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Impacts of future agricultural change on ecosystem service indicators

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Abstract. A future of increasing atmospheric carbon dioxide concentrations, changing climate, growing human populations, and shifting socioeconomic conditions means that the global agricultural system will need to adapt in order to feed the world. These changes will affect not only agricultural land, but terrestrial ecosystems in general. Here, we use the coupled land use and vegetation model LandSyMM to quantify future land use change and resulting impacts on ecosystem service indicators including carbon sequestration, runoff, and nitrogen pollution. We additionally hold certain variables, such as climate or land use, constant to assess the relative contribution of different drivers to the projected impacts. While indicators of some ecosystem services (e.g., flood and drought risk) see trends that are mostly dominated by the direct effects of climate change, others (e.g., carbon sequestration) depend critically on land use and management. Scenarios in which climate change mitigation is more difficult (Shared Socioeconomic Pathways 3 and 5) have the strongest impacts on ecosystem service indicators, such as a loss of 13–19% of land in biodiversity hotspots and a 28% increase in nitrogen pollution. Evaluating a suite of ecosystem service indicators across scenarios enables the identification of tradeoffs and co-benefits associated with different climate change mitigation and adaptation strategies and socioeconomic developments.

1 Introduction

Exploring how the agricultural system might shift under different plausible future climate and socioeconomic changes is critically important for understanding how the future world—with a population in 2100 larger than today's by anywhere from 1.5 billion to nearly 6 billion people (KC and Lutz, 2017)—will be fed. However, the implications of changing agricultural land area and management inputs go far beyond food security. The conversion of forests and other ecosystems to croplands or pasture—combined with the inputs required to produce food on those lands—emits large amounts of greenhouse gases, reduces the ability of the natural world to buffer against anthropogenic carbon dioxide emissions, results in pollution of important freshwater and marine ecosystems, harms biodiversity, and affects water availability and flood risk. Such impacts are not

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merely academic, because they affect the livelihoods of human societies which depend on a wide range of ecosystem services which broadly fall into three categories (IPBES, 2018a): regulating (e.g., greenhouse gas sequestration, flood control), material (e.g., food and feed production), and non-material (e.g., learning and inspiration). As global environmental and societal changes continue to accelerate over the coming decades, it is critical that we understand not just the impacts on the natural world, but how those impacts feed back onto humanity.

To explore the possible future evolution of the Earth system and society, models have been developed that simulate the global economy, natural world, and their interactions. A substantial body of research has been built up using such models to examine how future land-use change will affect individual ecosystem services such as carbon sequestration (Brovkin et al., 2013; Lawrence et al., 2018), biodiversity (Jantz et al., 2015; Hof et al., 2018; Di Marco et al., 2019), and water availability and flood risk (Davie et al., 2013; Elliott et al., 2014; Asadieh and Krakauer, 2017). Much less work has been undertaken to evaluate the future of a suite of ecosystem services in an integrated way (Krause et al., 2017; Molotoks et al., 2018). However, such analyses provide critically important evidence for balancing the many competing demands on the land system while achieving climate and societal targets such as those laid out in the Paris Agreement and Sustainable Development goals (Eitelberg et al., 2016; Benton et al., 2018; Verhagen et al., 2018).

Previously, we used the PLUM land-use model to estimate future land use and management change, based on changing socioeconomic conditions as well as climate effects on agricultural yield provided by the vegetation model LPJ-GUESS (Alexander et al., 2018). This coupled model system—the Land System Modular Model, or LandSyMM—is unique among global land-use change models in the high level of spatial detail that it considers in the response of agricultural yields to management inputs, as well as in allowing short-term over- and under-supply of commodities relative to demand (rather than assuming market equilibrium in every year). Here, we take advantage of the mechanistic modeling of terrestrial ecosystems provided by LPJ-GUESS to explore how PLUM-generated future land use and management trajectories—under different scenarios of future socioeconomic development and climate change—differ in their consequences for a range of regulating and material ecosystem services.

2 Methods

2.1 LPJ-GUESS and ecosystem services

The Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) is a dynamic global vegetation model that simulates—here, at a spatial resolution of 0.5 degrees—physiological, demographic, and disturbance processes among a variety of plant functional types (PFTs) on natural land (Smith et al., 2001, 2014). Agricultural land is also included, with cropland and pasture being restricted in the types of plants allowed and experiencing annual harvest. Transitions among land use types are given as an input, with LPJ-GUESS calculating the associated change in carbon pools and fluxes (Lindeskog et al., 2013). Four crop functional types (CFTs) are represented: C_3 cereals sown in winter and spring, C_4 cereals, and rice (Olin et al., 2015a). Nitrogen limitation on plant growth is modeled, with cropland able to receive fertilizer applications (Smith et al., 2014; Olin et al., 2015b). The mechanistic representation of wild plant and crop growth accounts for the CO_2 fertilization effect, by which

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productivity can be enhanced due to improved water use efficiency and (in C_3 plants) reduced photorespiration (Smith et al., 2014). Changes to irrigation, water demand, water supply, and plant water stress as described in the Supplementary Information of Alexander et al. (2018) were included.

LPJ-GUESS simulates indicators of a number of provisioning and regulating ecosystem services (see also Table 1 in Krause et al. (2017)). Along with providing some background information, the rest of this section will detail the relevant LPJ-GUESS outputs for the ecosystem service indicators analyzed in this paper having to do with carbon sequestration, water supply, nitrogen pollution, biogenic volatile organic compounds (BVOCs), and biodiversity.

The conversion of forests and other ecosystems to croplands or pasture has been responsible for about a third of humanity's CO_2 emissions since 1750. Land clearance for agriculture affects carbon storage by emitting vegetation and soil carbon from existing pools, as well as by reducing sequestration potential (Ciais et al., 2013). Land-based mitigation strategies—including reducing deforestation, increasing sequestration in natural and agricultural lands, and expanding biofuels' contribution to energy supply—could play a critical role in whether warming targets laid out in the Paris Agreement can actually be achieved (Rogelj et al., 2018; van Vuuren et al., 2018). The change in total carbon stored in the land system is used here as a measure of the carbon sequestration performed by terrestrial ecosystems.

Land use and management change can also impact how ecosystems regulate water quantity, quality, and flood risk (Wheater and Evans, 2009; Haddeland et al., 2014). Land use change affects runoff by changing how vegetation intercepts rainfall and takes up water from the soil. We consider average annual runoff as it contributes to water levels in lakes and rivers, which is important for not only freshwater ecosystems but also water availability for irrigation and other human uses (Davie et al., 2013). After Asadieh and Krakauer (2017), we also use the difference between 1971–2000 and 2071–2100 in the 95th percentile of monthly surface runoff ($P95_{month}$) as a proxy for changing flood risk (although note that those authors used daily values), and the difference in the 5th annual percentile ($P5_{year}$) for changing drought risk. Note that we are referring to hydrologic drought, which can be contrasted with, e.g., meteorological or socioeconomic drought (Wilhite and Glantz, 1985).

Crop fertilization is the main anthropogenic source of nitrous oxide (N_2O), a potent greenhouse gas responsible for the third-largest contribution of anthropogenic climate change (Fowler et al., 2009; Myhre et al., 2013; Shcherbak et al., 2014). Some is also emitted as nitric oxides (NO_x), which contribute to respiratory illnesses via surface-level air pollution (Yang and Omaye, 2009). Dissolved nitrogen compounds leach from agricultural land into freshwater and marine ecosystems, where they can contribute to their degradation via eutrophication and affect various ecosystem services, including fishery production (Vitousek et al., 1997). Here, we examine total nitrogen loss from terrestrial ecosystems as output by LPJ-GUESS.

