Future patterns of US agricultural land use with multiple stressors

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Abstract

Land use in the U.S. will be affected directly by local and regional forces and indirectly through international trade. In order to investigate the effects of several potential forces on land use changes in the U.S. at multiple spatial scales, we advanced the capabilities in representing the interactions between natural and human system by coupling a multi-sectoral and multi-regional socio-economic model of the world economy with detailed representation of land use and agricultural systems to an open-source downscaling model which enables translating regional projections of future land use into high-resolution representations of time-evolving land cover. We apply the framework over the U.S. with a particular interest in the Mississippi river basin and consider the effects of a range of global drivers and stressors, such as: high or low economic and population growth, more negative or more positive impacts of climate change, and more or less dietary change. The resulting regional land use changes are further translated into more detailed projections of land use changes through the downscaling model. Our results show that higher pressures on agricultural land will lead to shifts from cropland to pastures, with low impact on forests. High resolution results are needed to better understand the implications of land use change on carbon storage, soil erosion, chemical use, hydrology, and water quality in future work dealing with environmental impacts. The employed downscaling model facilitates interoperability among models and across various spatial scales. The framework can be readily applied to other basins with little effort.

1. Introduction

Climate change, income and population growth, and changing diets will be major stressors for global agricultural markets with implications for land use change at global, regional and local levels. Land use in any particular region will be affected directly by local and regional forces and indirectly through international trade. There are wide-ranging views on how climate change will affect agriculture, how diets will change, and prospects for economic and population growth. There are debates and uncertainty about the general direction of these forces as it could affect land use globally and in the U.S. (Hertel 2011). Conventional studies suggest relatively little change in cropland use in the near-term to 2050 (Schmitz et al. 2014; Villoria 2019). But others have asked whether the various forces operating globally are a perfect storm in the making (Hertel 2011).

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Land use and land use change are important considerations in projecting future agricultural and bioenergy supply, ecosystem losses and conservation, climate and environmental change (Smith, 2005; IPCC, 2023; Hasegawa et al., 2021; Roe et al., 2019). Different types of land cover store varying amounts of carbon and changes from one land cover type to another can be a source or sink for carbon (Houghton and Nassikas 2017). Different land uses and associated practices on land can change methane and nitrous oxide emissions as well (Tian et al., 2015; Smith, 2005). Changes in land cover can also affect the earth's albedo and the water cycle through changes in evaporation, evapotranspiration and run-off (te Wierik et al. 2021). These varying changes can have effects on the global climate and local and regional climates. Large scale integrated assessment models (IAMS) now often include projections of land use, land cover, and changes in use and cover that are driven by changes in human activity and/or efforts to protect or restore natural land cover (Reilly et al., 2012; Schmitz et al., 2014; Popp et al., 2017). Often, however, these projections are relatively coarse, spatially, with representation of large countries or multi-country regions, whereas large scale General Circulation Models (GCMs) have a spatial resolution of 0.5 x 0.5 lat. long. degrees or finer (O'Neill et al. 2016). Moreover, IAMS often do not track or report specific transitions of individual land parcels, yet ecosystem science finds that land has a long memory such that its ability to take up carbon or act as a sink depends on its use history over decades to centuries (Melillo et al., 2009).

Projecting land use change with great fidelity at high spatial resolution including the transition of individual parcels of land is a demanding task. Such projections will likely always be subject to great uncertainty. Never-the-less, there are few efforts to downscale such projections. And even if there are great uncertainties in such projections, it is useful to have tools that can downscale land use projections in a numerically efficient manner, with a goal of representing uncertainty/different downscaling assumptions to test how much difference these make for climate projections. Ultimately, a goal is to have downscaled land use projections produce feedback effects on the IAM projections, since how or where land use changes can affect emissions projections, the yields of crops, land prices, and other factors that may then change an IAM's projections of land use itself.

Gurgel et al. (2021) investigate how major drivers of agricultural markets forces will impact land use changes in the U.S. and their implications from a multisector, multisystem dynamics (MSD) perspective focused on understanding dynamics and resilience in complex interdependent systems (Moss et al. 2016). However, they only look at the aggregate contiguous U.S., neglecting how these forces impact the spatial allocation of alternative land uses. In the present study, we extend that analysis to a more refined geographical level by combining the strengths of a multiregional economy-wide model with a versatile land use downscaling tool, focusing in particular on the Mississippi river watershed. As such, we investigate how global stressors might, in combination, affect local and regional land use change. Assessing the effects of global stressors on the spatial distribution of agriculture and land use along the Mississippi river watershed is relevant to allow future investigations of environmental implications for agricultural and crop distribution, carbon storage, soil erosion, chemical use, hydrology, and water quality.

Alternative procedures have been developed to downscale land use changes from global integrated assessment models (IAMs) to more refined geographical resolutions (Verburg et al., 2006; Melillo et al., 2009; Reilly et al., 2012; Hasegawa et al., 2017). There are also attempts to build partial equilibrium models with spatial refined economic and environmental driven decisions on land use (Baldos et al., 2020). However, these attempts have the caveat of being hard to reproduce or adapt to alternative modeling structures and spatial resolutions, or lack general equilibrium effects and competition among alternative land uses. Le Page et al. (2016) attempted to minimize such limitation by developing a downscaling tool to distribute land use projections from a regional model to a spatial disaggregated resolution using a set of flexible rules defined by modelers. The approach was developed to connect a specific IAM to a spatial resolution, but it is flexible enough to be adapted to other models and grid resolution. Here we extend the efforts of Le Page et al. (2016) to spatially assess land use effects in the U.S. and the Mississippi river basin from global drivers projected by Gurgel et al. (2021).

2. Methods

We simulate the effects of several driving forces on land use changes in a general equilibrium model of the world economy with regional detail that includes projections of land use change (Chen et al. 2016; Gurgel et al. 2016). We further connect the outputs from the economic model to a downscaling approach developed in the literature (Vernon et al. 2018; Le Page et al. 2016) to generate detailed projections of land use change for the US, focusing in particular on the Mississippi river watershed. We consider a range of scenarios (high or low economic and population growth, more negative or more positive impacts of climate change, and more or less dietary change) based on a comprehensive review of the literature.

At the world and regional level, our modeling approach explicitly represents socio-economic behavior and natural resources, and also interactions and feedbacks among them. The economic model is a multi-region, multi-sector model of the global economy with a detailed representation of agriculture sectors. The model captures multiple socio-economic and environmental drivers of agricultural and land markets and its interlinkages with the overall economy and physical land resources. It then can simulate the effect of different forces and stressors, operating independently or jointly, as they affect land use. The model covers the global economy and is expanded to include links to natural resources, including energy and land resources. It tracks changes in these resources, maintaining consistent accounts of both value and physical terms, and includes estimates of emissions of pollutants and greenhouse gases from industrial, energy, and land use sources. The scenarios are designed to capture the possible divergence in the strength of these global forces from a Business-As-Usual (BAU) projection.

The 18 regions, global economic model is an extension of the MIT Economic Projection and Policy Analysis model, version 6, a recursive-dynamic computable general equilibrium (CGE) model of the world economy (Chen et al. 2016; Gurgel et al. 2016). The economic data is sourced from the Global Trade Analysis Project Version 8 (GTAP 8) database (Narayanan et al., 2012). It provides the base information on social accounting matrices and the structure for regional economies, including bilateral trade flows and energy markets in physical units and is regularly updated from its original version. The extended version of the model represents 18 regions and 28 sectors. It includes 11 crop and livestock sectors plus a forestry industry, and a number of primary factor inputs (see Table 1). Among them are both depletable and renewable natural capital inputs, as well as produced capital and labor. Among produced capital, EPPA treats cropland, pastures, and managed forest land as "produced" from natural capital of forest areas and grasslands.

Besides the conventional economic accounts and sectoral data from GTAP, the model includes several alternative energy sectors and detailed transportation choices for households (Chen et al, 2015). Further disaggregation and parameterization of transport and electric power generation go beyond the GTAP base data, taking into account bottom-up engineering analysis of costs, fuel use, and conversion efficiency. The model associates GHG emissions (CO2, CH4, N2O, HFCs, PFCs, and SF6) and conventional air pollutant emissions (SO2, NOx, black carbon, organic carbon, NH3, CO, VOC) with various activities from the combustion of fuels, production cement, waste disposal, and agricultural activities (Boden and Andres, 2010; IEA, 2012; Bond et al., 2007; European Comission, 2011).

