QUANTITATIVE MODELING OF LAND SYSTEM TRANSFORMATIONS WITHIN AN INTERDISCIPLINARY MODELING FRAMEWORK

Integrative assessments of agricultural land use change in the context of the Sustainable Development Goals

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Vorgelegt von
Julia Maximiliane Schneider

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Erstgutachter: PD Dr. Florian Zabel

Zweitgutachter: Prof. Dr. Wolfram Mauser

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SUMMARY

Agriculture can be identified as a key area of action in the transformation towards sustainability in the 21st century: On one hand, it is strongly affected by global change dynamics such as climate change, an increasing world population with changing dietary and demand patterns, and the globalization of markets. On the other hand, agriculture is also a significant driver of global change, contributing to climate change, land use change, and biodiversity loss, which represent central global sustainability challenges of this time. Accordingly, agriculture and land use are also relevant to various of the Sustainable Development Goals of the United Nations, for example to end hunger, or to protect life on land and the climate. A central question to reaching those goals thus is how agricultural production and its land use can be shaped under future environmental and societal conditions in a way that the changing demand for agricultural goods is met, the socio-economic framework is considered, and the potential environmental effects are minimized simultaneously.

Interdisciplinary approaches that integrate models from different research fields provide a possibility to investigate this question. They can be used to simulate potential dynamics in agricultural production and land use and assess their various effects across different research disciplines, e.g., the impacts on agricultural markets, on biodiversity, or generated greenhouse gas emissions. Such integrative research approaches thus enable a consistent interdisciplinary scenario analysis of agricultural dynamics and associated land use changes based on which potentially arising trade-offs between different interests can be identified, for example, between food production, environmental protection, and the socio-economic context.

The work presented in this doctoral thesis aimed to develop and apply an integrative land use change model that allows the spatially explicit simulation of agricultural production patterns, associated land use change dynamics and potential trade-offs between food production, socio-economic interests and environmental protection on a global scale. An established coupling approach of two models, the biophysical crop growth model PROMET and the computable general equilibrium model DART-BIO, was used to develop the spatially explicit integrative land use model iLANCE (integrative land allocation sequencer). Necessary research tasks for the model creation were, inter alia, the spatialization of the coupling approach and harmonization of the model input data, the integration of various agricultural management options, and the development of additional modules to simulate changes in total cropland area, e.g., cropland expansion or reduction. After implementing these steps, the iLANCE model was applied in the studies associated with this thesis to integratively address research questions on agriculture and land use in the context of global sustainability challenges, such as the debate on land sharing versus land sparing, profit-driven cropland expansion dynamics or the potential effects and trade-offs of conservation policies. In the first publication, the approach was used to investigate the potential of agricultural intensification to reduce the current cropland extent, for example to spare

land for nature protection, and analyze the resulting impacts on agricultural markets under different implementation strategies. In the second publication, the global resources of land potentially cultivable and available for cropland use were assessed under different future climate change scenarios. The third publication included in this thesis investigates the global spatial patterns of cropland expansion pressure, the potentially resulting socio-economic and environmental effects of converting the identified areas into cropland, and the potential of global conservation policies to reduce the environmental impacts of cropland expansion.

Primarily, this thesis and the results of the associated studies provide valuable insights into the potentials of the two central strategies discussed to increase agricultural production, cropland expansion and agricultural intensification, and their potential environmental and socio-economic implications under different implementation scenarios. The first publication demonstrates, for example, that intensifying agricultural production could halve the current global cropland extent, thereby sparing land for nature without compromising agricultural production. The resulting reduction in crop prices can, on the one hand, contribute to food security by improving the economic access to food, but on the other hand, can negatively affect smallholder farmers by reducing their income and thus reduce the food security of the rural population. While the second publication finds only around one-third of the potentially cultivable area globally already under cropland use, with the agriculturally suitable land resources being mainly located in Africa and South America, the third publication identifies the areas under globally highest expansion pressure to be mainly located in the tropics. For example, a global expansion of current cropland by 3.6%, as projected by the OECD and FAO until 2030, would particularly affect areas with tropical moist and seasonal forest potential natural vegetation. Converting the identified areas under pressure into cropland would reduce biodiversity intactness by -25%, and the CO_2 emissions generated by this land use change would be almost half of the current annual global CO_2 emissions. However, the study also shows that global conservation policies protecting forests, wetlands, and currently already protected areas from conversion into cropland could reduce the potential environmental impacts of cropland expansion by around a quarter. Such integrative findings are particularly relevant in the context of current discussions on measures to reconcile agricultural production with environmental protection, for example the Kunming-Montreal Global Biodiversity Framework and its commitment to put 30% of land and marine area under active restoration, the Glasgow Leaders' Declaration on Forest and Land Use, or the EU Regulation on deforestation-free supply chains. The results on the spatial dynamics and environmental and socio-economic effects of agricultural intensification, land saving and cropland expansion provide important insights into potential development paths for implementing such measures. Thus, integrative research approaches like the iLANCE model can identify potential conflicts as well as co-benefits, which is essential for an efficient policy design supporting the Sustainable Development Goals.

The work on the iLANCE model development and its application in the listed studies moreover provide methodological insights into the potentials and challenges of interdisciplinary modeling approaches. By considering various drivers of agricultural production and land use change, integrative modeling results enable a more detailed simulation of associated processes and thus provide a complementary perspective to purely biophysical assessments. The possibility to assess the potential to reduce the current cropland extent, for example, not solely based on environmental growing conditions, but additionally considering also the socio-economic context or specific land use policies contributes to assessing a potential corridor of action between what might be biophysically possible and what would be feasible given the socio-economic framework. This can be valuable in defining an option space for strategies and the implementation of different measures. The bridging of spatial scales and temporal reference frames across models from different disciplines as well as the harmonization of the data used are identified as major challenges in the model development. Yet, the application of the iLANCE model reveals also the potential of integrative approaches with spatially explicit output data to be used in various models from different research disciplines, for instance, when assessing the potential environmental implications of cropland expansion.

Overall, this thesis demonstrates the crucial role of interdisciplinary models such as the iLANCE model in exploring ways towards an agriculture and land use that both reconcile the defined sustainability goals to achieve food security, protect the environment, and support sustainable socio-economic development. The included scientific studies provide a first overview of potential application cases of the iLANCE model to investigate land use change dynamics resulting from changes in agricultural production and potentially arising trade-offs. However, there is a large potential to apply the model for further research questions, for instance, regarding the effects of different cultivation systems and their crop diversification on regional agricultural production patterns, or potential rebound effects of land saving. Further extending the iLANCE model, for instance by including further drivers of agricultural expansion, or by additionally coupling the iLANCE model with models operating on a local level, would enable simulating decisions at the farm level or at national level in more detail. This would allow further interesting research questions on the environmental and socio-economic implications of agricultural production and its associated land use change to be addressed and potential trade-offs as well as co-benefits to be identified.

ZUSAMMENFASSUNG

Landwirtschaft und damit verbundene Landnutzung stellen zentrale Handlungsfelder einer globalen, gesamtgesellschaftlichen Transformation hin zu mehr Nachhaltigkeit dar. Dies lässt sich daraus begründen, dass Landwirtschaft einerseits besonders stark von globalen Veränderungen, wie z.B. dem Klimawandel, der steigenden und sich verändernden Nachfrage nach landwirtschaftlichen Gütern, oder der Globalisierung von Agrarmärkten betroffen ist, andererseits jedoch auch einen wesentlicher Treiber der Dynamiken darstellt, die als zentrale Herausforderungen dieses Jahrhunderts gelten, wie beispielsweise steigende Treibhausemissionen und ihr Beitrag zum Klimawandel oder der stetig anwachsende Verlust von Biodiversität. Um die von den Vereinten Nationen definierten Nachhaltigkeitsziele zu erreichen stellt sich deshalb die Frage, wie Landwirtschaft unter den sich wandelnden gesellschaftlichen und klimatischen Bedingungen gestaltet werden kann, sodass die steigende Nachfrage unter Berücksichtigung des sozioökonomischen Kontexts bedient werden kann, zugleich jedoch trotzdem negative Umwelteffekte, z.B. auf Klima und Biodiversität, minimiert werden können.

Interdisziplinäre Forschungsansätze, die Daten und Modelle aus verschiedenen wissenschaftlichen Feldern integrieren, bieten die Möglichkeit, potentielle Veränderungen und Entwicklungen in der landwirtschaftlichen Produktion und Landnutzung unter verschiedenen Zukunftsszenarien zu simulieren und ihre Auswirkungen in unterschiedlichen Bereichen, z. B. in Bezug auf Nahrungsmittelpreise und globale Handelsmuster, aber auch auf Biodiversität und Treibhausgasemissionen, analysieren zu können und mögliche Zielkonflikte aufzuzeigen. Sie ermöglichen somit eine konsistente, integrative Szenarioanalyse landwirtschaftlicher Dynamiken und ihrer Auswirkungen, auf deren Basis potentiell entstehende Zielkonflikte zwischen landwirtschaftlicher Produktion, Umweltschutz und sozioökonomischen Rahmenbedingungen analysiert werden können.

Ziel der Arbeit dieser Dissertation war die Entwicklung und Anwendung eines integrativen Landnutzungsmodells, mit dem landwirtschaftliche Produktionsmuster und Landnutzungsänderungen global räumlich explizit simuliert und mögliche Zielkonflikte mit sozioökonomischen Interessen und Umweltschutz analysiert werden können. Aufbauend auf einem bereits bestehenden Ansatz zur Kopplung eines biophysikalischen Pflanzenwachstumsmodells (PROMET) und eines ökonomischen allgemeinen Gleichgewichtmodells (DART-BIO) wurde durch eine Verräumlichung der Modellkopplung, die Harmonisierung der verwendeten Input-Daten sowie die Erweiterung des Algorithmus durch die Integration verschiedener Management-Optionen und der Option zur Simulation von Flächenveränderungen das integrative Landnutzungsmodell iLANCE *(integrative land allocation sequencer*) entwickelt. Das Modell wurde anschließend in den in dieser Arbeit integrierten Studien angewandt, um sich verschiedenen Forschungsfragen zu nähern, die Gegenstand des aktuellen wissenschaftlichen Diskurses im Bereich Landwirtschaft und Landnutzung sind, wie

beispielsweise die Debatte um ‚*land sharing versus land sparing*', profitgetriebene Expansion landwirtschaftlicher Anbauflächen sowie die Potentiale und möglichen Zielkonflikte von Strategien zum Schutz von Klima und Biodiversität.

Die erste Publikation untersucht das Potential zur Verringerung der globalen Anbauflächen durch landwirtschaftliche Intensivierung. Ziel ist einerseits die Quantifizierung der durch Ertragssteigerungen reduzierbare Anbauflächen, die beispielsweise für Renaturierung oder Kohlenstoffspeicherung verwendet werden könnte, andererseits die Analyse der aus dieser räumlichen Konzentration landwirtschaftlicher Produktion resultierenden ökonomischen Effekte, z.B. auf Nahrungsmittelpreise oder Handelsmuster. In der zweiten Studie, die in diese Arbeit eingebunden ist, wurde die global potentiell für Ackerbau nutzbare Fläche unter verschiedenen Annahmen der Nutzbarkeit sowie unterschiedlichen zukünftigen Klimawandelszenarien bewertet, um darauf basierend in der dritten Publikation zu untersuchen, welche dieser aktuell noch nicht landwirtschaftlich genutzten, jedoch potentiell kultivierbaren Flächen unter besonders hohem Expansionsdruck stehen. Neben der Analyse räumlicher Muster von Expansionsdruck wurden mögliche sozioökonomische Auswirkungen der Umwandlung dieser Flächen in Ackerland sowie daraus resultierende Treibhausgasemissionen und Effekte auf die Biodiversität analysiert. Zudem wurde ermittelt, wie bestimmte Schutzmaßnahmen Expansionsdruck räumlich verlagern sowie dessen ökologische Effekte beeinflussen könnten.

Die Ergebnisse der Studien bieten einerseits spannende Einblicke in die Dynamiken, Potentiale und Hindernisse zweier als zentral betrachteter Strategien zur Steigerung der landwirtschaftlichen Produktion, landwirtschaftliche Intensivierung und Expansion der Anbauflächen, sowie deren potentielle Effekte auf Umwelt und Gesellschaft. Beispielsweise zeigte sich, dass durch eine nachhaltige Intensivierung von Ackerbau die derzeitige globale Ackerfläche nahezu halbiert werden könnte, und so Landressourcen für andere Verwendungszwecke, wie z.B. Kohlenstoffspeicherung oder den Schutz von Biodiversität, verfügbar gemacht werden könnten. Die durch die gesteigerte Effizienz der landwirtschaftlichen Produktion sinkenden Preise können einerseits zu einer Steigerung der Ernährungssicherung beitragen, indem der ökonomische Zugang zu Nahrungsmittel verbessert wird. Andererseits können sich sinkende Preise vor allem in Regionen mit überwiegend Nahrungsmittelerzeugern und vielen Kleinbauern durch die Verringerung ihres Einkommens negativ auf ihre Ernährungssicherung auswirken. Während die Analyse potentieller landwirtschaftlicher Flächenressourcen in der zweiten Publikation feststellt, dass aktuell lediglich etwa ein Drittel der potenziell kultivierbaren Fläche weltweit als Ackerland genutzt wird, wobei sich die landwirtschaftlich geeigneten Landressourcen vor allem in Afrika und Südamerika befinden, zeigt die dritte Publikation entsprechend die räumliche Lage der Gebiete mit dem weltweit höchsten Expansionsdruck auf, die sich vor allem in den Tropen befinden. Eine Ausweitung der derzeitigen globalen Anbauflächen um 3,6 %, wie sie von der OECD und der FAO bis 2030 prognostiziert wird, würde entsprechend vor allem in den Tropen stattfinden, wo insbesondere tropische Wälder in landwirtschaftliche Flächen umgewandelt werden würden. Die Intaktheit der Biodiversität auf diesen Flächen würde dadurch um ca. -25% sinken und die mit der Expansion verbundenen Landnutzungsänderungen in Ackerland CO_2 Emissionen in der Größenordnung von fast der Hälfte der derzeitigen jährlichen globalen CO_2 Emissionen verursachen. Gleichwohl zeigt die Studie auch, dass globale Schutzmaßnahmen von Wäldern, Feuchtegebieten und bereits etablierten Schutzgebieten die potentiellen Auswirkungen dieser Expansion um etwa ein Viertel reduzieren könnten. Entsprechend sind integrative Analysen wie die in dieser Arbeit vorgestellten besonders im Kontext aktueller Diskussionen über mögliche Maßnahmen zur Vereinbarkeit von landwirtschaftlicher Produktion und Umweltschutz relevant, z.B. dem Kunming-Montreal Abkommen und seines Schutzziels von 30 % der Land- und Meeresoberflächen, der Erklärung der 26. Klimakonferenz in Glasgow zur Beendigung der Abholzung von Wäldern bis 2030, oder der EU-Verordnung zu entwaldungsfreien Lieferketten. Durch den Einbezug der sozioökonomischen Dimension berücksichtigen integrative Forschungsansätze und Modelle die gesellschaftliche, wirtschaftliche und politische Relevanz landwirtschaftlicher Dynamiken und ermöglichen es, sowohl potentielle Zielkonflikte diskutierter Maßnahmen als auch mögliche Synergieeffekte zwischen landwirtschaftlicher Produktion, Umweltschutz und sozioökonomischen Interessen aufzeigen.