Ecosystem services related to climate change and human health can be strongly affected by biogenic volatile organic compounds (BVOCs), which are emitted by plants—especially woody species (Rosenkranz et al., 2014)—for a variety of physiological functions. In regions where nitrogen oxides are elevated, their reactions with BVOCs produce tropospheric ozone, which is harmful to human health (Ebi and McGregor, 2008), can negatively affect photosynthesis (Ashmore, 2005), and is a greenhouse gas (Myhre et al., 2013). BVOCs also warm the planet by increasing methane lifetime (Young et al., 2009), but on the other hand they help form tropospheric aerosols, which increase reflectance and boost photosynthesis via diffuse radiation (Rap et al., 2018; Sporre et al., 2019). The latter can improve crop yields, but BVOC-enhanced ozone formation can work

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against that effect (Feng and Kobayashi, 2009). LPJ-GUESS simulates the emission of isoprene and monoterpenes—the most prevalent BVOCs in the atmosphere (Kesselmeier and Staudt, 1999)—and accounts for three important factors regulating their emission: temperature, CO_2 concentration ($[CO_2]$), and changing distribution of woody plant species due to climate and land use change (Arneth et al., 2007; Schurgers et al., 2009; Hantson et al., 2017).

Biodiversity underpins a wide range of ecosystem services due to its importance for ecosystem functioning (Tilman et al., 2014) and the possible use of wild species in improving crops (Castañeda-Álvarez et al., 2016) and developing new medicines (Simpson et al., 1996). Land clearance has also been—and will continue to be—responsible for declining biodiversity due to the loss and degradation of habitat (Jantz et al., 2015; Newbold et al., 2015). In addition to raising moral and ethical questions regarding extinction, this negatively impacts ecosystem services and thus people's livelihoods (IPBES, 2018b). Here we assess how much land is converted to agriculture within the Conservation International (CI) hotspots, a set of 35 regions covering less than 3% of the Earth's land area but containing half the world's endemic plant species and over 40% of the world's endemic vertebrate animal species (Myers et al., 2000; Mittermeier et al., 2004; Henry et al., 2019). These regions each contain at least 1500 endemic vascular plant species and have already lost at least 70% of their original natural vegetation, thus representing highly diverse areas presently at high risk of habitat loss.

2.2 PLUM

The Parsimonious Land Use Model (PLUM) is designed to produce trajectories of land use and management based on socioeconomic trends and gridcell-level crop and pasture productivity at a resolution of 0.5 degrees (Engström et al., 2016b; Alexander et al., 2018). Food demand is projected into the future based on the Shared Socioeconomic Pathway (SSP) scenarios (O'Neill et al., 2014; IIASA, 2014), using the historical relationship of per capita GDP to consumption of each of six crop types—C_3 cereals, C_4 cereals, rice, oilcrops, pulses, and starchy roots—plus ruminant and monogastric livestock (FAOSTAT, 2018a, b). Demand of a seventh crop type—dedicated bioenergy crops such as Miscanthus—is specified according to the SSP2 scenario described by Popp et al. (2017); demand for bioenergy from food crops is specified to double from 2010 by 2030 and thereafter remain constant. Demand is satisfied at the country level by either domestic production or imports, the balance between which is determined using a least-cost optimization considering commodity prices as well as the cost of fertilizer, irrigation water, and land conversion. A more detailed explanation of PLUM can be found in Alexander et al. (2018).

2.3 Simulation details

After a spinup of 500 years to bring vegetation and soil pools to a realistic starting point, a historical run spanning 1850 to 2005 was performed in LPJ-GUESS. The model state at the end of this run was used as the starting point for runs generating potential yields under different Representative Concentration Pathway (RCP) scenarios of climate and atmospheric CO_2 (van Vuuren et al., 2011). In each scenario, every grid cell is planted with each crop type, each of which is given six different management treatments in a factorial setup: fertilization of 0, 200, and 1000 kgN ha^{-1} and either no irrigation or maximum irrigation. PLUM then uses these potential yield estimates to generate time series of land use and management that satisfy crop and livestock demand calculated based on socioeconomic projections from the SSPs. Each socioeconomic scenario (SSP) is paired with a

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climate scenario (RCP) based on what sort of climate change could be expected under each SSP's storyline: SSP1 uses RCP4.5, SSPs 3 and 4 use RCP6.0, and SSP5 uses RCP8.5. More details on the setup of the calibration and yield-generating runs can be found in the Supplementary Methods (Sect. SM1).

PLUM has been found to perform well in this coupled system; its recreation of historical patterns and projections into the future are discussed in Alexander et al. (2018). Here, after extending the historical run to 2010, we feed PLUM's projections of 2011–2100 land use, nitrogen fertilizer application, and irrigation intensity back into LPJ-GUESS to simulate their impacts over that period. We refer to these experiments as the "PLUM-forced" runs. The Supplementary Methods include a figure illustrating the overall workflow (Fig. SM1) and table summarizing a summary of the run types can be found in Table SM1.

In addition to PLUM-forced runs with time-varying future climate and atmospheric CO_2, we perform several experiments to examine the impact of different factors on the land-use and -management projections generated by PLUM and thus the ecosystem service indicators simulated by LPJ-GUESS in the PLUM-forced runs. By holding either climate, atmospheric CO_2, or land use and management constant over 2011–2100, we can estimate the contribution of each to changing ecosystem service indicators in the future. The indirect contributions of changing climate and atmospheric CO_2—i.e., how they affect the land use and management pathways chosen by PLUM—are not considered.

2.3.1 Input data: LPJ-GUESS

Here, we describe the climate and land use data used in LPJ-GUESS. A summary can be found in the Supplementary Methods, Tables SM2–SM5.

The calibration run was forced with climate data from CRU-NCEP version 7 (Le Quéré et al., 2016), but with CRU TS3.24 precipitation (Harris et al., 2014) due to problems discovered in the CRU-NCEP precipitation data. All other runs used the atmospheric CO_2 concentrations and climate forcings from the Fifth Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012): specifically, the IPSL-CM5A-MR forcings (Dufresne et al., 2013), which were bias-corrected (Ahlström et al., 2012) to the 1961–1990 observation-based climate used by the calibration runs. Because not all SSP-RCP combinations are equally plausible, the PLUM-forced runs used future climate forcings corresponding to the most likely RCP for each SSP, based on the SSP-RCP probability matrix from Engström et al. (2016a): i.e., RCP4.5 for SSP1, RCP6.0 for SSP3 and SSP4, and RCP8.5 for SSP5. Three instances of the yield-generating runs were performed: one with each of the RCP climate scenarios.

Time-evolving historical land use fractions—i.e., the fractions of land in each gridcell that are natural vegetation, cropland, pasture, or barren—were taken from the Land Use Harmonization v2 dataset (LUH2; Hurtt et al., in prep.). The MIRCA2000 dataset (Portmann et al., 2010) provided crop type distributions for the year 2000, which were used for all historical years. Some mapping between MIRCA, LPJ-GUESS, and PLUM crop types was required, details of which can be found in the Supplementary Methods (Sect. SM2). Fertilizer application for the calibration run was taken from the dataset prepared for the Global Gridded Crop Model Intercomparison exercise (Elliott et al., 2015) of the Agricultural Model Intercomparison Project (AgMIP; Rosenzweig et al., 2013). In the historical period of other runs, nitrogen fertilizer application rates were taken from LUH2 (Hurtt et al., in prep). Manure N was added in the historical period according to the annually-varying maps given in

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Zhang et al. (2017) held constant at year 2000 levels in the calibration run to match the use of the AgMIP fertilizer data. Simulation years outside the dataset's 1860–2014 range used 1860 and 2014 values, respectively.

The PLUM outputs at the beginning of the future period do not exactly match the land use and management forcings used at the end of the historical period. Feeding the PLUM outputs directly into LPJ-GUESS—causing large areas of agricultural abandonment and expansion between 2010 and 2011—would thus complicate interpretation of the results, especially of carbon cycling. We developed a harmonization routine based on that published for LUH1 (Hurtt et al., 2011, http://luh.umd.edu/code.shtml). Briefly, the code begins with land use from LUH2 in 2010, then attempts to apply changes in land use area between PLUM's 2010 and 2011 outputs. In gridcells with no space to apply those changes, the algorithm attempts to find space in neighboring gridcells, expanding the search radius until the changes are satisfied. This process is then repeated, with the PLUM changes for 2011–2012 being applied to the harmonized 2011 land use map, and so on. More details on the harmonization procedure can be found in the Readme of the harmonization code (see Code Availability).