The model explicitly treats all inter-industry interactions and bi-lateral trade in goods. It considers domestic production, exports, imports, government expenditures, investment and household demand for final goods, and the ownership and supply of labor, capital and natural resources, assuring microeconomic and macroeconomic balances and consistencies. Supplemental accounts link physical quantities of energy (exajoules), emissions (tons), land use (hectares), population (billions of people), natural resource endowments (exajoules, hectares) and efficiencies (energy produced/energy used) of advanced technology with the economic transactions. This treatment captures the physical depletion and use of natural resources, technical efficiencies and availability of renewable resources. Thus, for example, an increase in population, increases the demand for food and other goods, and at the same time, the labor supply. These will cause a cascade of economic and environmental effects, from higher agricultural output and more demand for agricultural land, to changes in economic growth and international trade, which are fully accounted for and will lead to a new equilibrium in all markets and economies with a consequent impact on land use and natural resources. Similarly, changing population, trade openness, and crop yields will have cascading effects on food demand, economic growth, and other sectors of the economy.

The model simulates historical economic trajectories recursively to the year 2010 and 2015, and then projects future economic pathways at 5-year intervals from 2015 to 2100. Historical and near-term economic development is benchmarked to IMF's historical data and short-term GDP projections (IMF, 2019). The model is formulated using the mixed complementary problems (MCP) approach (Rutherford, 1995) and solved using the MPSGE subsystem in GAMS programming language (Rutherford, 1999).

Table 1. Regions, sectors and Primary Factor Inputs in EPPA

Regions		**Sectors**		**Primary Factor Inputs**	
United States (USA)	Africa (AFR)	Rice (PDR)	Coal	*Depletable Natural Capital*	Conventional Oil Resources
Canada (CAN)	Middle East (MES)	Maize (GRO)	Crude Oil		Shale Oil
Mexico (MEX)	Latin America (LAM)	Soybean (OSD)	Refined Oil		Conventional Gas Resources
JAPAN (JPN)		Wheat (WHT)	Gas		Unconventional Gas Resources
Australia and New Zealand (ANZ)		Sugar Crops (SGR)	Electricity		Coal Resources
Europe (EUR)		Vegetables & Fruits (V_F)	Non-Metallic Minerals	*Renewable Natural Capital*	Natural Forest (NFORS)
Eastern Europe (ROE)		Fiber plants (PBF)	Iron & Steel		Natural Grasslands (NGRASS)
Russia (RUS)		Other crops (OCR)	Non-Ferrous Metals		Solar and Wind Resources
East Asia (ASI)		Bovine Cattle	Other Energy-intensive Industries		Hydro Resources
South Korea (KOR)		Poultry and Pork	Other Industries	*Produced Capital*	Conventional Capital (Bldgs & Mach.)
Indonesia (IDZ)		Other Livestock	Construction		Cropland
China (CHN)		Forestry	Other Services		Pasture and Grazing Land (PATURE)
India (IND)		Wood Products	Transport		Managed Forest Land* (FORS)
Brazil (BRA)		Food Products	Ownership of dwellings		*Labor*

Future projections are driven by economic growth resulting from savings and investment, and exogenously specified productivity improvement in labor, capital, land, and energy. GDP and income growth through time increase demand for goods and services, including fuels and food. Sectors compete for the available flow of services from renewable resources generating rents. Backstop and advanced technologies may become cost-competitive as regular energy sources become more expensive. These various economic drivers, combined with imposed policies, such as constraints on GHG emissions, determine the economic trajectories over time and across scenarios.

The economic accounting of land-use in the model retains consistency with the supplemental physical accounts on land so that simulated changes in economic use of land translate into hectares of land, preserving total land area constraints in each region. The approach considers five broad land use categories: cropland, pasture, forest, natural forest and natural grass. Several world-scale data sources are reconciled for the purpose of this study. These include the GTAP8 Land Use and Land Cover Database,2 which is built from FAOSTAT production data and additional cropland and pasture data (Ramankutty, 2012). Data from the Terrestrial Ecosystem Model (TEM) (Felzer et al., 2004), using historical land use transitions (Hurtt et al., 2006), complements the land use database. Land and the transformation of natural lands into managed land types in physical terms is represented (Gurgel et al., 2016). The model considers that through land improvements (draining, tilling, fertilization, fencing) pastureland can be converted to cropland, or forestland can be harvested, cleared and ultimately used as pastureland or cropland. If investment in cropland is not maintained, the land can then go back to a less intensely managed use (pasture, or forest) or be abandoned completely and returned to “natural” grass or forest land.

The land use transformation approach used in the model is well suited to longer term analysis where demand for some land uses could expand substantially. The approach explicitly represents conversion costs associated with preparing the soil, spreading seeds and managing the creation of a new agricultural system. In this regard, it is a better alternative than the more common Constant Elasticity of Transformation (CET) approach often used in CGE models. The CET function makes large transformations of land difficult because the function tends to preserve input shares (Gurgel et al., 2007). The CET approach also does not explicitly account for conversion costs. In addition, the CET approach does not retain consistent accounting of economic and physical units of land so that you cannot translate a change in the quantity of land use in value terms to a physical change in hectares (Schmitz et al., 2014), an important consideration in tracking land use emission. Finally, as the CET elasticities are symmetric to all changes, the ease of conversion from agricultural to forest land is the same as from forest to agriculture, which implicitly assumes the same “costs” and constraints on conversion in both directions.

In the case of conversion of natural forests, the model accounts for the production of timber products similarly to a forest harvest on managed forest land. Natural areas transformation to agricultural areas are calibrated to mimic a land supply response, based on rates of conversion observed over the last two decades. This last feature captures a variety of factors that may slow land conversion, including increasing costs associated with larger deforestation in a single period and institutional costs (such as limits on deforestation, public pressures for conservation, or establishment of conservation easements or land trusts). The current version of the model is calibrated to a land supply value as reviewed in the literature (Hertel, 2011).

Assuming equilibrium in the base year, conversion costs from one land use category to another as equal to the difference in value of these types, thus assuring "zero profit" conditions in the MCP equilibrium approach. One issue that arises is a value for natural forest and grassland that is not currently used. To appear in the CGE framework it must have an economic value. We develop a "non-use value" for these land areas using data from on timber value on the land (Sohngen, 2007; Sohngen and Tennity, 2004; Sohngen and Mendelsohn, 1998). This approach assumes that, at the margin, the cost of access to remote timber land must equal the value of the standing timber stock plus that of future harvests as the forest regrows. The net present value of the land and timber is calculated using an optimal timber harvest model for each region of the world and for different timber types. Setting the access costs to this value establishes the equilibrium condition that observed current income flow (i.e., rent and returns) from currently non-accessible land is zero because the timber there now, and in the future, can only be obtained by bearing costs to access it equal to its discounted present value. From these data, we calculate the value of an average standing stock of timber for each region and the separate value of the land based on the discounted present value of timber harvests of forest regrowth after the initial harvest of the standing stock.

The value of natural forest and natural grass areas are considered in the model as part of the initial endowment of households in each region. These areas may be converted to other uses or conserved in their natural state. The reservation value of natural lands enters each regional representative agent welfare function with an elasticity of substitution with other consumption goods and services. Hence, the value the agent derives from natural land itself, is a deterrent to conversion. Thus, if for example current timber demand rises and puts pressure to harvest more land, it creates a partly offsetting demand to conserve forest area because, implicitly, the agent sees it as more valuable in the future. In the recursive dynamic structure of the model, introducing the natural forest value into the representative agent's welfare function approximates this behavior.

Cropland is an input in the production of each separate crop sector in the model (listed in Table 1). Similarly, pastureland is used in each livestock sector. Managed Forest areas are only used for the production of managed and harvested forests. The land allocation of crop and pasture to the agricultural and livestock sectors is done by CET functions with elasticity equal to one, which is the common approach in all models dealing with broad land categories being allocated to alternative final uses.

Some other features regarding land use changes relate to technological change affecting land productivity and specification of food and agricultural demand. Base parameterization assumes that land is subject to an exogenous productivity improvement of 1% per year for each land type, reflecting assessments of potential productivity improvements showing similar historical crop yields growth, albeit with variations among regions, crops and time (Gitiaux et al., 2011; Ray et al., 2013). In addition to exogenous yield changes and land conversion, agricultural output can grow by intensification of land use through partial substitution of other inputs and other primary factors in the agricultural production functions as relative prices change over time.

