Comment

Supplementary information to:

EU climate plan boosts bioenergy but sacrifices carbon storage and biodiversity

A Comment published in *Nature* **612**, 27–30 (2022)
https://doi.org/10.1038/d41586-022-04133-1

Timothy D. Searchinger, Oliver James, Patrice Dumas, Thomas Kastner & Stefan Wirsenius

EU Climate Plan Boosts Bioenergy but Sacrifices Carbon Storage and Biodiversity

Supplementary Information

Timothy D. Searchinger*, Princeton University, Princeton, USA, tsearchi@princeton.edu

Oliver James*, Princeton University, Princeton, USA, ojames@princeton.edu

Patrice Dumas, Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Montpellier, France

Thomas Kastner, Senckenberg Biodiversity and Climate Research Centre, Senckenberganlage 25, 60,325 Frankfurt-am-Main, Germany

Stefan Wirsenius, Chalmers University of Technology, Gothenburg, Sweden

Corresondence should be directed to: tsearchi@princeton.edu; ojames@princeton.edu.

Acknowledgments: Funding for this research was provided by the David & Lucille Packard Foundation, the European Climate Foundation, Norway's International Climate and Forest Initiative, Deutsche Forschungsgemeinschaft project No. KA 4815/1-1, and the EU Horizon 2020 program (the Navigate project, grant agreement 821124).

Author contributions: TDS conceived, performed research, and wrote the article; OJ performed research and quantitative calculations and assisted writing; PD modeled future European food scenarios; TK and SW contributed to analysis of land and land carbon trade balances.

Additional Methodological Explanations

Europe definition for Globagri results and trade calculations: The Fit for 55 plan represents legislation of the European Union, which today consists of 27 countries. Europe, as defined in Globagri modeling and other analytical results here, represents the European Union prior to the exit of the United Kingdom; the four European Free Trade Association (EFTA) countries (Iceland, Lichtenstein, Norway and Switzerland), which are mostly subject to the same EU regulations; and we also include the candidate Balkan countries that are not yet part of the EU. We use this broader definition of Europe in our calculation of the European land carbon trade deficit (see below) to be consistent with Globagri modeling results presented, although this expanded definition does not substantially alter our results.

Recent global cropland expansion: Potapov et al. (2022) provides the first satellite-based estimate of net expansion of annual cropland[1], which averaged 10 Mha/y from 2012–2019 (see Table 4 in [1]). This estimate is roughly six times the estimate of annual cropland (i.e., arable land) expansion provided in FAOSTAT. Potapov et al. (2022) did not evaluate net increases in permanent crops, such as oil palm and rubber. FAOSTAT identifies permanent cropland expansion globally at round 1.3 Mha/y in this period. Although Potapov et al. do not analyze the conversion of native habitats or pasture to permanent crops, they does analyze conversion of annual crops to permanent crops (the primary conversion path of "other intensive agriculture," the category reported in the paper). This analysis estimated 0.93 Mha/y from 2003–2019. Overall, we consider ~11 Mha therefore to be a best estimate of recent net cropland expansion, which leads to an estimate of 440 Mha from 2010–2050 at present rates of net cropland expansion. Gross cropland expansion, which was estimated in the first half of this period, was roughly twice the size of net cropland expansion. Agricultural expansion therefore causes losses of biodiversity and at least temporal losses of carbon substantially higher than net losses.

Role of draught animals in Europe's forest regrowth: Malanima et al. (2020) recreated global energy consumption, and consumption by region and by ref. [2]. In Eastern and Western Europe combined from 1940–2016, biomass used by draught animals declined by 30 Mtoe while food biomass increased by 41 Mtoe.

Net use of cropland abroad. We estimate that Europe appropriated 24 Mha of foreign cropland on a net basis in 2010. This calculation is based on data underlying ref. [3] and employs the methods described in that reference.

Land carbon trade deficit: To estimate Europe's land carbon trade deficit, we use carbon opportunity costs (COCs) as calculated in [4]. This method provides an estimate of the effects on terrestrial carbon storage of Europe's trade in agricultural products (see definition of Europe above; excludes intra-European trade). COCs estimate, in effect, the global "fixed carbon costs" of producing a metric ton of each agricultural product. These fixed costs are the global average carbon losses from converting native vegetation to cropland or pasture used to generate a metric ton of output for each product. To annualize, the COCs used here are based on a discount rate of 4%, which can be thought of as an annual rental cost of this carbon of 4%. This estimate is also roughly equivalent to amortizing the carbon loss on each hectare for the crop production that occurs over a period of 30–35 years.

As mentioned, one way to conceptualize COCs is that they estimate the "fixed carbon cost" of producing food. Just as emissions involved in producing a car factory should be amortized across the cars produced to estimate their carbon cost, so the lost terrestrial carbon storage when producing cropland can be amortized across the crops produced.

To calculate Europe's net trade effect, we apply COCs to detailed FAO trade matrix data. Trade in the top 30 land-carbon intensive commodities capture over 90% of Europe's overall, annual average COC trade balance (see Table S3). Our calculation is limited to the major crops for which we have computed COCs. For this reason, our trade COC calculations do not include some significant imported crops, such as rubber and tobacco; for this reason, we expect our calculation of Europe's COC trade deficit to be underestimated.

The above analysis uses global average COCs in part because they are a straightforward way of calculating the opportunity cost (or benefit) of European trade. It is impossible to know exactly what lands in the world are cropped or not cropped, directly or indirectly, as a result of Europe's trade. For example, if Europe reduces its wheat exports, a significant portion of which are exported to northern Africa, responses could include increased wheat imports to Africa from a range of other regions. Similarly, farmers in northern Africa could switch some other crops to wheat and import more of other crops from other regions.

As a sensitivity analysis, Figure S1 shows Europe's net land carbon trade balance calculated using regional COCs. Regions include North America, North Africa and the Middle East, Europe, sub-Saharan Africa, China, etc. Using FAOSTAT, we calculated the three largest-producing regions for each of the 30 most land-intensive crops in European trade. For each, we estimated a regional COC by overlaying land devoted to each crop with the native carbon stock of those lands to determine the average carbon losses per hectare of each crop in the region. As described in reference [4], the estimate also relies on the average regional yields for that crop and a time-discounting approach of the pattern of carbon losses. The lower bound net trade COC estimate assumes that the counterfactual to Europe's exports would be production in that region from the top three-producing regions of each crop with the lowest COC for that crop. The upper bound net trade COC uses the highest COC region among those three top producers for each crop.

European biofuel import COCs: The calculation of COCs includes imported finished biofuels; crops imported to produce biofuels within Europe are embodied in the imports of those crops. The COCs for biofuels are the COCs for the crop components, e.g., vegetable oil, used to produce the bioenergy, which account for the co-products, such as protein feed from oilseeds or dried distillers grains from grain when producing ethanol. In a separate calculation, we estimate that imports of finished biofuels and imports of raw feedstocks ultimately destined for biofuel production in Europe together contributed 80 Mt CO_2e to the land carbon trade deficit at pre-pandemic levels of imports.

We generated these estimates by applying COCs calculated in [4] to data published in Biofuels Annual Reports by the United States Department of Agriculture's (USDA) Global Agricultural Information Network (GAIN) on (1) European production and trade balances of soy, palm, rapeseed, and sunflower oilseeds and oils; (2) European inputs of vegetable oil in the domestic production of finished biodiesel; and (3) European trade balances of finished biodiesel. Using these sources, we are able to estimate the gross COC of European consumption of soy, palm, rapeseed, and sunflower-based biodiesels derived from these feedstocks. We also estimate the net COC in trade of finished biodiesel of the same four feedstocks and factor this figure into our estimate of Europe's total net COC trade deficit (see above and Table S3). Note that Europe also consumes significant quantities of other biodiesel feedstocks, namely used cooking oils (UCO) and animal fats, in the production of biodiesel. The land and carbon costs associated with the consumption of these feedstocks are not considered here.