2.3.2 Input data: PLUM

In addition to the potential yields generated by LPJ-GUESS, PLUM considers a number of socioeconomic factors in estimating both future demand for commodities as well as how best to satisfy that demand. The Shared Socioeconomic Pathways (SSPs) provide a framework for generating scenarios of those socioeconomic factors' future evolution (O'Neill et al., 2014, 2015). Four of the five SSPs are used here. SSP1 characterizes a world shifting to a more sustainable pathway, with low population growth and strong technological and economic developments. SSP3 describes a pathway with strong population growth and intensive resource usage, low technological development and lessening globalization. SSP4 is a pathway of inequality with the potential for competition over resources and resource intensification. SSP5 is a pathway dependent on fossil fuels with low population growth, high economic and technological growth with strong globalization. (SSP2, a "middle of the road" pathway intermediate between the other four SSPs, is not considered here.) Scenario data on population (Jones and O'Neill, 2016) and GDP (Dellink et al., 2017) per country through 2100 were from version 0.93 of the SSP database (IIASA, 2014).

In addition to the input data provided by the SSPs, and following the approach described in Alexander et al. (2018), PLUM parameters—such as input and transport costs, tariffs, and minimum non-agricultural area—were also affected by the SSP narratives. Values were estimated for each SSP based on an interpretation of the storylines (O'Neill et al., 2015; Engström et al., 2016a) and can be found in Table SM6.

2.3.3 Experimental setups

In addition to the LPJ-GUESS runs forced with PLUM-output land use and management trajectories (harmonized as described in Sect. 2.3.1), six experimental runs were performed for each scenario, to disentangle the direct effects of climate change (including CO_2 concentration increases) from those of land use and management change. A "constant-climate+CO_2" 2011–2100 run used repeating 1981–2010 climate and constant 2010 CO_2 concentration; separate "constant-climate" and "constant-CO_2" runs were also performed. A "constant-LU" run used constant 2010 land use maps and management inputs. Finally, "onlyCO_2" and "onlyClimate" runs were performed using constant land use and either CO_2 concentrations or climate forcings

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from the RCP scenarios. The results of these experimental runs were used to inform interpretation of the results but are mostly not presented here. The Supplementary Results file contains figures (numbers prefixed with SR) supporting claims derived from the experimental runs, in addition to other figures that were not included here to conserve space.

3 Results and Discussion

3.1 Land use areas and management inputs

LandSyMM simulates net global loss of natural land area over the 21st century in all scenarios (Fig. 1), with SSP3 seeing the greatest loss of area (10%), SSP1 seeing the least (3%), and SSPs 4 and 5 seeing an intermediate loss (6%). These patterns are mostly reversed for pasture area change, in which all scenarios see an increase, although the trajectory for SSP5 is more similar to that of SSP3. PLUM also simulates net increased cropland area globally in all scenarios, with SSPs 1 and 5 seeing the least increase, SSP4 seeing more, and SSP3 seeing the most.

Cropland expansion happens at a more or less constant rate in SSP3 and SSP4, but these scenarios experience very different trajectories of crop commodity demand: SSP4 approximately levels off around midcentury, whereas SSP3 experiences only a brief slowdown in growth followed by constantly increasing demand through 2100 (Fig. SR1). The majority of the increased demand in the first half of the century is satisfied by fertilizer application, which increases by more than 75% from the 2010s to the 2050s while crop area increases by less than 15%. However, management inputs per hectare in SSP3-60 approximately plateau after midcentury (Fig. SR2), while crop demand rises 16%. Cropland area expands about 10% between 2050, with boosted productivity—thanks to climate change and/or CO_2 fertilization—helping to satisfy the rest of the increased demand. Since SSP4-60 experiences the same climate and CO_2 fertilization but with level crop demand during the second half of the century, management inputs decrease after about 2050.

Although population growth in SSP5-85 is more than twice that of SSP1-45, PLUM simulates very similar trajectories of global crop demand in both: an increase until about 2040 followed by a decrease for the rest of the century, with SSP5-85 crop demand ending slightly higher. SSP5-85 livestock demand increases about 20% more than in SSP1-45, which explains the rest of the difference in global caloric needs between the two scenarios (Fig. SR1). However, because SSP5-85 experiences much stronger climate change and CO_2 increase, the two scenarios differ importantly in how they satisfy their crop demand over the century. Whereas cropland area increases more or less constantly in SSP1-45 (slightly slowing throughout), in SSP5-85 it decreases over the first two or so decades, increases slowly after about 2050, and ends at a slightly lower global extent than in SSP1-45 despite a jump in the early 2090s as feed becomes more important in raising ruminant livestock (Fig. SR3). Crop production remains similar between the two scenarios, especially in the first half of the century, because SSP5-85 applies much more fertilizer and irrigation water per hectare (Fig. SR2). This gap in these inputs narrows in the second half of the century as climate change and the CO_2 fertilization effect become even stronger in SSP5-85 relative to SSP1-45, although the latter also begins to increase what PLUM calls “other management” intensity (representing, e.g., pesticide application).

Several regional patterns in crop area stand out:

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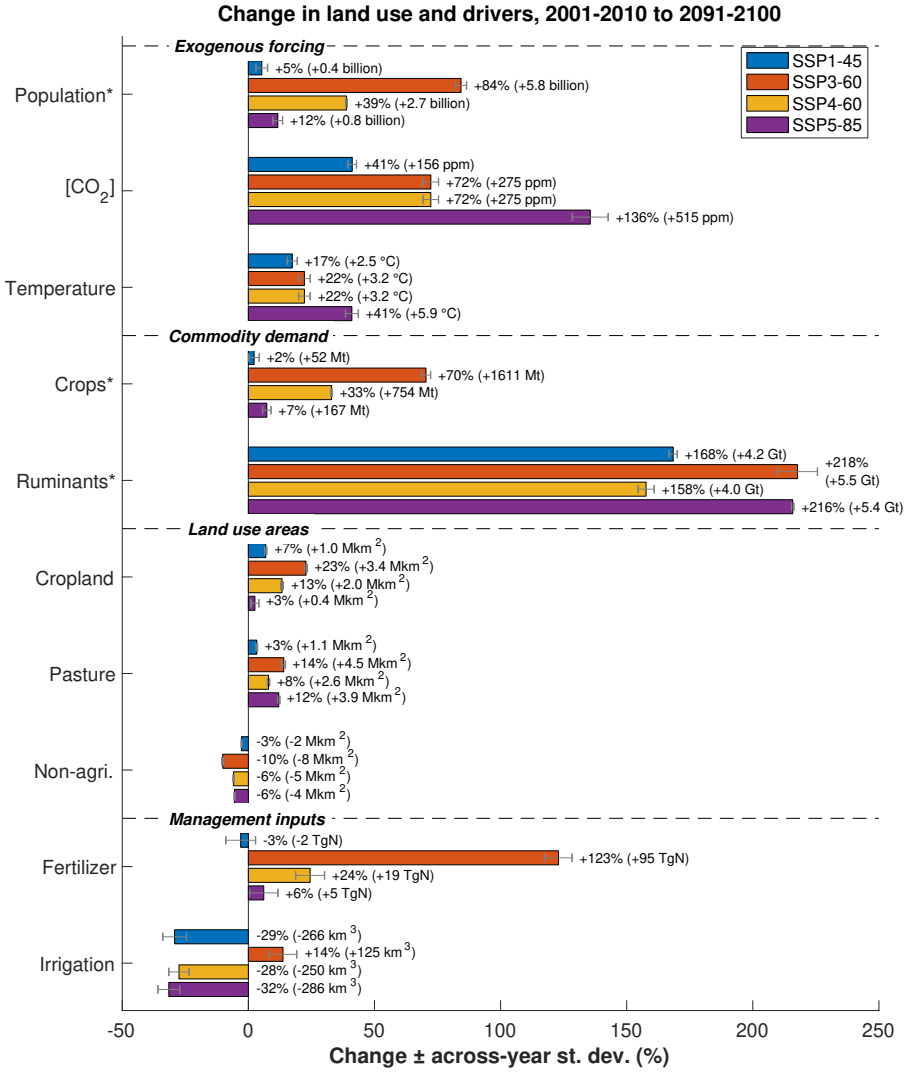