Neben inhaltlichen Erkenntnissen lassen sich durch die Anwendung des iLANCE Modells in den vorgestellten Studien auch Erkenntnisse zu methodischen Vorteilen sowie Herausforderungen interdisziplinärer Modellierungsansätze zur Simulation von Landnutzungsdynamiken gewinnen. Die Integration biophysikalischer und sozioökonomischer Treiber ermöglicht eine detailliertere Modellierung von z.B. Entscheidungen über Anbaumuster oder Landnutzungsveränderungen wie z.B. die Ausweitung von Anbauflächen, da diese Dynamiken nicht ausschließlich von lokalen Anbaubedingungen wie Boden, Klima oder Topographie beeinflusst werden, sondern beispielsweise auch von der regionalen Nachfrage nach landwirtschaftlichen Gütern und Preisentwicklungen. Die Ergebnisse der integrativen Modellierung bieten somit eine ergänzende Perspektive zu rein biophysikalischen Analysen, die mögliche Handlungsspielräume näher eingrenzen oder erweitern können. Im Rahmen der ersten Publikation zu globalen Flächeneinsparungspotentialen durch landwirtschaftliche Intensivierung konnte durch die Anwendung von iLANCE gezeigt werden, wie sich das Potential einer rein an biophysikalischen Kriterien orientierten Flächeneinsparung von einer Implementierung unter Berücksichtigung sozioökonomischer Kriterien unterscheidet, wie beispielsweise ob profitable Flächen aus der Produktion genommen werden oder ob einer räumlichen Konzentration landwirtschaftlicher Produktion aktiv entgegengewirkt wird. Schließlich zeigt die Anwendung des iLANCE Modells in interdisziplinären Studien, wie z.B. in der dritten Publikation zu landwirtschaftlicher Expansion und ihren Effekten auf Biodiversität, CO_2 Emissionen sowie Agrarmärkte, die Anschlussfähigkeit des Modells und der generierten Daten in anderen Forschungsdisziplinen und ihren Modellen.

Hierbei zeigt sich auch das große Potential, das iLANCE Modell für weitere Forschungsfragen zu erweitern und Modelle anderer Forschungsbereiche in den interdisziplinären Kopplungsansatz zu integrieren.

Insgesamt demonstriert die Arbeit das Potential interdisziplinärer Modellierungsansätze für die Erforschung landwirtschaftlicher Produktion und Landnutzung, ihrer möglichen zukünftigen Dynamiken, sowie von potentiell entstehenden Zielkonflikten mit Umweltschutz, wirtschaftlichen und gesellschaftlichen Interessen. Die vorgestellten wissenschaftlichen Studien bieten einen ersten Überblick über potenzielle Anwendungsmöglichkeiten des iLANCE Modells zur Analyse dieser Dynamiken und entstehender Zielkonflikte. Zudem weisen sie auf das Potential des Modells zur Erforschung weiterer relevanter Forschungsfragen hin, wie beispielsweise des Einflusses verschiedener Anbausysteme und deren Diversifizierungsgrad auf regionale landwirtschaftliche Produktionsmuster, oder ökonomische Rückkopplungseffekte einer Flächenreduktion durch landwirtschaftliche Intensivierung (Jevons-Paradoxon). Die zusätzliche Berücksichtigung weiterer Landnutzungstreiber würde es ermöglichen, Prozesse wie z.B. die Expansion von Anbauflächen, noch detaillierter zu modellieren. Die Einbindung von Modellen, die landwirtschaftliche Prozesse auf lokaler Ebene simulieren, wie beispielsweise Anbauentscheidungen auf Betriebsebene oder ökonomische Prozesse auf nationaler Ebene, könnten zudem die Verknüpfung und Integration von globalen, regionalen und lokalen Prozessen und deren Wechselwirkungen und Rückkopplungseffekte verbessern. Somit könnten die Effekte landwirtschaftlicher Produktion und mit ihr verbundenen Landnutzungsänderungen noch detaillierter untersucht und potenzielle Zielkonflikte mit Umweltschutz und sozioökonomischen Interessen analysiert werden.

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AES	Agro-Ecological Subregion
AEZ	Agro-Ecological Zone
AgMIP	Agricultural Model Intercomparison and Improvement Project
CGE Model	Computable General Equilibrium Model
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
GGCMI	Global Gridded Crop Model Initiative
IAM	Integrated Assessment Model
IBF	Integrated Biospheres Futures
IIASA	International Institute for Applied Systems Analysis
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
OECD	Organization for Economic Co-operation and Development
SDG	Sustainable Development Goal
UN	United Nations

1 INTRODUCTION

With the Sustainable Development Goals (SDGs), the United Nations (UN) agreed to address the major and most urgent global challenges of the 21st century, such as to end hunger and poverty, to support equality, prosperity and sustainable economic growth, to protect the climate and to safeguard the environment (United Nations 2015b). While achieving these goals requires action in various fields, many of the outlined sustainability challenges are strongly linked to land use and agriculture. First and foremost, efficient land use and a productive agriculture are essential to support SDG 2 to end hunger and achieve food security. With currently between 12 to 15 million km^2 cropland area (Potapov et al. 2021, FAO 2023) covering around 12% of the earth's ice-free land surface (Ramankutty et al. 2008), and almost 50 million km^2 of agricultural land (FAO 2023), agricultural land use and practices moreover play an essential role in promoting a sustainable use of terrestrial ecosystems (SDG 15) as well as in preventing adverse impacts on aquatic ecosystems (SDG 14). Particularly in the past 50 years, land use change and agriculture have been main drivers for biodiversity loss (IPBES 2019, Benton 2021), and more than half of the new agricultural area has been created at the expense of intact forests (Gibbs et al. 2010) and natural vegetation (Potapov et al. 2021). As a large share of the global land resources are cultivated, and 25% of the globally harvested area is irrigated (Portmann et al. 2010), agriculture can moreover quantitatively and qualitatively impact the water cycle and water bodies, e.g., by groundwater depletion due to intensive irrigation (Siebert et al. 2010) or water pollution and eutrophication due to leaching of fertilizers and pesticides. Furthermore, the emissions of agriculture and the food-system account for up to one third of the total global net anthropogenic Greenhouse Gas emissions (IPCC 2019, FAO 2020, Crippa et al. 2021), generated for example by deforestation, the drainage of soils or fertilization, or manure management, and thus are highly relevant regarding SDG 13 on climate action. Ultimately, with agriculture being an important activity for securing the livelihood of the poor in rural areas and a central factor for economic growth in many regions (Townsend 2015), agricultural production is also strongly intertwined with SDG 1 to end poverty, SDG 8 to promote sustainable economic growth and SDG 10 to reduce inequalities (Woodhill et al. 2022).

This exemplary selection of linkages to various SDGs demonstrates the role of agriculture and land use as a key area of action for a sustainable future development. Yet, the described interrelations also complicate a simultaneous achievement of the different sustainability goals, particularly in the context of the projected future dynamics: Global food demand is projected to increase by +30% to +62% between 2010 and 2050 (van Dijk et al. 2021), driven, inter alia, by a growing world population (United Nations Department of Economic and Social Affairs 2022) with changing dietary and consumption patterns (Alexandratos and Bruinsma 2012, Tilman and Clark 2014). Intensifying agricultural production or expanding current cropland in order to meet these needs and improve food security by increasing agricultural production, however, might negatively affect biodiversity and climate and thus jeopardize the achievement of the corresponding SDGs. Conventional agricultural intensification can, for example, lead to increased greenhouse gas emissions (Bouwman et al. 2002, Crutzen et al. 2008, Snyder et al. 2009, Burney et al. 2010) due to excessive or mismanaged fertilizer application, and, along with the use of pesticides, habitat homogenization and the loss of landscape elements, also endanger species richness (Kleijn et al. 2009, Beckmann et al. 2019) and reduce species diversity (Geiger et al. 2010, Newbold et al. 2015). Expanding cropland can be associated with a loss and fragmentation of natural habitat (Kehoe et al. 2017, de Andrade Junior et al. 2021), e.g., through deforestation (Geist and Lambin 2002), which is a main driver for biodiversity loss and moreover largely contributes to global warming (West et al. 2010, Houghton 2012, Tubiello et al. 2015, de Andrade Junior et al. 2021, Tubiello et al. 2021). Yet, projections indicate that cropland area is continuously increasing (Tilman et al. 2011, Alexandratos et al. 2012, Schmitz et al. 2014, Tilman et al. 2014), thereby threatening biodiversity (Tilman et al. 2017) mainly in the tropics (Gibbs et al. 2010, Laurance et al. 2014). In this context, also the socio-economic framework and its changes play an important role in the dynamics of agriculture and land use, with population growth and consumption preferences being for instance among the most influential determinants for future cropland extent (Stehfest et al. 2019) and deforestation in the first decades of the 21st century being mainly commodity driven (Geist et al. 2002, Curtis et al. 2018). Demand, prices, and trade patterns of agricultural goods have a strong impact on current and future agricultural production patterns, but on the other hand, are also affected by changes in agricultural production and land use (Lambin and Meyfroidt 2010).

Accordingly, research that provides a detailed understanding of agricultural production, associated land use dynamics, and potential environmental and socio-economic effects and feedbacks can contribute to creating a food system that supports food security without causing major environmental trade-offs or compromising socio-economic development, and thus to simultaneously achieving different SDGs.

1.1 Agricultural production, associated land use changes and trade-offs

Advances in remote sensing and the continuously increasing global availability of cropland statistics contributed to a detailed spatial picture of agricultural land use and its changes over time. Spatially explicit datasets on the extent of croplands and pastures are now available at a high spatial resolution (Ramankutty et al. 2008, ESA 2017) and even reach back to the beginning of the 20th century (Winkler et al. 2020). Global cropland can be allocated to different crops (Monfreda et al. 2008), and information on their irrigation is available at a high spatial resolution (Portmann et al. 2010, Meier et al. 2018), resulting in a detailed global picture of crop-specific cultivation patterns and their irrigation management.

Besides research in the field of agricultural land use, also research on agricultural production benefited from the increasing availability of global data. While current and past production volumes are recorded in global statistics, e.g., from the Food and Agriculture Organization of the United Nations (FAO), or the Organization for Economic Co-operation and Development (OECD), and are largely publicly accessible, the continuous development and improvement of crop models enables the investigation of crop production under different (future) scenarios, e.g. changing environmental conditions or varying crop management, globally at a high spatial resolution (0.5°) (Müller et al. 2019, Franke et al. 2020). Combined with land use/ land cover data, potential dynamics in future agricultural production can be investigated in detail from a biophysical point of view, for example, how climate change impacts the crop growth and attainable yields of specific crops in different regions (Müller and Robertson 2014, Rosenzweig et al. 2014, Franke et al. 2020, Jägermeyr et al. 2021), arising possibilities and challenges of adapting agricultural practices to climatic changes (Minoli et al. 2019, Zabel et al. 2021), or the potential of optimized crop management to increase food production on current cropland (Mueller et al. 2012, Koh et al. 2013, Mauser et al. 2015b, Pradhan et al. 2015, Davis et al. 2017).

With land being an economic production factor and agricultural production an important contributor to the Gross Domestic Product (GDP) in many regions, economic models allow for investigating the impacts of changes in agricultural production and land use on prices, production and trade patterns and vice versa in the context of different socio-economic scenarios, e.g. changing population, dietary patterns or policies. Various model types operating at country level or regionally aggregated, capturing the whole economy and the interaction between markets or only a subset of sectors, can simulate the economic processes of agricultural production and the resulting impacts on and feedbacks with agricultural markets (Sohngen et al. 2009, Lotze-Campen et al. 2014, Valin et al. 2014, von Lampe et al. 2014). Such economic models are for example applied to investigate the economic impacts of climate change (Nelson et al. 2014), how food prices change under different socio-economic scenarios (OECD/ FAO 2023) or how the demand for agricultural commodities might evolve in the future (Valin et al. 2014).

While potential environmental impacts of agricultural production and land use change are investigated in various research disciplines, this thesis focuses on biodiversity and land use change related carbon emissions. A central subject of current research in this context, for instance, is the debate on land sparing vs. land sharing. It discusses whether increasing production on existing cropland to potentially reduce its extent and thus spare land for nature is more beneficial for biodiversity than extensive farming that might come along with lower yields and an accordingly higher land requirement to maintain agricultural production (Borlaug 1972, Green et al. 2005, Phalan et al. 2011, Tscharntke et al. 2012, Fischer et al. 2014, Phalan et al. 2016, Balmford et al. 2018, Phalan 2018). Land use change impacts on biodiversity are investigated on global scale and in the context of the planetary boundaries (Newbold et al. 2015, Newbold et al. 2016), for instance the effect of a conversion of native forest or grassland into cropland (de Chazal and Rounsevell 2009). Also in this field of research, the increasing availability of (global, high spatial resolution) data (Hudson et al. 2016) supports the development and application of modeling approaches (Chopin et al. 2019) and indices (De Palma 2021) that enable simulation of the interaction between agriculture and biodiversity under different scenarios and on different spatial levels up to global scale. Past and current greenhouse gas emissions induced by agricultural production and land use change are captured in global assessments such as the Global Carbon Budget (Friedlingstein et al. 2022), in which anthropogenic carbon dioxide (CO_2) emissions are monitored based on measurements and model simulations. CO_2 assessments in the context of agriculture and land use change often refer to international and national census data (Houghton et al. 2012), while, particularly for future projections, models such as bookkeeping models (Houghton and Nassikas 2017) or dynamic global vegetations models (Arneth et al. 2017) are applied to investigate carbon fluxes under different socio-economic and land use scenarios.

In summary, past and future changes in land use and agricultural production, and their environmental and socio-economic effects are investigated in detail from different scientific fields and perspectives. Yet, consistently integrating these results of various disciplinary research to obtain a big global picture of potential future land use changes and their implications under different scenarios remains challenging: Research disciplines often differ largely in their scenario definitions, the spatial level and resolution as well as the temporal scale they are working at, and subsequently also the data they refer to. Cross-disciplinary effects, mutual dependencies and feedbacks between fields can moreover hardly be captured.

Integrative modeling frameworks, e.g. Integrated Assessment Models (IAMs), that link models or research approaches from different scientific disciplines, natural and social sciences, can provide the possibility to capture these dynamics and are thus particularly valuable in inherently interdisciplinary fields like agriculture, land use and the food system. By harmonizing and integrating information from different disciplines within such frameworks, the various drivers of changes in agricultural production and land use, e.g., biophysical and socio-economic drivers, can be taken into account and potential impacts in different fields as well as cross-disciplinary feedbacks can be assessed and quantified (Füssel 2010). Integrated approaches thus enable a consistent interdisciplinary investigation of environmental and socio-economic effects of agricultural dynamics and the possibility to detect potentially arising trade-offs between food production, environmental protection and socio-economic sustainability goals (Ruane 2017). The variation of the models or scientific fields combined and represented within different IAMs leads to different fields being represented in varying degrees of detail, for example, regarding the amount of considered agricultural crops, land use classes or economic sectors. This results in different (thematic as well as spatial) research foci of IAMs, for example on the land use competition between agriculture and forestry to be applied for agriculture and timber market foresights (IBF-IIASA 2023), the performance and development of energy-supply technologies and potential land use interaction (Ferreras-Alonso et al. 2024), or a focus on a specific world region (Hibino and Masui 2024).

1.2 Outline of the thesis

The aim of the work presented in this thesis was to create and apply an interdisciplinary land use change model with which agricultural production patterns, associated land use change dynamics and potential trade-offs between food production, socio-economic interests and the protection of the environment can be investigated spatially explicitly and on a global scale. The following model requirements were defined:

- The model should be able to capture regional agricultural production patterns and their potential changes under changing environmental conditions like climate change, along with socio-economic changes, for example in population, demography or consumption patterns.
- The cropland extent and agricultural land use should be modelled dynamically and spatially explicitly, thereby taking socio-economic drivers, the environmental framework and assumptions on the crop management, the agricultural system and potential land use regulations into account.
- The model should provide the possibility to assess potential impacts of changes in agricultural production and land use on agricultural markets and the socio-economic framework as well as on the environment, e.g., related carbon emissions or biodiversity impacts. Therefore, a global perspective is required to be able to capture also telecoupling effects.