Description of Globagri model: Globagri is a global accounting and biophysical model developed by researchers with the Centre de coopération internationale en recherche agronomique pour le développement (CIRAD) and Institut national de la recherche agronomique (INRA), the World Resources Institute (WRI), and Princeton University. The model estimates land use demands and GHG emissions related to agricultural product consumption scenarios, including GHG emissions from land-use change as agricultural land demand grows or shrinks. It links food consumption, which in the past is based on FAO Food Balance Sheets, and FAO data on agricultural production, and accounts for the multiple products (e.g., food, feed, energy) generated by the world's crops as well as food loss and waste. Production-side parameters can be altered such as yields, inputs and other factors that influence land use or emissions intensity, along with consumption-side parameters such as human population, dietary patterns, trade patterns, and levels of waste. The model incorporates the results of several sub-models. For example, feed requirements of livestock are adapted from reference [5], rice methane emissions are adapted from reference [6], and for nitrogen use is adapted from reference [7]. An extensive description of the Globagri model is provided as Appendix A-1 of the report, *Creating a Sustainable Food Future*, by the World Resources Institute, the World Bank and the United Nations[8].

For this paper, the model was used only to estimate future EU food production and land use requirements, and imports and exports. For baseline 2050 scenarios, the model uses UN population projections and FAO projections of future diets by country[9]. It also uses methods for estimating gains in livestock production efficiencies from a variety of sources but that in Europe are primarily based on projections from Europe's Animal Change project[10]. The model analyses used here also keep trade relationships fixed. For the EU in 2050, the model therefore estimates that it will continue to import the same share of each food item consumed, and it will contribute the same percentage of global exports of each food item. Changes in trade patterns could lead to less or more land in crop production in Europe but would have at least somewhat offsetting effects on Europe's land carbon trade deficit. For example, greater exports than estimated would increase Europe's cropland area but decrease the net footprint of Europe's consumption outside of Europe.

Estimating baseline yield growth in Europe by 2050 used in Figures S2 and S3. Table S1 presents the yield gains for key crops that are incorporated into the scenarios presented in Figure 1 of the main text, and which show future potential scenarios of reduced cropland in Europe and reduced land carbon trade deficits. Table S4 shows these results in tabular form using two future yield estimates. The second figure in the range presented in Table S4 is based on yields projected by the FAO[9]. However, these projections were based on a combination of trend data and expert judgment that are now a decade old.

We therefore also developed an alternative baseline yield projection for Europe based on trend lines since 1990, which is represented by the first figure in the ranges presented in Table S4. To do so, for Europe's cereals, oilseed crops, tubers, sugar beets and legumes (except for pulses), we used linear regression to estimate annual rates of yield gain for the EU27 as a whole and separately for Western and Eastern Europe. (We did not include pulses because yields decreased sharply, probably due to a change in the land quality they are grown on, which is not the effect we wished to capture; doing so has limited effect because pulse areas are small.) Eastern European yield growth rates were substantially higher than Western rates, which is likely due to their lower yields in 1990 and the agricultural development that occurred after the decline of Communist regimes. As Eastern European yields approach Western European yields, we expect the rates of yield gain are likely to decline. We therefore selected a trend line that assumes yields in Western Europe continue to grow at rates from 1990–2020, while yields in Eastern Europe grow at a rate that is the average of Eastern European and Western European growth rates for this period.

The purpose of these yield projections is not to offer a prediction but only to provide an instructive benchmark by which to evaluate the yield growth rates required to achieve specified levels of reduced cropland area in Europe and land carbon trade balances.

Conservation status and priorities for major European taxa: European conservation status data is primarily drawn from the latest "State of Nature in the EU" (2020) report from the European Environment Agency (EEA). Citations for conservation and restoration priorities across taxa are drawn from IUCN Red List reports for European taxa and peer-reviewed and grey literature as cited in Table S2. The biodiversity and conservation status information presented in this table is intended to describe a high-level menu of conservation priorities for which land in Europe could be dedicated for habitat restoration. The biodiversity information in this table should not be understood as comprehensive.

European area of semi-natural grasslands. The total estimated area of "semi-natural" grasslands in Europe is contested, due to inconsistent definitions, methodologies, and data challenges. Following ref. [11], roughly up to 30 million hectares of "semi-natural" grasslands is estimated present in Europe (but the definition of Europe differs in significant ways from our analysis). However, others use estimates of "rough grazing" land (Farm Structure Survey) as a loose proxy for the area of semi-natural grassland in Europe[12]. According to Eurostat, this area comprised over 18 Mha in 2016, the latest data available. (We estimate that our extended definition of Europe likely comprises closer to 20 Mha).

Key legislative components of the Fit for 55 Plan and related EU legislation: The key energy components of the Fit for 55 plan related to biofuels are as follows:

- A proposed revised Renewable Energy Directive (RED II), requiring EU Member States to achieve 40% renewable energy by 2030. Amendments passed by the European Parliament would raise that objective to 45%[13].
- A strengthened Emissions Trading System (ETS), requiring larger emissions reductions from factories and power plants, and incorporating in part the transportation and building sectors[14]. The European Parliament agreed to an amended version[15], and negotiations for a final version continue at the time of this comment.
- A regulation that requires airlines to reduce emissions by switching to "sustainable aviation fuels" (SAF)[16]. The SAF requirement reaches 63% by 2050[17]. SAF will consist primarily of biofuels with some synthetically produced renewable fuels (e-fuels).
- A regulation[18] that requires maritime shipping to reduce the greenhouse gas intensity of fuels by 75% by 2050[17].

Additional legislation discussed in the main comment article include anti-deforestation provisions[19], regulations on emissions from land use and land use change[20], and a proposed nature restoration law restoration law[21] by the European Commission.

Carbon neutral language in Fit for 55 legislation: The proposed changes to the RED II and ETS and relevant implementing legislation do not alter the critical provisions related to calculating emissions factors of biomass, which will remain at zero. The relevant language in the proposed changes to the ETS is modified to state that the "emission factor for biomass" must comply with the "sustainability and greenhouse gas emission saving criteria" established in RED II (see original language in Annex IV of the ETS[22] and modification in part in Item 3 in [14]). See the relevant original language at Article 29 and Annex V (Part C, item 13) and Annex VI (Part B, item 13) in RED II[23] and modification in part by item 18 in [24]. The emission factor for biomass remains at zero despite these changes.

Commission impact assessment modeling: This paper is primarily based on analysis of the legislative text of the Fit for 55 plan of the European Commission, with all provisions referenced in the main text, and the modeling results presented in the Commissions' Fit for 55 Impact Assessment of the 2030 Climate Target Plan[25]. The Commission relies on the PRIMES model to estimate future energy sources and uses, and the GLOBIOM model to estimate land use effects and specific sources of biomass. The model outputs referenced in the main text refer to the "Mix" scenario, which most closely resembles the Fit for 55 legislation as proposed.

Role of waste wood in present European bioenergy: The doubling of bioenergy will require more than a doubling of biomass from either dedicated wood harvests for bioenergy or from the use of land to grow energy crops. The reason is that much of Europe's existing bioenergy uses wastes, particularly of existing wood production. According to modeling in the official Impact Assessment of the 2030 Climate Target Plan, biosolids (essentially wood), municipal and industrial solid waste, and waste gas comprised 113 of the 139 Mtoe of biomass in 2015 (see Figure 78 in [25]). Some of these biosolids were in the form of deliberately harvested wood, but most wood included in this analysis represents the burning of wood as part of paper and wood product manufacturing or the burning of residues[26]. As these resources are nearly all utilized, new bioenergy must primarily come from more dedicated sources.

