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Impacts of a 32-billion-gallon bioenergy landscape on land and fossil fuel use in the US

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Sustainable transportation biofuels may require considerable changes in land use to meet mandated targets. Understanding the possible impact of different policies on land use and greenhouse gas emissions has typically proceeded by exploring either ecosystem or economic modelling. Here we integrate such models to assess the potential for the US Renewable Fuel Standard to reduce greenhouse gas emissions from the transportation sector through the use of cellulosic biofuels. We find that 2022 US emissions are decreased by 7.0 ± 2.5% largely through gasoline displacement and soil carbon storage by perennial grasses. If the Renewable Fuel Standard is accompanied by a cellulosic biofuel tax credit, these emissions could be reduced by 12.3 ± 3.4%. Our integrated approach indicates that transitioning to cellulosic biofuels can meet a 32-billion-gallon Renewable Fuel Standard target with negligible effects on food crop production, while reducing fossil fuel use and greenhouse gas emissions. However, emissions savings are lower than previous estimates that did not account for economic constraints.

The Energy Independence and Security Act of 2007 established the Renewable Fuel Standard (RFS) that sets annual targets for biofuels from various feedstocks, including the amount of ethanol that must be produced from cellulosic biomass versus corn grain[1]. As originally conceived, the RFS targeted the production of 36 billion gallons (136 billion litres) of biofuel in 2022, of which at least 16 billion gallons (60 billion litres) were to be from cellulosic sources with a greenhouse gas (GHG) intensity of less than 60% relative to conventional gasoline. A cap of 15 billion gallons (57 billion litres) was set for corn-grain ethanol. The RFS provides the flexibility for the total volume of cellulosic biofuels to be larger than 16 billion gallons if the mix of feedstocks (for example, harvest residues, perennial grasses, wood) is economically viable. These feedstocks differ widely in their GHG intensity, their land-use requirements, and production costs[2]. To promote cellulosic ethanol production and market competitiveness, supplemental policies have been implemented, particularly a cellulosic biofuel production tax credit[1]. These policies affect the competitiveness of biofuel pathways differently, the mix of biofuels produced, and the GHG emissions savings from the same total volume of biofuels[3].

Several experimental and ecosystem modelling studies have investigated optimum yields for perennial grasses such as prairie[4], switchgrass[5–7] and miscanthus[8,9], as well as the GHG mitigation potential of cellulosic crops[10]. GHG reductions from perennial grass management (versus corn) are because of reduced fertilizer requirements[11,12], little to no soil cultivation, and greater allocation to belowground biomass leading to an increase in soil carbon[13]. Other studies have examined the effects of the RFS and biofuel and climate policies on land use and GHG emissions using economic modelling frameworks and relying on yields and GHG emissions that were not estimated using an integrated ecosystem model[1,3,14]. Our aim here is to improve on previous studies that have considered primarily economic drivers[1,3] or ecological and biophysical drivers[10,15] through model integration, thus providing a more realistic estimate of land allocation, biofuel mix, and the associated GHG consequences of new energy pathways.

In this study, we combine empirical observations, ecosystem modelling of yield and GHG balance (DayCent[10,16,17]), and economic modelling (BEPAM-F; refs 14,18) to provide economically feasible bioenergy landscapes under alternative policy scenarios (Fig. 1). Because we include an interlinked transportation sector in our economic modelling, we are able to examine how reductions in domestic and global gasoline displacement impact GHG emissions. Using this approach, we determine the GHG implications of a 32-billion-gallon (121-billion-litre) bioenergy landscape under the RFS (the rest of the 36-billion-gallon mandate being potentially met by waste sources) in the US by 2022, and examine the changes in land allocation and GHG balance when a cellulosic biofuel production tax credit (RFS + Tax Credit; $1.01 per gallon) is applied, while meeting the demand for food, fuel, and feed crop production. This demand is determined by exogenous market demand curves for food crops and endogenously determined crop prices. We quantify the major factors influencing the above- and belowground GHG balance due to bioenergy crop production and the effects on GHG emissions in each policy scenario, including both domestic and global indirect land-use change and domestic and global gasoline market rebound effects due to the changes in food and fuel prices induced by biofuel production. This rebound effect arises as large-scale biofuel production in the US reduces demand for gasoline in the world market, thus lowering its domestic and world market price, leading to a feedback on gasoline consumption; the consequential impact of this on the extent to which a gallon of biofuel displaces less than an energy equivalent gallon of gasoline differs across studies[19–24].

