demand [17, 18]. Previous attempts to control deforestation have included sustainable intensification of agriculture, which improves food provision by reducing yield gaps [13, 19–21] and 'forest conservation', which places restrictions on agricultural expansion [16]. In both cases, interventions on the production side of agriculture alone were unsuccessful, either having limited effects or causing counter-productive 'leakage' of deforestation to displaced areas [16, 19, 20]. Increases in European forest extent have largely occurred at the expense of deforestation elsewhere, in particular, with increasing food imports from tropical countries [22, 23].

The mitigation potential of changes in the demand side of agriculture has become increasingly recognised in recent years [14, 24, 25]. Dietary change (i.e. changes in the types of food commodities consumed) is especially important. It has been estimated that global adoption of a 'low meat' diet could lead to emissions reductions up to 4.6 $GtCO_2e\ yr^{-1}$ because agricultural land can instead be forested [13, 26, 27]. However, relevant studies have focused either on a single sector (e.g. the livestock sector [27]) or on generalised models and assumptions (e.g. trade levels, displacement effects, policy options), potentially overlooking the multiple, cross-sectoral aspects of actual land use changes [28]. Furthermore, while several studies have investigated the feasibility of achieving afforestation/reforestation targets at a global scale [6, 29], none have done so at the regional scale, where decisions about afforestation/reforestation are made in practice. This also means that simulated pathways tend to place an unreasonable burden on areas such as the tropics, where substantial forest carbon sinks exist, but which are not necessarily best-placed to resist the pressures of agricultural expansion [30]. To guide mitigation planning and policy, we therefore need more realistic analyses of regional pathways to achieving the Paris target within their global context.

Amongst world regions, the European Union (EU) presents a particularly compelling example. Historically, EU member states are among the largest greenhouse gas emitters and consequently have accepted responsibility for establishing robust and ambitious plans for emissions reductions [31]. In principle, the EU and its Member States act jointly to implement development trajectories and mitigation strategies that meet mandatory emissions reduction targets without further transferable harm outside Europe. Nevertheless, although the EU leadership played a significant role in developing global climate change policies including the Paris Agreement [32], practical implementation has been dissatisfying. The EUs NDC is notably vague and inexplicit, making it difficult to implement [30].

In this study, we investigate whether Europe can make a proportional contribution to the 1.5 °C target through afforestation/reforestation while still producing sufficient food to feed the European population, and without relying on other world regions to make up shortfalls in either food production or carbon sequestration. In doing so, we explicitly do not account for potential win-win arrangements that increase the efficiency of food production and climate mitigation overall, noting the dependency of such arrangements on accurate accounting of direct and indirect impacts, on stable, predictable political and economic relationships, and on an assumption that Europe would have a legitimate claim to benefit from any spare capacity in the global land system. The European scale is also significant since the EU has the capacity to implement policy in support of land-based mitigation that member states apply. This is the first study to look at rigorous, regional strategies that are consistent with global achievement of the Paris Agreement, without shifting responsibilities to other regions. The study applies a regional integrated assessment platform (IAP) for Europe [33] to explore stylised future scenarios of the food system that cover both food supply (i.e. technological change) and food demand (i.e. calorific intake and dietary change focusing on meat consumption) with the aim of providing additional land for afforestation/reforestation.

2. Method and materials

2.1. The IAP

The impacts and risks from high-end scenarios: strategies for innovative solutions (IMPRESSIONS) IAP is an interactive web-based platform to assess climate change impacts, vulnerability and adaptation [28, 33–36]. The platform integrates a series of interlinked meta-models representing urban development [37, 38], water resources [39], flooding [40], forests and agriculture [41], and biodiversity [42] (supplementary figure SF1 is available online at stacks.iop.org/ERL/14/104009/mmedia). Land use is modelled on a 10-arcmin grid across the EU-28 plus Switzerland and Norway, resulting in a total of 23,871 grid cells. Each cell can contain multiple land uses proportionally. Hereafter we refer to the study region as the 'EU28 + 2'.