***Bioenergy increase as percentage of European wood harvest*:** The increase of 184 Mtoe (7,704 GJ) requires 951 million cubic meters compared to roughly 120 million cubic meters annual fuelwood harvest today (FAOSTAT), an eight-fold increase. This calculation assumes 18 GJ per ton of dry matter and an average weight of .45 tons of dry matter per cubic meter of European wood harvest (see Table S1 in).

Increased wood imports in Fit for 55 Impact Assessment: According to modeling in the official Impact Assessment of the 2030 Climate Target Plan, imported "solid biomass" for energy would increase from 3 Mtoe in 2015 to 13 Mtoe in 2050, instead of declining to 0 Mtoe in the baseline (see Figure 80 in [25]). These imports would require roughly 30 Mt of dry matter in wood, which is roughly equivalent to 65 million cubic meters of harvested wood. In comparison, Canada, one of the world's largest wood producers, harvested ~150 million cubic meters of wood annually between 2010–2018[29].

Limited availability of forest residues relative to modeling projections: The 2030 Climate Target Impact Assessment claims that forest residues will supply 31.65 Mtoe of energy in the "Mix" 2050 scenario that most closely resembles Fit for 55 proposals (see Figure 79 in [25]). At 18 GJ/tDM, this energy supply requires 73.7 Mt of dry matter. Verkerk et al. (2019) estimate 50 Mt of DM from forest residues available with maximum harvest of forests in 40

European countries under current harvest rules, of which 84% is available in the EU-27 plus the UK, or 42 Mt of DM[30]. This figure includes stumps, whose harvest for bioenergy would be prohibited under the new rules of the Renewable Energy Directive (see amendments to Article 29 at p. 46 in [24]). At existing wood harvest levels, available residues would proportionately drop to 28 Mt of DM. For more information on proposed rule changes, see [31].

Impacts of Fit for 55 plan on European carbon sequestration: The conversion to energy crops should sequester some carbon although mostly in the form of unstable, particulate soil organic carbon, and with the amount highly uncertain, particularly if the cropland is occasionally plowed[32–34]. On the other hand, the decline in semi-natural grasslands and grassland-woodland complexes, even with conversion to energy crops, has potential to cause losses of both soil organic carbon and vegetative carbon in shrubs and scattered trees[35]. The large reliance on forest and crop residues for bioenergy also poses a threat to soil carbon[36–39].

EU Forestry Strategy and Greenhouse Consequences of Harvesting Wood for Bioenergy: Although the European Commission's Forest Strategy for 2030 announces a broad goal to increase the use of wood, it also states in a single sentence on pp. 5: "As indicated in recent studies, in the short to medium term, i.e. until 2050, the potential additional benefits from harvested wood products and material substitution are unlikely to compensate for the reduction of the net forest sink associated with the increased harvesting"[40]. As discussed in our paper, Europe claims a "net forest sink," which means forests are growing and accumulating carbon. "Reduction of the net forest sink" by 2050 therefore means increasing carbon in the atmosphere by that year. The Strategy includes a reference to a paper by the European Commission Joint Research Centre, which provides citations[41]. For a further list of relevant papers, see the supplement to reference [27].

Greenhouse gas balance between use of land for energy crops and preservation of native habitat or restoration of forest: Compared to saving even one hectare of forest or savanna abroad, diverting a hectare of European cropland to energy crops is likely to increase emissions for decades (see calculations in Table 1 of ref. [42]). This is equally true when comparing a hectare of energy crops versus reforestation (see calculations in table 2 of ref. [42]). The likelihood is even greater at the average biomass yields of 11 tDM/ha/year implied by the Commission's own modeling, which can be inferred from the quantity of biomass from energy crops and the area of energy crops indicated in the Fit for 55 Impact Assessment[25]. The carbon costs of diversions are likely even higher under these assumptions because lower yields outside Europe typically entail greater than a 1:1 land requirement to offset the lost cropland for food within Europe[43]. These calculations also assume that the alternative would be use of fossil fuels while low carbon alternatives are also possible, potentially even including some waste biomass.

Net greenhouse gas benefits relative to a reforestation alternative might be possible with high energy crop yields if carbon capture and storage is added and achieved with high efficiencies[42]. But achieving higher yields is challenging. So, too, is avoiding significant carbon losses during the carbon capture process, which includes carbon lost during storage, during processing (particularly if wood is turned into wood pellets), and during carbon capture from flue gases[44]. Moreover, there is no advantage in using carbon capture and storage with biomass relative to fossil fuels unless the biomass is itself low carbon.

Ukrainian exports as a fraction of EU and USA biofuel production: To produce these calculations, we rely on Grain and Feed Update reports from USDA's Global Agricultural Information Network (GAIN) for estimates of Ukrainian grain exports; Oilseeds and Products Annual Reports from USDA GAIN for estimates of Ukrainian oilseed and vegetable oil exports; Biofuels Annual Reports from USDA GAIN for estimates of EU production, consumption, and trade of biofuels; and Monthly Biofuels Capacity and Feedstock Update reports from the United States Energy Information Agency (EIA) for estimates of feedstocks consumed for American production of ethanol.

Data availability statement: The datasets generated during and/or analyzed in this comment article are all publicly available data sets and are also available from the corresponding author on reasonable request.

Supplemental Tables and Figures

Table S1. Yield growth of Europe's five largest crops by area harvested required to satisfy scenarios.†

Crop	Total Harvested Area, 2018 (Mha)	2016–2020 yields (avg, tons/ha) (FAOSTAT)	2050 yields (tons/ha), FAO "Baseline"	2050 yields (tons/ha), Trendline
Wheat	24.1	5.48	6.89 (+26%)	6.65 (+17%)
Barley	11.1	4.80	5.04 (+5%)	5.96 (+25%)
Maize	8.7	7.75	8.12 (+5%)	10.07 (+28%)
Rapeseed	5.8	3.04	4.03 (+32%)	3.84 (+20%)
Sunflowerseed	4.2	2.29	2.62 (+15%)	2.91 (+20%)

† Baseline represents estimated business as usual based on 2050 yield projections by the FAO. Trendline yields assume that Western European crop yields grow at the same linear rate as they did between 1990 and 2020 and Eastern European growth rates grow at an average of Western European growth rates and Eastern European growth rates for that period. Harvested area 2018 and yields 2016-2020 data source: FAOSTAT. Olive production covered 5 Mha in 2018 but are not tracked separately by Globagri and is excluded from the table above.

Table S2. **Conservation Status and Priorities for Major Terrestrial European Taxa**.