The basic idea was that such a model could be created by building up on an approach from Mauser et al. (2015b) developed to simulate the economic optimization of current cropping patterns by coupling the biophysical crop growth model PROMET with the computable general equilibrium model DART-BIO. The coupling approach combines data on the biophysical yield potentials of crops from PROMET with information on the profitability of their cultivation from DART-BIO to globally simulate profit-maximized cropping patterns, with the most profitable crops being cultivated at the most high-yielding locations (for details, see 2.1). To move beyond this application and extend the approach to create a spatially explicit, integrative model to simulate agricultural production and land use change under varying scenario assumptions, the main research tasks were (Figure 1):

- Coupling the models in a gridded approach and at a high spatial resolution to enable the spatially explicit modeling of cropping patterns and land use change dynamics (research task 1)
- Integrating scenario options for the simulation of cropping patterns to enable flexible assumptions on the degree of intensification, commercialization and profit-maximization within the simulated agricultural systems (research task 2)

- Extending the coupling approach to integratively simulate changes in cropland extent, namely land saving and cropland expansion, thereby integrating also the option to simulate land use regulation and policy scenarios (research task 3)

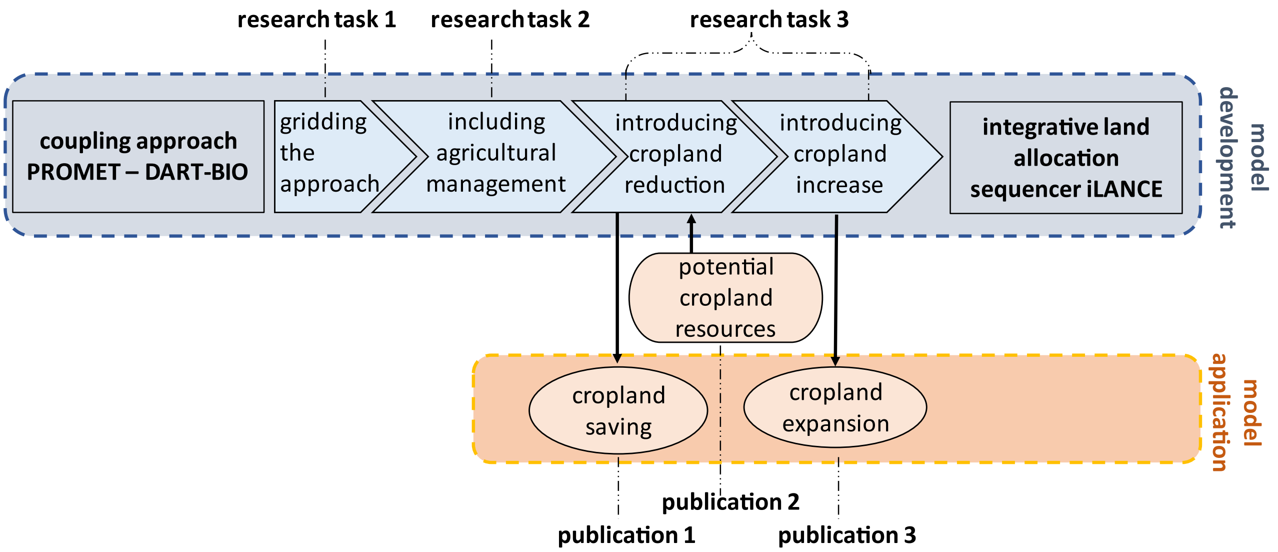

Figure 1: Overview of the research framework and the publications associated with this thesis. *The upper part of the figure shows the different steps of the model development (blue) from the existing coupling approach to simulate profit-optimized cropping patterns to the spatially explicit integrative land use allocation sequencer, the iLANCE model. The three research tasks associated with the model development are displayed on top of the blue bar. The lower part of the figure shows the application of the iLANCE model at the different development steps (orange), with the associated publications displayed below the orange bar. The reduction of cropland under different agricultural management options is investigated in publication 1, while the expansion of cropland under different land use regulation scenarios is investigated in publication 3. The assessment on potential resources for crop cultivation, described in publication 2, provides an essential input for the development of the cropland expansion module in iLANCE.*

The cropland and land use change model created according to these requirements, iLANCE (integrative land allocation sequencer), was then applied to integratively investigate changes in agricultural land use and crop production at a global level, taking economic drivers as well as socio-economic feedbacks into account and assessing the environmental impacts of the induced changes. Specifically, the following three research questions have been addressed in the three main publications associated with this thesis:

- Publication 1: What is the global potential of agricultural intensification to reduce the current cropland extent in order to save land for nature, and how would this reduction impact agricultural markets?
- Publication 2: Which areas can now and under future climate conditions be considered as potentially cultivable and available for cropland use, and how do those areas change under different climate change scenarios?

- Publication 3: Where might future profit-driven cropland expansion take place, and which implications would this have on agricultural markets, biodiversity and climate? Which impact would global conservation policies have?

The following Chapter 2 gives a short overview of the steps and methods towards the creation and set-up of the iLANCE model, which builds the basis for the publications related to this thesis presented in Chapter 3.

2 THE iLANCE-MODEL: METHODS AND PREPARATORY WORK

To transform the existing coupling algorithm for simulating profit-optimized cropping patterns into an integrative, spatially explicit land use change model, modifications of the input data, the coupling algorithm itself and the generated output were necessary. This chapter provides an overview of the preparatory work and the applied methods by describing the coupling concept of PROMET and DART-BIO from Mauser et al. (2015b) (2.1) and the steps taken to create the iLANCE model in more detail: The spatialization and preparation of data to set up a gridded model (research task 1, chapter 2.1), the integration of different management options (research task 2, chapter 2.3) and the extension of the model to simulate land use change (research task 3, chapter 2.4).

2.1 Coupling PROMET and DART-BIO

Mauser et al. (2015b) couple the biophysical crop growth model PROMET with the computable general equilibrium (CGE) model DART-BIO to simulate profit-maximized crop allocation on current cropland. The approach is based on the assumption that actors in an increasingly commercialized agriculture aim to maximize their attainable profit, and it can be used to assess the effects of profit-maximized cropping patterns on agricultural production and markets.

PROMET is a biophysical land surface process model (Mauser and Bach 2009, Mauser et al. 2015a), which has been extended by a biophysical dynamic vegetation component to simulate crop growth and yield formation (Hank et al. 2015, Mauser et al. 2015b). The simulations can be performed at sample or grid cell level at an hourly time step for a wide range of different food and energy crops, including globally important staple crops (e.g., maize, wheat, rice), regionally important food crops (e.g., millet, cassava) and predominant bioenergy crops (e.g., oil palm, sugarcane, rapeseed). The model has been applied in regional studies (Degife et al. 2019, Degife et al. 2021) as well as global (Mauser et al. 2015b, Zabel et al. 2019, Schneider et al. 2022) studies, and takes part in the Global Gridded Crop Model Initiative (GGCMI) within the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Müller et al. 2017, Minoli et al. 2019, Franke et al. 2020, Jägermeyr et al. 2020). A detailed technical description of the model is provided in Mauser et al. (2015a).

The CGE model DART-BIO is a multi-regional and multi-sectoral model of the world economy, in its current version structured into 21 regions with homogeneous economic conditions and 53 sectors representing for example agricultural products, energy products and forest products (Delzeit et al. 2020, Delzeit et al. 2021). It simulates a competitive economy with flexible prices and market clearing in all regions, and with consumers maximizing their utility and producers maximizing their profit. The model provides information on the profitability of different agricultural activities, and resulting prices, production quantities and trade-patterns. A detailed technical description of the model is provided in Delzeit et al. (2021).

The two models are coupled at the spatial level of 178 Agro-Ecological Subregions (AES). These subregions result from subdividing the 21 economic regions according to the global Agro-Ecological Zones (Baldos 2017) (AEZs), that are defined by parameters relevant for land use and agricultural productivity, such as the climatic zone and the length of the growing period (Ramankutty et al. 2004). Thus, dividing the 21 homogeneous economic regions according to these parameters into AES allows for considering the production factor land in a spatially more differentiated way at a subregional level in DART-BIO, thereby taking environmental heterogeneities within the economic regions into account (for details, see Calzadilla et al. 2016).

In the coupling approach from Mauser et al. (2015b), PROMET provides biophysical yield potentials, which are simulated assuming an optimized crop management regarding nutrient supply, the realization of multiple harvests and an optimized pest and disease management. The yields are available for a set of samples representative of the cropland in each AES (for details, see Mauser et al. 2015b). DART-BIO, on the other hand, provides information on the economical profitability of crop cultivation for different crops for each AES. This profitability is described by marginal profit functions, describing the potentially attainable profit for allocating a certain crop on an additional unit of land as a function of the total cropland area of a crop within an AES (marginal profits to land). The function is crop-specific and varies between the sub-regions, as it depends, inter alia, on the productivity of land in relation to other factor inputs (capital, labor, energy) and thus also on the subregional environmental conditions. Let Θ_{Lc} be defined as the factor income share of land for each crop category and each AES, Θ_{KLEc} the factor income share of the other factor inputs capital, labor and energy, and ρ the elasticity of substitution, the marginal profit [$/hectare (ha)] attainable by allocating a cropland area L is calculated as follows:

Marginal profit function (Equation 1):

$$\text{MP}\left[\frac{\$}{\text{ha}}\right] = \left[\Theta_{KLEc} + \sum_{B \neq A} \Theta_{Lc} + \Theta_{Lc}^{1-\rho} * L_{Lc}^{\rho}\right]^{\frac{1-\rho}{\rho}} * \Theta_{Lc}{}^{1-\rho} * L_{Lc}^{\rho-1} - 1$$

The attainable marginal profit is highest for the first cultivated hectare of a crop and decreases with the share of cropland being allocated (Figure 2). In the coupling approach of Mauser et al. (2015b), i is assumed that the attainable marginal profit approaches zero when the current cropland area of the crop within an AES is reached, as otherwise a change in cropland area would have already taken place within a profit-optimized agricultural framework. Further details on marginal profit functions are described in Mauser et al. (2015b).

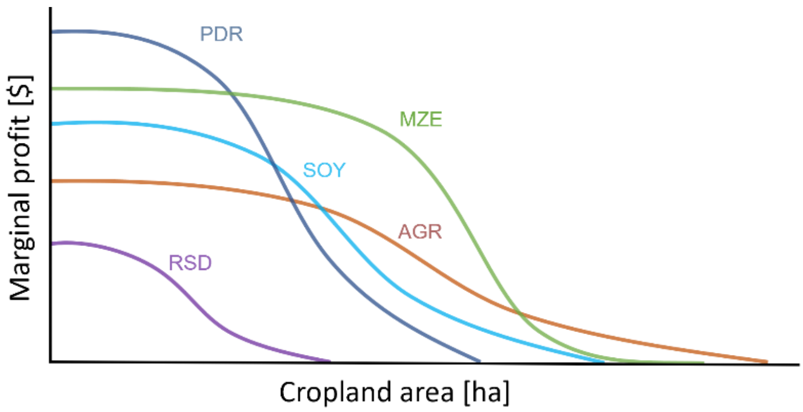

Figure 2: Visualization of the marginal profit functions*. The functions describe the marginal profit to land for different crop categories within an Agro-Ecological Subregion (AES). The potentially attainable marginal profit [$] for allocating a crop category at an additional area unit [ha] is highest for the first hectare of cropland allocated and decreases until it is assumed to approach zero when current cropland area is reached.*

The output of both models, PROMET and DART-BIO, is combined to convert the calculated attainable marginal profit per ha [$/ha] under current agricultural yields from DART-BIO to a potential marginal profit per hectare [$/ha] that could be attained under the regional potential yields derived from PROMET. Based on this, the profit-maximized cropping patterns can be modelled: As the simulated yields for each crop differ between the sample locations within an AES, also the potential marginal profit per hectare [$/ha] differs between the sample locations. Accordingly, a maximum achievable total potential profit [$] and thus a profit-maximized cropping pattern can be modelled by allocating each crop at the locations with the highest potential marginal profit per hectare. Since, as described above, the attainable marginal profit changes with the area of total cropland already allocated within an AES, the cropland reallocation is carried out sequentially. As soon as all cropland of the different crops cultivated within an AES are redistributed across the current cropland area, and thus a new, profit-maximized cropping pattern is established, the reallocation is stopped. The changes in regional agricultural production of each crop category, resulting from reallocating crops at locations with different yield potentials, are then fed back into the economic model. This change in agricultural productivity then affects prices, production and trade in DART-BIO and accordingly also the marginal profitability of crops. Thus, an iterative process starts, in which the models are again coupled, applying the new marginal profit functions to simulate profit-optimized cropping patterns, and again feeding back the resulting changes in agricultural productivity in DART-BIO. This iteration is carried out until a stable profit-maximized cropping pattern is established in all AES.

By coupling a biophysical crop growth model with a global economic model, the approach takes environmental conditions affecting crop growth into account as well as socio-economic drivers of agricultural production, such as population growth, demography or consumption preferences. Moreover, the approach is able to capture global dynamics like international trade. The approach has been used to investigate the global potential to increase crop production on current cropland by changing the current cropping patterns towards profit-optimized cropping patterns and fully closing the yield gap. The results from Mauser et al. (2015b) show that, combined with agricultural intensification and the realization of multiple harvests, a spatial redistribution of cultivation areas that maximizes farmers' profit could increase the global biomass production potential by +148%.

Since the coupling is based on samples representative of the current cropland within each AES, the effects of the simulated optimized cropping patterns can be analyzed aggregated for each AES, but cannot be localized within the AES or analyzed and visualized in a spatially explicit way. This, however, complicates the use of the results in further models and assessments that require gridded input data, for example spatially explicit impact assessments of biodiversity effects, land use related changes in the carbon storage potential or social implications of altered cropping patterns. Moreover, the output cannot be used by models that refer to a different spatial level, operating for example at national level or referring to a different region mapping. Additionally, as the samples of the coupling algorithm are only representative of the cropland area, dynamics that go beyond current cropland extent and result in changes in the absolute cropland area, such as cropland expansion or land saving, cannot be simulated with this coupling approach. Accordingly, the steps described in the following three chapters have been carried out to transform the coupling approach into the spatially explicit land use change model iLANCE.

2.2 Spatialization of the coupling: Creating a gridded model coupling approach (research task 1)

Spatial explicitness is among the most important requirements for the iLANCE model, as it allows changes in cropping patterns and land use to be localized precisely, which in turn enables detailed analyses, particularly of potentially resulting environmental impacts. Gridded information at a high spatial resolution moreover offers the advantage that it can be aggregated to various spatial levels, which makes the model output applicable to different fields of research working at various spatial levels. To spatialize the coupling as a first step towards the iLANCE model, gridded input data is required, for example on potential yields or land use. Thereby, the consistency of the data used in the coupling to the data used in both input models, PROMET and DART-BIO, needs to be guaranteed, and data must be harmonized if necessary. In the following, the creation of gridded data on potential yields with the PROMET model, the harmonization of cropland data across models by spatializing economic cropland data, as well as the harmonization of crop representation across the models is described in detail.

2.2.1 Gridded yield input

With 0.5° being a common spatial resolution for global crop models (Müller et al. 2017, Müller et al. 2019, Franke et al. 2020, Jägermeyr et al. 2021), yield outputs of various crop models could be used as gridded yield input into the iLANCE model. Yet, at 0.5° spatial resolution, one grid cell represents an area of approximately 50 x 50 km (at the equator). In regions with heterogeneous growing conditions, average values of the environmental conditions across the grid cell area might not reflect the agricultural growing conditions in reality, such as for instance in mountainous regions, where cropland is more likely located in the valleys instead of the steep slopes or mountain tops, with implications on soils and climate that largely determine yields. To take this drawback of gridded models into account when creating gridded yield data, an approach was developed to select samples that are representative of the agriculturally suitable area within each 0.5° grid cell at a 1 km spatial resolution. The crop growth simulations can then be carried out at the sample location, thereby taking into account the heterogeneity of the environmental conditions relevant to crop growth instead of being based on average values for the 0.5° grid cell. The representativity of the samples within each grid cell, however, allows for aggregating the resulting simulated sample yields to the 0.5° grid cell level to obtain gridded yields. As the samples are not exclusively located on current cropland but represent the total area potentially suitable for agriculture at the grid cell, the resulting yields can also be used to investigate crop growth beyond the current cropland extent.