Regarding the demand for agricultural, livestock, forestry and food products, most of the output of primary land use sectors end up as inputs in the food, energy, and other sectors of the economy. Food and agriculture production, and hence the amount of land used is strongly influenced by the growth in population and incomes. Most studies find that, as income grows, the expenditure shares on food will decrease although food consumption levels may increase (Zhou et al., 2012; Haque, 2006), which suggests an income elasticity of less than unity. This relationship is represented following the approach using a Stone-Geary preference system, as described in detail by Chen et al. (2015).

The model is able to represent several existing and future pressures on land use, and also the dynamics effects on conversion among alternative agricultural uses, intensification through the use of inputs and capital, and also possible land abandonment, allowing land to revert to natural forms. Scenario exploration analysis allow testing alternative assumptions about population and economic growth, yield and productivity growth, trade and tariffs, climate change, changing patterns of food demand and land supply behavior.

The downscaling method is a land use and land cover downscaling model designed to distribute regional land use projections from economic models to fine spatial resolutions (Vernon et al. 2018). The tool allows users to choose rules and constraints to assign the patters of land expansion and contraction in each grid cell, including transition priorities and limits of expansion of specific land use types in each grid cell. Figure 1 shows a schematic representation of the combined use of the economic model and the downscaling tool.

Demeter is a land use and land cover change detection model that produces fine resolution maps of LULC change based on regional projections of land from the EPPA model. The main advantage of utilizing a model such as Demeter, is that rather than downscaling LULC using a statistical approach, the LULC is actually modelled at a 0.5 degree resolution respecting the relationship between different land types. This means that Demeter produces scenarios of land use and transitions across different land types so that users can identify not only what maps of LULC look like , but how land transitions between land types over time. Users can also parameterize Demeter to produce maps based on a certain criteria (e.g. Users can specify a transition matrix to restrict or dictate how land will transition between land types). Demeter has been used previously with other IAMs such as the Global Change Analysis Model (GCAM) to produce fine resolution projections of land use and land cover change for alternative socio-economic and climate scenarios.

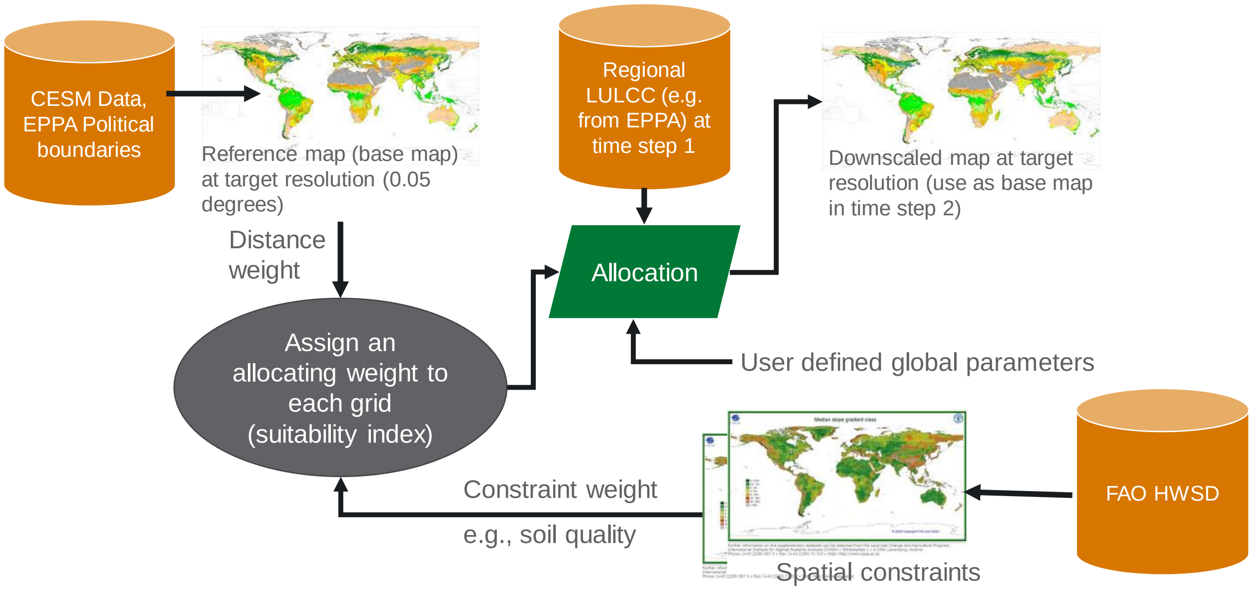

Figure 1. Schematic representation of the connections between the economic model and the downscaling tool.
Source: adapted from Vernon et al. (2018).

The Demeter-EPPA framework can be explained using the steps below (see Figure 1)

i) Demeter first requires an initial base map of LULC. This map is used as a starting point by the model. We utilize a map from the Community Land Model (CLM 5.0) which is harmonized with EPPA's LULC (See section below on the harmonization of the base map)
ii) This base map is used by Demeter to determine spatial constraints which will determine how land will change in the future (e.g. crop pixels are most likely to expand near other crop pixels)
iii) Demeter is also provided with other fine resolution constraints (e.g. keeping with the example above, Demeter can be provided with a map of nutrient availability so that crops are most likely to be planted where nutrients are available)
iv) The user can also provide Demeter with global level parameters (e.g. the user can provide transition rules so that certain land types are given priority over others when land transitions occur. Therefore user can specify that biomass expansion can occur primarily through converting grasslands)
v) Finally, Demeter is also provided with the regional land change projections (from EPPA). These ultimately dictate the net regional land use across land types.
vi) Demeter utilizes i-v above to generate "gross" land use across land types at a pixel level. The final output is a map of LULC in the current time step (let's say t) which becomes an input to the next timestep (t+1).

3. Scenarios

We tested a total of 16 alternative global scenarios designed to explore a range of values for different factors (stressors) that will affect land used change at global level, from dietary changes, to economic growth, and climate change effects on crops and livestock (Table 2), as discussed in Gurgel et al. (2021). These scenarios capture potential divergence in the strength of these global forces from the "BAU" projection. We also consider the combined set of forces that together would put greatest pressure on the US land use ("more" scenarios) or put the least pressure on the US land use ("less" scenarios) as shown in Table 2.

Table 2. Scenarios (shocks applied to all regions of the model)

Name	Brief explanation
BAU	Baseline scenario
low trade	Less trade due to higher import tariffs globally (tariffs 50% higher)
low clim. imp. crops	Positive climate impacts on crop yields from Global Gridded Crop Models (GGCMs)
low clim. imp crops&livest.	Positive climate impacts on crop and pasture yields from GGCMs
low yield constraint	Higher annual increase in crop yields (1.5% per year)
low meat demand	Changing diets toward lower income elasticity on meat demand
low pop. growth	Lower population growth (1% lower than "*BAU*")
low econ. growth	Lower GDP growth (20% lower than "*BAU*")
low all	All "*less*" impacts together
high trade	More trade due to lower import tariffs globally (tariffs 50% lower)
high clim. imp. crops	Negative climate impacts on crop yields from IPCC local crop models
high clim. imp crops&livest.	Negative climate impacts on crop yields and livestock from IPCC local crop models
high yield constraint	Lower annual increase in crop yields (0.5% per year)
high meat demand	Changing diets toward higher income elasticity on meat demand
high pop. growth	Higher population growth (1% higher than "*BAU*"))
high econ. growth	Higher GDP growth (20% higher than "*BAU*"))
high all	All "*more*" impacts together

Trade barriers are increased by 50% in the "less trade" scenario, or reduced by 50% to induce "more trade". In the "less climate impacts" scenarios we shock crop yields and livestock productivity by the average and median impacts from global gridded crop models (GCCMs), usually beneficial to crop yields, following Gurgel et al. (2021). The "more climate impacts" scenario assumes a central value of crop yield impacts from the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment report (Porter et al., 2014), most negatively affecting yields and varying by region. Decreases in the income elasticity of demand for meat affect the preferences for meat in developed countries in the "less meat demand" scenario, and the opposite change in income elasticity is considered in "more meat demand" scenario. The "less population growth" and "more population growth" scenarios assume population growth 1% lower and higher than in the BAU, respectively. Similarly, "less" and "more" "economic growth" scenarios assume 20% lower or higher growth in Gross Domestic Product (GDP) than BAU. All those forces combined together are tested in “less all” and “more all” scenarios.