Taxonomic Group	EU Status[45]	EU Conservation and Restoration Priorities
Habitats	• Only 15% of habitat assessments have a good conservation status, 81% have "poor" or "bad" status, and 4% unknown. • Forest habitats show the highest proportion of improving trends (13%) among major habitat types but have the largest area under the Habitat Directive in need of improvement from restoration. (>100 Mha). • Grasslands, especially managed grasslands, have one of the highest shares of assessments with "bad" and deteriorating conservation status. >33 Mha of grassland areas under the Habitat Directive need to be restored. • Over half of wetland (bog, mire, and fen) habitats have a "bad" conservation status, many of which continue to deteriorate. • Conservation challenges differ across regions of Europe: at last review, for instance, only 4% of habitat assessments in the Atlantic region were labeled "good", while 72% achieved this status in the Steppic region.	• Abandonment of extensive agricultural management and agricultural intensification are the most frequent pressures on habitats and species, followed by pollution[45]. Forest management practices are one of the primary pressures on protected species[45]. • The relative biodiversity value of grasslands greatly differs: "improved" grasslands typically comprise one or at most a few species of highly productive grass species while "semi-natural" grasslands are some of the most species-rich habitats in Europe[11]. Preserving and restoring the latter is a conservation priority, especially for vascular plants, butterflies, pollinators, and birds. • Only 3% of EU forests are old-growth or primary: surveying, protecting, and enhancing these remaining forests is a conservation priority[46,47]. The benefits to biodiversity of enhancing dead and dying wood in forests is well-established[48–50]. Though linking forest management to biodiversity impacts is complex (e.g., depends on how biodiversity is defined and measured), increasing diversity of forests (from the level of individual trees to whole landscapes) generally enhances biodiversity[51]. • >226 Mha of Annex 1 habitats need to be restored to ensure long-term viability. >11 Mha of Annex 1 habitats need to be added to current habitat area to ensure long-term functioning of each habitat. Up to 189 Mha of "carbon-rich" Annex 1 habitats need to be improved[45].
Birds	• 39% of bird species are Threatened or Near-threatened. • The proportion of Annex I species listed with "good" status has decreased by 8% and "bad" status by 6%. • Despite relatively high coverage compared to other taxa in biodiversity monitoring schemes, data gaps persist: population trends are unknown or missing in 20% of reports for breeding birds, and 30% for wintering birds.	• Farmland and grasslands have the highest number of associated bird species (30%) that are declining. Farmland birds show the fewest improving trends. • Only 16% of forest bird species are declining while 32% show an improving trend. Common forest bird species are relatively stable, but threatened forest bird populations show few improving trends[52,53]. • Waterbirds (shorebirds and waterfowl) have among the highest proportion of Threatened and Near Threatened species. • Breeding bird abundance has declined by 17–19% since 1980 (representing a loss of 560–620 million birds), driven by a decline of a few relatively abundant species typically associated with agricultural land[54].
Mammals	• 60% of assessed mammal populations have a "poor" or "bad" conservation status.	• Though the percentage of large mammals threatened with extinction is higher than the average of all European mammals[55], larger mammals appear to have a higher number of increasing population trends, while information remains scarce for small mammals[45]. • Large mammals have large habitat area requirements, making them especially sensitive to habitat loss, whether due to land-use or climate change[56]. Mammal diversity is particularly high in south-eastern Europe and in the mountain regions of Mediterranean and temperate Europe[57].
Reptiles & Amphibians	• 60% of assessed reptile population and 70% of amphibian populations have a "poor" or "bad" conservation status.	• The poor status of Europe's freshwater habitats is strongly correlated with amphibian declines. Protecting and restoring wetland habitats can be a win-win for amphibians and the climate[58]. • In addition to the primary threats of habitat loss and fragmentation, the expansion of energy crops and GM crops into previously uncultivated or non-arable land (e.g., former mining areas) can impact reptiles which may rely on these areas as crucial secondary habitats[59,60].

Insects	• 60% of assessed insect populations have a "poor" or "bad" conservation status. • 20% of assessed butterfly species are Threatened or Near-threatened[61].	• Grassland and forest insect biodiversity is declining and associated with landscape-level agricultural impacts[62]. • Grassland butterfly populations have declined by as much as 40% since 1990[63,64]. • Pollinator species, which provide important benefits to society, are rapidly declining across Europe[65,66].
Plants	• 25% of assessed native plant species are threatened[67]. • At least 37% of native tree species are threatened[68].	• Relatively high species richness and endemism is present in the Mediterranean and Balkan regions, especially mountain regions[45]. Semi-natural grasslands host especially high vascular plant species richness at small spatial scales[69]. • Vascular plants have relatively high coverage in the Natura 2000 network[45].
Fungi	• Poorly monitored; of an estimated 75,000+ species only 125 have been assessed in Europe[70–72].	• Fungi play critical ecological roles in the basic functioning of soils and ecosystem processes[73–76] and some have important symbiotic relationships with most of the world's plant species[70].

Table S3. Top 15 Land Carbon Intensive Imports and Exports to/from Europe in 2018, ranked by "COC trade balance" (avg, 2012–2020).†

Top 15 Land Carbon Intensive Imports	Global Average COC Coefficient ($t\ CO_{2e}$/t fresh weight)	Average Gross Trade COC (2012–2020) ($t\ CO_{2e}$)
Coffee, green	31.3	(94,085,448)
Cake, soybeans	4.9	(90,379,771)
Soybeans	5.9	(82,656,943)
Cocoa, beans	40.4	(66,604,825)
Oil, palm	9.3	(63,047,222)
Meat, sheep	285.7	(35,679,810)
Crop-based biodiesel	Weighted by feedstock*	(25,413,807)
Meat, cattle, boneless (beef & veal)	208.6	(25,190,875)
Maize	2.1	(24,750,706)
Rapeseed	5.8	(22,150,078)
Oil, coconut (copra)	33.1	(19,835,903)
Cake, sunflower	3.3	(10,324,900)
Cake, palm kernel	4.3	(9,818,460)
Oil, sunflower	7.5	(7,582,193)
Bananas	1.1	(6,526,368)
TOTAL IMPORTS		(584,047,308)

Top 15 Land Carbon Intensive Exports	Global Average COC Coefficient ($t\ CO_{2e}$/t fresh weight)	Average Gross Trade COC (2012–2020) ($t\ CO_{2e}$)
Wheat	1.9	38,926,261
Meat, pig	20.2	27,235,569
Cheese, whole cow milk	41.3	25,850,427
Milk, whole dried	47.7	17,067,710
Barley	2.6	16,266,392
Meat, pork	20.2	14,580,878
Meat, chicken	12.6	11,053,939
Meat, cattle	221.2	10,379,898
Oil, soybean	10.8	6,698,537
Malt	2.6	5,998,478
Butter, cow milk	38.8	4,881,876
Offals, pigs, edible	3.2	3,858,255
Milk, whole fresh cow	6.2	3,545,364
Broad beans, horse beans, dry	8.9	2,673,311
Oil, olive, virgin	4.1	1,696,217
TOTAL EXPORTS		190,713,113
NET TRADE DEFICIT		**(393,334,195)**

* Crop-based biodiesel trade COC figure is average of years 2012, 2018, and 2020. Feedstocks include soy, palm, and canola/rapeseed. COCs for finished FAME biodiesels are 9.4, 7.7, and 7.9 (kg CO_2eq/L), respectively.

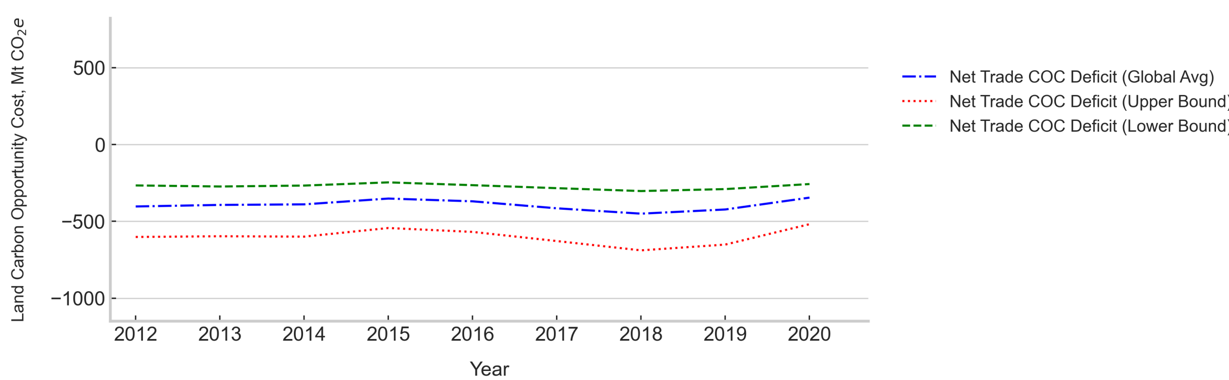
† Excludes intra-European trade. Trade data in parentheses indicates negative numbers (i.e., trade deficits). Trade data source: FAOSTAT.