Within each 0.5° grid cell, the samples are randomly selected across the agriculturally suitable area, thereby referring to the agricultural suitability data (Zabel et al. 2014, Zabel 2022) as a proxy for the environmental growing conditions, as it is based on a set of environmental parameters determining crop growth. The required number of samples to represent the agriculturally suitable area within each grid cell is assessed successively: Starting with a small number of samples, the random sample selection is carried out 1000 times, and the representativity of the samples for the agriculturally suitable area within the grid cell is tested with a Kolmogorov-Smirnov test (Massey 1951), which compares the distribution of agricultural suitability of the chosen samples with the distribution across the grid cell. If the number of samples is not sufficient to represent the agricultural suitability at the grid cell according to the preset level of significance, i.e., the difference in the suitability distribution of the samples and the grid cell is too large, the sample size is increased and the representativity is tested again with the Kolmogorov-Smirnov test, again referring to 1000 random sample selections with the increased sample size. This successive sample number increase is repeated until the sample size is sufficiently large to represent the agricultural suitability at the grid cell. Generally, more samples are needed for the representation of grid cells in regions with high heterogeneity of soil, topography, and climate, such as mountainous regions, while in regions with a relatively homogeneous land surface, a lower number of samples is sufficient to represent the agriculturally suitable area within a grid cell. For the studies associated with this doctoral thesis, 169,647 samples have been used to represent the agriculturally suitable areas (Figure 3).

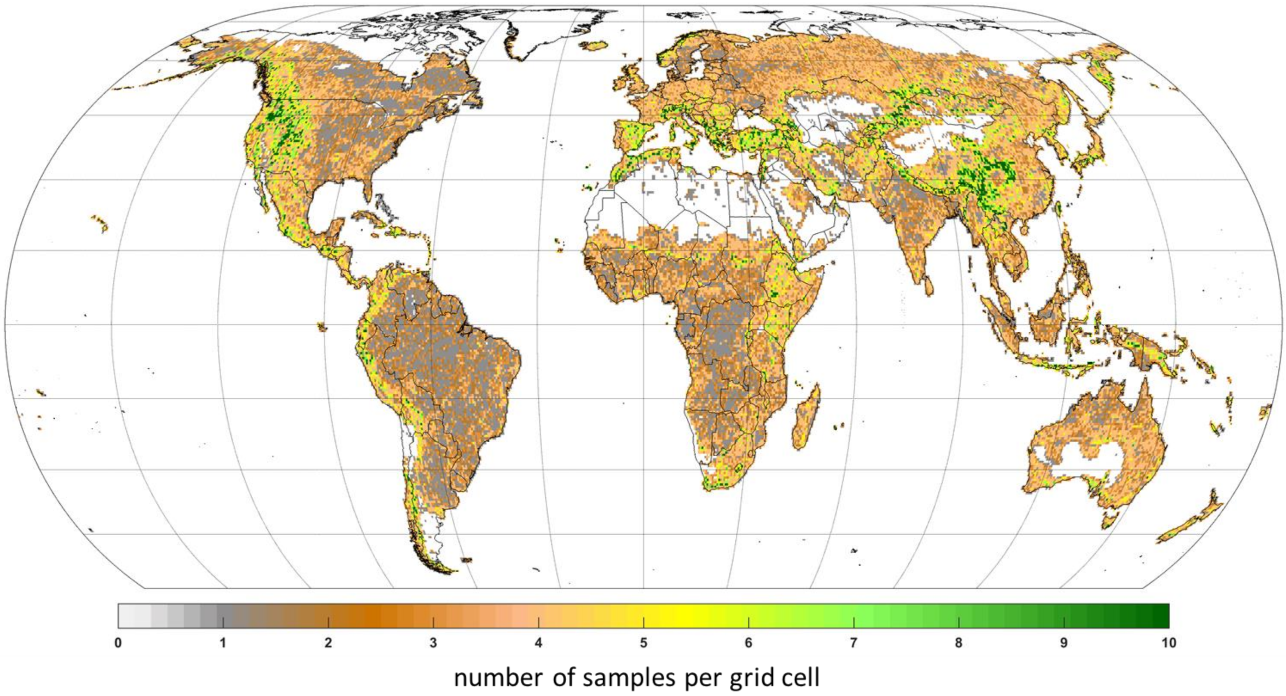

Figure 3: Visualization of the required number of samples within each grid cell*. The map displays the number of samples determined to be required for the representation of the growing conditions within each 0.5° grid cell. Particularly heterogeneous regions require up to 10 samples per grid cell, while regions with particularly homogeneous growing conditions can be represented by 1 sample per grid cell. In total, 169,647 samples have been selected.*

2.2.2 Spatialization of economic cropland data

The economic model DART-BIO refers to the GTAP 9 database (Aguiar et al. 2016) for regional data on cropland. This data is also used in the coupling algorithm, e.g., to obtain the marginal profit functions. However, gridded, crop-specific cropland data is required to set up the iLANCE model and conduct spatially explicit simulations of cropping patterns and land use change. To be consistent with the economic model and its data while providing spatial cropland data for the iLANCE model, the cropland data from the GTAP 9 database is spatialized. This is done by using the spatial data on cropland, production and yields for different crops from Monfreda et al. (2008) and the MIRCA2000 dataset (Portmann et al. 2010) to obtain a crop-specific relative spatial distribution pattern of cropland for each AES. The regional crop-specific cropland area of the GTAP database is then distributed based on this spatial distribution pattern. Thereby, the physical restrictions of land potentially cultivable at each grid cell are taken into account by redistributing the allocated GTAP area at a grid cell if it exceeds the physical area that could potentially be cultivated. The resulting spatial dataset of the GTAP cropland areas represents approximately 99.7% of the GTAP cropland and is consistent with the economic model while at the same time being spatially explicit at 0.5° spatial resolution, as required for the iLANCE model.

2.2.3 Harmonization of crop representation

With a spatially explicit model referring to crop-specific cultivation areas, the representation of crops in the two coupled models, PROMET and DART-BIO, must be consistent. While the yield simulations of PROMET refer to specific biophysical crops, e.g., maize, wheat, barley, sunflower, rapeseed, the economic model DART-BIO distinguishes between 10 economic crop categories that either describe single crops, such as maize, wheat or soy, or specific groups of crops, e.g., 'sugar cane & sugar beet', 'other cereal grains' or 'other oil seeds'. Within the coupling approach of Mauser et al. (2015b), each economic crop category is represented by selected representative crops simulated with PROMET (see Table 1 below). Some economic crop categories in DART-BIO, such as maize, wheat, soy, rapeseed or paddy rice, are represented by one crop that can be modelled with PROMET. Other DART-BIO crop categories including more than one crop, e.g., 'sugar cane & sugar beet', 'other cereal grains', 'other oil seeds' and 'rest of crops', are represented by a number of crops simulated with PROMET.

***Table 1: Overview of the Crops and Crop Categories considered within the coupling approach and the iLANCE model**. The crops simulated with PROMET are listed in the left column, while the crop categories the simulated crops and their abbreviations are representing in DART-BIO are listed in the right column.*

PROMET Crops	DART-BIO crop categories
Sugar cane Sugar beet	Sugar cane & sugar beet (cb)
Maize	Maize (mze)
Paddy rice	Paddy rice (pdr)
Oil palm	Oil palm fruit (plm)
Rapeseed	Rapeseed (rsd)
Soy	Soybean (soy)
Summer wheat Winter wheat	Wheat (wht)
Barley Millet Rye Sorghum	Other cereal grains (gron)
Groundnut Sunflower	Other oil seeds (osdn)
Potato Cassava Maize silage	Rest of crops (agr)

However, for several crop categories, not all crops included in the crop category definition in the economic model are simulated with the crop model, but specific proxy crops are defined, which are then simulated with PROMET. For example, the crop category 'other cereal grains' is represented by the PROMET simulations of barley, millet, rye and sorghum, while the definition of this crop category in DART-BIO contains 12 different crops, including for example also buckwheat, oats and quinoa. To match these differences in the representation between DART-BIO and PROMET in the iLANCE model, statistical weighting factors for each crop category are calculated on AES level to scale the simulated yield level of a crop category to match the yield level of the economic crop category definition. The weighting factors refer to GTAP 9 data (Aguiar et al. 2016) on cropland area and production and indicate the ratio between the statistical yield of a crop category based on the crops included in the economic model DART-BIO versus based on the crops simulated with PROMET to represent the crop category. The weighting process is then integrated into the iLANCE model before the coupling process to scale simulated crop yields of biophysical crops to the economic crop categories.

The spatialization and harmonization of the coupling approach created a gridded global model, with which cropping patterns and their reallocation according to specific criteria, for example for profit maximization or the maximization of production, can be simulated within the boundaries of current cropland extent on a local level at 0.5° spatial resolution. The economic model, on the other hand, captures global market dynamics, their impacts on agricultural production factors on a regional level and resulting implications on marginal profit functions at AES level. With these economic data as input into the gridded global model, and the simulated changes in land use and agricultural production being fed back into the economic model, global, regional and local dynamics are spatially linked (Figure 4) and a global-to-local-to-global framework is created (Hertel et al. 2019, Baldos et al. 2023, Hertel et al. 2023). It is thus possible to capture linkages of global dynamics and local processes with the developed model, such as the effects of changing global prices and trade patterns on local land use decisions and cropping patterns and vice versa.

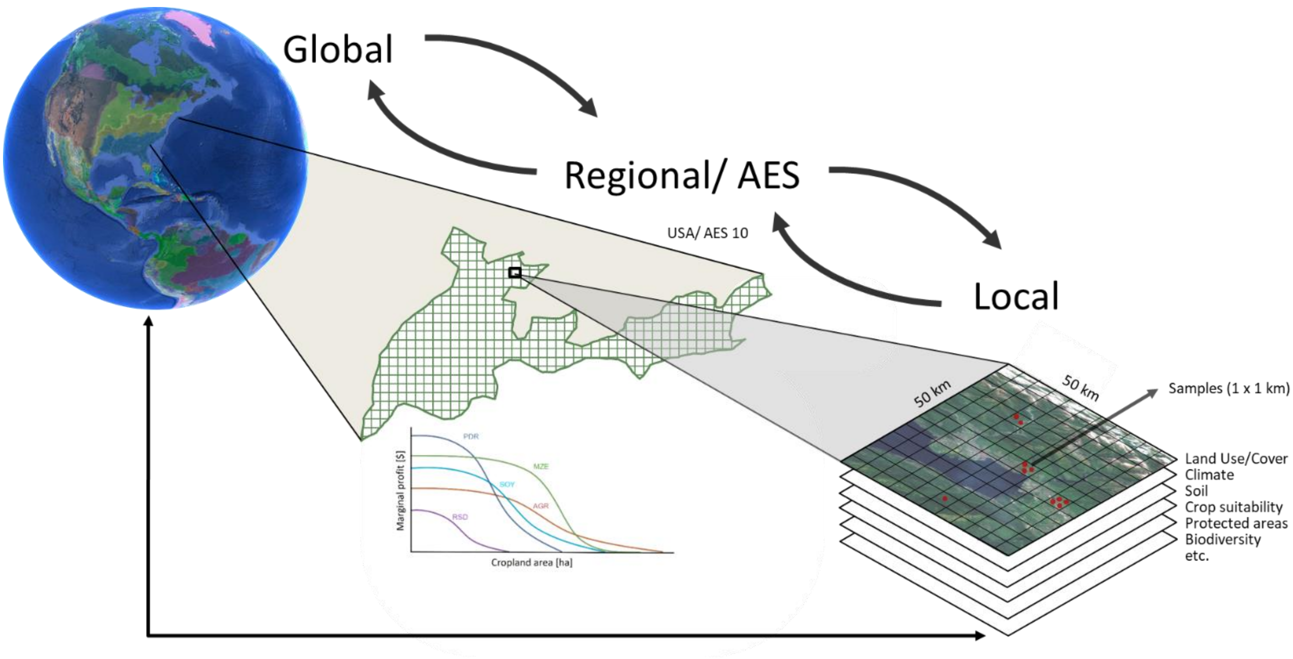

Figure 4: Spatial levels of the integrative modeling framework and their interaction. *Displayed are (1) the global level, at which the economic model captures global market dynamics, (2) the regional level and the level of the Agro-Ecological Subregions (AES), at which regional production and production factors are taken into account as well as the differences between the AES regarding the input factor land and the corresponding differences in the marginal profit functions, and (3) the local level at which land use is simulated on grid cell level and different global gridded data is taken into account, e.g. on land use/ cover, protected areas or crop suitability. The different spatial levels are interconnected within the modeling framework: The global market and its dynamics affect regional prices and production and accordingly trade patterns, and thus influence also the marginal profit functions at AES level. The marginal profit functions additionally depend on the local growing conditions, specifically the relevance of land as a production factor in relation to the further production factors capital, labor, energy. The changes in cropping patterns and land use simulated at the local grid cell level are fed back into the economic model and thus regionally impact the supply of agricultural goods in certain AES and regions, which leads to global economic implications. The figure moreover displays the sample selection for the crop growth simulations with PROMET at local level within the 0.5° grid cell, which is based on global gridded data at 1km spatial resolution.*

2.3 Integrating agricultural management options (research task 2)

The next step towards an integrative land use change model is to provide the possibility to make different assumptions on the agricultural management and structure of the modelled cropland. The integration of different options within iLANCE to define the degree of agricultural intensification, irrigation, and crop diversification at landscape level is described in the following.

2.3.1 Agricultural management

For the iLANCE model development and the publications associated with this thesis, gridded potential yields are used as an input. They are derived from the PROMET model, assuming an optimized crop management considering for example nutrient supply, and no harvest losses, e.g., due to pests and diseases. On one hand, potential yields are helpful in exploring biophysical potentials and limits as upper benchmarks, and thus can be an interesting input for scenario analysis. On the other hand, several constraints can limit the actual realization of potential yields, such as (socio-)economic or technological factors (Lobell et al. 2009, Jiren et al. 2018). Accordingly, certain scenario definitions might require the assumption of imperfect crop management conditions or less intensified agricultural management.

Thus, an option is integrated into the iLANCE model that allows for flexible assumptions on the degree of agricultural intensification by individually defining the percentage of yield gap closing, ranging from 0% to 100%. Hereby, the yield gap is assessed at AES level and defined by the difference between the currently achieved statistical yield within the AES according to the GTAP 9 database and the area-weighted mean of the potential yields across the AES simulated with the crop model. Depending on the defined degree of yield gap closure, a mean potential yield share is calculated for each AES, which can then be used to scale the simulated potential yields at each 0.5° grid cell according to the yield gap closing assumption without losing the spatial yield variability. Under a yield gap closing scenario of 0%, for instance, which assumes that current agricultural management is maintained and no additional agricultural intensification is implemented, the simulated potential yields would be scaled in a way that the average yield across the AES equals the current statistical yield.

Besides agricultural intensification, also assumptions on the irrigation of cropland can be made in iLANCE. Within the developed model setup, the yield input, here the potential yields from PROMET, is provided under irrigated and rainfed conditions separately, assuming perfect irrigation management and no water stress for the simulated irrigated yields. Thus, the rainfed and irrigated yields can be combined and weighted according to individual assumptions regarding the spatial pattern of irrigation or the irrigation of certain crops. For example, to obtain yields under current irrigation patterns, the simulated irrigated and rainfed yields are combined based on spatial data on the currently irrigated cropland of each crop (Meier et al. 2018), whereas it is also possible to assume that only certain crops, for example cash crops, or certain regions are irrigated. Accordingly, the simulation of various irrigation scenarios for different crops or areas is possible within the iLANCE model.

2.3.2 Crop diversification

Besides crop management, also the diversification of crops at a location determines the intensity of agricultural production, ranging from highly diversified cropping patterns to monocultures. The profit-maximized cropping patterns simulated with the coupling approach from Mauser et al. (2015b) assume a crop mix of all crops that can potentially grow at a location, thereby representing the most diversified crop mix feasible to account for the risk aversion of farmers. Such a high crop diversification can be assumed to simulate, for example, smallholder farmers and regions with small-scale farmers. In highly commercialized and industrialized agricultural systems, on the other hand, cropping patterns are often less diversified.