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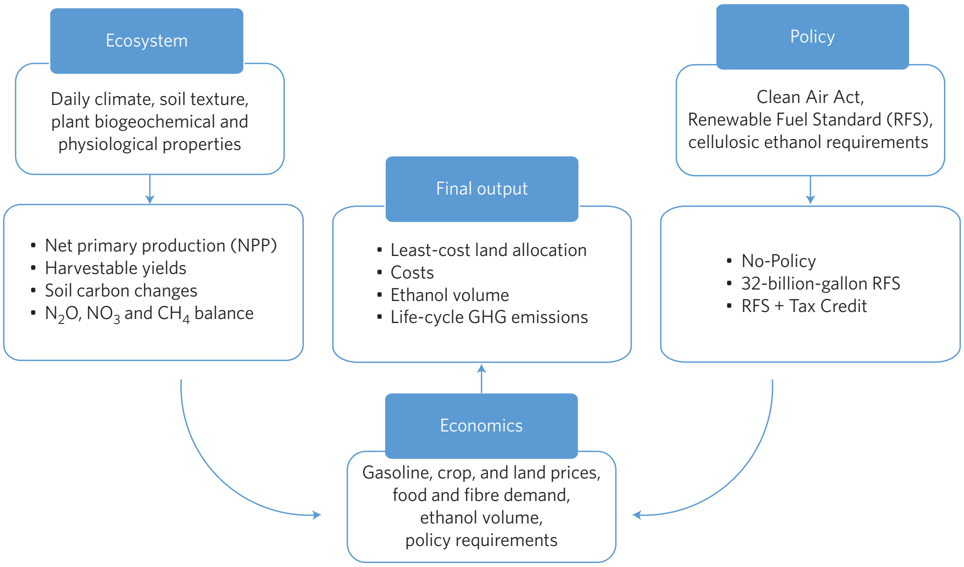

Figure 1 | Integrated modelling framework of combined ecosystem and economic modelling. We combined process-based ecosystem modelling with economic modelling to test different biofuel policy scenarios. Ecosystem model outputs of biomass yield, soil carbon, and GHG balance are used as inputs to the economic model. The economic model then predicts land allocation while accounting for cost, life-cycle GHG emissions, ethanol volume, available land, and food requirements. Different policy scenarios (no biofuel policy, RFS, the RFS including a tax credit) are used to test the different land allocations and associated GHG emissions that can result.

Combined ecosystem–economic modelling

The ecosystem model (DayCent) simulates the effects of climate and land-use change on carbon and nutrient cycling and has been validated for use in crop ecosystems, including perennial grass yield and GHG balance[25–27]. The economic model (BEPAM-F) is a multi-market, dynamic, open economy model that integrates the agricultural, forestry, and transportation fuel sectors in the US. The model extends BEPAM (ref. 14) by adding a forestry sector and allowing for shifts between cropland and forestland based on the net land returns in the two sectors, and by including bioenergy crop yields and GHG estimates from DayCent. Market equilibrium is achieved by maximizing the sum of consumers' and producers' surpluses in the agricultural, forestry, and transportation fuel sectors, and government revenue subject to various material balance, technological, land availability, and policy constraints over the 2007–2022 period. The model endogenously determines the domestic direct and indirect land-use change and the domestic and global gasoline consumption, prices and market displacement effects. Estimates of international indirect land-use change due to different types of biofuel feedstocks are based on existing studies[28].

Feedstock yields and land allocation

Ecosystem modelled yields of miscanthus and switchgrass dry biomass averaged 22.0 and 10.3 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$, respectively (Supplementary Fig. 1), with the highest yields in the central and southeastern states. Corn stover harvests averaged 0.5 to 5.0 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ across the nation, depending on tillage practices and removal rates (30–50%), with the highest yields in irrigated portions of west Texas and portions of the central states. Modelled yields agreed with reported values across the region (Supplementary Fig. 2; $r^2 = 0.62$ and 0.86 for switchgrass and miscanthus, respectively).