Table S4: Modeled land use change and land carbon trade balances for possible European food scenarios.†

Scenario Description	Cropland Reduction Compared to 2010 (Mha)	2050 Land Carbon Trade Balance (Export COCs – Import COCs) (Mt CO_2e)
Baseline scenario	16.5–20.8	(20.2–25.7)
10% avg. global reduction in animal products; Europe 17% reduction	28.0–31.3	(27.0–29.1)
17% reduction in animal products (Europe Only)	27.4–30.6	.83–(1.3)
European and global food waste reduced by 10%	18.8–22.9	(25.2–30.0)

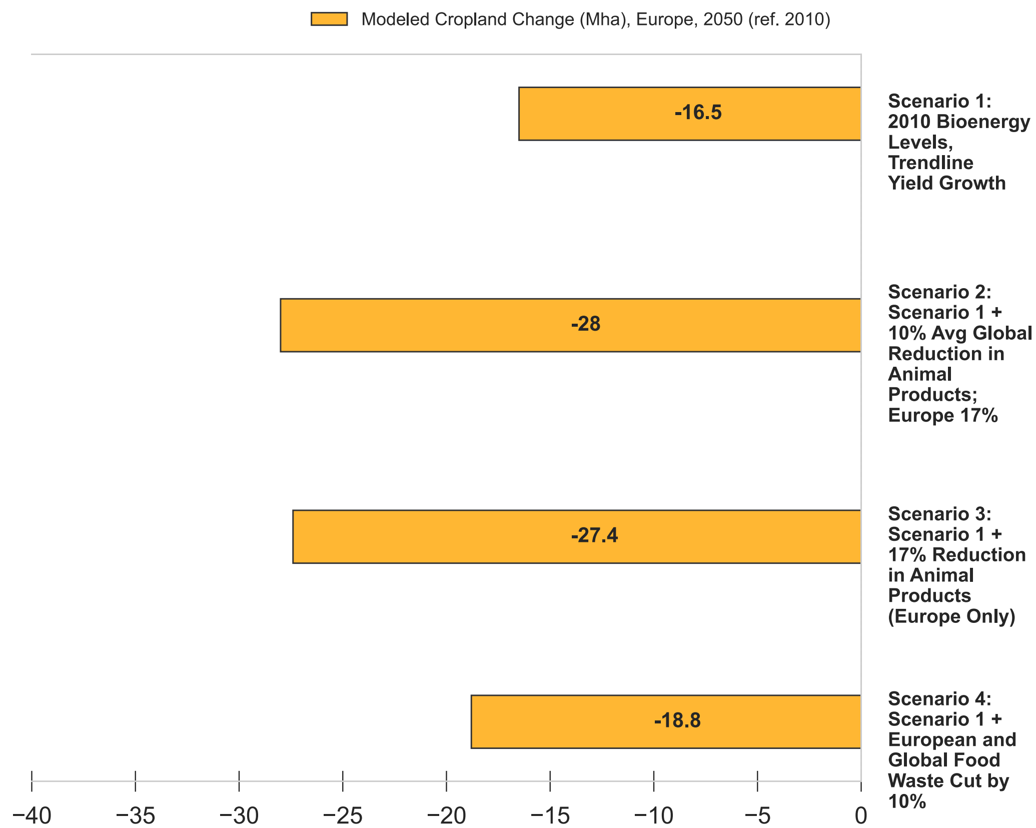
†Table data represents Globagri modeling projections of changes in European cropland and the land carbon trade balance measured by carbon opportunity costs. First figure in result range is based on European trend line yield projections; second figure based on FAO yield projections (see "Additional Methodological Explanations" and Table S1 above). Figures in parentheses are negative, i.e., trade COC deficits. Note that all modeled scenario trade COC deficits represent large reductions from Europe's present estimated deficit.

Figure S1: Europe's land carbon trade deficit, using high and low-efficiency regions.



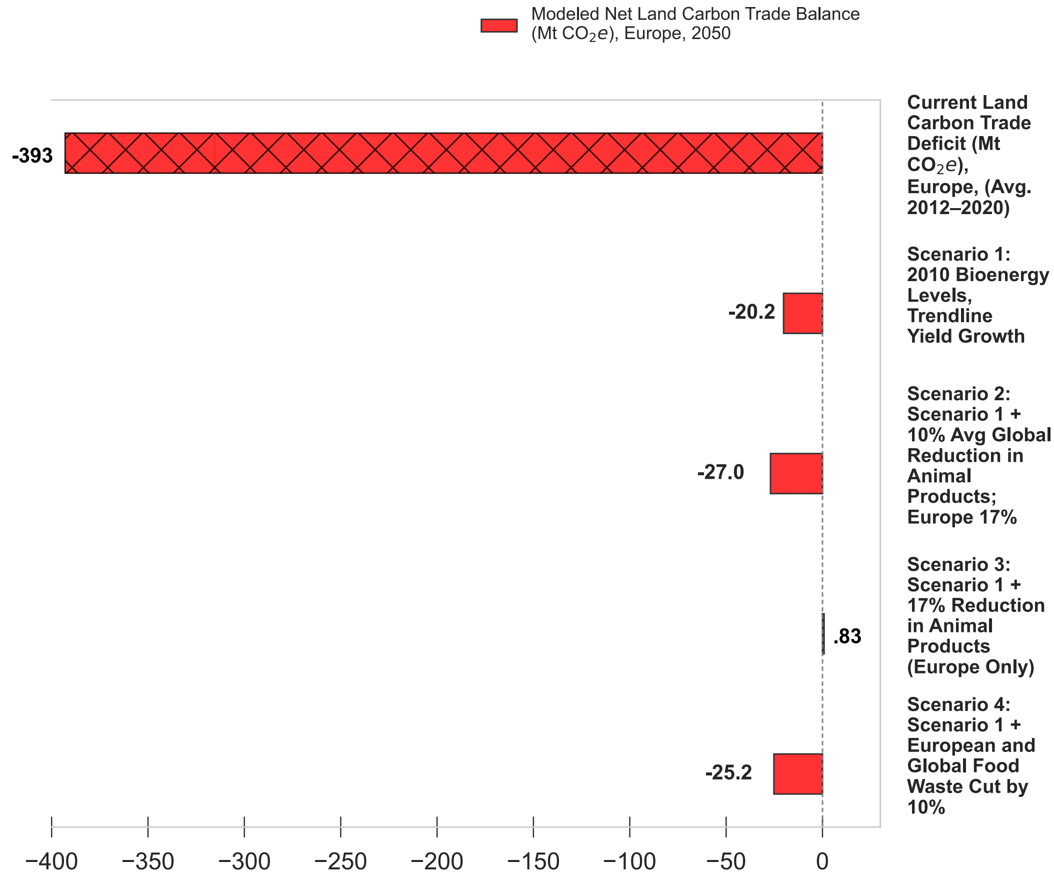
See explanation of sensitivity analysis above. Source: Author's calculations.