Figure 1. Percent change in global socioeconomic, land management, and atmospheric variables between 2001–2010 and 2091–2100. Whiskers represent interannual variability as standard deviation of the difference (i.e., $\sqrt{\sigma^2_{2001\text{-}2010} + \sigma^2_{2091\text{-}2100}}$). Ruminant demand given in units of feed-equivalent weight. *Asterisk indicates variables whose baseline is 2010 instead of 2001–2010 mean.

– North America loses cropland in parts of the Great Plains (mainly C_3 cereals; Fig. SR4) and the Midwestern U.S. (mainly oilcrops; Fig. SR5) in all scenarios. This is at least partially replaced—to a varying extent among the scenarios—with land in Alaska and the southeastern U.S. In the latter, new cropland is mostly planted with energy crops (SSP3-60 and SSP4-60; Fig. SR6) and rice (SSP3-60; Fig. SR7). New cropland in Alaska is entirely planted with spring wheat and is most extensive in SSP5-85 (Fig. SR4), which sees the largest increase in North American cereal demand—nearly 250% by the end of the century (Fig. SR8)—but also the largest potential yield increase in Alaska, thanks to RCP8.5's high

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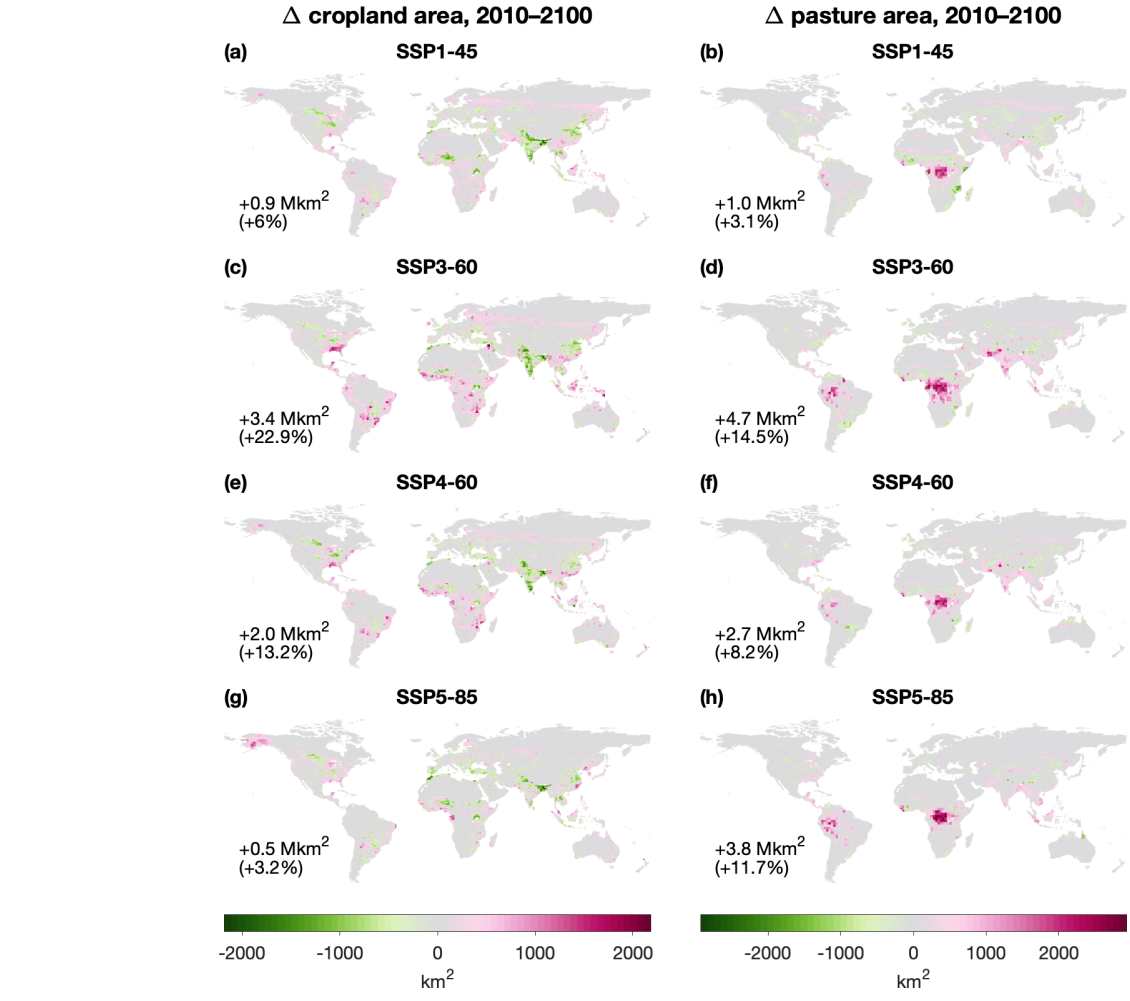

Figure 2. (**Left column**) Change in cropland area from 2010 (LUH2) to 2100 (harmonized PLUM) under each SSP-RCP scenario. (**Right column**) As left column, but for pasture. Note that color scales differ between columns.

warming and CO_2 fertilization. Indeed, by 2091–2100, the potential yield of rainfed C_3 cereals there is similar to or exceeds that of the parts of the Great Plains where cropland is lost (Fig. SR9).

– Although crop demand in South Asia increases by more than 100% in SSP5-85 and 170% in SSP3-60 (Fig. SR10), that region loses large amounts of cropland. Imports increase from zero to 5–30% of South Asia's food and feed crop demand (respectively) by the end of the century, but to satisfy the remaining 70–95%, PLUM calculates that the region's crop production would approximately double in both scenarios (Fig. SR11). While some of this is accomplished through increased management inputs in a region where the yield gap is large in the baseline, it also depends markedly on yield boosts due to climate change and rising CO_2 concentrations: C_3 cereal yields in the constant land-use experiments triple

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(RCP 6.0) or quadruple (RCP 8.5) across large parts of Pakistan and India. This is mostly due to a CO_2 fertilization effect, especially in RCP 8.5, which sees widespread areas of yield decline in the onlyClimate experiment (Fig. SR12).

– Sub-Saharan Africa sees even larger crop production increases, ranging from +200% in SSP1-45 to +500% in SSP3-60 (Fig. SR13). In contrast to South Asia, nearly the entire region experiences negative yield effects from the changing climate, and the counteracting effect of CO_2 fertilization results in yields that are only net slightly boosted in the constant-LU experiments (e.g., Fig. SR12). The heightened production comes instead from increased management inputs and, to a much smaller degree, cropland expansion.

Pasture is projected to expand significantly in the western Amazon in SSP3-60 and SSP5-85, and even more so in all scenarios in the African rainforest (Fig. 2). This tropical deforestation is largely driven by the increasing consumption of ruminant products in those regions: As incomes increase in developing tropical countries, PLUM forecasts greater consumption of commodities such as meat and milk and a reduction in staples such as starchy roots and pulses (Keyzer et al., 2005; Tilman et al., 2011). Depending on the SSP, ruminant products are simulated to account for 23–43% of calories in central Africa by 2100, compared to only 4–7% of calories consumed in 2010 (caloric density derived from FAOSTAT, 2018c). Between 50 and 98% of the ruminant production increase in central Africa goes to this domestic consumption.