Compared to a No-policy scenario (no biofuel policy), both the RFS and RFS + Tax Credit policy scenarios increased land allocated to energy crops (Table 1; 4.2 and 12.0 million hectares, respectively), whereas the RFS scenario alone increased land allocated to corn and corn-grain ethanol (7.5 million hectares). The RFS + Tax scenario actually reduced corn-grain ethanol land compared to No-policy scenario. Land was acquired from both marginal land (grazing or idle land) and cropland used for food and fibre sources; however, the amounts and relative contributions varied. For the RFS only scenario, land converted to perennial grasses (3.9 million hectares) was mostly from grazing or idle land (Fig. 2a), with a smaller portion coming from food and fibre cropland. In addition, 7.5 million hectares of food and fibre land were transferred to corn for grain and ethanol. In contrast, the RFS + Tax Credit scenario resulted in 10 million hectares converted to perennial grasses, with nearly equal contributions from grazing and idle land and food and fibre cropland sources (Table 1 and Fig. 2a). However, because corn ethanol land was reduced compared to the No-policy scenario, this scenario resulted in negligible effects on total land allocated to food production.

In the RFS scenario, perennial grasses were primarily located south of the Corn Belt, from eastern Kansas to Virginia, east Texas, and in part of Alabama (Fig. 3a). The tax credit increased the number of counties with perennial grasses, extending into North and South Dakota and portions of the Corn Belt (Fig. 3b). The distribution of corn stover land changes in the RFS + Tax Credit scenario compared to the RFS scenario (Fig. 3d) by doubling the number of counties participating.

Under the RFS only scenario, 15 billion gallons of the mandated 32 billion gallons was corn-grain ethanol. In contrast, supplementing the RFS with a \$1.01 per gallon tax credit for cellulosic biofuels increased the competitiveness of cellulosic ethanol relative to corn-grain ethanol, and induced an additional 15 billion gallons of cellulosic biofuel that displaced corn-grain ethanol while meeting the overall mandated quantity of biofuel. This reduced the demand for corn, such that the amount of land allocated to corn decreased from 32.2 million hectares with the No-policy scenario to 29.6 million hectares under the RFS + Tax Credit scenario.

GHG implications

We used the ecosystem modelled GHG balance (CO_2, N_2O, CH_4) for perennial grass and corn stover agriculture combined with life-cycle emissions to calculate the net GHG emissions for the land allocation scenarios. Compared to the No-policy scenario, total 2022 US GHG domestic emissions (including domestic ILUC and

Table 1 | Total land allocation, biofuel production, and 2022 GHG emissions.

Scenario	No-policy	RFS only	RFS + Tax Credit
2022 Land allocation (million hectares)			
Forestland	151.6	149.9	149.8
Idle land	15.1	14.1	13.6
Grazing land	9.1	5.2	3.4
Corn-grain and grain ethanol	32.2	39.7	29.6
Other food and fibre	92.0	87.0	91.4
Perennial grass ethanol	0.0	3.9	10.0
Other cellulosic ethanol*	0.0	0.3	2.0
Total land allocated	*300.0*	*300.0*	*300.0*
2022 Fuel consumption (billion gallons)			
Gasoline and diesel	173.3	157.4	157.4
Corn-grain ethanol	3.9	15.0	0.0
Corn stover ethanol	0.0	7.1	11.1
Perennial grass ethanol	0.0	5.1	13.4
Other cellulosic ethanol	0.0	3.9	6.9
Other biofuels	0.4	0.9	0.6
Total biofuel production	*4.3*	*32.0*	*32.0*
2022 GHG emissions (million Mg CO_2e)			
US Direct[†]			
US Gasoline and diesel	2,097.0	1,891.7	1,887.6
Corn (grain and stover)	69.0	89.0	56.0
Perennial grasses	0.0	−22.5	−61.8
Other crops[‡]	10.0	7.0	10.0
Production emissions	12.0	48.4	2.1
Indirect			
Domestic rebound effect	0.0	20.8	24.4
2022 Total domestic GHG emissions	*2,188.0*	*2,034.4*	*1,918.3*
Global direct and indirect			
Global gasoline and diesel	4,303.0	4,095.0	4,091.0
Domestic biofuel emission	91.0	121.9	6.3
ILUC	1.1	1.7	0.6
Global rebound effect	0.0	97.5	102.0
2022 Total global GHG emissions	*4,395.1*	*4,316.1*	*4,199.9*