Figure S2: **Modeled Scenario Cropland Changes (Mha), Europe, 2050.** †



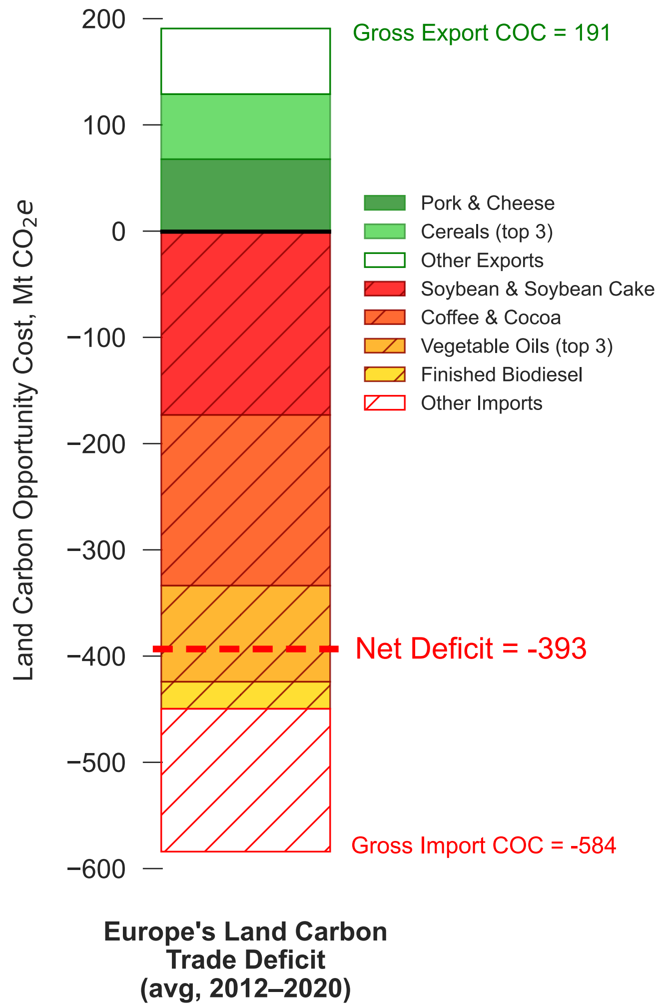
†Globagri modeling results for four potential European land futures. Orange bars represent change in European cropland area in 2050 over 2010 (Mha). Europe's land carbon trade balances for these Scenarios are presented in Figure S3. Scenario 1 contemplates that yield growth in Europe will increase along trendline to 2050 and that Europe's bioenergy consumption is held to 2010 levels. (Note: Scenario 1 is not the "do-nothing" scenario, nor does it represent proposed policies of the Fit for 55 plan). Scenarios 2–4 are all cumulative to Scenario 1 (but not cumulative among themselves). Scenario 2 contemplates a 10% global reduction in animal product consumption (i.e., below that of Scenario 1). This global reduction includes a 17% reduction in animal product consumption in Europe, Europe's "fair" contribution to global reductions. Note that a 10% global reduction in animal production consumption from baseline in 2050 still represents a large *net* increase in animal product consumption over today. Even if Europe's demand for animal products falls, Europe will continue to supply growing demand around the world. Note that the absolute different in modeled cropland area change between Scenario 1 and Scenario 2 is ~11 Mha, an area larger than the size of Austria, or about a third of all of Germany. Scenario 3 contemplates a 17% reduction in animal product consumption in Europe only (extra-European consumption is unchanged from baseline). Scenario 4 contemplates a reduction in global and European food waste of 10%. For more explanation of the Globagri model and discussion of important methodological approaches and assumptions see "Additional Methodological Explanations" above.

Figure S3: Current and Modeled Net Land Carbon Trade Balances (Mt CO_{2e}). †



†Europe's current estimated net land carbon trade deficit (avg. 2012–2020) is shown in the cross-hatched red bar. The four solid red bars represent Europe's modeled (Globagri) net land carbon trade balance in 2050 across four Scenarios. Net land carbon trade balances are calculated using "carbon opportunity costs" applied to individual crop and animal product items. Europe's net land carbon trade balance is the difference between Europe's gross export land carbon balance and Europe's gross import land carbon balance (excludes intra-European trade). A negative land carbon trade balance represents a trade "deficit" and a positive balance a surplus. Note that the land carbon trade balances modeled in scenarios 1–4 all represent significant reductions in Europe's current estimated land carbon trade deficit. The modeled cropland area change associated with each scenario is presented in Figure S2 above. Scenarios are explained in greater depth in Figure S2. For more explanation of the Globagri model and discussion of methodological approaches and assumptions see "Additional methodological Explanations" above.

Figure S4: Europe’s Current Land Carbon Trade Deficit (Mt CO_{2e}).†



†Europe’s land carbon trade balance measured by carbon opportunity costs. A carbon opportunity cost (COC) is the annualized, global average terrestrial carbon lost to produce a tonne of an agricultural product. Subtracting Europe’s total gross import COCs from total gross export COCs measures Europe’s overall net land carbon balance in trade, a large deficit (393 Mt CO2e). Unless fixed, the Fit for 55 Plan will enlarge Europe’s deficit at a time when Europe must reduce it. See Table S3 above for full crop-disaggregated balance sheet.

Additional Citations from the Main Text

… New energy laws are at its centre: a revised directive to increase renewable energy to 40%–45% by 2040[24], tighter caps on emissions from factories and power plants[14], and requirements that the aviation and maritime industries shift to alternative fuels[16,17] (see also SI above)…

…forests in Europe have recovered to 40%[77]…

…European meat consumption has likely peaked[78]…

…as the "sink" mainly reflects the fertilizing effects of higher CO_2, warmer weather, and the regrowth of forests established before 1990[79–84]…

…each hectare saved in the tropics generally has more carbon and biodiversity than a hectare restored in Europe[85–87]…

…Rewetting Europe's drained peatlands is a priority because they emit at least 100 Mt CO_{2e} per year—possibly twice that amount. Preserving older forests from harvest is another, for both carbon and biodiversity[88–90]…

… Biodiversity priorities include buffering the remnant habitats on which rare species survive and preserving the 20–30 million hectares of diverse, semi-natural grasslands[69,91]…

…A proposed EU anti-deforestation law[19] will not halt these effects…

… Nor can a proposed nature restoration law shore up Europe's biodiversity without even more outsourcing, if bioenergy expansion leaves no land to restore as native habitats[21]…

… Although energy crops provide more habitat for common species than annual crops, the loss of semi-natural grasslands means less habitat for many rare plants, butterflies, and birds [45,92,93,94] (see also SI above)…

… Removal of virtually all residues from forests contradicts the priority to need to leave more deadwood for many rare species[40]…

…The Commission says that strengthened climate rules on land use compensate for this problem[95,96]…

… These rules require that countries increase efforts to expand their forest carbon sinks and correct some accounting abuses[97]…

…The decline in traditional bioenergy from reductions in the numbers of working animals has also reduced the need to devote vast areas to pasture and feeds[2]…

…Commission modelling predicts that bioenergy will more than double every year between 2015 and 2050, from 152 Mtoe to 336 Mtoe (see Figure 79 in [25])…

…By 2050, Europe will devote 22 Mha of cropland to energy crops, or roughly 20% of cropland, and import four times as much wood for bioenergy (see Figure 80 in [25])…

…Roughly half of Europe's semi-natural grasslands are expected to generate energy crops or intensively managed forests (see Figure 85 in [25])…

…Owing to higher yields, global exports from European countries require less land and sacrifice less carbon storage than does production in most other countries[43]…

REFERENCES

1. Potapov, P. *et al.* Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nat. Food* **3**, 19–28 (2022).
2. Malanima, P. World Energy Consumption: A Database. 1820–2018. (2020).
3. Kastner, T. *et al.* Global agricultural trade and land system sustainability: Implications for ecosystem carbon storage, biodiversity, and human nutrition. *One Earth* **4**, 1425–1443 (2021).
4. Searchinger, Wirsenius, S., Beringer, T. & Dumas, P. Assessing the efficiency of changes in land use for mitigating climate change. *Nat. Lett.* **564**, 249–253 (2018).
5. Herrero, M. *et al.* Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl. Acad. Sci.* **110**, 20888–20893 (2013).
6. Yan, X., Akiyama, H., Yagi, K. & Akimoto, H. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006

Intergovernmental Panel on Climate Change Guidelines. *Glob. Biogeochem. Cycles* **23**, GB2002 (2009).