The African pasture expansion even occurs in SSP1-45, the "Sustainability" scenario (O'Neill et al., 2015), in which LandSyMM simulates a net global pasture expansion of about 1 Mkm^2. For comparison, five other land use models all saw SSP1 pasture area decrease, by an average of about 3.4 Mkm^2 (Popp et al., 2017). Some of the discrepancy between the LandSyMM land-use trajectories and those of the other models is likely due to inherent differences in how processes are represented. Several factors related to experimental setup and overall model structure may contribute as well.

First, PLUM makes no assumption about changes in food production needs besides what occurs due to population and GDP changes. The storyline for SSP1, however, with its "low challenges to mitigation," suggests that people will gradually shift to lower-meat diets (O'Neill et al., 2015) than would be expected given GDP levels, at first at least in high-income countries. IMAGE—which simulates a decrease in pasture area of about 7 Mkm^2 by the end of the century (Doelman et al., 2018)—incorporates this dietary shift as a 30% (global) reduction in meat consumption relative to what would have otherwise been simulated, and additionally includes a 33% reduction in food supply chain losses to represent efficiencies from improved management and infrastructure (Doelman et al., 2018). Weindl et al. (2017) use the MAgPIE model to show that, under a scenario like ours where historical differences in livestock production efficiency are maintained or exacerbated, a shift to lower-meat diets can reduce the expansion of pasture in sub-Saharan Africa by over 50%.

Second, the land-use modeling components of most integrated assessment models (IAMs)—for example, all those contributing to the LUH2 trajectories (Hurtt et al., 2011)—include demand for timber and other products. The carbon value of forests (and land more generally) can also be included by some, even if forest products are not explicitly modeled (e.g., MAgPIE; Humpenöder et al., 2014), which could come into play in scenarios with policy-based incentives designed to minimize emissions from deforestation and degradation and/or to maximize carbon sequestration. In contrast, PLUM includes neither forest products nor land carbon value. The only "friction" PLUM considers in converting a forest to agriculture is the cost

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of conversion, with the opportunity cost of lost forest products or services ignored. Similarly, the only incentive to replace existing agricultural land with forest would be to avoid costs associated with production. Work currently underway to include forest products, payments for carbon sequestration, and managed forestry into LandSyMM may result in more forest simulated over the course of the century. This is especially likely for SSP1, whose storyline specifies a gradual improvement in how the global commons are managed (O'Neill et al., 2015). As an example, IMAGE represented this improvement in SSP1-45 by (a) disallowing clearing of forests with carbon density greater than 200 tons ha^{-1} and (b) reforesting half of the world's degraded or former forest.

The difference in land-use area between the most extreme scenarios is much higher in this work than in Alexander et al. (2018), by around 500% for cropland and 700% for pasture. The primary reason for this increase in inter-scenario variation is that Alexander et al. (2018) used the SSP2 socioeconomic scenario for all RCPs, whereas here we compare different SSPs paired with appropriate RCPs. Even with this increased spread, however, the LandSyMM trajectories are more closely clustered than those from some other land use models. IMAGE, for example, projects a range of cropland area increase from 0.4 Mkm^2 to 5.3 Mkm^2 across the five SSPs, and pasture trajectories ranging from a decrease of 7.3 Mkm^2 to an increase of 4.4 Mkm^2 (Doelman et al., 2018). As described above, IMAGE makes a number of assumptions (based on the SSP storylines) regarding future deviations from historical "business-as-usual" trends and relationships, including dietary shifts, infrastructure efficiency improvements, and forest conservation.

3.2 Ecosystem service indicators

3.2.1 Carbon storage

Carbon stored in the land system increases for all SSP-RCP scenarios, primarily due to an increase in vegetation carbon (Fig. 3). The increase in each scenario relative to the others depends on both intensity of climate change as well as amount of natural land lost. The large increase of atmospheric CO_2 (and thus greater carbon fertilization) in RCP 8.5 compared to RCP 6.0 means that SSP5-85 has a much greater increase in terrestrial carbon storage than SSP4-60, despite those scenarios having similar trajectories of natural land area (Fig. 1). SSP3-60, which had the most natural land lost but only intermediate carbon fertilization, sees the lowest increase in terrestrial C storage over the century—less than a third that of SSP4-60, which has the same trajectory of changing climate and atmospheric CO_2 concentration but a much smaller population increase.

The contrast between effects of changing climate and atmospheric CO_2 concentration vs. changing land use and management is starker for vegetation carbon than any other indicator variable examined here. In the constant-LU experiment, vegetation carbon increased 35%, 43%, 43%, and 54% for SSP1-45, SSP3-60, SSP4-60, and SSP5-85, respectively. The constant-climate+CO_2 experiment, on the other hand, saw respective *decreases* of 5%, 15%, 8%, and 9%.

Vegetation carbon increases are most pronounced in the tropical and boreal forests (Fig. 4) and are due primarily to CO_2 fertilization, although increasing temperatures and growing season length also contribute in the boreal zone (Fig. SR14). Extensive conversion to pasture far outweighs any carbon fertilization effect in the African tropical forest, which loses nearly all of its vegetation carbon and up to half its total carbon by 2100 in all scenarios.

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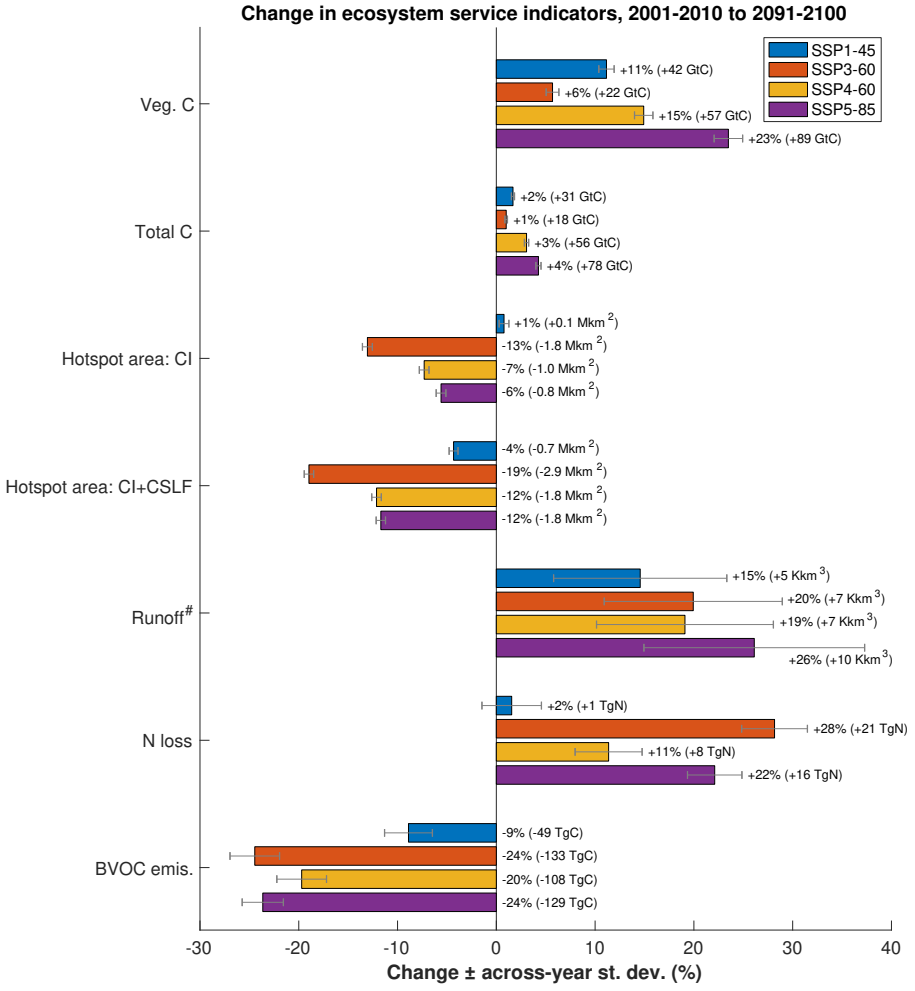

Figure 3. Percent global change in ecosystem service indicators between 2001–2010 and 2091–2100. Whiskers represent standard deviation of the difference (i.e., $\sqrt{\sigma^2_{2001\text{-}2010} + \sigma^2_{2091\text{-}2100}}$). CSLF: Congolian swamp and lowland forests (see Sect. 3.2.5). #The time periods compared for runoff were 1971–2000 and 2071–2100 due to high interannual variability.