In the IAP, land use is allocated based on both biophysical conditions such as soil type, climate suitability and water use, and economic aspects considering gross margins determined by prices, support rules and costs [43]. Modelled land use is first constrained by non-agricultural land (urban, protected and flooded areas) and then divided into intensive agriculture, extensive agriculture, managed forest, unmanaged forest or unmanaged land based on their relative profitability, which depends on water availability, climate and potential yields. The IAP iterates prices to allow the allocated areas to expand or contract to meet net food demand. Food demand is

Table 1. Overview of the stylised scenarios as applied in the IAP. Each parameter scenario was combined with all others, giving 324 scenarios in total.

Category	Parameter	Scenario counts	Settings (+% increase, −% decrease)
Demand side	Dietary preference (ruminant, non-ruminant)	9	(−100, +100), (−75, +75), (−50, +50), (−25, +25), (0, 0)
			(−100, −100), (−75, −75), (−50, −50), (−25, −25)
Supply side	Yield improvement	6	0, +15, +30, +45, +60, +75
	Irrigation improvement	2	0, +25
	Bioenergy crop production	3	+4, +8, +12
Total number of scenario combinations		324	

simulated based on population, net imports (i.e. as a proportion of food demand), dietary preferences (for crops and different animal products), and bioenergy production [41]. If profit is above a threshold (set at €350/ha), land is allocated as intensive agriculture (e.g. crop or dairy agriculture). If profit meets a lower threshold (set at €150/ha), it is allocated as extensive agriculture or managed forest, depending on suitability. Otherwise, it is allocated either as unmanaged forest or unmanaged land [36]. Simulated crops include winter and spring wheat and barley, oilseed rape, potatoes, maize, sunflower, sugar beet, soya, and cotton. The IAP contains a subset of crops that are used to represent the range of crops that provide the major production across commodity groups (cereals, oils, roots, protein and fibre) and for livestock feed (continuing towards the production of meat and milk) in the EU28 + 2. Grass is simulated for livestock farming (e.g. meat and milk production). 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. A detailed description of the meta-models included in the IAP is provided in the supplementary material (supplementary table ST1).

Climate change was simulated based on a radiative forcing level (Representative Concentration Pathway: RCP) in different climate models. RCP 2.6 was used to simulate climate change consistent with the 1.5 °C target. Three available combinations of global and regional climate models were used (*NorESM1-M-RCA4*, *EC-EARTH-RCA4* and *MPI-ESM-LR-REMO*). In this study, the IAP version 2 was used [33]. All calculations were performed in R version 3.5.1 [44] using the packages `raster` [45], `rgeos` [46], `rgdal` [47], and `Gmisc` [48].

2.2. Stylised land-based mitigation scenarios

To consider both the supply and demand sides of the food system, we constructed stylised scenarios combining five variables: ruminant and non-ruminant meat demand, bioenergy crop production, irrigation efficiency, and yield improvement under a radiative forcing level of 2.6 W m^{-2} (RCP 2.6) in the 2050s (table 1). On the supply side, technological change is critical in increasing production without expanding arable land areas. Technological change was applied here to improve irrigation efficiency and crop yields. Irrigation efficiency improvements use less water for the same yield, while crop yield improvement incorporates biotechnology (e.g. breeding technology [49]) and intensification. In addition, bioenergy production is included in the supply side of the food system as it can limit available land for food production. On the demand side, dietary preferences were modelled to account for different levels of meat consumption. We used a population projection of 8% increase by the 2050s compared to the base year 2010 [50]. Net imports were fixed at today's levels to avoid displacement of food production outside the EU28 + 2.