7. Zhang, X. *et al.* Managing nitrogen for sustainable development. *Nature* **528**, 51–59 (2015).
8. Searchinger, T., Waite, R., Hanson, C. & Ranganathan, J. *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. (World Resources Institute, World Bank, UNDP, UNEP, 2019).
9. Alexandratos, N. & Bruinsma, J. *World agriculture towards 2030/2050: the 2012 revision*. (2012).
10. Soussana, J. F. *et al. Storylines for the livestock sector scenarios in EU, studied SICA regions and global level. Deliverable 2.1. EU FP7 project AnimalChange.* (2012).
11. Dengler, J., Biurrun, I., Boch, S., Dembicz, I. & Török, P. Grasslands of the Palaearctic Biogeographic Realm: Introduction and Synthesis. in *Encyclopedia of the World's Biomes* 617–637 (Elsevier, 2020). doi:10.1016/B978-0-12-409548-9.12432-7.
12. Herzon, I. *et al.* Semi-natural habitats in boreal Europe: a rise of a social-ecological research agenda. *Ecol. Soc.* **26**, (2021).
13. European Parliament. *Amendments adopted by the European Parliament on 14 September 2022 on the proposal for a directive of the European Parliament and of the Council amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 (COM(2021)0557 – C9-0329/2021 – 2021/0218(COD))*. https://www.europarl.europa.eu/doceo/document/TA-9-2022-0317_EN.html (2022).

14. European Commission. *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0551 (2021).
15. European Parliament. *Amendments adopted by the European Parliament on 22 June 2022 on the proposal for a directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757 (COM(2021)0551 – C9-0318/2021 – 2021/0211(COD))*. https://www.europarl.europa.eu/doceo/document/TA-9-2022-0246_EN.html (2022).
16. European Commission. *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ensuring a level playing field for sustainable air transport*. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561 (2021).
17. Searle, S. Alternative transport fuels elements of the European Union's "Fit for 55" package. (2021).
18. European Commission. *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0562 (2021).

19. European Parliament. *Amendments adopted by the European Parliament on 13 September 2022 on the proposal for a regulation of the European Parliament and of the Council on making available on the Union market as well as export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010 (COM(2021)0706 – C9-0430/2021 – 2021/0366(COD))*. https://www.europarl.europa.eu/doceo/document/TA-9-2022-0311_EN.html (2022).
20. European Parliament. *Amendments adopted by the European Parliament on 8 June 2022 on the proposal for a regulation of the European Parliament and of the Council Amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review (COM(2021)0554 – C9-0320/2021 – 2021/0201(COD))*. https://www.europarl.europa.eu/doceo/document/TA-9-2022-0233_EN.html (2022).
21. European Commission. *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on nature restoration*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0304 (2022).
22. European Commission. *Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. OJ L* vol. 275 (2003).

23. European Commission. *DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). OJ L* vol. 328 (2018).
24. European Commission. *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0557 (2021).
25. European Commission. *Impact Assessment Accompanying the Document Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Stepping up Europe's 2030 Climate Ambition, Investing in a climate-neutral future for the benefit of our people. Part 2/2.* (2020).
26. Cazzaniga, N., Jonsson, K., Pilli, R. & Camia, A. *Wood resource balances of EU-28 and Member States*. https://publications.jrc.ec.europa.eu/repository/handle/JRC114889 (2019) doi:10.2760/020267.
27. Searchinger, T. *et al.* Europe's renewable energy directive poised to harm global forests. *Nat. Commun.* **9**, 3741 (2018).
28. Searchinger *et al.* Europe's renewable energy directive poised to harm global forests. *Nat. Commun.* **9**, 3741 (2018).

29. Natural Resources Canada. *The State of Canada's Forests Annual Report 2021*. 90 https://www.nrcan.gc.ca/our-natural-resources/forests/state-canadas-forests-report/timber-being-harvested-sustainably/16494 (2021).
30. Verkerk, P. J. *et al.* Spatial distribution of the potential forest biomass availability in Europe. *For. Ecosyst.* **6**, 5 (2019).
31. European Commission. Commission presents Renewable Energy Directive revision. *European Commission. News.* https://ec.europa.eu/info/news/commission-presents-renewable-energy-directive-revision-2021-jul-14_en (2021).
32. Georgiadis, P., Stupak, I., Vesterdal, L. & Raulund-Rasmussen, K. Conversion from cropland to short rotation coppice willow and poplar: Accumulation of soil organic carbon. in *EGU General Assembly* 6752 (2015).
33. Hansen, E. M., Christensen, B. T., Jensen, L. S. & Kristensen, K. Carbon sequestration in soil beneath long-term Miscanthus plantations as determined by 13C abundance. *Biomass Bioenergy* **26**, 97–105 (2004).
34. Lockwell, J., Guidi, W. & Labrecque, M. Soil carbon sequestration potential of willows in short-rotation coppice established on abandoned farm lands. *Plant Soil* **360**, 299–318 (2012).
35. Holder, A. J. *et al.* Measured and modelled effect of land-use change from temperate grassland to Miscanthus on soil carbon stocks after 12 years. *GCB Bioenergy* **11**, 1173–1186 (2019).
36. Achat, D. L., Fortin, M., Landmann, G., Ringeval, B. & Augusto, L. Forest soil carbon is threatened by intensive biomass harvesting. *Sci. Rep.* **5**, 15991 (2015).
37. James, J. & Harrison, R. The Effect of Harvest on Forest Soil Carbon: A Meta-Analysis. *Forests* **7**, 308 (2016).

38. Repo, A., Böttcher, H., Kindermann, G. & Liski, J. Sustainability of forest bioenergy in Europe: land-use-related carbon dioxide emissions of forest harvest residues. *GCB Bioenergy* **7**, 877–887 (2015).

39. Olofsson, J. Time-Dependent Climate Impact of Utilizing Residual Biomass for Biofuels—The Combined Influence of Modelling Choices and Climate Impact Metrics. *Energies* **14**, 4219 (2021).

40. European Commission. *New EU Forest Strategy for 2030*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0572&qid=1644259486741 (2021).

41. Grassi, G. *et al. Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution*. https://publications.jrc.ec.europa.eu/repository/handle/JRC124374 (2021).

42. Searchinger, Beringer, T. & Strong, A. Does the world have low-carbon bioenergy potential from the dedicated use of land? *Energy Policy* **110**, 434–446 (2017).

43. Johnson, J. A., Runge, C. F., Senauer, B., Foley, J. & Polasky, S. Global agriculture and carbon trade-offs. *Proc. Natl. Acad. Sci.* **111**, 12342–12347 (2014).

44. Harper, A. B. *et al.* Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nat. Commun.* **9**, 2938 (2018).

45. European Environment Agency. *State of nature in the EU: Results from reporting under the nature directives 2013–2018.* https://www.eea.europa.eu/publications/state-of-nature-in-the-eu-2020 (2020).

46. Barredo, J. *et al. Mapping and assessment of primary and old-growth forests in Europe.* https://data.europa.eu/doi/10.2760/797591 (2021).

47. Sabatini, F. M. *et al.* Protection gaps and restoration opportunities for primary forests in Europe. *Divers. Distrib.* **26**, 1646–1662 (2020).

48. Bauhus, J., Baber, K. & Müller, J. Dead Wood in Forest Ecosystems. *Adv. Ecol. Res.* **15**, (2018).

49. Pötzelsberger, E., Schuck, A. & den Herder, M. *Question 6: How does forest management affect biodiversity? Knowledge to Action.* https://efi.int/forestquestions/q6 (2021).

50. Tomao, A., Antonio Bonet, J., Castaño, C. & de-Miguel, S. How does forest management affect fungal diversity and community composition? Current knowledge and future perspectives for the conservation of forest fungi. *For. Ecol. Manag.* **457**, 117678 (2020).

51. Ampoorter, E. *et al.* Tree diversity is key for promoting the diversity and abundance of forest-associated taxa in Europe. *Oikos* **129**, 133–146 (2020).

52. Birdlife International. *European Red List of Birds. 2021.* https://www.birdlife.org/wp-content/uploads/2021/10/BirdLife-European-Red-List-of-Birds-2021.pdf (2021).