We show the 2022 projected LCA emissions for the US (domestic) and global fuel transportation sector associated with No-policy, a 32-billion-gallon RFS, and RFS including a cellulosic tax credit for the year 2022. The LCA includes aboveground GHG emissions (N_2O and CO_2) associated with planting, cultivation, and harvest of the crop biomass and the emissions associated with production of ethanol. *BEPAM land allocation and the 32 billion gallon total includes wheat and forestry residues in addition to corn grain, corn stover, and the perennial grasses. [†]Direct US emissions include domestic ILUC due to changes in the returns to land in different uses due to biofuel-policy-induced changes in prices of agricultural commodities and forest products. [‡]Includes emissions associated with wheat residues, rotation crops with corn (for example, soy) and forestry residues.

fuel market effects) were reduced by 154 ± 51 (7%) million tons CO_2e for the RFS only scenario and reduced by 270 ± 65 (12%) for the RFS + Tax Credit scenario (Table 1). When international ILUC and global fuel market effects were included that take into account the rebound in gasoline consumption due to a lowering of its world price as gasoline is displaced by biofuels, the GHG savings achieved by the RFS were reduced. However, despite a reduction in displacement due to ILUC and global rebound effects, we found that the RFS has the potential to reduce US GHG emissions by 4% (80 ± 51 million tons CO_2e) relative to the No-policy level of 2,188 million tons in 2022. The corresponding reduction in GHG emissions under the RFS + Tax Credit case was 9% (196 ± 65 million tons CO_2e).

These GHG emissions reductions were significantly lower (by at least 50%) than estimates obtained by other studies that were based on ecological models only and did not consider the market responses of land use and gasoline consumption to changes in crop and fuel prices due to biofuel production[10,15]. Previous estimates simulated either conversion of all Midwest agricultural land[15] or only prime corn-producing acres[10] to fuel production. In this analysis, economic constraints guided the placement of bioenergy feedstocks on land uses with lower opportunity costs of conversion, some of which (for example, pasture and marginal land) have lower baseline GHG emissions compared to corn-producing areas, thereby reducing the estimated reduction in emissions. The US GHG reductions achieved by biofuel policies were primarily due to the reliance on perennial energy crops that are net sinks of carbon when used as biofuel feedstocks to displace gasoline in the transportation sector.

To ascertain the relative contributions of above- and belowground emissions to the total GHG balance, we compared the N_2O emissions (Fig. 2b), the aboveground CO_2 emissions (planting, harvest, transport, conversion to ethanol), and the belowground CO_2 emissions (soil carbon changes and CH_4 flux) for switchgrass, miscanthus, and corn stover. Net GHG emissions for each of these feedstocks compared to the baseline land use were totalled and divided by the land allocated. For the RFS + Tax Credit scenario, and in agreement with numerous studies[9,13,29], we found that the belowground CO_2 emissions were largely responsible for the net GHG reduction by switchgrass and miscanthus on a per hectare basis (Fig. 2b). Compared to net belowground CO_2 emissions by corn residue removals as reported in other studies[30], the perennial grasses could sequester an average of 6–9 tons of CO_2e per hectare. N_2O emissions by the perennial grass systems were half of the