We explored a range of changes in each variable from a 'no-change' condition to a hypothetical maximum level of change (table 1) and quantitatively evaluated the consequences for land use relative to a 2010 baseline. As the bioenergy production in the IAP is set as '0' by default (meaning no bioenergy production in Europe), we set 4% as a baseline to approximate current production levels. To avoid the harmful side-effects of bioenergy production on food supplies, the EU established a cap of 7% of arable land being used for bioenergy production [51]. We included a higher maximum (12%) to reflect current projections suggesting that bioenergy production requires as much as 12.4% of cropland by the 2030s [52]. The impact of bioenergy production was additionally analysed in terms of directly-caused land use transitions. The maximum yield improvement level (= 75%) was set to match the maximum possible yield gap in Europe [53] and to allow yield improvement across all crops due to crop breeding [49]. All of these values were designed to provide broad limits within which simulated change could occur, rather than predictive pathways, in order to assess the scale of change required for simultaneous achievement of food security and climate mitigation targets.

For each combination of parameter values ($n = 324$), the three climate model combinations were run, giving 972 individual model runs. Dietary energy production (kcal/capita/day) and corresponding forest

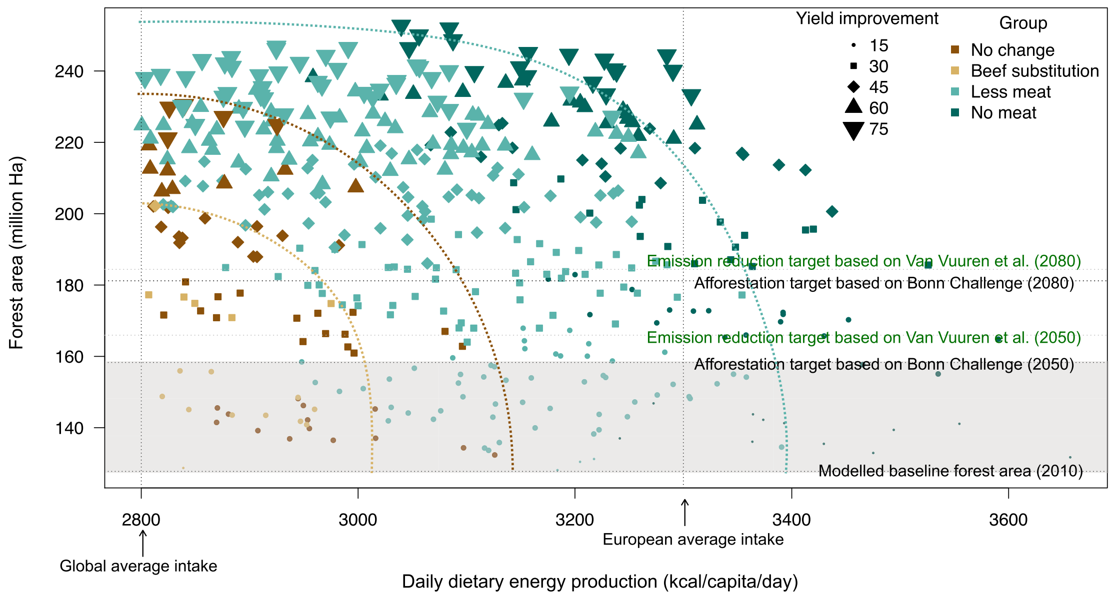

Figure 1. Modelled daily dietary energy production and forest area in scenario simulations that resulted in forest areas at least as large as those of the present day and in an average calorie intake at least as large as the current global average ($n = 434$). The size and shape of the symbols refers to the level of yield improvement. The grey box refers to the afforestation/reforestation targets in the 2050s. The symbols above the grey box were considered as successful simulations ($n = 351$). The envelope lines of the groups are drawn (dotted lines) to highlight the 'frontiers' of each dietary change.

areas for each scenario were quantified to assess the implications of each scenario. Indicators of land use change were selected to compare scenarios; these included the extent of intensive arable land, intensive grassland (dairy), extensive grassland (sheep and rough grazing), very extensive grassland (heath and moor), forest (managed forest for timber, unmanaged forest), unmanaged land (no productive purpose), and urban areas.

2.3. Normative targets

2.3.1. Food security target

A global daily calorie intake of 2800 kcal/capita/day was used as a threshold for the food security target [13]. While nutritionally sufficient, this threshold is substantially below current consumption levels in Europe, and so we also used the current European average of 3300 kcal/capita/day as a secondary threshold to highlight how reducing food consumption from current levels could contribute to mitigation efforts.