4. Results

Our land use projections for the world under BAU conditions in the EPPA model suggest increases in pasture and cropland at expenses of natural forests and natural grasslands (Figure 2). In the U.S., however, BAU trajectories follow trends observed in the past 50 years, which were characterized by expansion of natural forests and pastures and decreases in total cropland. Considering multiple future scenarios of diverging strength of forces affecting land use, we project these trends are intensified under higher pressures for agriculture land or reduced under lower pressures. Figure 3 shows the net changes in land use by 2050 in the alternative forcing scenarios relative to BAU.

The “BAU” scenario is in line with conventional views on agriculture development through 2050, similar in broad trends to projections by the OECD and FAO. In general, we did not find evidence of strong deviations toward large deforestation or toward land abandonment in the scenarios tested. While in the “BAU” scenario we saw a continuation of recent trends in the US, the “high” and “low” pressure scenarios affected the strength of this shift but did not reverse it, nor magnify it dramatically. The major change seems to be substitution among managed agricultural areas, from cropland to pastures under “high” pressures. In general, the more stress on land deviations, the more pasture and grassland expansion, reflecting comparative advantage in the US in livestock production.

EPPA regional results are downscaled by Demeter to generate spatial distribution of changes over the U.S. The base map in Demeter treats forests areas as a broad land use category, which requires the aggregation of EPPA natural forests and managed forests. Similarly, Demeter does not distinguish between natural grasslands and pastures, which are combined as a single category in Demeter. However, Demeter can track separately land use by each EPPA agricultural sector, which allows to break-up cropland projections in EPPA demanded by different crop types. Figure 4 shows the global land use trajectories for 10 crop types land use categories. Pasture and natural grassland areas in EPPA are aggregated as “grass” as also as natural forest and managed forest areas as “fors” to match correspondent land use categories in the base map used in Demeter.

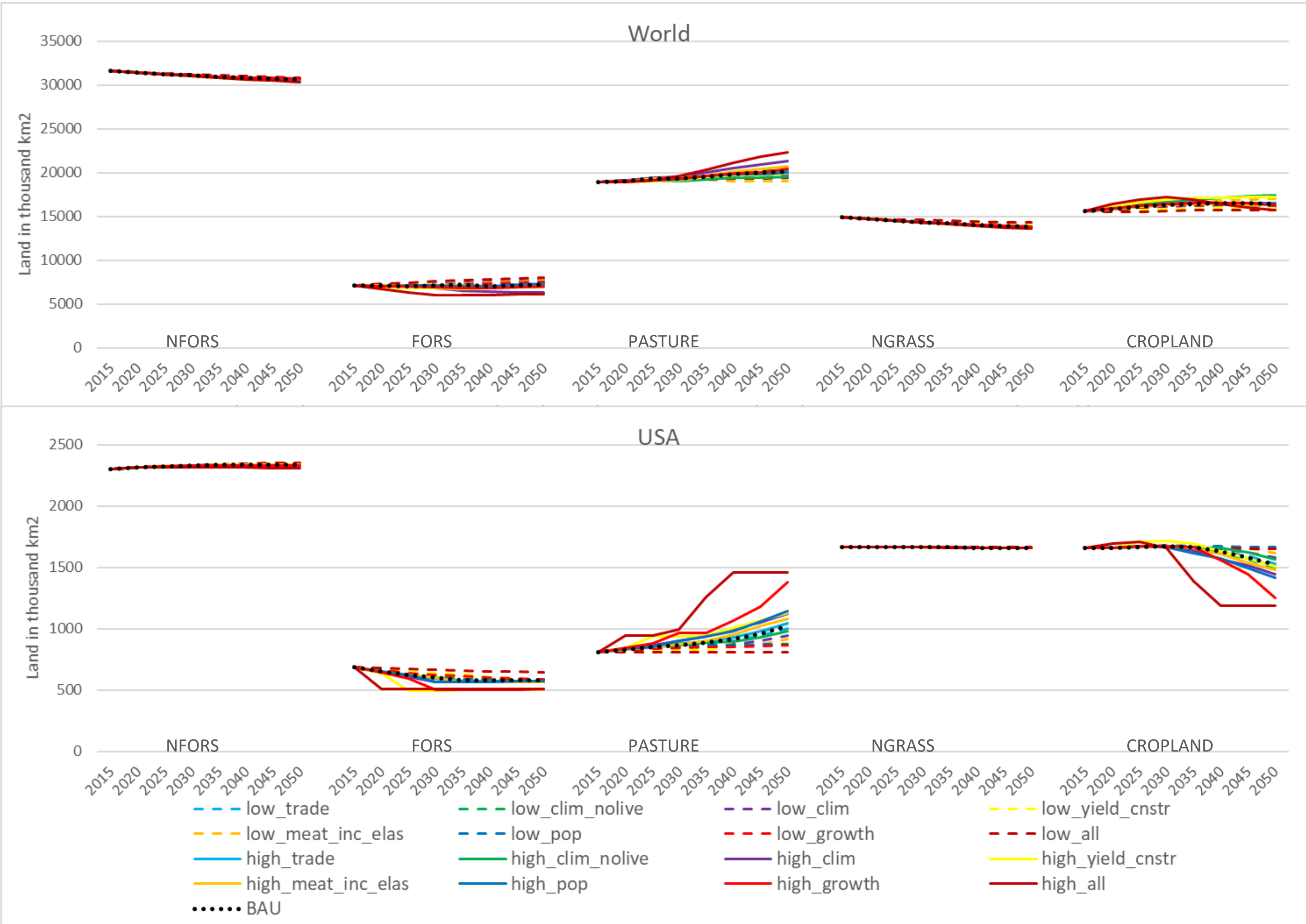

Figure 2. Trajectories of total land area in the World and the U.S. for five land cover types projected by EPPA.

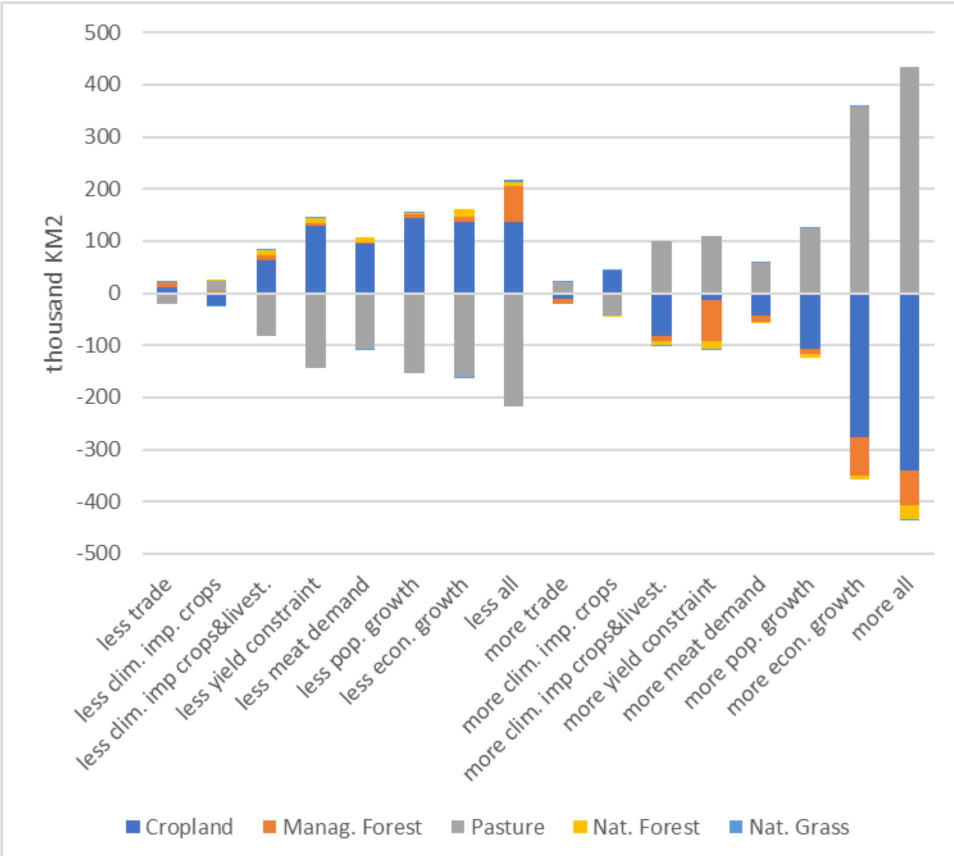

Figure 3. Land use changes in 2050 compared to BAU.