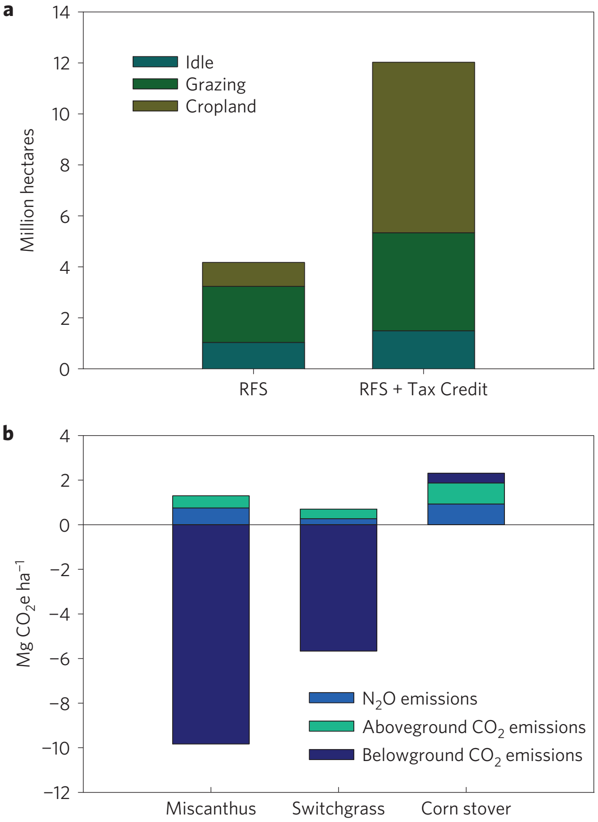

Figure 2 | Sources of land converted to energy-only crops and GHG contributions. a, Land flux to energy crops: we considered only land that is cropland (arable or marginal) at present and is for food and fibre (brown), is idle (blue), or is used as pasture land for grazing (green). Cropland includes land used for corn-grain ethanol. **b**, Contribution of each GHG to the total GHG balance for the RFS + Tax Credit scenario only. N_2O emissions (light blue) include direct (DayCent) and indirect (IPCC Tier 1 emissions factors). CO_2 emissions include belowgound (dark blue; soil C, CH_4) and aboveground CO_2 emissions (green) associated with feedstock production. Positive numbers indicate CO_2e emissions to the atmosphere whereas negative numbers indicate removals.

corn stover emissions because of the low fertilizer requirements for switchgrass and miscanthus (0–100 kg N ha^{-1}; refs 11,12) compared to corn (70–220 kg N ha^{-1}; USDA usage data). Overall, we found that total GHG emissions from the US transportation sector decreased under the RFS scenario relative to No-policy scenario, largely owing to the negative GHG intensity of perennial grasses and the displacement of fossil fuels even after leakage effects were incorporated (Supplementary Table 1).

Uncertainty analysis

The majority of the uncertainty in our ecological modelling estimates was due to the lack of observed GHG and yield data for perennial grasses at the more northern and southern locations of the study region. DayCent modelled output of yield, soil carbon, and total land-based GHG balance were comparable with other results, both observed and modelled, although there still remains uncertainty considering changes to growth potential with technology[31] and lack of measurements documenting changes in soil carbon. Reported data of soil carbon sequestration are limited to a few sites and difficult to detect quantitatively over time periods less than ten years. Measurements of net carbon uptake using eddy-covariance and biometric estimates suggest the perennial grasses are storing 1–2 Mg C ha^{-1} yr^{-1} (refs 32,33) and, because the aboveground biomass is harvested and removed annually, the storage must be belowground. Moreover, long-term measurements of soil carbon revealed an increase of 2–3 Mg C ha^{-1} yr^{-1} under miscanthus in Ireland[34], 1.1 Mg C ha^{-1} yr^{-1} under miscanthus in Germany[35], and ∼1 Mg C ha^{-1} yr^{-1} under switchgrass in Nebraska[36], and could continue for several decades depending on the soil capacity to store carbon. The modelled estimates reported here average 2.4 (miscanthus) and 1.4 (switchgrass) Mg C ha^{-1} yr^{-1}, at the upper range of reported values, indicating a potential high bias in our net GHG reduction estimates. To assess the sensitivity of the economic model land allocation and GHG balance to the uncertainty in yield and GHG projections from the ecosystem model, we calculated the final GHG balance and land allocations for yields ±20%, soil carbon changes ±40% and N_2O ±30%, based on a previous model evaluation[27] (Supplementary Fig. 2).

The majority of uncertainty in our economic modelling and final GHG balance is a combination of the propagated error in our ecological model output (input to the economic model) and economic parameters, whose estimates are likely to be uncertain in the future, as well as the assumptions regarding ILUC and global rebound effects of the gasoline market. These include the elasticity of supply of gasoline, the elasticity of demand for vehicle miles travelled, the availability of cropland pasture for conversion to energy crops, the elasticity of corn yields to corn price, the rate of growth of food crop yields, and the cost of cellulosic biofuel production (see Supplementary Methods). Using the propagation of error approach[37], we estimate a total uncertainty of 33% (±51 million Mg CO_2e) and 24% (±65 million Mg CO_2e) for the RFS and RFS + Tax Credit scenarios, respectively (Fig. 4). After accounting for the uncertainty in yields, GHG changes, the economic parameters, and ILUC and rebound effects, the total transportation sector GHG balance for the scenarios was still changed compared to the No-policy scenario, and more carbon was stored in soils with perennial grass management included.