Our results for carbon sequestration fall near the lower end of previously-reported projections. Brovkin et al. (2013) examined the change in land carbon storage over 2006–2100 for a number of climate and land surface models. They found that the IPSL-CM5A-LR Earth system model, when forced with emissions and land use change from RCP8.5, simulated uptake of ~400 GtC. This is much greater than our finding of ~78 GtC under SSP5-85 (Fig. 4) despite their land use change scenario (from LUH1; Hurtt et al., 2011) having lost about 30% more non-agricultural land. The difference is probably due in large part to our pasture expansion in the central African and western Amazon rainforests (and to a lesser extent, cropland expansion in Alaska). Most of their agricultural expansion occurs in the northern sub-Saharan African savannas, and even there the change (in units of percentage of the grid cell) only reaches about 30%. Moreover, none of the models in Brovkin et al. (2013) limit

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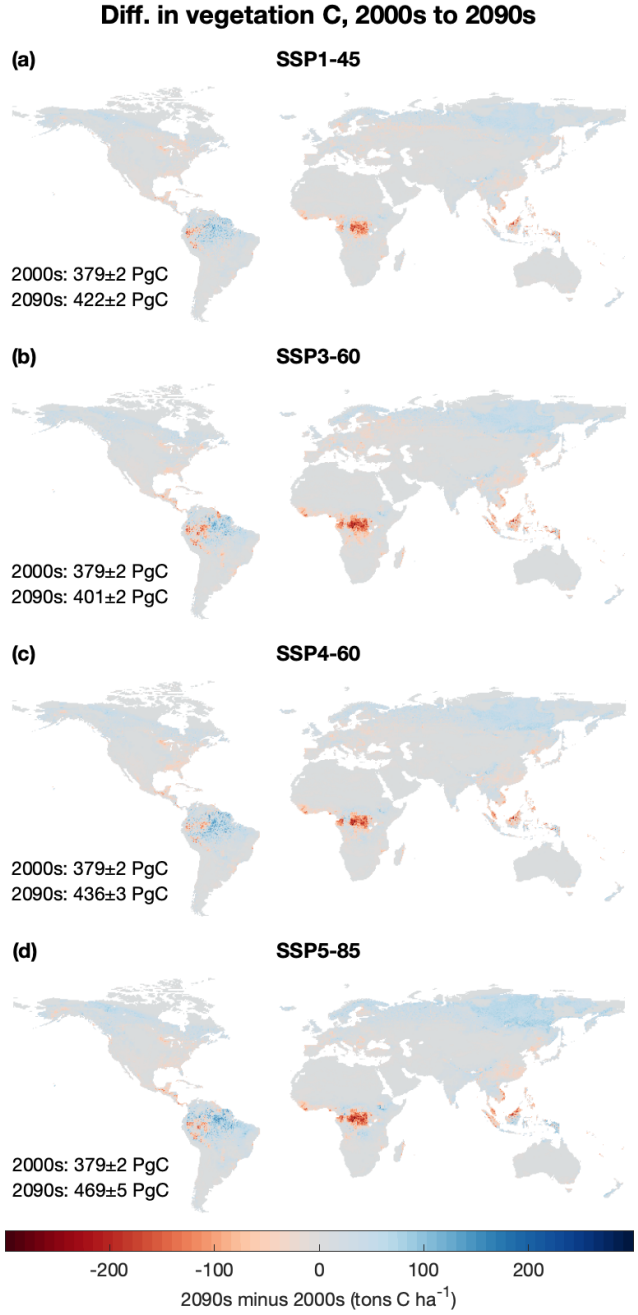

Figure 4. Maps showing difference in mean vegetation carbon between 2001–2010 ("2000s") and 2091–2100 ("2090s") for (**a**) SSP1-45, (**b**) SSP3-60, (**c**) SSP4-60, (**d**) SSP5-85. Overlaid text provides decadal means and standard deviations.

photosynthesis based on nitrogen availability. However, we also see low simulated carbon sequestration under constant land use compared to the models in Nishina et al. (2015), even when excluding models that did not simulate nitrogen limitation.

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Another study with LPJ-GUESS, Krause et al. (2017), used land use trajectories from the IMAGE and MAgPIE IAMs given RCP2.6 and SSP2, finding an increase in total land carbon pools of 34 GtC and 64 GtC, respectively. Land use scenario played an important role in those results and likely contributes to the discrepancy with ours: Their IMAGE pasture area increased from ~35 Mkm^2 to ~40 Mkm^2, whereas their MAgPIE pasture area decreased to ~30 Mkm^2 and our SSP1-45 pasture stays around ~32 Mkm^2.The IMAGE cropland area used in the baseline run of Krause et al. (2017) stayed approximately constant at ~18 Mkm^2, as does our SSP1-45's (although at ~15 Mkm^2), but their MAgPIE cropland area increased to ~20 Mkm^2. Other important differences between the runs in Krause et al. (2017) and ours include our use of different climate forcings and associated photosynthesis scaling parameters.

3.2.2 Runoff

Global runoff increases in all scenarios (Fig. 5). Again, SSP3 and SSP4 (the two RCP6.0 scenarios) see similar changes; SSP1-45 sees a smaller increase, and SSP5-85 sees the greatest. Comparison of the experimental runs shows that climate change is the most important factor in this increase at a global level in all scenarios (Fig. SR15). Increasing CO_2 levels generally tend to decrease runoff, a result also seen in two global vegetation models analyzed by Davie et al. (2013), although two others in that comparison showed the opposite effect. Land-use change makes the least difference in terms of global annual runoff, but can be important at the regional level. Deforestation in central Africa, for example, is the primary driver of increasing mean annual runoff there.

Such regional patterns in runoff change are arguably more important than global means, since impacts of low water and flooding are actually felt at the level of individual river basins. Between 1971–2000 and 2071–2100 under SSP5-85, 44% of land area saw increasing flood risk, with a mean $P95_{month}$ increase of 48%. Drought risk increased in 34% of land area, which saw a mean $P5_{year}$ decrease of 59%. At the same time, however, 43% of gridcells saw decreasing flood risk (mean $P95_{month}$ decrease 50%), and 44% saw decreasing drought risk (mean $P5_{year}$ increase 88%). Other scenarios saw similar fractions of area affected, but smaller mean magnitude of change in flood or drought metric.

Most of the changes in SSP5-85 result from climate change, with some notable exceptions. Land-use change alone contributes notably to increasing drought risk in Iraq, Pakistan, India's Punjab province, the Great Plains of the U.S., and eastern China (Fig. 5); it contributes to increasing flood risk in northeastern China, India's Rajasthan province, and the central African rainforest. Land-use change can also serve to counteract the impacts of climate change on runoff. For example, the severity of very low runoff events increases in central America, but it would have increased more if not for the expansion of agriculture there. The effects of land-use change on runoff might be stronger and more widespread if LPJ-GUESS were run coupled with a climate model, which would account for associated changes in land-atmosphere water and energy fluxes that can have similar impacts on the hydrological cycle as greenhouse gas emissions (Quesada et al., 2017).