2.3.2. Afforestation/reforestation target

Afforestation and reforestation were combined into 'forest area' targets. To translate global policy targets into European targets, we used the Bonn Challenge target of restoring 150 million ha of deforested and degraded land globally by 2020. The Bonn Challenge was extended to a target of restoring 350 million ha by 2030 by the New York Declaration on Forests at the 2014 UN Climate Summit [54]. This target would sequester up to 1.7 $GtCO_2e\ yr^{-1}$ [55], which is equivalent to 9.7 tCO_2e/ha/year for 20 years. Currently, the EU contains 4.36% of the global forest area [56]. We linearly extrapolated the Bonn reforestation area target of 2030–2050 and applied this proportionally to Europe on the basis of current (modelled) forest area. A target based on a global CO_2 reduction projection [6] was also used for comparison. In this comparison, we assumed 30% of the CO_2 reduction attributed to afforestation/restoration actions [11].

3. Results

3.1. Successful scenarios and the impacts on land cover in the 2050s

Of the 972 simulations, 351 (36.1%) met both the minimum food security and forest area targets in the 2050s (figure 1). These successful simulations could be divided into four groups based on dietary preferences: 42 with 'no change' in preferences, 6 with 'beef substitution', 215 with 'less meat' (with between 25% and 75% reduction in both ruminant and non-ruminant meat), and 88 with 'no meat' (both ruminant and non-ruminant meat consumption were reduced by 100%). The majority of the successful simulations (86.3%) belonged either to the 'less meat' or 'no meat' groups, highlighting the importance of dietary change in achieving food security and forest area targets. On average, to achieve these targets, a drastic reduction in meat demand is required; 57.5% and 56.7% of the ruminant and non-ruminant meat demand, respectively. All successful simulations also included at least 15% yield improvement (figure 1). Critically, if meat demand was not reduced (the 'no change' group), at least 30% yield improvement was required. About 19% of successful runs required the

Table 2. Successful scenarios and the average corresponding daily dietary energy and total forest area projections for Europe (2050).

Group	Description	Daily dietary energy production kcal/capita/day (avg. (s.d.))	Forest area size Million *ha* (avg. (s.d.))
No change	No change in dietary preference	2896.3 (75.8)	191.9 (20.8)
Beef substitution	Ruminant meat is substituted by non-ruminant meat	2861.2 (62.3)	179.4 (11.4)
Less meat	Reduce both ruminant and non-ruminant meat consumption	3035.9 (127)	206.8 (23.5)
No meat	Eliminate both ruminant and non-ruminant meat consumption	3246 (118.1)	212.3 (25.5)

maximum level of yield improvement ($n = 67$). Average bioenergy production of the successful runs was 8.23% across groups. Competition between bioenergy and food crop production within arable areas was therefore not apparent, although the analysis of land use transitions with increasing bioenergy production showed additional loss of forest areas to arable land (supplementary figure SF4). Irrigation efficiency improvement was the least influential factor (supplementary figure SF2).

The level of food production and forest areas varied across the different scenario groups (figure 1 and table 2). Interestingly, less or no meat diets produce the highest level of food energy, showing a trade-off between calorific intake and meat consumption. By producing more meat, more land is allocated to produce fodder crops and grassland, which reduces the efficacy of the food supply. For this reason, scenarios with high meat demand resulted in meat dominating consumption. The 'beef substitution' group produced the lowest level of food energy, which is largely because cereals are used to feed monogastric livestock, resulting in a reduction of total food calories. For 351 successful simulations, only 29 (8.2%) produced food calories at or above the current European average level, and all but one required the 'no-meat' diet. There was also a clear positive relationship between agricultural intensification and forest areas (figure 1) with more intensification providing more available area for forests.