Economic cost of biofuel policies

We estimated the economic cost of biofuel policies by comparing the change in the discounted value of the consumer and producer surplus in the agricultural, forestry and transportation sectors and government revenue in the US under the RFS (and the RFS + Tax Credit) scenario over the 2007–2022 period with that in the No-policy case (see Supplementary Methods). We found that the RFS leads to net economic benefits for the US in addition to the environmental benefits, because it improves the US terms of trade. The rise in agricultural commodity prices caused largely by the 15 billion gallons of corn ethanol production increases the value of US agricultural exports, while the displacement of fuel imports by the 32 billion gallons of biofuels reduces the price of US fuel imports[14,38–40]. The addition of the subsidy imposes a net discounted cost of $75 billion over the 2007–2022 period relative to the RFS alone due to smaller beneficial effects on agricultural producers and higher government costs. As a result, the additional cumulative reduction in global GHG emissions (0.5 billion Mg CO_2e) over 2007–2022 due to the addition of the subsidy to the RFS was obtained at a cost of $150 per ton of additional CO_2e abated.

Conclusions

Our findings show that a 32-billion-gallon ethanol mandate with significant reliance on perennial energy grasses as feedstocks can result in US agricultural and transportation sector GHG reductions of 7.0 ± 2.5% through displacement of fossil fuel even after accounting for uncertainty and considering the market-mediated effects of biofuel production on land use and domestic fossil fuel consumption in 2022; this is in contrast to previous findings[41]. The provision of a cellulosic biofuel production tax credit had