Figures 5a, 5b, 6a and 6b show the downscaled land use allocation in the U.S. as the differences in fractional land cover between 2050 and 2020 for 5 combined land use categories and high and low scenarios. Red squares in the maps at the top of these figures delineate the Mississippi River Basin area. The maps show pasture areas experiencing positive and more pronounced changes than other land uses, while these other uses experience more decreases than increases. Comparing the alternative forcing scenarios with the BAU, the "high economic growth" and "high all" scenario are the ones generating more relevant spatial changes in land use. When these "high" forces are in place, pastureland expands mostly in areas where it already exists, and most at the expenses of cropland. The majority of these transitions is observed in the Mississippi river basin, which means potential changes in the environmental footprint of agricultural practices in the region. The increase in pasture areas in the "high" scenarios seems to reproduce the current technology mix where livestock and beef production heavily relies on pasture/grazing areas. The EPPA model assumes some substitution among land and other resources and inputs, capturing potential intensification and switches toward more feedlots, but these seem limited in our results and ignore potentially radical changes, which may be a caveat of our approach. On the other hand, grass fed beef has some environmental and dietary benefits which may favor a persistence of this system in the future.

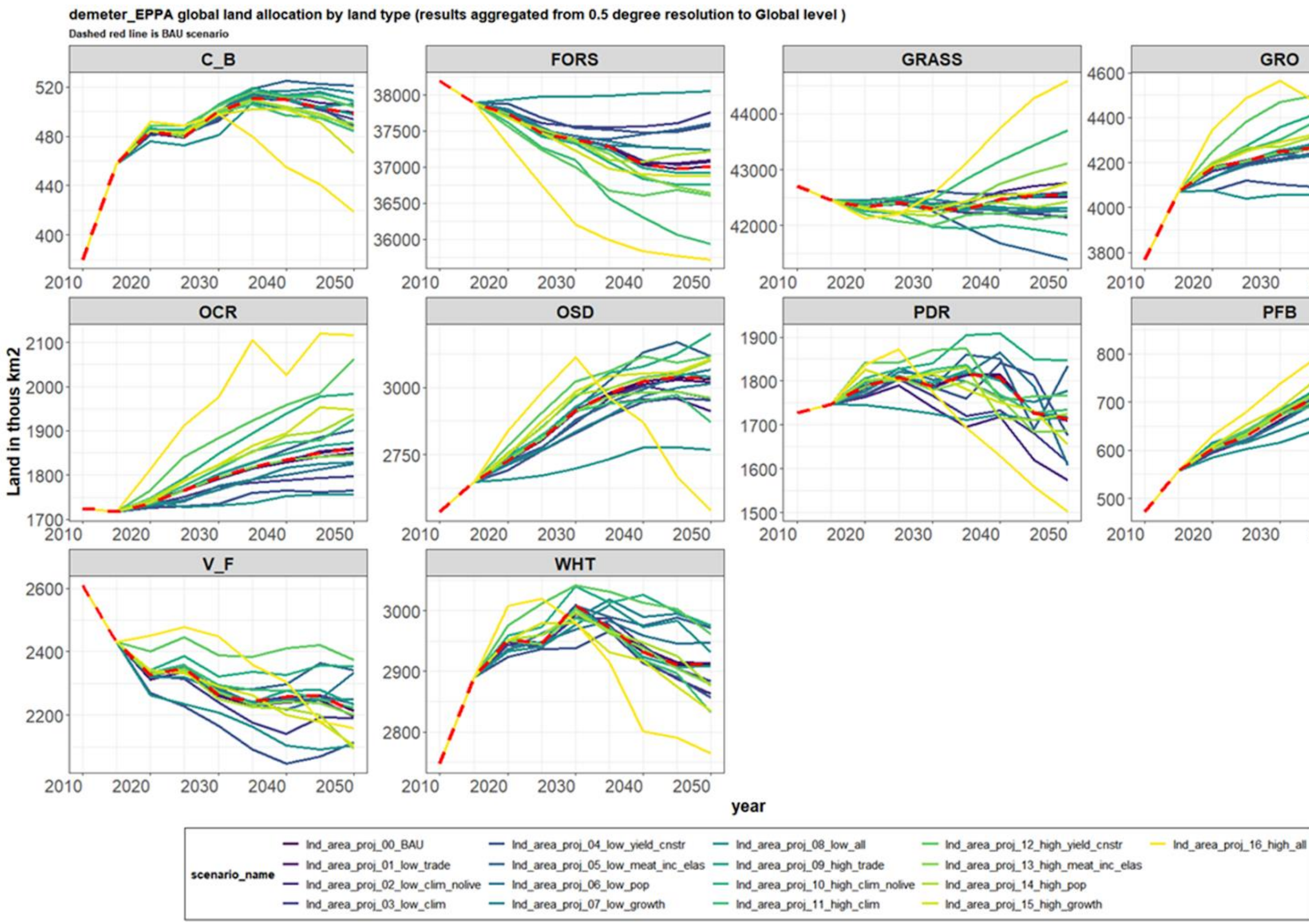

Figure 4. Trajectories of global aggregated land area for Demeter land use categories.

Forest and pasture/grasslands don't change in the scenario "low all" from 2020 to 2050. EPPA projects some transitions between natural forest and managed forests, but the net total forest doesn't change in that scenario. The same happens in the case of pasture and natural grassland, there are some transitions among them, but the total aggregated pasture+ngrass does not change after 2020. It happens since the "low all" scenario considers a relief in all pressures that would require producing more agricultural and livestock goods in the US, but these are not enough to make the prices of cropland areas cheaper than the prices of natural grassland and forest lands, which means farmers would incur in some opportunity cost in converting cropland and pastures back to natural state. This is not observed in some other regions of the world.

Comparing figures 5 with figures 6, we notice that "high" and "low" impacts are not symmetric, since several "high" scenarios lead to land use changes toward less forest areas, while "low" scenarios don't increase such areas. It means that, while "high" scenarios are associated with intensification of agriculture and livestock systems, such as higher use of fertilizers and machineries, low scenarios may just imply in more extensive and less efficient use of land, but they do not lead to land abandonment or reversion to natural states.

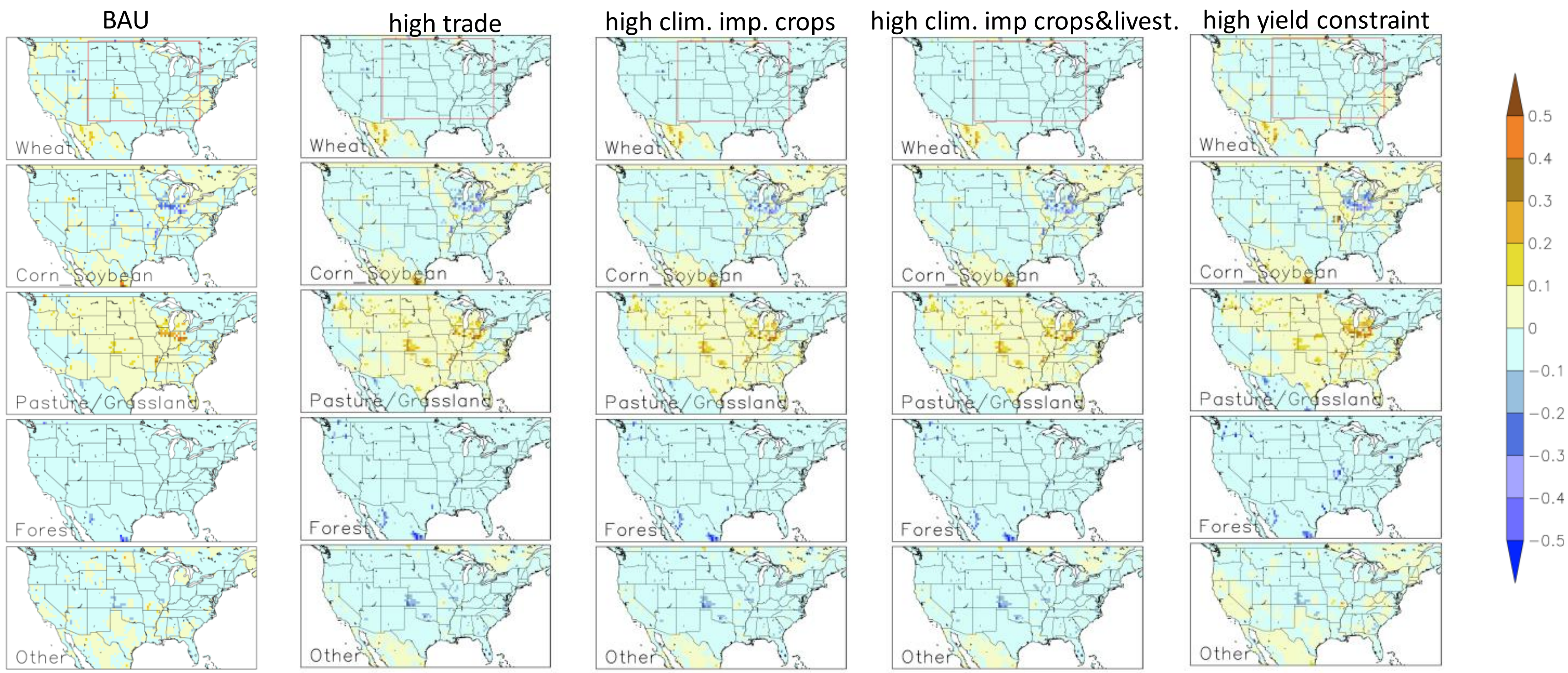

Figure 5a. Differences in Fractional Land Cover between 2050 and 2020 in the BAU and "high" scenarios in the U.S.