To allow for different assumptions on the crop diversification and the degree of profit-maximization under cropland reallocation, which enables simulation of various agricultural systems and risk aversions of farmers, an allocation strategy module has been developed and included in iLANCE. By defining the number of crops to be allocated within each grid cell (k-factor) when simulating the reallocation of crops, the degree of diversification can be set individually at global, regional or grid cell level. It is thus possible to simulate landscapes ranging from monocultures, in which only one or a few crops are grown at each location, to highly diversified cropping patterns, where all crops are allocated at a location for which yields can be achieved and that are already cultivated in this region according to the GTAP database.

Besides the number of crops grown at each location, also the distribution of the cropland area between the different crops can be modified within the iLANCE model based on the assumed aim to redistribute cropland, e.g., to maximize profit or production. So far, only one option has been implemented in the model: The implemented strategy aims to simulate a maximization of the attainable economic profit and accordingly distributes the available area for crop cultivation among the crop categories according to their profitability. Thus, the relative share of cropland area for each crop at the grid cell is determined by each crop's relative share of profitability based on the marginal profit functions (see Figure 5 below). More profitable crops with high yields and higher marginal profits to land receive a higher share of the cropland area, while less profitable crops with lower yields and lower marginal profits are assumed to receive only a small area share. The methodological background of different strategies for cropland allocation is described in more detail in publication 1.

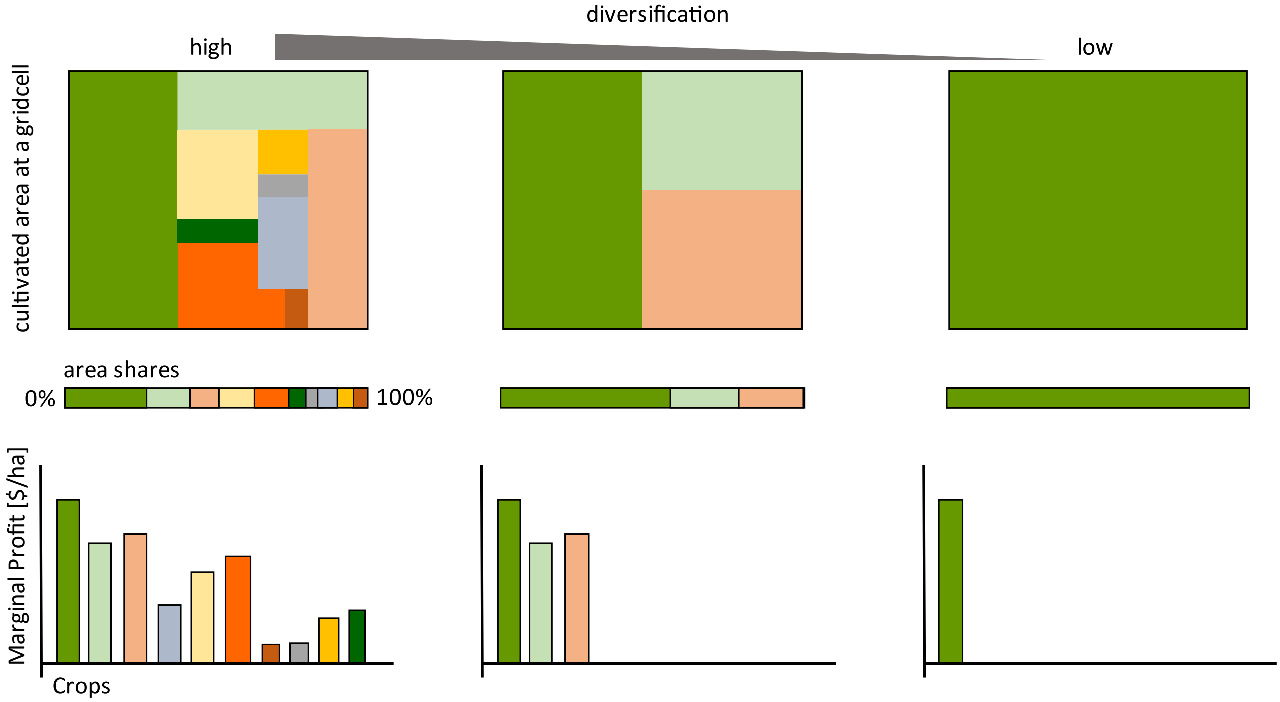

Figure 5: Implemented crop reallocation strategies. *The figure provides an overview of the different options to simulate changes in current cropping patterns towards a more profitable cropland allocation with iLANCE. An individual degree of diversification can be assumed, ranging from highly diversified cropping patterns that include all crops that are potentially cultivable at the location and economically profitable (left) to monocultures that assume that solely the crop with the highest attainable marginal profit is allocated at each location (right). The area share of each crop at the grid cell is defined by its relative marginal profit compared to the other crops, resulting in larger areas for more profitable crops.*

2.4 Enabling land use change modeling (research task 3)

Based on the preparatory work described in 2.2 and 2.3, a spatially explicit coupled model has been created, with which agricultural production and (profit-driven) changes in cropping patterns can be simulated, enabling various assumptions on agricultural management and crop diversification.

To enable the simulation of agricultural land use change with iLANCE, particularly the reduction and expansion of the total cropland area, information on the spatial distribution of land potentially cultivable and its agricultural productivity is required. While the creation of the former, global data on potentially cultivable areas, is described and analyzed in detail in publication 2, the latter is provided by the developed sampling approach applied for the crop growth simulations with PROMET, with which crop yields are available globally at 0.5° spatial resolution.

Moreover, it is necessary to integrate the option for a flexible, changing land input into the coupling and the feedback loop within iLANCE. Therefore, firstly, changes in crop- and region-specific cropland area must be fed back to the economic model in addition to the production changes. With land being one of the economic production factors in the DART-BIO model, changes in cropland area impact agricultural markets on the supply side and thus affect region prices, production quantities, and the profitability of specific crop categories. Secondly, the marginal profit functions, which are the central element of the coupling and refer to the current statistic cropland extent defined in the economic model, need to react flexibly and must be rescaled under a changing cropland extent according to the increase or decrease in cropland area of each crop individually.

Integrating these changes in principle allows agricultural land use change simulations with the iLANCE model. The detailed modifications of the coupling mechanism to enable simulating land saving and cropland expansion and to address the defined research questions are described in the corresponding publications 1 and 3, respectively.

With the created integrative land use change model iLANCE, it is possible to simulate global dynamics in cropping patterns and cropland extent driven by environmental conditions and socio-economic factors, which both determine the profitability of land to be agriculturally used (Figure 6). The simulations are spatially explicit and at 0.5° spatial resolution. The integrated options for agricultural management allow for simulating different scenarios to economically optimize cropping patterns, while the integrated land use change module enables modeling (profit-driven) changes in cropland extent. The simulated changes in agricultural productivity and cropland extent are fed back into the economic model DART-BIO to assess the economic impact of simulated land use changes within an iterative coupling process. Moreover, the spatial explicitness of the results allows the model output to serve also as an input for further impact assessments within other disciplines, for instance to investigate biodiversity impacts or land use change emissions. In the following chapter, the three publications on which this thesis is based on are presented and put into context. They were created at different stages of the model development process (Figure 1) and apply the iLANCE model to investigate different aspects of agriculture and land use change in the context of the SDGs.

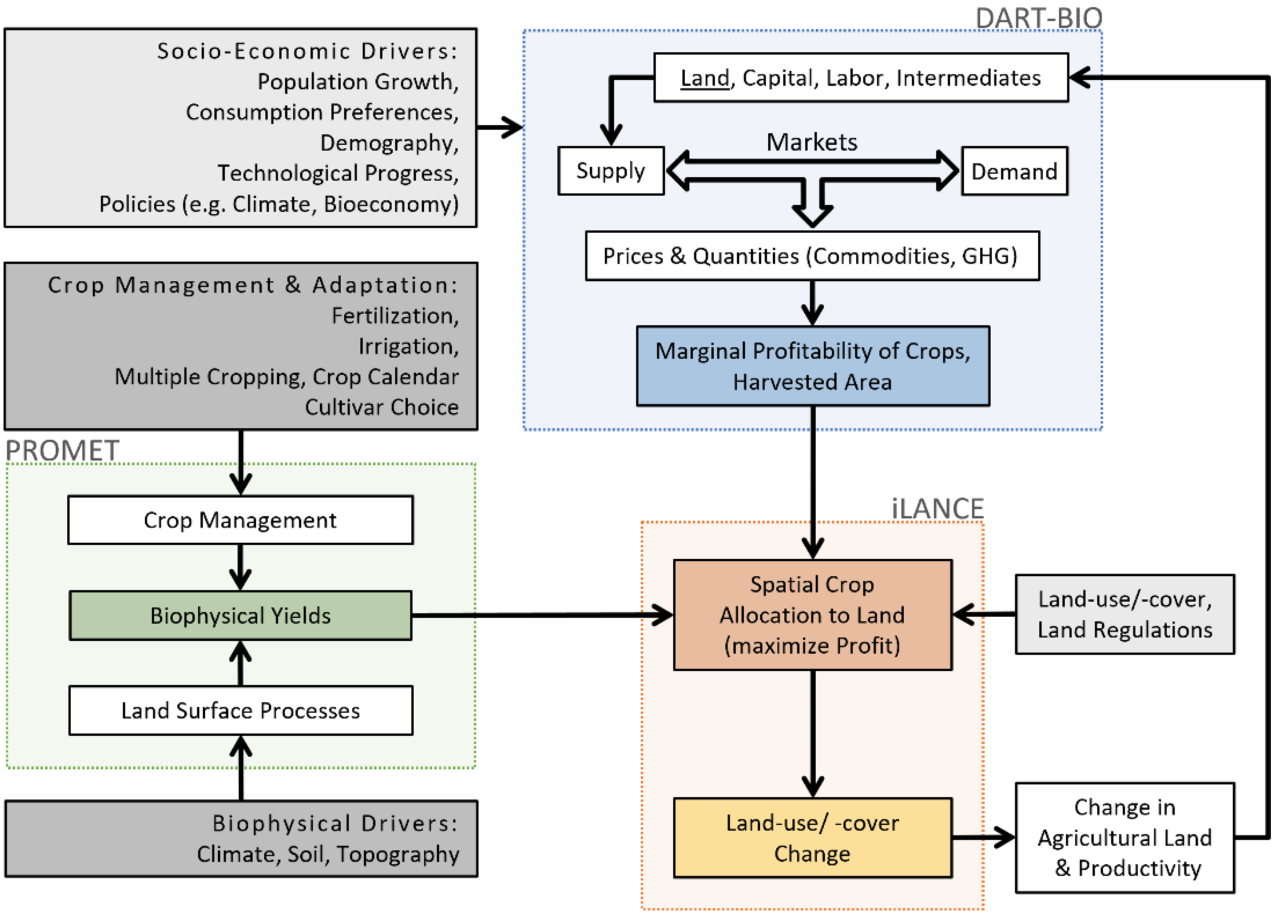

Figure 6: Overview of the iLANCE modeling framework*. The figure displays the input for both primary models, PROMET and DART-BIO, and their integration into the iLANCE model to simulate crop allocation to land. Within PROMET, land surface processes and crop growth are simulated based on biophysical drivers as well as different assumptions regarding crop management, e.g., irrigation, fertilization or sowing dates. The processes in DART-BIO are driven by the socio-economic framework and its dynamics, e.g., population growth, consumption preferences and policies. The allocation of cropland within the iLANCE model is based on the biophysical yield input from the PROMET model and the information on the crop-specific marginal profits to land and the total cropland area assumed in the investigated socio-economic scenario. The simulated changes in cropping patterns or cropland, leading to changes in cropland and/ or agricultural productivity, are fed back into the economic model DART-BIO, causing supply changes and thus impacting the marginal profitability of crops. These changes are then again fed back into iLANCE, where they impact the crop allocation and thus the resulting changes in cropland and/ or agricultural productivity. This iterative process is repeated until a stable cropland allocation is reached. The visualization is based on figures from Mauser et al. 2015 and Zabel et al. 2019.*

3 PUBLICATIONS

The publications related to this thesis explore the interrelations and feedback between agricultural production, the socio-economic framework, and the environment in the context of two strategies discussed to increase global agricultural production, agricultural intensification and cropland expansion, and investigate their global and regional potentials and perils with regard to agricultural markets and environmental impacts. The order of the three publications associated with this cumulative thesis follows the progress of the model development: Publication 1 investigates the potential to reduce the global cropland area by intensifying agriculture and assesses the potential implications of such land saving on agricultural markets. While this publication refers to the current cropland extent and focuses on different scenarios of agricultural management and cropping patterns, publications 2 and 3 move beyond current cropland boundaries. In publication 2, the global resources of land potentially cultivable and potentially available for cropland use are assessed under different future climate change scenarios. The thereby created dataset, published together with the publication, serves as an important input for publication 3, in which the spatial patterns of future profit-driven cropland expansion and the resulting socio-economic and environmental implications are investigated under two different policy scenarios.

The publications thus provide a first overview of potential application cases of the iLANCE model to explore trade-offs between agricultural production, environmental protection and the socio-economic context.

3.1 Publication 1: Land saving potentials and effects on agricultural markets

Julia M. Schneider, Florian Zabel, Franziska Schünemann, Ruth Delzeit, Wolfram Mauser (2022): Global cropland could be almost halved: Assessment of land saving potentials under different strategies and implications for agricultural markets. PLOS ONE. DOI: 10.1371/journal.pone.0263063.

In the context of how biodiversity conservation can best be reconciled with agricultural production, the debate on land sparing vs. land sharing discusses which strategy is more beneficial for biodiversity: To intensify agriculture on existing cropland in order to reduce the cropland area necessary for agricultural production and thus being able to save land for nature (land sparing), or to implement extensive, eco-friendly farming in order to support biodiversity on cultivated land and thus share cropland with nature/ biodiversity (land sharing), which however in turn might lead to a larger cropland area necessary to maintain agricultural production volumes. While the impact of both strategies on biodiversity is studied and controversially discussed (Borlaug 1972, Green et al. 2005, Phalan et al. 2011, Tscharntke et al. 2012, Fischer et al. 2014, Phalan et al. 2016, Balmford et al. 2018, Phalan 2018), quantitative perspectives on the global potential to spare land by intensifying agriculture have been rare (Folberth et al. 2020) and detailed assessments of the potential socio-economic impacts of this strategy have been missing.

In publication 1, the iLANCE approach was applied to simulate a global land saving scenario in which agriculture is intensified globally in order to reduce the current cropland extent. The study aimed to quantify the global and regional potentials to save cropland by agricultural intensification, taking different saving strategies into account, and to assess their effects on agricultural markets in terms of prices, production and trade patterns. The results show that if yield gaps were closed by 80%, almost half of the global current cropland could be sufficient to provide current agricultural production volumes, leading moreover to falling prices in all regions for all crops, with the strongest economic effects occurring in densely populated regions with high pressure on land. The renaturation of the identified areas could potentially contribute to sequester between 114 Gt and 151 Gt CO_2 on the saved land.

Global cropland could be almost halved: Assessment of land saving potentials under different strategies and implications for agricultural markets

3.1.1 Abstract

The pressure on land resources continuously increases not only with the rising demand for agricultural commodities, but also with the growing need for action on global challenges, such as biodiversity loss or climate change, where land plays a crucial role. Land saving as a strategy, where agricultural productivity is increased to allow a reduction of required cropland while sustaining production volumes and meeting demand, could address this trade-off. With our interdisciplinary model-based study, we globally assess regional potentials of land saving and analyze resulting effects on agricultural production, prices and trade. Thereby, different land saving strategies are investigated that (1) minimize required cropland (2) minimize spatial marginalization induced by land saving and (3) maximize the attainable profit. We find that current cropland requirements could be reduced between 37% and 48%, depending on the applied land saving strategy. The generally more efficient use of land would cause crop prices to fall in all regions, but also trigger an increase in global agricultural production of 2.8%. While largest land saving potentials occur in regions with high yield gaps, the impacts on prices and production are strongest in highly populated regions with already high pressure on land. Global crop prices and trade affect regional impacts of land saving on agricultural markets and can displace effects to spatially distant regions. Our results point out the importance of investigating the potentials and effects of land saving in the context of global markets within an integrative, global framework. The resulting land saving potentials can moreover reframe debates on global potentials for afforestation and carbon sequestration, as well as on how to reconcile agricultural production and biodiversity conservation and thus contribute to approaching central goals of the 21st century, addressed for example in the Sustainable Development Goals, the Paris Agreement or the post-2020 global biodiversity framework.