Changing dietary preferences changed land use considerably. Reduced ruminant meat demand drastically decreased grassland areas from 11.8% to 3.7% of the land system in the EU28 + 2 between 2010 and the 2050s on average. The increase in forest area was largely driven by decreases in the area of land used to produce food. When both ruminant and non-ruminant demands were decreased, intensive arable land and grasslands were converted to forest areas (figure 2). The area of unmanaged land also increased from 17.8% to 22.3% of the EU28 + 2, mainly from very extensive grassland (unmanaged land in the IAP represents land that is unsuitable or not needed for either agricultural production or grassland). The impact varied spatially (figure 3), with intensive arable land mainly increasing in Poland, producing a corresponding decrease in managed forest areas. Intensive grassland increased in the northern UK and France at the expense of forests.

4. Discussion

Land systems around the world need to make substantial contributions to climate mitigation if high-end climate change is to be avoided. A proportional contribution by the EU28 + 2 to land-based mitigation (on the basis of area, rather than emissions) will require immediate and dramatic changes. Meeting the forest area target consistent with the Paris Agreement requires an expansion of forest area of approximately 23% by the 2050s (compared to 2010) according to the Bonn Challenge. Given the fact that afforestation and reforestation have the maximum mitigation potential and cost-effectiveness of land-based measures [57, 58], other strategies would likely require even greater levels of land conversion.

Historically, Europe has expanded its forest areas by about 30% from 1900 to 2010 due to agricultural intensification and increasing imports [59, 60]. At the same time, there is concern that the rate of forest expansion in Europe has slowed during the last decade due to increased deforestation [61]. Previous studies suggest that there is still potential to mitigate 441 Mt CO_2 yr^{-1} in Europe through afforestation on abandoned farmland (15 Million ha) and improving forest management [62]. This suggests that better integration of forest regrowth within the EU climate policy framework should be a priority [62]. However, the projected extent of abandoned farmland is still insufficient to achieve the normative afforestation target as shown in our study (figure 1), and is largely driven by increased food imports; something that is unlikely to be consistent with global climate mitigation efforts, and which is precluded here [63, 64].

In our analysis, we fix the level of proportional net import as constant in the 2050s with increasing population, which led to reduced available abandoned farmland for reforestation. Although trade could potentially improve on this outcome if it were to reliably shift production to more efficient land, or spare