The LandSyMM results for SSP5-85 are compared with the RCP8.5 ensemble from Asadieh and Krakauer (2017) in Table 1. Our results for fraction of land in each class are roughly similar for most classes, except for increasing drought risk, more of which is found in the Asadieh and Krakauer (2017) ensemble. In all categories, LandSyMM finds a mean effect of stronger magnitude. Some differences between our results and those of Asadieh and Krakauer (2017) might be expected because we

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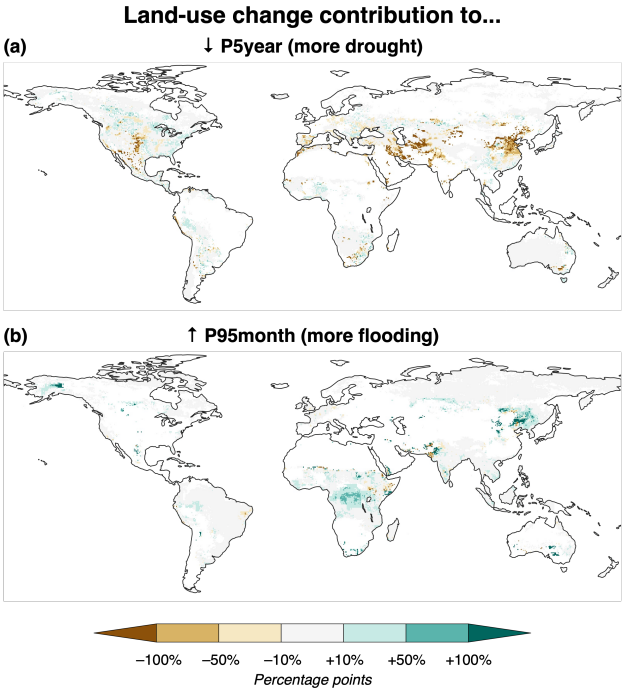

Figure 5. Contribution of land-use change in SSP5-85 to (**a**) decreasing $P5_{year}$ (drought) and (**b**) increasing $P95_{month}$ (flooding) between 1971–2000 and 2071–2100. White areas either did not have decreasing $P5_{year}$ or increasing $P95_{month}$, respectively, or were excluded due to low baseline runoff (after Asadieh and Krakauer, 2017). Contribution calculated as difference between full run and constant-LU run.

used a single climate model and monthly instead of daily values for P95. Perhaps more importantly, however, LPJ-GUESS is not a full hydrological model: e.g., it does not include river routing. The effect of this can be somewhat explored by aggregating our results to the basin scale, at which LPJ has been shown to compare well to dedicated hydrological models (Gerten et al., 2004). Aggregating to the basins with which PLUM determines irrigation water availability does not change the fraction of included land area in any class by more than two percentage points, except for decreasing drought risk, which goes from 49% to 58% of included land. The mean change within every class is reduced in absolute terms, bringing our results closer to those from Asadieh and Krakauer (2017).

3.2.3 Nitrogen losses

While the evolution of total global nitrogen loss is fairly similar for all scenarios over the first two decades of the simulation, there are notable differences by the end of the century. N loss showed little net change over the century in SSP1-45, whereas SSP3-60 saw a large increase in total N losses. SSP4-60 did not see a notable change in total N losses. SSP5-85 saw an increase in total N losses, although less than that of SSP3-60.

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Table 1. Fraction of included land in each group of changing drought and flood risk. Numbers in parentheses give each group's mean percent change. Increasing and decreasing drought risks correspond respectively to decreasing and increasing P5; increasing and decreasing flood risks correspond respectively to increasing and decreasing P95. AK2017: Asadieh and Krakauer (2017).

Class	By gridcell	By basin	AK2017
↑ drought risk	38% (–59%)	39% (–58%)	57% (–51%)
↓ drought risk	49% (+88%)	58% (+49%)	43% (+30%)
↑ flood risk	49% (+48%)	51% (+32%)	48% (+25%)
↓ flood risk	47% (–50%)	46% (–42%)	52% (–21%)

Our N loss at the end of the historical period was similar to that of Krause et al. (2017), but whereas their runs estimated an increase in N losses of 60–80% under RCP2.6, ours under SSP1-45 increased only 2%. Krause et al. (2017) used fertilizer information from IMAGE and MAgPIE, which they note often exceeded what plants in LPJ-GUESS could actually take up. Coupling LPJ-GUESS with PLUM provides for a more internally consistent estimate of future N losses.

One interesting pattern is that climate and management changes can have similar effects on N losses. SSP3-60 sees global fertilizer application more than double by the end of the century, while SSP5-85 fertilizer application at end of the run is slightly lower than in 2011 (Fig. 1). This is reflected in the N losses for the constant-climate+CO_2 experiment, which increase 25% by the 2090s in SSP3-60 but only 7% in SSP5-85. However, in the full run, SSP3-60's N losses increase only about 27% more than SSP5-85's (Fig. 3). This is because the latter experiences higher average global temperatures (increasing gaseous losses) and a greater increase in runoff (increasing dissolved losses), due to the extreme RCP8.5 climate change scenario; in the constant-LU experiment, N losses in SSP3-60 and SSP5-85 increase by 15% and 24%, respectively. In either case—but especially under SSP3-60—these increases in fertilizer usage and concomitant nitrogen pollution would exacerbate humanity's already unsustainable impacts on nutrient cycling (Rockström et al., 2009).

3.2.4 BVOCs

Global combined BVOC emissions over 2001–2010 totaled ~546 TgC yr^{-1} (~503 and ~43 TgC yr^{-1} for isoprene and monoterpenes, respectively), which compares well with estimates from LPJ-GUESS (without PLUM) and other models (Arneth et al., 2008; Hantson et al., 2017; Szogs et al., 2017). Emissions decline in all scenarios: by the most in SSP3-60 and SSP5-85, slightly less in SSP4-60, and the least in SSP1-45 (Fig. 3). This reflects a combination of the effects of land-use change and [CO_2] increases. In the "constant-climate+CO_2" experiment, declines in combined BVOC emissions closely reflect declines in non-agricultural land area (most decrease in SSP3-60, less in SSP4-60 and SSP5-85, and least in SSP1-45; Fig. SR16). This is a function of the much higher BVOC emissions potential of forests relative to cropland and pasture, as also seen in results from Hantson et al. (2017) and Szogs et al. (2017). In the full experiment, BVOC emissions decline more in SSP5-85 than in SSP4-60 because the former has higher atmospheric [CO_2], which suppresses BVOC formation.

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Decreases in isoprene emissions are primarily driven by tropical deforestation for agriculture, especially the expansion of pasture in central Africa and South America, and to a lesser extent by the expansion of cropland for bioenergy in the south-eastern U.S (Fig. SR17). The suppressive effect of increasing [CO_2] is mostly counteracted in all RCPs by rising temperatures, which increase BVOC volatility. Monoterpene emissions in what is now tundra increase as woody vegetation expands there, but present-day boreal forests are the main drivers of declining monoterpene emissions. This is primarily due to the BVOC-suppressing effect of increasing [CO_2], but land-use change also contributes, especially in Alaska (Fig. SR18).

The globally decreased BVOC emissions in all scenarios could contribute a cooling effect in the future, due to expected lower tropospheric ozone concentrations, shorter methane lifetime, and enhanced photosynthesis thanks to more diffuse radiation. This would be counteracted somewhat by warming arising from the reduced formation of secondary aerosols, and it is important to note that the effects on climate are likely to vary from region to region (Rosenkranz et al., 2014). Southeast Asia and the southeastern U.S. are populous areas that could see public health benefits from the deforestation-induced reduction of isoprene emissions and associated ozone levels. However, note that in the latter (and to a lesser extent the former), agricultural expansion is mainly for growing bioenergy crops simulated in LPJ-GUESS as Miscanthus; BVOC levels would be reduced much less (or perhaps even increased) if woody bioenergy crops were grown instead on the same area (Rosenkranz et al., 2014). Moreover, the loss of natural land is itself associated with myriad negative health impacts (Myers et al., 2013), so it would be shortsighted to view deforestation-induced BVOC reductions as a public health boon.