3.1.2 Introduction

With rising global demand for agricultural commodities for food, feed, bioenergy, and the emerging bioeconomy, the pressure on land as a resource and production factor continuously increases [1-4]. At the same time, land for biodiversity conservation, carbon sequestration and further ecosystem services is crucial to tackle main challenges of the 21st century, such as climate change and biodiversity loss, which are also addressed in the Sustainable Development Goals [5]. Land use competition and inherent trade-offs are thus becoming an increasingly important research subject [6-9].

Improving the efficiency of land use in agricultural production systems by increasing the crop production per unit of cultivated land is one strategy to address this land use trade-off. It is often referred to as the Borlaug hypothesis, according to which achieving higher yields results in agricultural land being saved and thus freed up for other uses [10, 11]. In particular, the resulting potential for biodiversity conservation is controversially discussed within the debate on land-sparing vs. land-sharing [12-17], as there is also clear evidence of negative effects of agricultural intensification on biodiversity and ecosystems, such as freshwater depletion, soil erosion, increasing greenhouse gas emissions, habitat homogenization or the loss of habitat availability for wild species [18-27].

Indeed, research findings indicate high potentials for agricultural intensification and optimization of crop and farm management [28-32]: Global crop production on currently cultivated land could be more than doubled [28] and a recent study from Folberth et al. [33] suggests that closing yield gaps would enable to take nearly 50% of current global cropland out of production.

However, land use and cropping patterns are strongly intertwined with economics and policy: Within an ongoing commercialization and globalization of agricultural systems, spatially distant drivers and interconnections gain importance and global crop prices and trade flows affect local land use decisions and cropping patterns [8, 34-36]. Additionally, land use patterns are embedded within their regional socio-economic framework, and shaped by regional drivers such as land use regulations and policies [13, 37], population and consumption changes [38], and can play a crucial role regarding regional societal structures and livelihoods [39]. When investigating the potential of agricultural intensification to save cropland, it is thus important to consider the interaction and feedback between local land use decisions and global markets, as well as to account for regional markets and demand structures.

Previous research on land saving is mainly based on statistical data: Studies either focus on past potentials, based on the evaluation of the correlation between yield increase and cultivated area over time [37, 40, 41], or investigate future potentials via extrapolation of statistics, that thus strongly depend on assumptions on future development paths of demand, dietary patterns, and yield increase [42]. Model-based assessments of land saving potentials are rare [33, 43, 44], and even though economic and societal implications and feedbacks on land saving are widely discussed [8, 36], their quantitative effect so far remains understudied.

Our model-based study aims to evaluate the potential of land saving and analyze the resulting effects on agricultural markets from an interdisciplinary perspective by coupling a process-based biophysical crop model and a computable general-equilibrium (CGE) model of the world economy. In a first step, we globally assess the potential of agricultural intensification to reduce the required cropland for current agricultural production on a regional scale by referring to the simulated yield potentials of the crop model. The resulting land saving and yield potentials are then integrated into the CGE model to investigate in a second step the impact of land saving on agricultural markets in terms of changing crop prices, production volumes and trade flows on a regional and global scale.

The land saving potential is assessed under three land saving strategies that differ in their main driving factor: (1) A production-optimized strategy that is solely driven by biophysical yield potentials to minimize required cropland area (2) a policy-driven land saving strategy that aims to counteract a spatial concentration of land saving to avoid creating or increasing spatial inequalities, and (3) a profit-optimized implementation of land saving that considers biophysical and socio-economic aspects to maximize the value of production. These three different strategies lead to different spatial patterns of land saving, which allows us to investigate, how different assumptions on the drivers and the spatial implementation of land saving affect its potential.

By applying our integrative coupling approach, we can quantitatively link the three land saving scenarios with their global and regional economic implications which are derived from the CGE model, such as changes in staple crop prices or shifting import and export patterns of specific crops. This makes it possible to investigate the socio-economic effects of land saving, for example on food security, in a more comprehensive and differentiated way, which is crucial to evaluate potentials and challenges of land saving to contribute to a more efficient and sustainable use of land as a resource.

3.1.3 Materials and Methods

We refer to the term 'land saving' [8, 11, 40] to describe the potential reduction of required cropland to reach a defined reference production under the assumption of agricultural intensification. Contrary to the term 'land sparing', where freed up land is used for biodiversity conservation, 'land saving' does not predefine the usage of land that could potentially be taken out of agricultural production [11].

Conceptual framework

Within this study, the land saving potential is assessed for 15 globally important agricultural food and energy crops that together represent 70% of global cropland area and 65% of global crop production [45] (S2 Appendix). Our model framework is spatially structured into 17 regions, that are divided into sub-regions according to Agro-Ecological Zones (AEZs) [46, 47] (S3 Appendix). The sub-regions account for the heterogeneity of the primary production factor land by reflecting the varying productivity characteristics for agriculture within a region regarding environmental and climatic conditions [48]. Land saving and impacts on agricultural markets are analyzed at sub-regional level. This spatial structure allows, firstly, to capture differences in (sub-)regional production factors. Secondly, by maintaining sub-regional production volumes as reference production, we account for the relevance of regional agricultural production and specific crops for local economies, employment, culture and society. Thirdly, we can thereby account for linkages across different spatial scales [49, 50], considering local and regional conditions as well as global-scale dynamics and distant drivers.

Models and data

We refer to statistical data on harvested areas and yields from the Global Trade Analysis Project (GTAP) 9 database [51] to determine current crop production as reference production target to be achieved in each sub-region. Holding crop-specific production volumes constant at current levels allows us to focus on land saving and differences between the strategies by avoiding an overlapping with effects resulting from assumptions on the future development of agricultural production.

Potential yields under local climate and environmental conditions are derived from Mauser et al. [28]. Based on simulations with the biophysical process-based crop model PROMET (S1 Appendix), they describe biophysical yield potentials attainable under 1981 to 2010 climate conditions. Therefore, perfect crop management conditions, e.g. regarding sowing and harvest, fertilization, pest and disease control, and a realization of multiple harvest potentials are assumed. The potential yields are provided for rainfed and irrigated conditions separately as 30-year mean at representative sample locations within each sub-region for the 15 considered agricultural crops (S4 Appendix). To be consistent with the coarser representation of crops in the economic model, the biophysical yield potentials are grouped into 9 crop categories (Table in S2 Appendix). Furthermore, we assume that yield gaps are closed by 80%, to take factors into consideration that limit the realization of potential yields (S4 Appendix).

To account for the interplay of agricultural markets and land saving, we apply the CGE-model DART-BIO that represents the world economy in our integrative approach. DART-BIO is a multi-sectoral model that includes all production and consumption linkages through product and factor markets in the global economy and simulates the interplay of demand and supply through a system of nonlinear equations based on Walrasian general equilibrium theory. The model is calibrated to the GTAP 9 database [51] and includes 52 sectors with 10 dedicated crop production sectors that use intermediate inputs and production factors in the form of labor, capital and 18 land types corresponding to the above-mentioned AEZs. An implementation of land saving changes two economic parameters in the model: The land productivity increases and the land endowment decreases. In DART-BIO these two effects are implemented by a productivity shock on the land input in the production function of agricultural crops on the one hand, and by decreasing the availability of the production factor land for each crop according to the results of the land saving assessment on the other hand. This results in two opposing effects on input costs: While increased productivity makes the land input relatively cheaper, the reduction of cropland makes the land input relatively more expensive compared to other inputs (as land becomes scarcer). For most crops and regions, the productivity shock dominates in the net effect, so that producers have lower average input costs for land. While land prices decline, the costs of other inputs, such as labor, capital, and intermediates such as fertilizer, increase, partly representing intensification costs. Under the perfect competition assumption in our model, this leads to decreasing output prices and thus also lower consumer prices of crops. Consumers react to lower prices with higher demand, which motivates producers to increase their output. An increase in production means an increase in producer demand and competition for scarce inputs such as land, labor and capital, which increases input prices and as such crop production prices. Consumer demand decreases as prices for crops rise. This interplay happens simultaneously on factor and product markets until prices are found where demand equals supply on all markets. With DART-BIO, we are thus able to model the through land saving induced supply shock, the resulting demand response and subsequent interplay between demand and supply on markets until a new market equilibrium is reached. In this approach, costs of intensification are only partly considered via higher input costs of other inputs than land. Additional costs, such as investment costs and costs for research and development, are not taken into account. Considering regional socio-economic conditions (e.g. consumption patterns, land regulations, economic policies) as exogenous factors and the relation between supply and demand, DART-BIO furthermore provides crop category-specific marginal profit functions for each sub-region. The functions describe the (marginal) profit that can be achieved by growing a certain crop on an additional unit of land, depending on the productivity of land as primary production factor in relation to other primary factor inputs such as labor and capital (S5 Appendix). This information is used to simulate the socio-economic land saving strategy (see below).

Land saving strategies

We developed three algorithms to evaluate the potential of different implementation strategies of land saving (Fig 1). The algorithms differ in their main driving factor and in their initial assumption to maintain current cropping patterns, defined as the current crop-specific spatial location of cropland:

(1) Biophysical land saving (BLS) that minimizes required cropland

(2) Uniform land saving (ULS) that minimizes spatial marginalization

(3) Socio-economic land saving (SLS) that maximizes the attainable profit

Within all three strategies, we preclude expansion of total cropland and of irrigated land by setting their maximum extent and spatial location to current cropland distribution and irrigation infrastructure according to Portmann et al. [52]. The algorithms operate at sub-regional scale to assess the land saving potential.

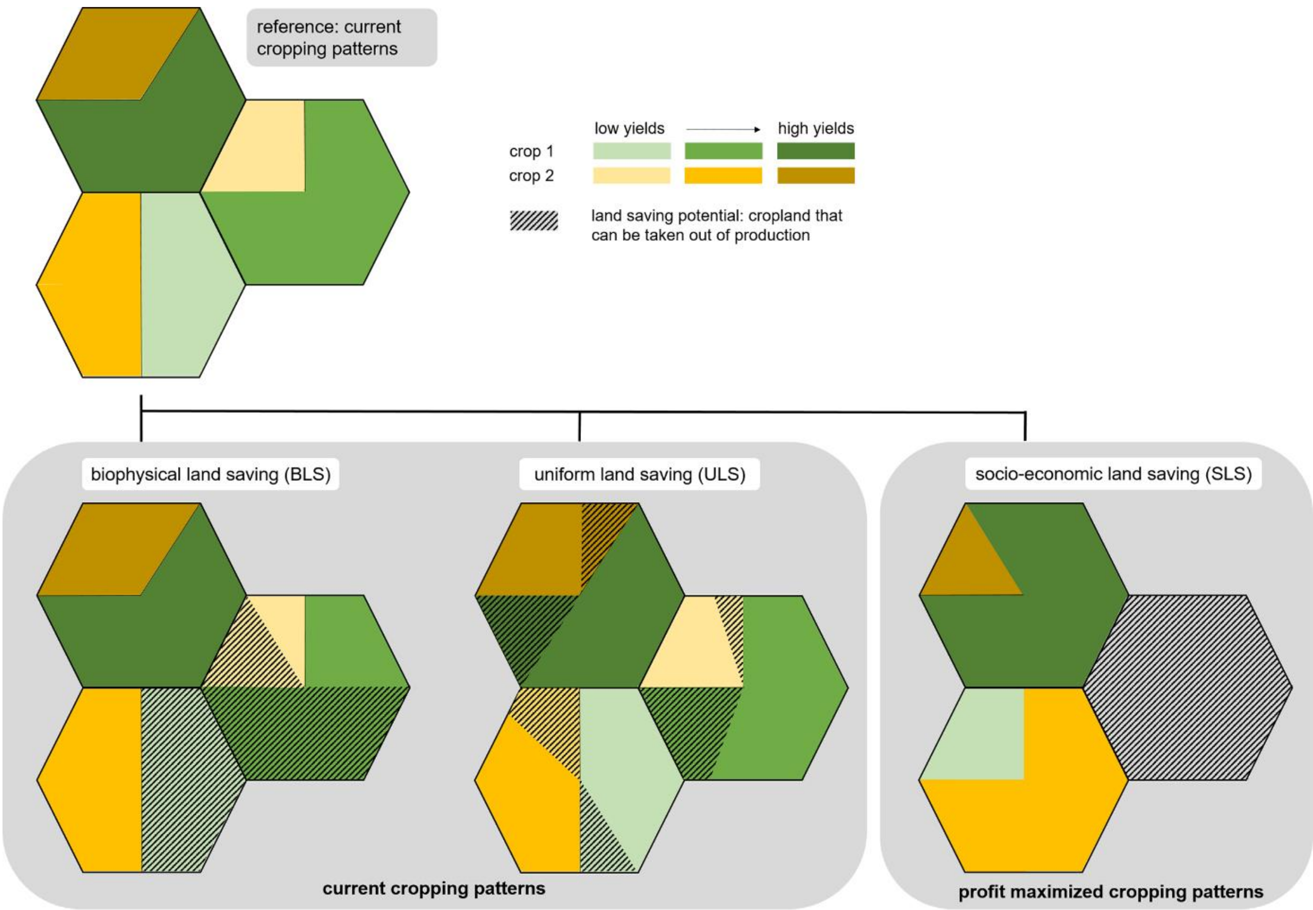

Fig 1. Schematic overview of the three different land saving strategies biophysical land saving (BLS), uniform land saving (ULS) and socio-economic land saving (SLS). *The strategies differ in their assumptions on maintaining current cropping patterns (BLS, ULS) versus their change towards profit-optimized cropping patterns (SLS), and the spatial implementation of land saving at locations with the lowest yields (BLS), uniformly across the region at high- and low-yielding locations (ULS), or the least profitable locations (SLS).*

(1) Biophysical land saving

The BLS strategy assumes that the implementation of land saving is based solely on biophysical yield potentials under current cropping patterns. Therefore, the agricultural production of each crop category is concentrated on its current cropland with the highest potential yields, saving land at biophysically less productive current growing locations with low yield potentials (Fig 1). Thus, the production per area is optimized and the resulting land saving potential serves as an upper biophysical benchmark to minimize the required cropland for current production under current cropping patterns.

To simulate this strategy, we developed an allocation algorithm that, starting from locations with the highest potential yields within the sub-region for a crop category, successively accumulates the attainable production at each current cropland location under potential yields. By accumulating production along the potential yield gradient and stopping when the production target is reached, the lowest-yielding cropland for each crop category within a sub-region is taken out of production.

(2) Uniform land saving

Taking cropland out of production at specific locations can go along with social implications [39], for example by affecting the livelihood of farmers, and thus can reproduce and even foster existing spatial inequalities. We therefore simulate a uniform land saving scenario, where regional policies counteract to balance potentially emerging spatial disparities and a marginalization of people living and working at locations with unfavorable environmental conditions and resulting low yield potentials. Thereby, current cropping patterns are maintained and the cultivated area of each crop category is reduced uniformly across the cropland within a sub-region to avoid a spatial concentration of agricultural production at only the most productive locations for each crop category. Contrary to the BLS, spatial differences in biophysical yield potentials within a sub-region are not taken into account, and cropland of each crop category is taken out of production at low- as well as high-yielding locations (Fig 1). The result can thus serve as a lower bound and rather a conservative estimate of the land saving potential.

The algorithm to simulate ULS calculates for each crop category the attainable production surplus under potential yields on current cropland within each sub-region. With the area-weighted mean potential yield in the sub-region and the current statistical production target, this crop-specific surplus can be converted into an area surplus, which represents the land saving potential that can be realized for each crop category when cropland is uniformly reduced at low- and high-yielding locations of each crop category by the share of the area surplus on the current statistical cropland area.

For both, the BLS and ULS strategy, the land saving induced changes in agricultural productivity and cropland requirements are integrated in DART-BIO to assess the effects of land saving on prices, production and trade.