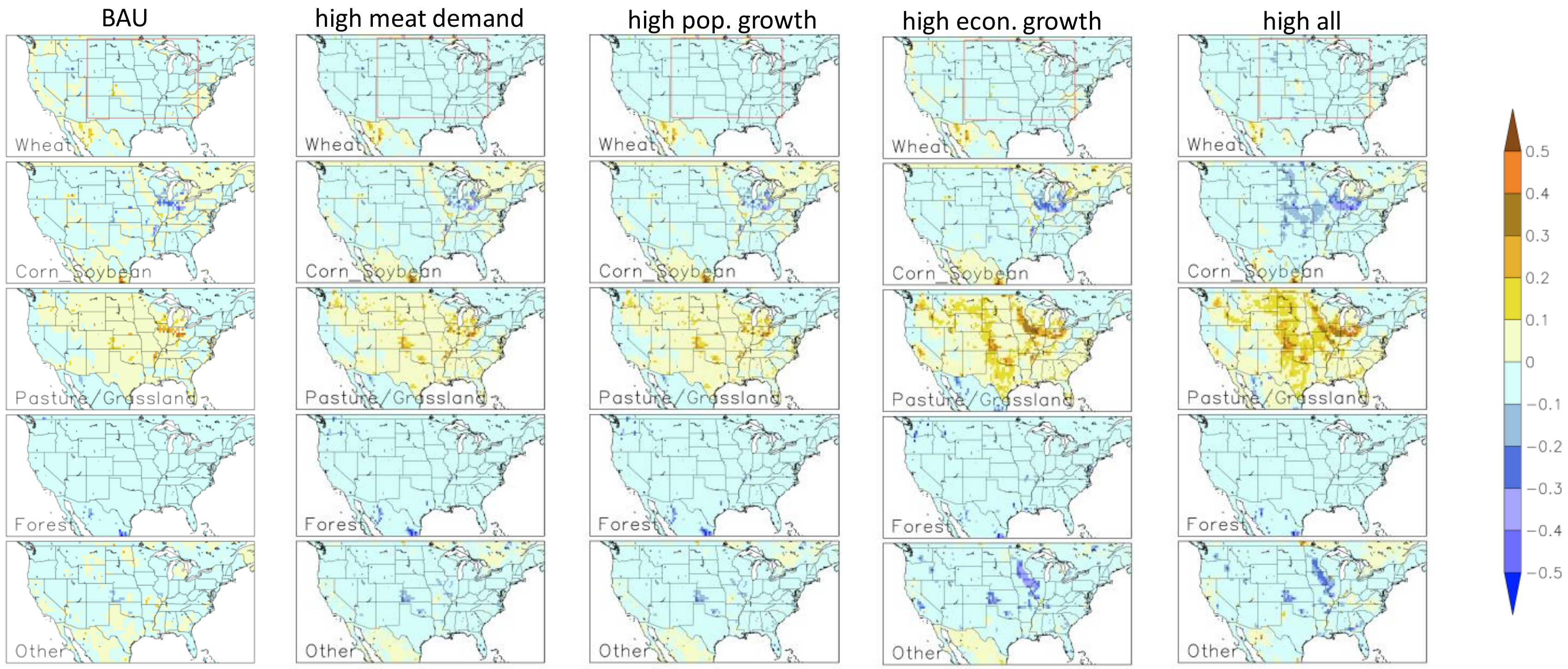

Figure 5b. Differences in Fractional Land Cover between 2050 and 2020 in the BAU and "high" scenarios in the U.S.

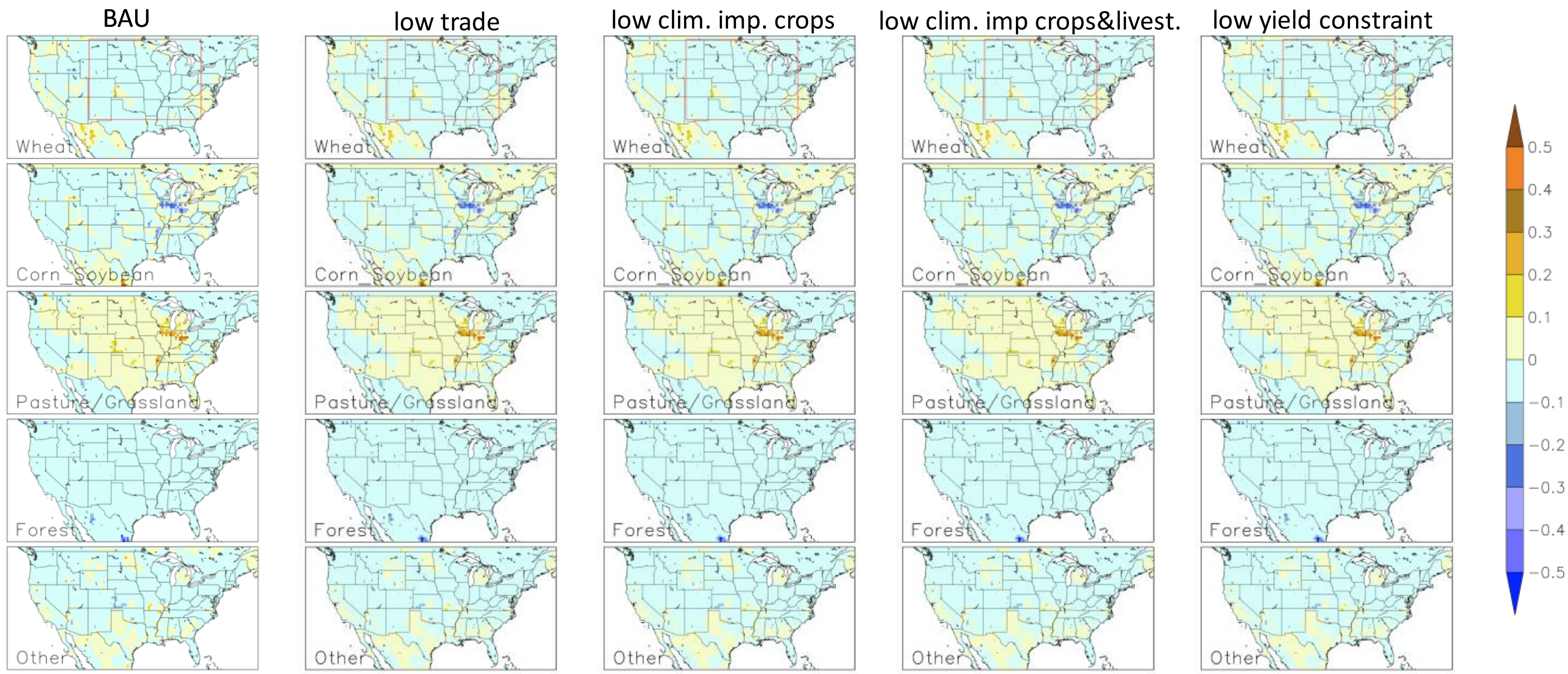

Figure 6a. Differences in Fractional Land Cover between 2050 and 2020 in the BAU and “less” scenarios