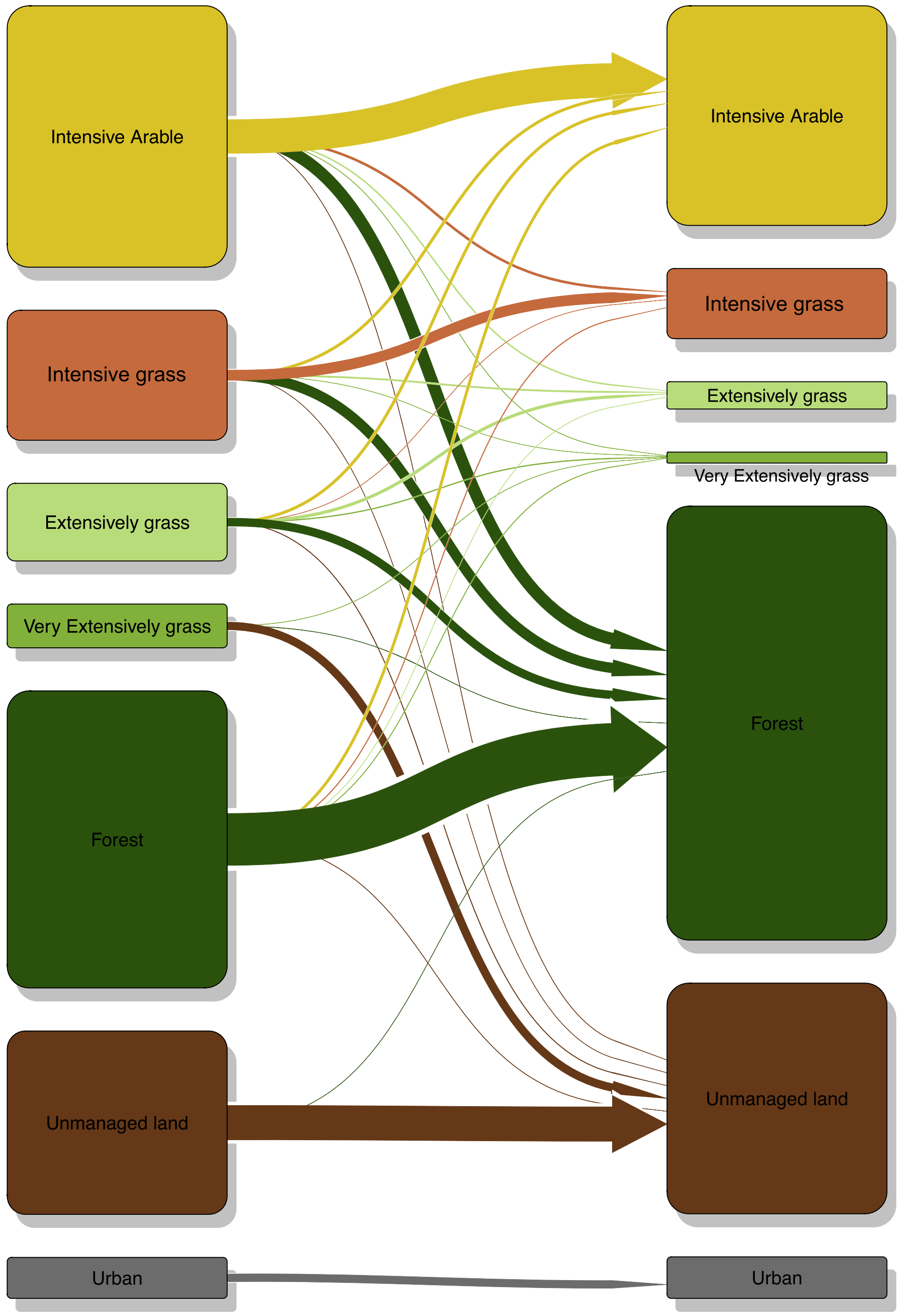

Figure 2. Average land cover transitions between 2010 and 2050 in successful simulations ($n = 351$).

other land more capable of providing carbon sequestration (e.g. the tropics), an assumption of fixed net imports ensures that European progress towards global targets is not at the expense of other countries. While this is a simplification, it avoids the need for assumptions about developments in the rest of the world and their effect on international trade, introducing a number of other contingencies and uncertainties.

Increasing forest area will therefore undoubtedly be difficult without major changes in agriculture [65], including changes in both the supply and demand sides of the food system. By simulating scenarios that meet both food security and forest area targets, we found dietary change to be the most critical factor in achieving these targets. The consequences of these scenarios were complex. For instance, the impacts of human diets on the land system vary widely because different types of meat production have different implications for land use [18].

In the IAP, intensive grassland is land not suitable for arable use, but highly productive for dairy. Extensive grassland is land not suitable for arable or dairy, and considered as land for beef or sheep grazing. We