(3) Socio-economic land saving

Within the third strategy, land saving is additionally driven by regional socio-economic conditions. We assume that land saving is implemented in a commercialized agricultural framework and thus in a way that simultaneously aims to maximize the value of production and accordingly the attainable profit of crop producers. Therefore, current cropping patterns are reorganized to more profitable ones, so that the most profitable crop categories are allocated at the highest yielding locations within each sub-region.

To simulate this land saving strategy, we couple the biophysical yield potentials of PROMET with DART-BIO, based on the coupling approach from Mauser et al. [28]. It uses the marginal profitability of crop categories within a sub-region together with the spatially heterogeneous biophysical yield potentials to create cropping patterns that maximize the attainable marginal profit. This is achieved by re-allocating the most profitable crop categories at the most productive (considered as high yielding) locations within a sub-region (Fig 1), accounting for the profit-maximization behavior of crop producers. However, we assume that the emergence of monocultures is disrupted by risk aversion of farmers, and crop rotation is nonetheless practiced. Thus, the coupling algorithm allocates a crop mix at each location which reflects the ratio of profitability between the crops, determined by their marginal profitability and yield potential (S5 Appendix) [28]. For the application within this study, the established coupling approach is extended so that land saving potentials can be evaluated: By successively accumulating the attainable production under potential yields and optimized cropping patterns, the (re-)allocation of a crop category is disrupted as soon as its statistical reference production is reached on the already (re-)allocated cropland. We furthermore modified the coupling approach to allow expansion of specific crop categories into already saved cropland of other crop categories within the sub-region, if an increase of current cropland is necessary to sustain reference production under the new, profit-maximized cropland allocation. This can occur when less profitable crop categories are shifted to less productive locations, where the attainable yields are lower than under current cropping patterns and thus more cropland is required for current production. Nevertheless, an overall expansion of cropland into currently uncultivated land is not possible.

The marginal profitability of a crop category depends, inter alia, on the productivity of land as a primary production factor in relation to the other factor inputs labor and capital. Thus, within the land saving strategy assumed changes in cropland and cropping patterns entail changes of land input and consequently affect the price of land and indirectly the profitability of crop allocation. These feedbacks are taken into account within the SLS by coupling the models iteratively: As for the two other strategies, the effects of the profit-maximized land saving on cropland requirements and associated changes in agricultural productivity are fed back into DART-BIO, resulting in changes of production, demand, trade and crop prices. These changes in turn alter the marginal profitability of crop categories and thus affect the profit-maximized cropping patterns, which, contrary to the BLS and ULS, changes the resulting land saving potentials. Within our iterative coupling approach, the induced changes of marginal profitability therefore again enter the socio-economic land saving algorithm, and new cropping patterns and land saving potentials are simulated. The iteration is carried out until a stable crop-allocation is established (S5 Appendix). To focus on the aim of our study to assess the land saving potential under current production patterns, changes in agricultural production resulting from the economic model are not fed back into the socio-economic land saving algorithm. This moreover allows us to be consistent in our production targets across all three land saving strategies and thus maintain comparability between the strategies.

The resulting SLS potential takes changes in current cropping patterns due to more profit-oriented cropping decisions of crop producers into account, and thereby considers the feedbacks between agricultural intensification, changing land requirements and agricultural markets in terms of prices, production and trade, which are key influencing variables of land use decisions [38].

3.1.4 Results

Land saving potentials

Globally, between 37% and 48% of currently cultivated cropland could be taken out of production, depending on the implemented land saving strategy (Fig 2). The largest land saving potentials can be realized under BLS, when crop production is focused on high-yielding cropland. With a profit-optimized allocation and land saving strategy (SLS), this biophysical potential is only slightly reduced, still allowing to save 45% of current cropland. Under the assumption of a ULS strategy, the biophysical land saving potential decreases by 21 percentage points (pp) against the BLS, resulting in a global land saving potential of 37%.

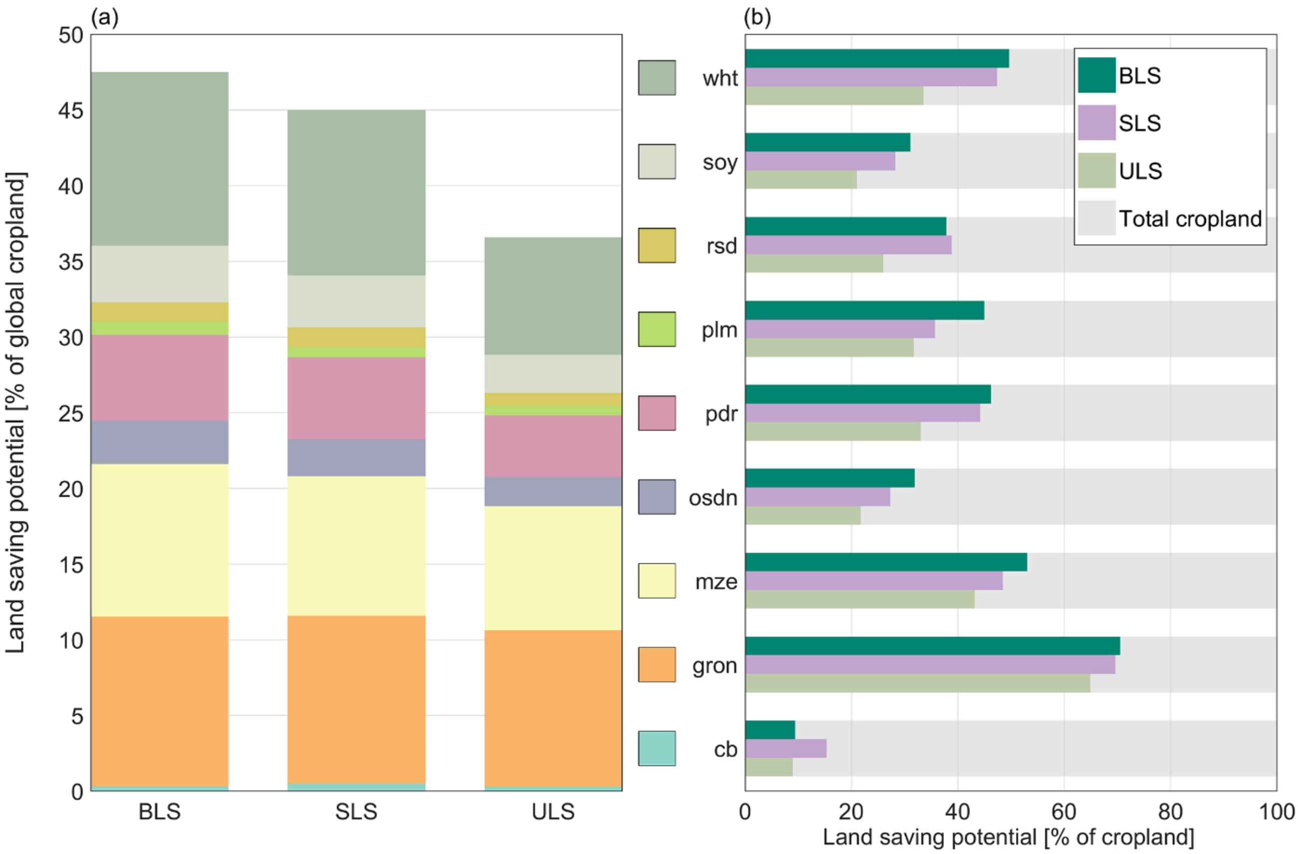

Fig 2. Global land saving potentials. *The land saving potential [%] describes the percentage share of cropland that could be taken out of production on the total global cropland area. (a) Global land saving potential for the three different land saving strategies, biophysical land saving (BLS), socio-economic land saving (SLS) and uniform land saving (ULS), further disaggregated into crop categories. (b) Global land saving potential for each crop category as a percentage share of the crop-specific global cropland. For the different crop categories, the following abbreviations are used (Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat.*

The potential to save cropland varies between different crop categories (Fig 2): Regardless of the strategy, the largest land saving potentials can be achieved for the crop category 'rest of cereal grains', which includes crops like sorghum and millet, mainly resulting from large yield gaps in their main growing regions (Figure E and F in S7 Appendix) in Sub-Saharan Africa, India, or the Middle East and Northern Africa. Globally, 65% (ULS) to 70% (BLS, SLS) of current cropland cultivated with ‘rest of cereal grains’ could be taken out of production. Maize, wheat, and paddy rice show medium global land saving potentials between 43% and 53%, 34% to 50%, and 33% to 46%, respectively, depending on the land saving strategy. The lowest land saving potential can be realized for sugar cane and sugar beet, crops that are often cultivated with a high degree of intensification and thus show rather low yield gaps. Only 9% to 15% of global cropland currently cultivated with sugar cane and sugar beet could be taken out of production. In summary, we see large land saving potentials for typical smallholder crops, which are predominantly cultivated with large yield gaps in developing regions [53], while crops that are already intensively cultivated, and thus show rather low yield gaps, have correspondingly lower land saving potentials.

Regionally, the largest land saving potentials across all strategies can be found in Sub-Saharan Africa, where 76% to 83% of current cropland could be saved. Also, India (44% to 57%), Rest of Latin America (44% to 56%), and Former Soviet Union (42% to 56%) show high land saving potentials across all three strategies. With the BLS and SLS strategy, land saving potentials above 50% can additionally be achieved in Australia and New Zealand, with 62% and 59%, respectively, and both land saving strategies enable to take 55% of current cropland out of production in the Middle East and Northern Africa (Fig 3). These six top regions for land saving currently represent 41% of global cropland and account for 56% of the global land saving potential. Strategically sparing low-yielding or unprofitable cropland in these regions by implementing BLS or SLS could thus reduce the global cropland requirement by 25% (SLS) to 27% (BLS). Even uniform land saving across those six regions could save 20% of currently cultivated global cropland.

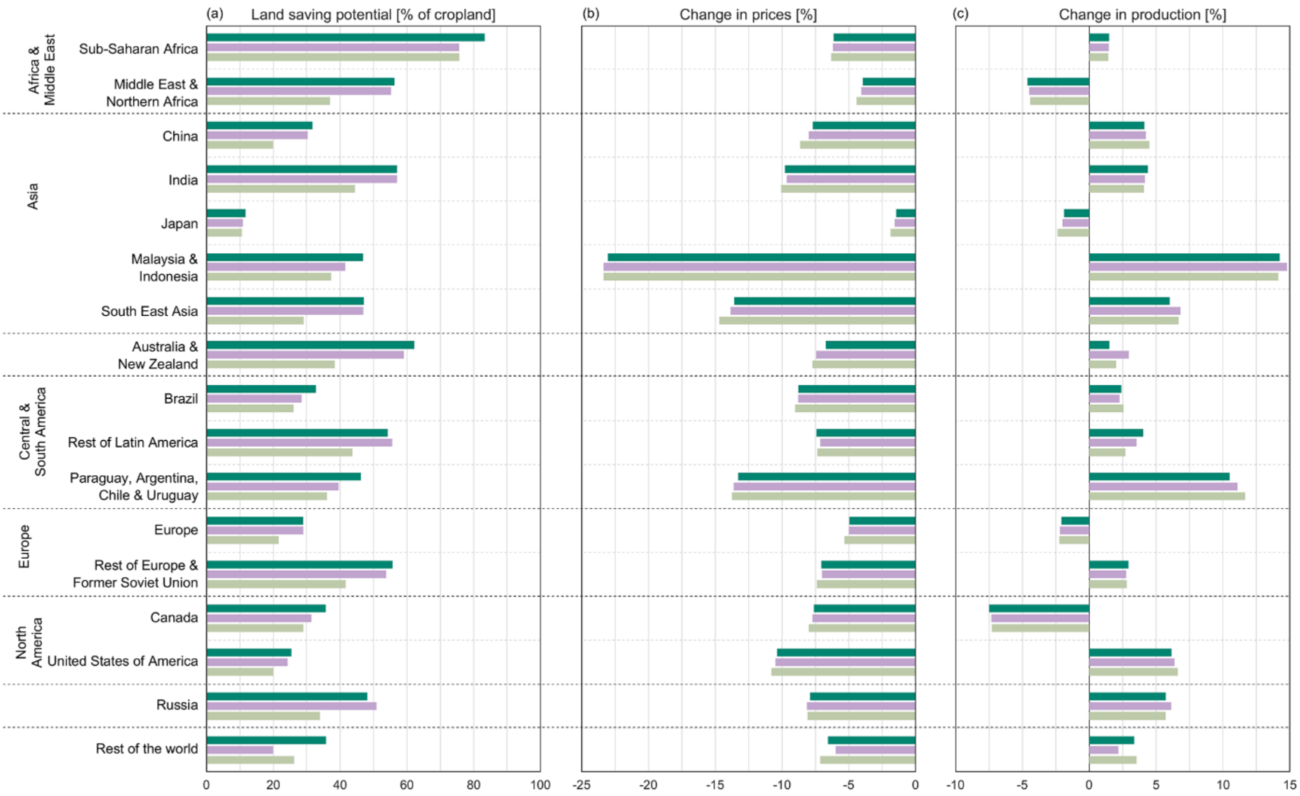

Fig 3. Regional potentials of land saving (a) and resulting regional effects on agricultural markets in terms of changes in crop prices (b) and production (c) for each land saving strategy. *Land saving potentials [%] describes the percentage share of cropland that could be taken out of production relative to the total regional cropland across all crop categories. The relative changes in prices and production [%] refer to a baseline without the implementation of land saving.*

Despite rather low relative land saving potentials of 20% to 32%, China is the region with the third largest absolute potential for land saving after Sub-Saharan Africa and India, due to its large absolute cropland area. Together, those three regions account for over a third (37%) of current global cropland and the implementation of land saving in those regions could save between 17% (ULS) and 21% (BLS) of global cropland requirement.

The smallest land saving potentials over all three strategies occur in Japan, the United States of America (USA) and Europe, with 11% to 12%, 20% to 24% and 22% to 29%, respectively (Fig 3; Table A-C in S7 Appendix).

Impacts on agricultural markets

The implementation of land saving in the economic model causes global crop prices to fall and triggers an increase in global crop production by +2.8% under all land saving strategies. However, while crop prices fall for all crops and in all regions due to the more efficient use of land, the effect of land saving on production as well as the magnitude of price and production change varies strongly between regions (Fig 3).

Our results indicate that the strongest impacts on agricultural markets do not occur in regions with the largest land saving potentials (Fig 4): The largest increases in total crop production can be observed in Malaysia and Indonesia and in Paraguay, Argentina, Chile and Uruguay, which are regions with medium land saving potentials between 36% and 47%. Regional crop production in Malaysia and Indonesia increases by almost +15%, mainly for maize, oil palm and paddy rice, the crops with the largest land saving potential in the region (Figure C in S7 Appendix). As a result, their prices fall by -49% (paddy rice), -36% to -37% (oil palm) and -34% to -38% (maize). Even though the absolute productivity and subsequently output increases for Paraguay, Argentina, Chile and Uruguay are small compared to other regions, the relative increase in output of +10% to +12% compared to a baseline without land saving is large. It mainly results from a rise in the production of soy (+16% to +18%) and wheat (+15% to +16%). Since more than half of the cropland in this region is cultivated with soy, the rather medium land saving potential for soy (32% to 42%) entails a large absolute effect of productivity increase. Soy prices fall accordingly by -16%. In Sub-Saharan Africa, the region with the globally largest land saving potential, the increase in crop production is rather small at +1.4% to +1.5%. Production increases only marginally, mainly for the ‘rest of cereal grains’ (+8% to +10%) and maize (+7% to +8%) and even decreases for wheat by -23% to -30%. In India, on the contrary, where overall land saving potentials are on average across all strategies 25pp lower than in Sub-Saharan Africa, crop production increases by around +4% (+4.1% to +4.5%), mainly resulting from an increase of +17% to +30% in the production of maize, ‘rest of cereal grains’, soy and the ‘rest of oil seeds’, while prices fall by -22% up to -37% (Table D-F and Table G-I in S7 Appendix).