It is important to keep in mind that the implications of changing BVOC emissions depend on complex, regionally-varying atmospheric chemistry that governs their effects on existing species (e.g., methane) and the formation of secondary products (e.g., ozone and aerosols). The LandSyMM framework, lacking as it does an atmospheric chemistry model, can thus inform only a surface-level discussion of the possible effects of changing BVOCs.

3.2.5 Biodiversity hotspots

The large expansion of agricultural land in SSP3-60 has direct consequences for habitat in biodiversity hotspots, which lose over 13% of their non-agricultural land in that scenario (Fig. 3). No other scenario lost more than 8%, and SSP1-45 actually saw a slight gain. However, note that the central African rainforest is not included in the CI hotspots, since that region did not meet the criterion regarding how much of its primary vegetation had been lost (Myers et al., 2000; Mittermeier et al., 2004). The amount of deforestation projected there in all scenarios would undoubtedly result in great impacts to regional and global biodiversity. We thus checked how much hotspot area is lost if we include the five ecoregions classified by Olson et al. (2001) as Congolian swamp and lowland forests (CSLF), which together roughly correspond to the area of pasture expansion common to all scenarios, into a new "CI+CSLF" hotspot map. This paints a worse picture in all scenarios, nearly doubling hotspot area loss in SSP3-60, more than doubling it in SSP4-60 and SSP5-85, and changing the 1% gain of SSP1-45 to a 9% loss.

Previously, Jantz et al. (2015) performed a similar analysis using the same hotspots, but with the LUH1 land-use scenarios over 2005–2100. Although they considered only primary land as habitat—i.e., any land that had once been agriculture or experienced wood harvest was "uninhabitable"—their results can still provide a useful perspective. Jantz et al. (2015) found losses of primary natural hotspot land of 25% in RCP4.5, 40% in RCP6.0, and 58% in RCP8.5. However, they found a smaller

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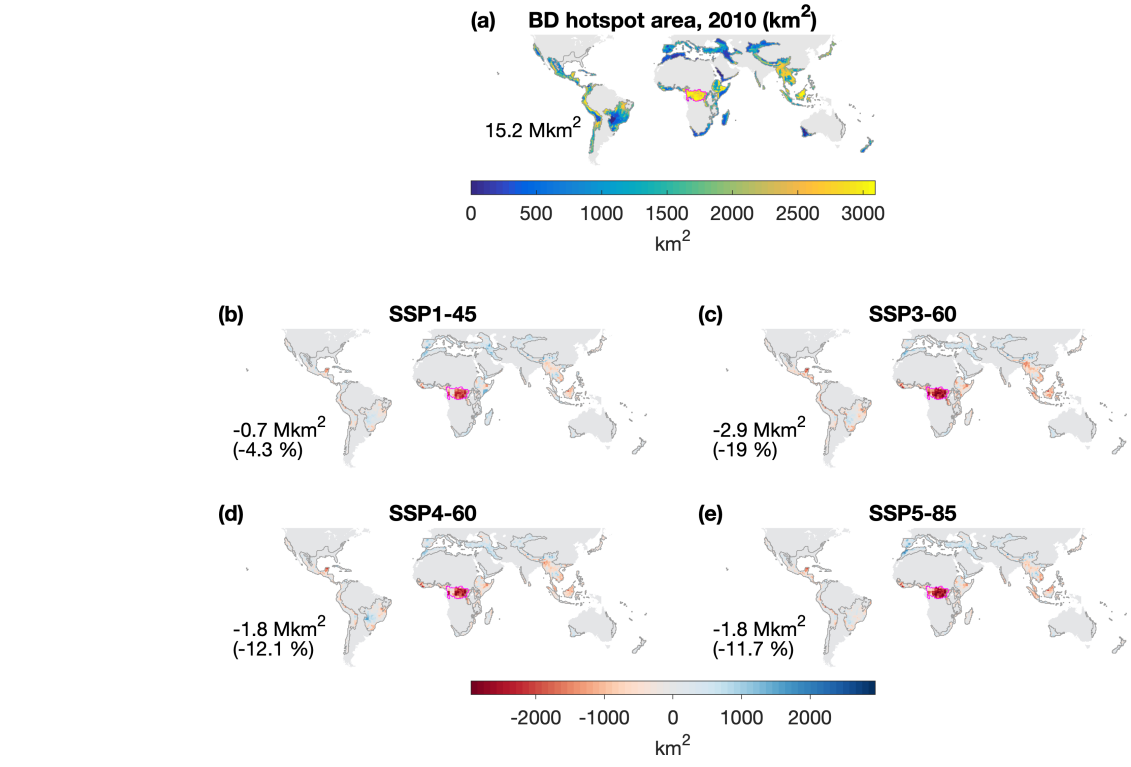

Figure 6. (**a**) Area (from LUH2) of non-agricultural land in "CI+CSLF" hotspots in 2010; (**b–e**) change in non-agricultural land area there by 2100 for each scenario. Black outlines indicate CI hotspots; magenta outline indicates CSLF region.

effect of land-use change using species-area curves to estimate the number of endemic species driven to extinction: 0.2–25% between 2005 and 2100. This is in part due to the shape of the species-area curves used in their calculations, in which the rate of extinctions per hectare lost is high at the beginning of land clearance in a region but falls as more area is cleared. This nonlinear effect is important to consider, especially considering how much land has (by definition) been cleared already in the hotspots, but such an analysis is beyond the scope of the present study.

Hof et al. (2018) considered the effects of both climate and land-use change under RCPs 2.6 and 6.0 on species distribution models of amphibians, birds, and mammals. They found that the area of land impacted by these combined threats was approximately equal between the two scenarios for birds and mammals (with more area affected for amphibians under RCP6.0), because although climate change was less detrimental under RCP2.6, to meet such an ambitious climate change target, that scenario required more land devoted to growing bioenergy crops. We may see a similar effect between SSP4-60 and SSP5-85: if ignoring cropland planted with Miscanthus, we see losses of natural land area in the CI+CSLF hotspots of approximately 1.1 and 1.5 Mkm^2, respectively, compared to about 1.8 Mkm^2 lost in both scenarios with Miscanthus cropland included. Ignoring Miscanthus cropland results in a CI+CSLF hotspot area net gain of <0.1 Mkm^2 for SSP1-45 and a loss of 2.0 Mkm^2 for SSP3-60.

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4 Conclusions

This work is among the first to consider the impacts of future land use and land management change on a suite of ecosystem services under different scenarios of climate and socioeconomic change. We show that storylines with high socioeconomic challenges to climate change mitigation—SSP3 and SSP5—consistently have some of the most severe consequences for the natural world and the benefits it provides humanity via carbon sequestration, biodiversity, and water regulation. These two scenarios also most strongly affect biogeochemical cycling of nitrogen and BVOCs; while increases in nitrogen losses are generally detrimental, the impact of decreased BVOC emissions is likely to vary regionally.

Policymakers and other stakeholders need options for how we can meet the needs of a growing and changing society while achieving climate and sustainable development goals (Benton et al., 2018). Some progress has already been made in this regard at landscape and global scales (Eitelberg et al., 2016; Verhagen et al., 2018). LandSyMM, and analyses it enables such as the ones presented here, can be another powerful tool in this aspect of the science-policy interface.

Code availability. The code for harmonizing land use and management is available for download on GitHub (Rabin, 2019).

Author contributions. All authors contributed to the conceptual design of LandSyMM. S. Rabin composed most of this manuscript, although all authors contributed to its editing. S. Rabin performed most analyses, with R. Henry helping to interpret PLUM results. P. Alexander and R. Henry managed PLUM code and performed PLUM runs. S. Rabin made changes as described to LPJ-GUESS code and performed LPJ-GUESS runs.

Competing interests. The authors declare that they have no conflict of interest.

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