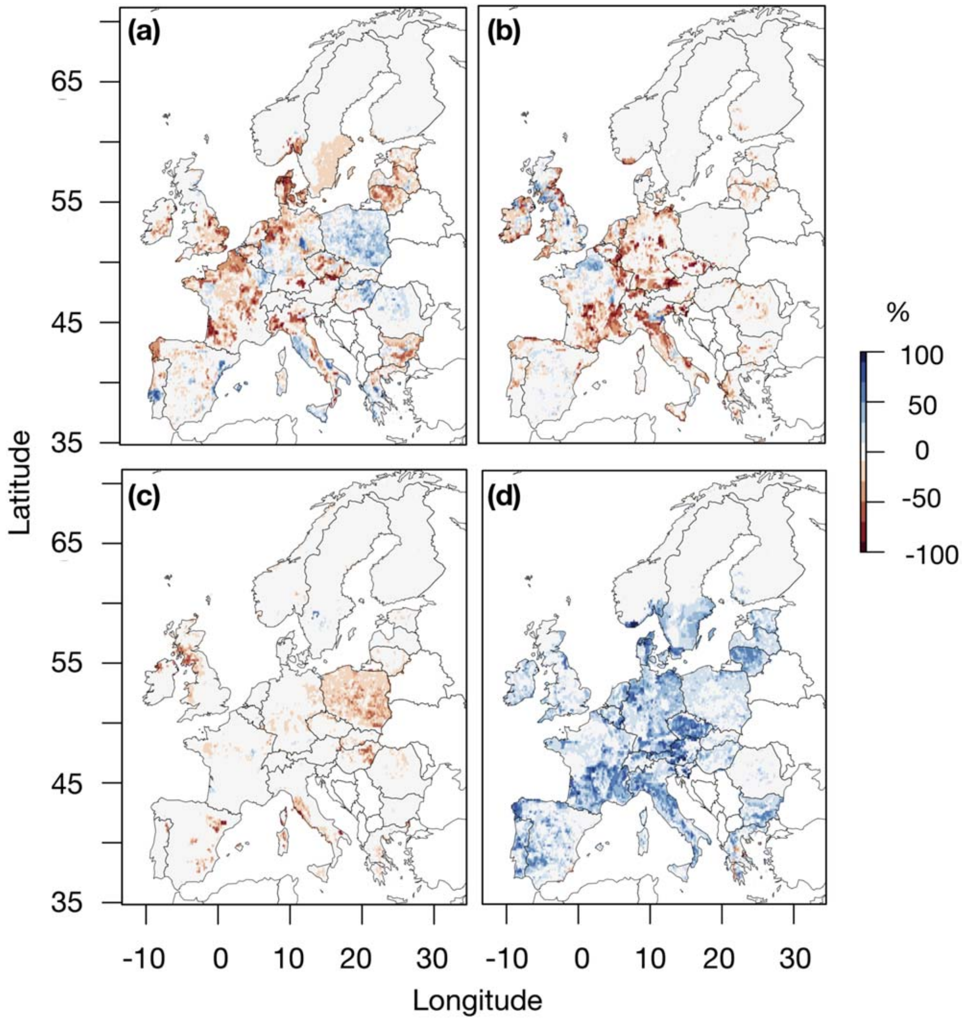

Figure 3. Comparison of the simulated distribution of (a) intensive arable land, (b) intensive grassland, (c) managed forest and (d) unmanaged forest for the 2050s with the baseline simulation (2010).

assumed that 50% of cereals from arable land is for livestock feed. Monogastrics are more efficient to produce than ruminant meat for a unit of calorific consumption [66]. Changing preferences from the consumption of ruminant to non-ruminant meat also decreases the demand for grassland substantially, but may increase the area and intensity of arable land for fodder crops. This result is, however, sensitive to uncertainties in grassland productivity in different regions [67].

'Beef substitution' scenarios were not effective in increasing forest areas as the area of land used for feed crops for other livestock increased. Instead, the successful scenarios mostly contained less or no meat consumption. As highlighted elsewhere, reduced beef consumption reduces not only greenhouse gas emissions, but also environmental impacts such as nitrogen pollution [68–70]. The level of the EU's food self-sufficiency also increases with less or no meat consumption because of the increased availability of land for food production [69]. In our results, increased monogastric meat demand produced the least calorific intake. Furthermore, plant-based diets within the EU decrease the footprint of food production in the rest of the world as, currently, the majority of the outsourced emissions is from feed production [71]. Even though the trend in Europe is for decreasing meat consumption, European diets are still largely dependent on animal products. The average per capita annual meat consumption in Europe is 80 kg, which is about 1.9 times higher than the global average (43 kg) [72]. Compared to the Indian diet, European meat intakes are six times higher [73]. While meat intakes provide necessary nutrients for human, reductions in meat consumption as modelled in our study can be associated with health benefits especially in the US and Europe by reducing total and cancer mortality [74]. It should be noted however that major socio-economic impacts would arise from less or no meat diets, with significant changes in the rural economy, socio-ecological systems, and cultural norms. For example, a drastic reduction in livestock production would lead to a loss of grassland associated with high value biodiversity and cultural landscapes [75].