53. Pan-European Common Bird Monitoring Scheme. European wild bird indicators, 2020 update. *PECBMS* https://pecbms.info/european-wild-bird-indicators-2020-update/ (2020).

54. Burns, F. *et al.* Abundance decline in the avifauna of the European Union reveals cross-continental similarities in biodiversity change. *Ecol. Evol.* (2021) doi:10.1002/ECE3.8282.

55. Rondinini, C. & Visconti, P. Scenarios of large mammal loss in Europe for the 21st century. *Conserv. Biol.* **29**, 1028–1036 (2015).

56. Schipper, J. *et al.* The Status of the World's Land and Marine Mammals: Diversity, Threat, and Knowledge. *Science* **322**, 225–230 (2008).

57. Temple, H. J. & Terry, A. European mammals: Red List status, trends, and conservation priorities. *Folia Zool.* **58**, 248–269 (2009).

58. Temple, H. J. & Cox, N. A. *European Red List of Amphibians*. (2009).

59. Böhme, W. *Handbuch der Reptilien und Amphibien Europas*. (AULA, 1999).

60. Günther, R. *Die Amphibien und Reptilien Deutschlands*. (Gustav Fischer, 1996).

61. Van Swaay, C., Warren, M. & Loıs, G. Biotope use and trends of European butterflies. *J. Insect Conserv.* **10**, 189–209 (2006).

62. Seibold, S. *et al.* Arthropod decline in grasslands and forests is associated with landscape-level drivers. *Nature* **574**, 671–674 (2019).

63. Warren, M. S. *et al.* The decline of butterflies in Europe: Problems, significance, and possible solutions. *Proc. Natl. Acad. Sci.* **118**, (2021).

64. Butterfly Conservation Europe. *Butterflies as Indicators.* https://butterfly-monitoring.net/sites/default/files/Pdf/Reports/ABLE_PolicyBrief_Interactive_Finalv2_Jan21.pdf (2020).

65. Soroye, P., Newbold, T. & Kerr, J. Climate change contributes to widespread declines among bumble bees across continents. *Science* **367**, 685–688 (2020).

66. De Palma, A. *et al.* Dimensions of biodiversity loss: Spatial mismatch in land-use impacts on species, functional and phylogenetic diversity of European bees. *Divers. Distrib.* **23**, 1435–1446 (2017).

67. IUCN. The IUCN Red List of Threatened Species. Version 2020-1. (2020).

68. Rivers, M. *et al. European Red List of Trees*. https://portals.iucn.org/library/node/48512 (2019) doi:10.2305/IUCN.CH.2019.ERL.1.en.

69. Dengler, J., Janišová, M., Török, P. & Wellstein, C. Biodiversity of Palaearctic grasslands: a synthesis. *Agric. Ecosyst. Environ.* **182**, 1–14 (2014).

70. Gonçalves, S. C., Haelewaters, D., Furci, G. & Mueller, G. M. Include all Fungi in Biodiversity Goals. *Science* **373**, 403 (2021).

71. Ainsworth, A. M. *et al. State of the World's Fungi 2018*. 12 (2018).

72. European Council for the Conservation of Fungi. *200 Fungal Species Published on The IUCN Red List, Including 125+ From Europe.* http://www.eccf.eu/poster-iucn_red_list.pdf.

73. White, N. A. The importance of wood-decay fungi in forest ecosystems. in *Fungal biotechnology in agricultural, food, and environmental applications* 375–392 (Marcel Dekker Inc., 2004).

74. Clemmensen, K. E. *et al.* Carbon sequestration is related to mycorrhizal fungal community shifts during long-term succession in boreal forests. *New Phytol.* **205**, 1525–1536 (2015).

75. Cairney, J. W. & Meharg, A. A. Interactions between ectomycorrhizal fungi and soil saprotrophs: implications for decomposition of organic matter in soils and degradation of organic pollutants in the rhizosphere. *Can. J. Bot.* **80**, 803–809 (2002).

76. Steidinger, B. S. *et al.* Climatic controls of decomposition drive the global biogeography of forest-tree symbioses. *Nature* **569**, 404–408 (2019).

77. Eurostat. Land cover overview by NUTS 2 regions. *Eurostat Data Browser* https://ec.europa.eu/eurostat/databrowser/view/LAN_LCV_OVW__custom_1670798/default/table?lang=en (2021).

78. European Commission. *EU agricultural outlook for markets and income 2020-2030*. https://data.europa.eu/doi/10.2762/252413 (2020).

79. Pretzsch, H., Biber, P., Schütze, G., Uhl, E. & Rötzer, T. Forest stand growth dynamics in Central Europe have accelerated since 1870. *Nat. Commun.* **5**, 4967 (2014).

80. Ciais, P. *et al.* Carbon accumulation in European forests. *Nat. Geosci.* **1**, 425–429 (2008).

81. Kauppi, P. E., Posch, M. & Pirinen, P. Large Impacts of Climatic Warming on Growth of Boreal Forests since 1960. *PLOS ONE* **9**, e111340 (2014).

82. Kint, V. *et al.* Radial growth change of temperate tree species in response to altered regional climate and air quality in the period 1901–2008. *Clim. Change* **115**, 343–363 (2012).

83. Hellmann, L. *et al.* Diverse growth trends and climate responses across Eurasia's boreal forest. *Environ. Res. Lett.* **11**, 074021 (2016).

84. de Wergifosse, L. *et al.* CO2 fertilization, transpiration deficit and vegetation period drive the response of mixed broadleaved forests to a changing climate in Wallonia. *Ann. For. Sci.* **77**, 70 (2020).

85. Searchinger *et al.* High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. *Nat. Clim. Change* **5**, 481–486 (2015).

86. Jenkins, C. N., Pimm, S. L. & Joppa, L. N. Global patterns of terrestrial vertebrate diversity and conservation. *Proc. Natl. Acad. Sci.* **110**, E2602–E2610 (2013).

87. Kier, G. *et al.* Global patterns of plant diversity and floristic knowledge. *J. Biogeogr.* **32**, 1107–1116 (2005).

88. Martin, N. & Couwenberg, J. *Organic Soils in National Inventory Submissions of EU Countries.* greifswaldmoor.de/files/dokumente/GMC%20Schriften/2021_Martin%26Couwenberg.pdf (2021).

89. Barthelmes, A. Reporting greenhouse gas emissions from organic soils in the European Union: challenges and opportunities. 17 (2018).

90. Tanneberger, F. *et al.* Mires in Europe—Regional Diversity, Condition and Protection. *Diversity* **13**, 381 (2021).

91. Palaearctic Grasslands in Transition: Overarching Patterns and Future Prospects. in *Grasslands of the World* (eds. Squires, V. R., Dengler, J., Hua, L. & Feng, H.) 29–40 (CRC Press, 2018). doi:10.1201/9781315156125-9.

92. Tudge, S. J., Purvis, A. & De Palma, A. The impacts of biofuel crops on local biodiversity: a global synthesis. *Biodivers. Conserv.* **30**, 2863–2883 (2021).

93. Bellamy, P. E. *et al.* The impact of growing miscanthus for biomass on farmland bird populations. *Biomass Bioenergy* **33**, 191–199 (2009).

94. Vanbeveren, S. P. P. & Ceulemans, R. Biodiversity in short-rotation coppice. *Renew. Sustain. Energy Rev.* **111**, 34–43 (2019).

95. European Commission. *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0554 (2021).

96. European Commission. Land use and forestry regulation for 2021–2030. *Climate Action* https://ec.europa.eu/clima/eu-action/forests-and-agriculture/land-use-and-forestry-regulation-2021-2030_en.

97. European Commission. Land Use, Forestry and Agriculture. https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/land-use-forestry-and-agriculture_en.