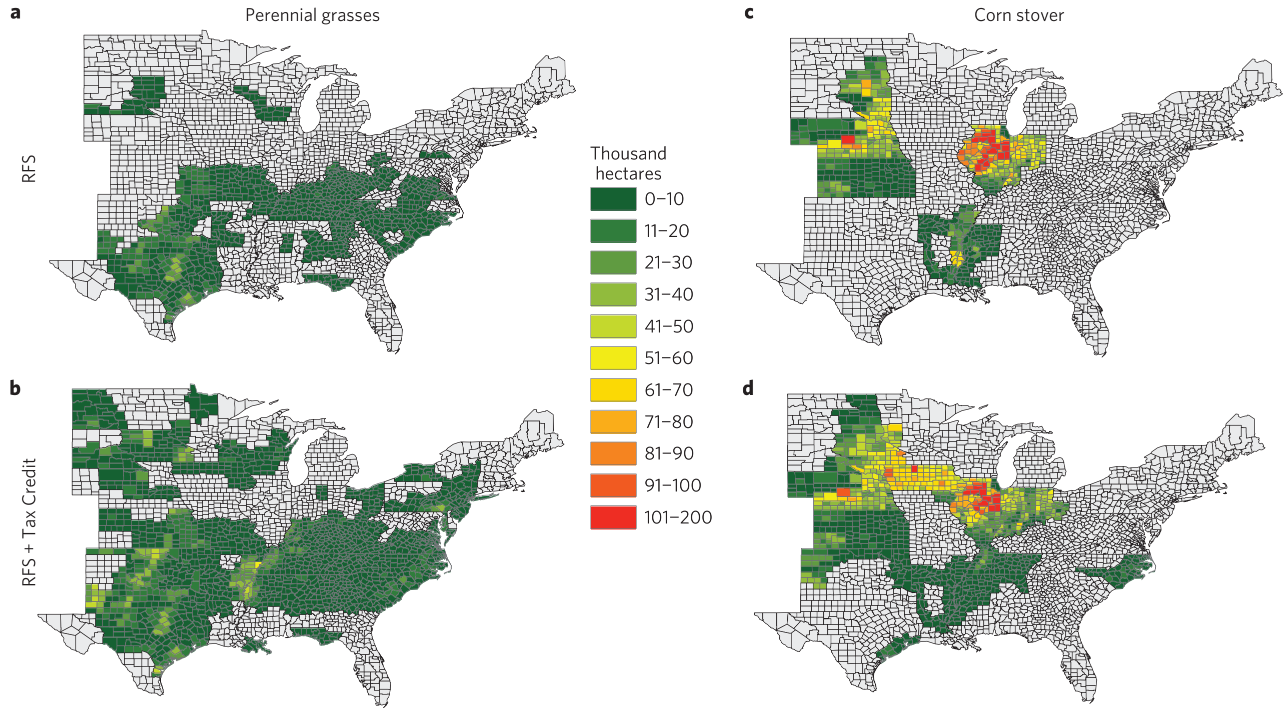

Figure 3 | Land allocation of perennial grasses and corn stover for the biofuel policy scenarios. BEPAM land allocation in thousand hectares for the RFS (**a**,**c**) and RFS + Tax Credit (**b**,**d**) scenarios is based on the crop yield and GHG balance modelled by DayCent, for perennial grasses (**a**,**b**) and corn stover removals (**c**,**d**). Corn stover removals are 30% if the baseline system is conventional till and 50% if the baseline system is no-till. Perennial grasses include miscanthus and switchgrass.

the potential to further expand cellulosic biofuel production and displace 15 billion gallons of corn ethanol while meeting the same overall mandate; this nearly doubles the annual reduction in US GHG emissions that can be achieved by a 32-billion-gallon mandate to 12.3 ± 3.4% relative to a no biofuel policy scenario in 2022. However, the additional reduction in cumulative GHG emissions over the 2007–2022 period is achieved at an economic cost of over \$150 per ton of CO_2e abated. The GHG reductions were partly due to increased soil carbon storage, because more land was allocated to perennial grass management, and due to displacement of gasoline in the transportation sector. The RFS resulted in 3.9 million hectares of US land converted to perennial grasses supplemented with corn residue to meet cellulosic ethanol requirements, and the addition of the tax credit increased land under perennial grasses to 10 million hectares. In contrast to the recent assertion that biofuels rely on reduced food production to provide a GHG benefit[42], our integrated economic–ecosystem modelling approach predicts that changing the mix of biofuel feedstocks from corn ethanol to high-yielding perennial crops could meet the 32-billion-gallon mandate without significantly reducing food production and with modest GHG savings.

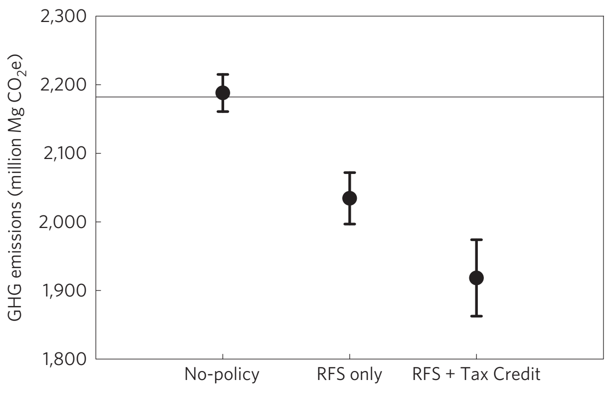

Figure 4 | Total US 2022 projected GHG balance estimates for each scenario. Total GHG balance (dots) includes domestic ILUC and domestic rebound effects. The error bars represent the combined GHG balance uncertainty from the ecological model output (yield, soil carbon, and N_2O emissions), the sensitivity of the economic parameters (elasticity of gasoline supply, the elasticity of demand for vehicle miles travelled, the availability of cropland pasture for conversion to energy crops, the elasticity of corn yields to corn price, the rate of growth of food crop yields and the cellulosic biofuel production cost) and the uncertainty associated with global ILUC and rebound effects.

Methods

Yield and GHG modelling. DayCent calculates plant growth as a function of water, light, and soil temperature, and limits actual growth based on soil nutrient availability. Model outputs include harvested yields, soil carbon uptake and loss, direct N_2O emissions (indirect calculated using IPCC Tier 1 factors), nitrate leaching, and methane flux. Required inputs for the model include vegetation cover, daily precipitation and temperature, soil texture, and current and historical land-use practices. Soil organic carbon is estimated from the turnover of soil organic matter pools, which change with the decomposition rate of dead plant material. For the perennial grasses, crop specific physiological parameterizations were performed using the values from a synthesis of studies (Supplementary Fig. 2). We simulated county-level yields for corn grain and stover removals, soy, miscanthus and switchgrass in the Eastern US states (Supplementary Table 2) on cropland and marginal land. We define marginal land as land that has been historically less productive cropland and has been idle or set aside as pasture for grazing. We also simulated the associated direct N_2O, CH_4, NO_3 leaching, and soil organic carbon changes for each crop using DayCent.