On the supply side, technological change is critical in increasing food production without expanding arable land areas [17]. Generally, yield improvements have been realised through the intensive use of fertiliser and technological changes. In the IAP, the role of biotechnology and fertiliser use improvement were considered in the technological improvement for yield gain across crops. Yet, it is also important to note that the EU had reached its peak of fertiliser use intensification in 1961 [76]. Also, the average yield gap (difference between actual gain and estimated potential gain) in Europe for cereal crops is about 42%, with a range between 10% and 70% depending on the region, making simulated yield improvements of up to 75% by the 2050s in the scenarios reported here questionable. There is, nevertheless, potential for large increases in crop yields in Eastern Europe including Romania, Ukraine and Poland [53]. This is in line with our result of a large-scale yield improvement occurred in Poland (figure 3). Another aspect of technological improvement considered in this study was irrigation efficiency, but this was found to have the least influential effect on the model results. Nevertheless, a warming climate will likely affect water availability, especially in Southern Europe [77], requiring widespread application of irrigation water. This is likely to depend, however, on farmers knowledge and capacity to adapt [78, 79].

While the impact of bioenergy production was not clearly separable in our study, we did find evidence in modelled land use transitions (supplementary figure SF4) that increasing bioenergy production occurred at the expense of forest areas. This is in line with several studies that have shown substantial negative impacts of bioenergy production when full, cross-sectoral or cross-locational impacts are considered [14, 80]. Furthermore, bioenergy production typically takes place on land that was previously used for food or feed crop farming. Growing more bioenergy crops in Europe could cause the displacement of food production from Europe to the rest of the world or lead to the expansion of bioenergy crops into European grassland or forest. In addition, the IAP only considers a sub-set of bioenergy (crop-based, within integrated production systems) on arable land. Further research is needed to investigate the trade-off between food and bioenergy crops and the various bioenergy feedstocks.

While our analyses provide an illustrative envelope in which the selected targets can be achieved, uncertainties remain. Model uncertainty in integrated modelling frameworks is an important aspect of land cover projections [36, 81]. For example, the baseline forest area in the IAP is relatively low compared to the current forest extent [56]. To account for this, we adjusted the forest target according to the modelled baseline. In addition, as meta-models represent a simplification of reality, they inevitably introduce uncertainties [82, 83]. However, they also enable the exploration of multiple scenarios in a short period of time by improving simulation efficiency [84]. For example, the IAP enables exploration of cross-sectoral interactions by improving simulation efficiency, and removing the very large biases associated with single-sector analyses [28]. Finally, uncertainties and sensitivities in each of the 10 models included in the IAP, and in the integrated IAP itself, have been extensively tested in previous studies [39, 41, 83, 85, 86], showing limited and non-biased uncertainties.

5. Conclusion

Land-based mitigation commitments for achieving the Paris target require considerable expansion of forest areas, yet large-scale afforestation/reforestation conflicts with other land use objectives. This study has shown that satisfying food security and forest area targets requires substantial changes in both the supply and demand sides of the European food system. While technological improvements (through yield and irrigation efficiency improvements) may be achievable in some regions of Europe, shifting to diets with less or no meat consumption will be most critical and challenging in practice. Furthermore, this leads to land use changes and regional trade-offs in the 2050s, with Eastern Europe increasing agricultural land areas, but decreasing forest areas, and central Europe producing less food. Our regional, model-based experiments highlight that increasing forest areas in Europe will require a fundamental transformation of the food system to avoid shifting responsibilities to other regions. This study can contribute to the current EU Land Use, Land Use Change and Forestry policy which lacks a comprehensive overview on the necessary action for the afforestation, or the role of dietary change in the food system. Decision making should also take account of the potential trade-offs for ecosystem services and biodiversity of increasing forest areas.

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Data availability

The model used in this study (The IMPRESSIONS IAP2) is publicly available at http://impressions-project.eu/show/IAP2_14855. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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