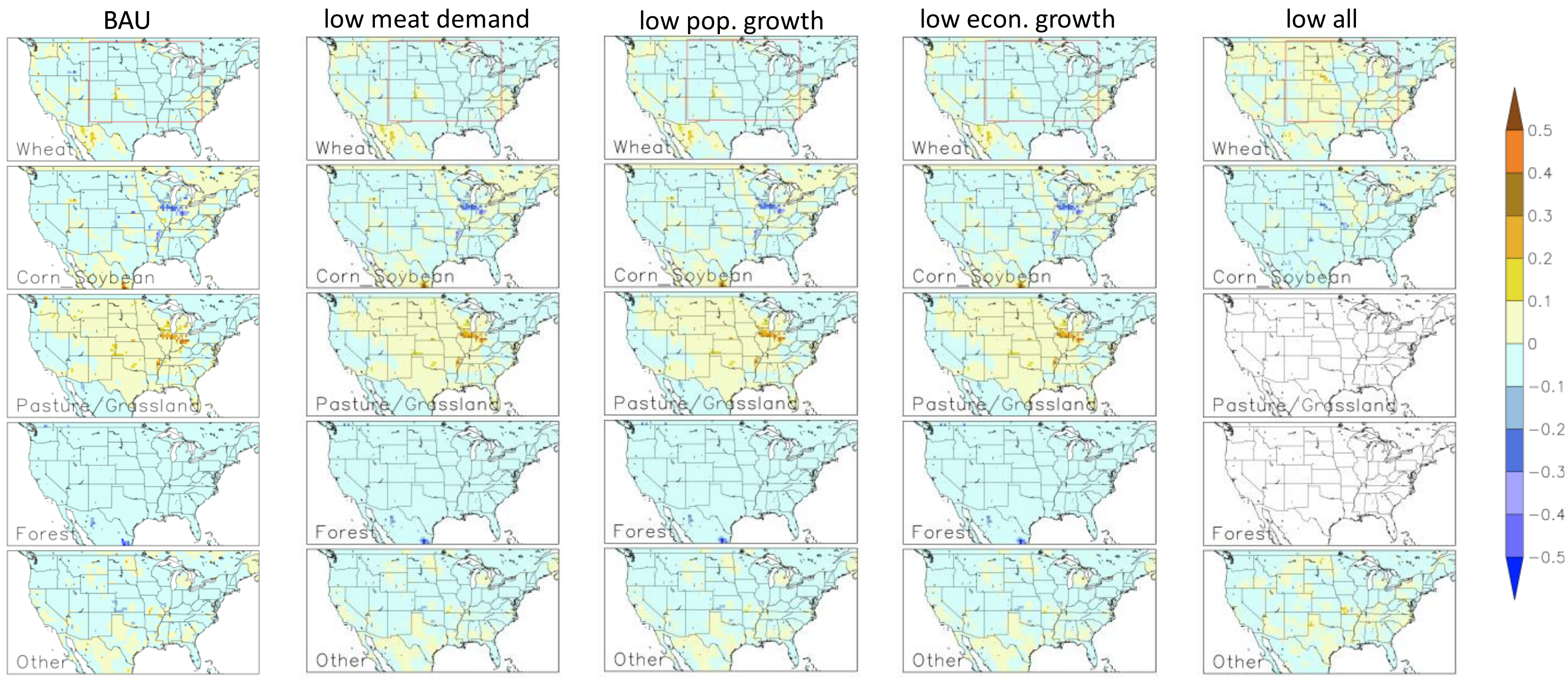

Figure 6b. Differences in Fractional Land Cover between 2050 and 2020 in the BAU and "less" scenarios

5. Conclusion

We investigate how different global forces and stressors may affect future land use in the U.S. at the regional and local levels, with a particular interest in the Mississippi River Basin. We combine a multi-sectoral and multi-regional socio-economic model of the world economy to an open-source downscaling model, which allows us to translate the regional land use projections to high-resolution representations of time-evolving land cover. We test several scenarios considering global drivers, including economic and population growth, climate impacts, changes in yields and changes in diets. The resulting regional land use changes are further translated into more detailed projections of land use changes through the downscaling model.

Our results show that past trends will be replicated in the future under BAU conditions, since pasture and forests lands increase overtime in the U.S. by 2050, while cropland decreases. This result suggests a long run trend of increase in the U.S. comparative advantage in livestock production. The alternative forcing scenarios affected the strength of these changes, but with minor impact at land use changes at the local level. Exceptions are the high economic growth scenario, or when we combine all pressures related to higher needs for agricultural land. We then see relatively large changes in land use at the U.S. regional and local levels, primarily a shift from cropland to pastures, reflecting the comparative advantage the US has in livestock production. The major impacts are observed along the Mississippi River Basin, which means these scenarios may lead to substantial changes in environmental consequences from agricultural production. Forest areas do not show significant changes under our scenarios.

There are several sources of uncertainty in our projections, which require further investigation. In particular, the fundamental behavioral parameters in both models need to be tested. In the case of EPPA, previous work has shown low sensitivity to most parameters and moderate sensitivity to a few parameters, such as agricultural intensification elasticities and crop income elasticities (Gurgel et al., 2021). In the case of Demeter, there is room to test downscaling parameters, such as the “intensification ratio”, which defines how much of an expanding land use category will be placed on grids cells where it already exists, and how much will be placed in nearby grid cells. Exploring these senstiviities is a focus of ongoing work. Also, the detailed land use scenarios will be used in physical land system models to investigate the earth system consequences of these changes.

The combination of the economic model with the downscaling tool facilitates a more dynamic connections between human and earth system model components that operate across different spatial scales, and ultimately enables more explicit multi-sector feedbacks between socioeconomics, bio-geophysics, biogeochemistry, atmospheric chemistry, and land use changes and subsequent effects on land-energy-water resources. In particular, these results are relevant to further understand the implications of land use change on carbon storage, soil erosion, chemical use, hydrology, and water quality. The employed downscaling model facilitates interoperability among models and across various spatial scales. The presented framework can be readily applied to other basins with little effort.

References

Baldos, U L C, I Haqiqi, T W Hertel, M Horridge, and J Liu. 2020. "SIMPLE-G: A Multiscale Framework for Integration of Economic and Biophysical Determinants of Sustainability." Environmental Modelling & Software 133: 104805. https://doi.org/https://doi.org/10.1016/j.envsoft.2020.104805.

Boden, T.A., and R.J. Andres. 2010. "Global, Regional, and National Fossil-Fuel CO2 Emissions." Oak Ridge, Tennesee.

Bond, Tami C., Ekta Bhardwaj, Rong Dong, Rahil Jogani, Soonkyu Jung, Christoph Roden, David G. Streets, and Nina M. Trautmann. 2007. "Historical Emissions of Black and Organic Carbon Aerosol from Energy-Related Combustion, 1850-2000." Global Biogeochemical Cycles. https://doi.org/10.1029/2006GB002840.

Chen, Y. H.Henry, Sergey Paltsev, John M. Reilly, Jennifer F. Morris, and Mustafa H. Babiker. 2016. "Long-Term Economic Modeling for Climate Change Assessment." Economic Modelling 52 (January): 867–83. https://doi.org/10.1016/J.ECONMOD.2015.10.023.

Chen, YHH, S Paltsev, J Reilly, J Morris, and MH Babiker. 2015. "The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption." MIT Joint Program on the Science and Policy of Global Change Report, no. Report 278: 43p. https://globalchange.mit.edu/publication/16262.

European Commission. 2011. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2. http://edgar.jrc.ec.europa.eu.

Felzer, B, D Kicklighter, J Melillo, and C Wang. 2004. "Effects of Ozone on Net Primary Production and Carbon Sequestration in the Conterminous United States Using a Biogeochemistry Model." Tellus B. http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0889.2004.00097.x/full.

Gitiaux, X, JM Reilly, and S Paltsev. 2011. "Future Yield Growth: What Evidence from Historical Data?" Joint Program Report Series, Report 199, 26 p. https://globalchange.mit.edu/publication/14009

Gurgel, A., J.M. Reilly, and S. Paltsev. 2007. "Potential Land Use Implications of a Global Biofuels Industry." Journal of Agricultural and Food Industrial Organization 5 (2).

Gurgel, Angelo C., John Reilly, and Elodie Blanc. 2021. "Agriculture and Forest Land Use Change in the Continental United States: Are There Tipping Points?" IScience 24 (7): 102772. https://doi.org/10.1016/j.isci.2021.102772.

Gurgel, Angelo, Y.-H. Henry Chen, Sergey Paltsev, and John M. Reilly. 2016. "CGE Models: Linking Natural Resources to the CGE Framework." In Natural Resources and Environmental Policy in the Era of Global Change: Computable General Equilibrium Models, edited by A. Dinar and W. D. A. Bryant, 57–98. New Jersey: World Scientific Co. Pte. Ltd. https://doi.org/10.1142/9789813208179_0003.