Land allocation. BEPAM-F determines the optimal land use and feedstock mix by maximizing the aggregated economic welfare subject to various resource balance and technological constraints for the years 2007–2022, represented in five-year time steps. The agricultural sector includes all major conventional crops and livestock animals, four bioenergy crops (miscanthus, switchgrass, hybrid poplar and willow) and two crop residues (corn and wheat) at the 295 Crop

Reporting District (CRD) level in the US. Five types of agricultural land (irrigated and non-irrigated cropland, idle cropland, cropland pasture and pasture land) are specified for each CRD. Land availability is responsive to crop and livestock prices and marginal lands can be used for energy crop production. Cropland can move freely between production of alternative crops with no extra cost, but subject to a complex combination of both historical and synthetic crop mixes and across uses[43]. We imposed a 25% limit on the amount of total agricultural land in a CRD that could be converted to perennial grasses for biodiversity considerations (see Supplementary Methods—economic modelling).

GHG life-cycle assessment. BEPAM-F estimates direct emissions from the use of gasoline and diesel in the transportation sector. It also includes emissions due to the direct change in land use (for example, for energy crop production). The aboveground emissions related to feedstock production (planting, maintenance and harvest) are estimated by multiplying various inputs in BEPAM-F with corresponding factors extracted from the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) model. These emissions were combined with the crop-based GHG emissions, including soil carbon sequestration, predicted by DayCent. Assumptions about emissions due to changes in forest cover, harvesting, planting and forest operations were obtained from FASOM (ref. 3). The life-cycle emissions intensity of gasoline and diesel were obtained from GREET (Supplementary Table 3). Although, BEPAM-F allows for trade in agricultural commodities, biofuels and gasoline, it does not model land-use change internationally. The emissions intensity of each biofuel feedstock due to indirect land-use change (ILUC) was obtained from the literature[28] and multiplied by the policy-induced amount of that feedstock used for biofuels predicted by BEPAM-F to obtain the change in total ILUC-related emission in each time period in each scenario (Supplementary Table 1).

Scenarios for integrated modelling. The DayCent model output was used to simulate three scenarios (No-policy, RFS, RFS + Tax Credit) in the BEPAM-F economic model. The No-policy scenario represented the land usage and crop production in the absence of any biofuel policy. The DayCent output for both conventional and no-till corn cultivation (that is, rotations varied such as corn-soy, continuous corn and so on) were considered the baseline scenarios on cropland for comparisons with perennial grass replacement. The Renewable Fuel Standard (RFS) scenario was based on the RFS established by the Energy Independence and Security Act (EISA), 2007 which mandates a 36-billion-gallon ethanol standard by 2022. We model a lower mandate of 32 billion gallons by 2022 that included a minimum of 16 billion gallons of cellulosic ethanol, a maximum of 15 billion gallons of corn ethanol and 1 billion gallons of advanced biofuel that could be met by imported sugarcane ethanol or domestic biodiesel from soy and corn; assuming the remaining volumes could be met by sources not included in the model, such as municipal solid waste, animal fats and waste oil. The RFS + Tax Credit scenario included a cellulosic biofuel production tax credit of $1.01 per gallon (27 cents per litre) (in addition to the 32-billion-gallon RFS) and is paid to fuel blenders for blending ethanol with gasoline to comply with the RFS.

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Author contributions

T.W.H., E.H.D., W.W. and M.K. designed and implemented the study with help from P.D., S.P.L., W.J.P. and M.H. T.W.H., W.W., E.H.D. and M.K. co-wrote the paper and W.J.P. and M.H. contributed to parts of the analysis. S.P.L. provided essential data and methods for the analysis and valuable comments on the manuscript.

Additional information

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Competing interests

The authors declare no competing financial interests.