Haque, M. O. 2006. Income Elasticity and Economic Development: Methods and Applications. Springer Netherlands.

Hasegawa, Tomoko, Shinichiro Fujimori, Stefan Frank, Florian Humpenöder, Christoph Bertram, Jacques Després, Laurent Drouet, et al. 2021. “Land-Based Implications of Early Climate Actions without Global Net-Negative Emissions.” Nature Sustainability 4 (12): 1052–59. https://doi.org/10.1038/s41893-021-00772-w.

Hasegawa, Tomoko, Shinichiro Fujimori, Akihiko Ito, Kiyoshi Takahashi, and Toshihiko Masui. 2017. “Global Land-Use Allocation Model Linked to an Integrated Assessment Model.” Science of The Total Environment 580: 787–96. https://doi.org/https://doi.org/10.1016/j.scitotenv.2016.12.025.

Hertel, Thomas W. 2011. “The Global Supply and Demand for Agricultural Land in 2050: A Perfect Storm in the Making?” American Journal of Agricultural Economics 93 (2): 259–75. https://doi.org/10.1093/ajae/aaq189.

Houghton, R A, and Alexander A Nassikas. 2017. “Global and Regional Fluxes of Carbon from Land Use and Land Cover Change 1850–2015.” Global Biogeochemical Cycles 31 (3): 456–72. https://doi.org/https://doi.org/10.1002/2016GB005546.

Hurtt, George C., S. Frolking, M. G. Fearon, B. Moore, E. Shevliakova, S. Malyshev, S. W. Pacala, and R. A. Houghton. 2006. “The Underpinnings of Land-Use History: Three Centuries of Global Gridded Land-Use Transitions, Wood-Harvest Activity, and Resulting Secondary Lands.” Global Change Biology 12 (7): 1208–29. https://doi.org/10.1111/j.1365-2486.2006.01150.x.

International Energy Agency. 2012. World Energy Outlook 2012. 672.

International Monetary Fund. 2019. World Economic and Financial Surveys: World Economic

IPCC [Intergovernmental Panel on Climate Change]. 2023. AR6 Synthesis Report: Climate Change 2023. https://www.ipcc.ch/report/ar6/syr/

Melillo, J.M., J.M. Reilly, D.W. Kicklighter, A.C. Gurgel, T.W. Cronin, S. Paltsev, B.S. Felzer, X. Wang, A.P. Sokolov, and C. Adam Schlosser. 2009. “Indirect Emissions from Biofuels: How Important?” Science 326 (5958). https://doi.org/10.1126/science.1180251.

Moss, R., K. Fisher-Vanden, A. Delgado, S. Backhaus, C. L. Barrett, B. Bhaduri, I. P. Kraucunas, et al. 2016. “Understanding Dynamics and Resilience in Complex Interdependent Systems.” https://www.globalchange.gov/reports/understanding-dynamics-and-resilience-complex-interdependent-systems

Narayanan, Badri G., Angel Aguiar, and Robert McDougall. 2012. “Global Trade, Assistance, and Production: The GTAP 8 Data Base.” https://www.gtap.agecon.purdue.edu/databases/v8/v8_doco.asp.

O’Neill, B C, C Tebaldi, D P van Vuuren, V Eyring, P Friedlingstein, G Hurtt, R Knutti, et al. 2016. “The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6.” Geoscientific Model Development 9 (9): 3461–82. https://doi.org/10.5194/gmd-9-3461-2016.

Page, Yannick Le, Tris O. West, Robert Link, and Pralit Patel. 2016. “Downscaling Land Use and Land Cover from the Global Change Assessment Model for Coupling with Earth System Models.” Geoscientific Model Development 9 (9): 3055–69. https://doi.org/10.5194/GMD-9-3055-2016.

Popp, Alexander, Katherine Calvin, Shinichiro Fujimori, Petr Havlik, Florian Humpenöder, Elke Stehfest, Benjamin Leon Bodirsky, et al. 2017. “Land-Use Futures in the Shared Socio-Economic Pathways.” Global Environmental Change 42 (January): 331–45. https://doi.org/10.1016/J.GLOENVCHA.2016.10.002.

Ramankutty, Navin. 2011. “Global Cropland and Pasture Data: 1700-2007.” 2011. http://www.geog.mcgill.ca/~nramankutty/Datasets/Datasets.html.

Ray, Deepak K, Nathaniel D Mueller, Paul C West, and Jonathan A Foley. 2013. “Yield Trends Are Insufficient to Double Global Crop Production by 2050.” PloS One 8 (6): e66428. https://doi.org/10.1371/journal.pone.0066428.

Reilly, John, Jerry Melillo, Yongxia Cai, David Kicklighter, Angelo Gurgel, Sergey Paltsev, Timothy Cronin, Andrei Sokolov, and Adam Schlosser. 2012. “Using Land to Mitigate Climate Change: Hitting the Target, Recognizing the Trade-Offs.” Environmental Science and Technology 46 (11): 5672–79.

Roe, Stephanie, Charlotte Streck, Michael Obersteiner, Stefan Frank, Bronson Griscom, Laurent Drouet, Oliver Fricko, et al. 2019. “Contribution of the Land Sector to a 1.5 °C World.” Nature Climate Change 9 (11): 817–28. https://doi.org/10.1038/s41558-019-0591-9.

Schmitz, Christoph, Hans van Meijl, Page Kyle, Gerald C. Nelson, Shinichiro Fujimori, Angelo Gurgel, Petr Havlik, et al. 2014. “Land-Use Change Trajectories up to 2050: Insights from a Global Agro-Economic Model Comparison.” Agricultural Economics 45 (1): 69–84. https://doi.org/10.1111/AGEC.12090.

Smith, Keith A. 2005. “The Impact of Agriculture and Other Land Uses on Emissions of Methane and Nitrous and Nitric Oxides.” Environmental Sciences 2 (2–3): 101–8. https://doi.org/10.1080/15693430500370423.

Sohngen, B, and R Mendelsohn. 1998. “Valuing the Impact of Large-Scale Ecological Change in a Market: The Effect of Climate Change on US Timber.” American Economic Review. http://www.jstor.org/stable/117001.

Sohngen, Brent. 2007. “Global Timber Market and Forestry Data Project.” 2007. http://aede.osu.edu/research/forests-and-land-use/global-timber-market-and-forestry-data-project.

Sohngen, Brent; Tennity, Colleen. 2004. “Country Specific Global Forest Data Set v.1.” https://aede.osu.edu/sites/aede/files/!import/GTAP_datareport_v1(3).pdf.

Tian, Hanqin, Guangsheng Chen, Chaoqun Lu, Xiaofeng Xu, Wei Ren, Bowen Zhang, Kamaljit Banger, et al. 2015. “Global Methane and Nitrous Oxide Emissions from Terrestrial Ecosystems Due to Multiple Environmental Changes.” Ecosystem Health and Sustainability 1 (1): 1–20. https://doi.org/10.1890/EHS14-0015.1.

Verburg, Peter H, C J E Schulp, N Witte, and A Veldkamp. 2006. "Downscaling of Land Use Change Scenarios to Assess the Dynamics of European Landscapes." Agriculture, Ecosystems & Environment 114 (1): 39–56. https://doi.org/https://doi.org/10.1016/j.agee.2005.11.024.

Vernon, Chris R., Yannick L. Le Page, Min Chen, Maoyi Huang, Katherine V. Calvin, Ian P. Kraucunas, and Caleb J. Braun. 2018. "Demeter – A Land Use and Land Cover Change Disaggregation Model." Journal of Open Research Software 6 (1). https://doi.org/10.5334/JORS.208.

Villoria, Nelson B. 2019. "Technology Spillovers and Land Use Change: Empirical Evidence from Global Agriculture." American Journal of Agricultural Economics 101 (3): 870–93. https://doi.org/10.1093/AJAE.

Wierik, Sofie A te, Erik L H Cammeraat, Joyeeta Gupta, and Yael A Artzy-Randrup. 2021. "Reviewing the Impact of Land Use and Land-Use Change on Moisture Recycling and Precipitation Patterns." Water Resources Research 57 (7): e2020WR029234. https://doi.org/https://doi.org/10.1029/2020WR029234.

Zhou, Z, W Tian, J Wang, H Liu, and L Cao. 2012. "Food Consumption Trends in China." … . Au/Market access trade/Food consumption …. https://scholar.google.com/scholar?q=zhou+tian+wang+liu+cao+food+consumption&btnG=&hl=pt-BR&as_sdt=0%2C22#4.