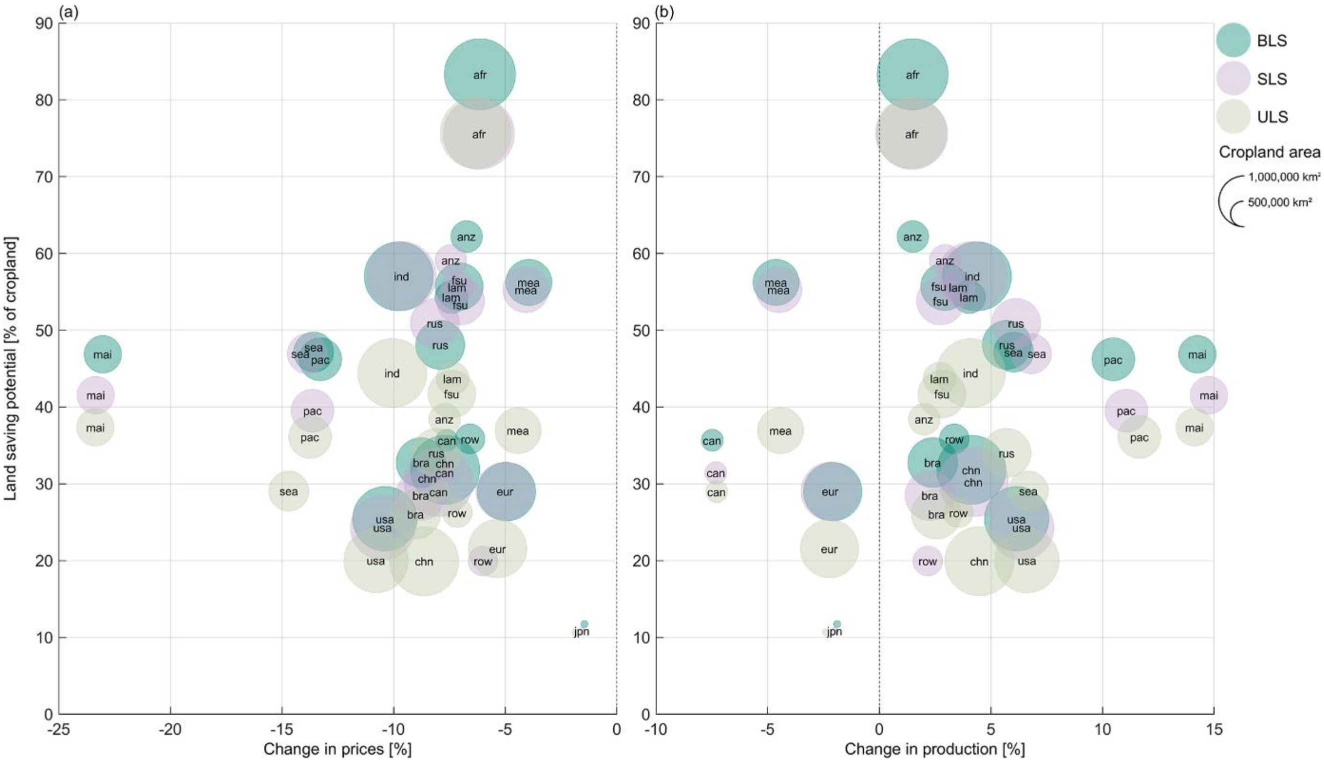

Fig 4. Land saving potentials and their resulting changes in production (a) and prices (b) aggregated over all crop categories for each region. *The sizes of the dots reflect current statistical cropland area over all considered crop categories, while the colors of the dots display the different land saving strategies biophysical land saving (BLS), socio-economic land saving (SLS) and uniform land saving (ULS). For the abbreviations and further information on the regions of the analysis, see S3 Appendix.*

We find that the magnitude of the impact of land saving on production and prices in a region strongly depends on the value share of land in the production costs of crops relative to all other inputs, i.e. labor, capital and intermediate goods such as fertilizer. While the land value shares are roughly in the same order of magnitude for most crops in each region, the differences among regions are large (Table in S1 Appendix). In particular, in Sub-Saharan Africa, the value share of land in the production costs of crops is rather low at 8% to 12%, indicating the relative abundance of land relative to labor and capital in these regions. Hence, a change in this production factor (as it occurs when implementing land saving) has only a minor impact on production outputs. In contrast, highly populated regions such as Malaysia and Indonesia, India and China exhibit high land value shares, as land is a scarce and therefore expensive resource. It amounts to more than 40% in Malaysia and Indonesia, and in India, where globally the second largest land saving potential occurs, the input share in crop production ranges between 19% and 35%. As a result, the effects of our land saving scenario are for example stronger on the Indian agricultural markets compared to those in Sub-Saharan Africa, even though the land saving potential in India is lower.

The results furthermore show that, due to the globalization of agricultural markets, the observed regional impacts of land saving on agricultural markets are not only driven by regional land saving effects, but also by those in spatially distant regions as well as by global markets and crop prices. The Middle East and Northern Africa for example has been a net importer of crops all along. But as the increase in land productivity does not have a large impact on crop production due to a low land value share of 7% to 10%, the falling world market prices within our land saving scenarios lead to a reduction of domestic crop production (-4.4% to -4.6%) and a drastic increase in crop imports (+28% to +29%), mainly wheat and maize from the USA, Russia, and Paraguay, Argentina, Chile and Uruguay. In contrast, in the Rest of Latin America, high potentials to save land and increases in agricultural productivity for soy and maize cause their domestic production to rise by +27% (ULS), +37% (BLS) to +75% (SLS), and +48% (ULS), +56% (SLS) to +65% (BLS), respectively, so that overall crop production increases by +3% to +4%, while net exports of all crops increase by +28% to +50% relative to the baseline. As a consequence, crop consumption rises by +1.3% to +1.5%.

Land saving induced changes in agricultural productivity can thus affect crop import and export in specific regions and consequently lead to a restructuring of trade patterns. This can be observed e.g. when looking at global soy trade under land saving: The high yield potentials for soy in China lead to a reduction of net imports of soy by -11% to -13% and a doubling of domestic soy production (+95% to +108%). This affects the two biggest exporters of agricultural goods, Brazil and the USA.

While in Brazil soy exports decline by -22% to -23% and soy production is reduced by -15% to -16%, soy production in the USA decreases by -4% to -6% and net exports are reduced by -5% to -8%. These changing trade patterns are a direct result of the increase in productivity of soybean in China, which led to higher domestic production and lower domestic prices. As a consequence, more soybean is bought domestically and less soybean is imported from Brazil and the USA, which has become relatively more expensive than the domestically produced soybean. The two regions with the highest output increases, Malaysia and Indonesia and Paraguay, Argentina, Chile and Uruguay also exhibit larger exports and smaller imports of agricultural products. Malaysia and Indonesia can increase the exports of palm oil by +21% and decrease maize and soy imports by around -90%. Similarly, Paraguay, Argentina, Chile and Uruguay show higher exports of all agricultural crops, ranging between an increase of +25% for wheat and +12% for soy. In general, we see a reduction of imports of agricultural commodities indicating that more crops are produced domestically.

Overall, we find for all three land saving strategies that the effects on agricultural markets are determined by the interaction of three different effects: Firstly, the magnitude of the land productivity shock is very sensitive to the value share of land in the production function. As it is larger in regions, where land is a scarce and therefore expensive resource, also the impacts of land saving on prices and production are stronger in those land scarce regions, even though the land saving potentials might be smaller than in other regions. A second important factor affecting the economic effects of land saving is the relative relevance of a crop within a region in terms of cropland area: The land productivity shock also depends on the absolute cropland area of the crop that exhibits productivity increase through land saving in a region. So even if the productivity increase for a certain crop is relatively small, large productivity shocks can occur, if the crop accounts for a large proportion of total cropland in the region. Thirdly, the regional economic effects of land saving are also influenced by global market prices and trade patterns and can be displaced to distant regions by trade, as it can be seen in the case of global soy trade or the domestic wheat production in the Middle East and Northern Africa.

Yield gap closing and strategic land saving

In general, the land saving potential mainly depends on the potential for agricultural intensification and thus the current yield gap. Accordingly, the results show that regions with larger yield gaps tend to have higher land saving potentials (Fig 5). Yet, this correlation varies for the different land saving strategies and is strongest for ULS with a Pearson's correlation coefficient of +0.93, as land saving is implemented uniformly across sub-region and thus strongly depends on the mean yield gap closing across the whole region. The BLS is focused on high yielding locations, so that locations with lower yields have a lower impact on the land saving potential and accordingly, the correlation coefficient is slightly lower at +0.86. As the SLS potential is moreover influenced by the profitability of crops, the correlation of the land saving potentials with the mean regional yield gaps is lowest for this land saving strategy at +0.75.

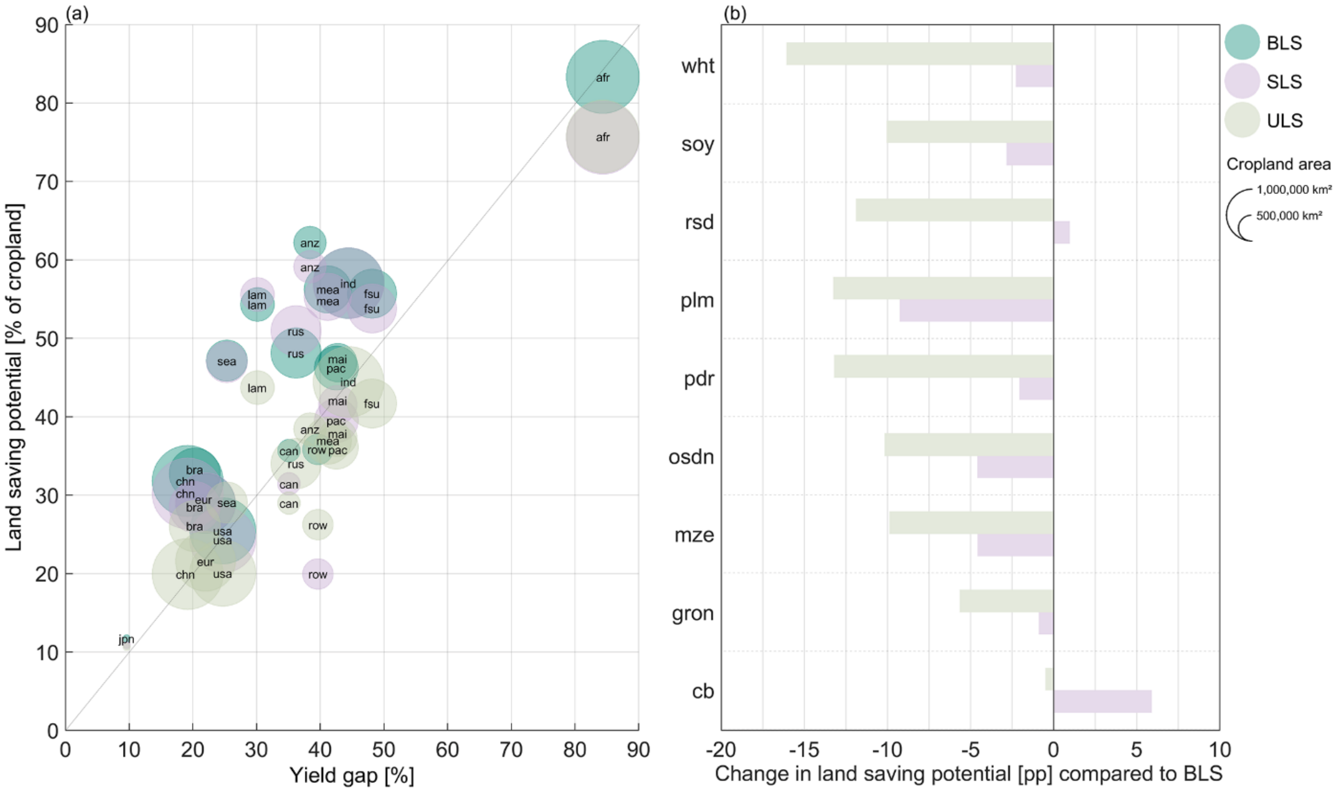

Fig 5. Differences between the land saving strategies in their correlation with current yield gaps and their land saving potential. *(a) Regional yield gaps [%] accumulated over all crops and associated regional land saving potential [% of cropland] for biophysical land saving (BLS), socio-economic land saving (SLS) and uniform land saving (ULS). The yield gap is defined as the percentage difference between statistical and potential yields. (b) Change in global land saving potential in percentage points (pp) for each crop category compared to the BLS as upper benchmark for realizable land saving. For the different crop categories, the following abbreviations are used (Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat. For the abbreviations and further information on the regions of the analysis, see S3 Appendix.*

In addition, also the spatial implementation of land saving itself, represented by the different strategies for land saving, impacts the realizable cropland reduction. We expected the SLS and ULS potential to be substantially lower than the BLS, as the strategies aim to maximize profit (SLS) or to minimize spatial concentration of land saving (ULS) instead of maximizing the land saving potential by sparing the lowest yielding cropland within each region (BLS). Yet, our results show that, especially between the SLS and the BLS strategy, the differences in realizable land saving potentials are surprisingly low (Table A and B in S7 Appendix). Globally, the land saving potential decreases by -3pp under SLS. However, the resulting cropping patterns differ from the cropping patterns under BLS, as through profit-optimized reallocation and land saving, the relatively less profitable crops within a region are shifted to locations with less optimal growing conditions and accordingly lower yield potentials. This can reduce their land saving potential, while the potential of more profitable crops increases. The strongest effects can be observed for the two cash crops oil palm and sugar beet and sugar cane (Fig 5), looking at their main growing regions. For example, in Malaysia and Indonesia, the main growing region for oil palm, the land saving potential for oil palm decreases by -13pp, as other relatively more profitable crops, such as maize, soy, paddy rice or sugar cane and sugar beet, are allocated to productive locations with high yields and thus oil palm is reallocated to less favorable locations. The overall land saving potential in Malaysia and Indonesia decreases with SLS by -5pp. On the other hand, in Brazil, the main growing region for sugar cane, SLS allows to save 22% instead of 9% (BLS) of current sugar cane cropland in the region. Yet, the land saving potential decreases especially for maize (-17pp), but also for paddy rice (-13pp) and soy (-4pp), so that the overall land saving potential in Brazil declines by -4pp compared to a BLS (Figure D in S7 Appendix).

Due to the assumptions of the strategy, the ULS potential is lower than the BLS potential in all regions and for all crops (Fig 5): Globally, the land saving potential decreases and cropland requirement increases by +11pp, as high- as well as low-yielding cropland is taken out of production. The largest difference can be observed for wheat, where globally -16pp less cropland can be saved than under BLS. This mainly results from reduced land saving potentials under ULS in the main growing regions in Russia, Former Soviet Union, Middle East and Northern Africa and China, where up to -30pp less cropland for wheat cultivation can be taken out of production compared to BLS. Further regions with strong changes are South East Asia and India, mainly resulting from decreased land saving potentials for paddy rice of -20pp and -19pp, respectively (Figure D in S7 Appendix).

The globally small differences in land saving potentials between the three strategies indicate that (1) the large biophysical potential for land saving persists when socio-economic conditions are considered and current cropping patterns change towards a profit-maximized cropland allocation. (2) Even an implementation of land saving to strategically counteract spatial concentration of agricultural production could make a major contribution to reduce current cropland requirements.

3.1.5 Discussion

Land saving and the Sustainable Development Goals

Reducing cropland extent by increasing land use efficiency via intensification and optimized land use patterns could contribute to important fields of action of the Sustainable Development Goals [5], such as climate change mitigation (SDG 13) or conservation of terrestrial ecosystems and biodiversity (SDG 15). By reducing global cropland extent, greenhouse gas emissions from fertilized soils as well as the water requirements for irrigation are likely to decrease: Folberth et al. [33] show that reducing the extent of cropland is a main driver of reduced irrigation volume, so that land saving could substantially decrease the water requirements for irrigation, if it is implemented without expanding irrigation. Moreover, especially a reduction in paddy rice cultivation area could contribute to a decline in greenhouse gas emissions [33], as the associated CH_4 emissions largely contribute to total cropland emissions [20]. We identified large potentials to reduce the cultivated area of paddy rice in its top growing regions, India and South East Asia, by 70% and 51%, respectively, but also in Malaysia and Indonesia (61%) and Sub-Saharan Africa (69%) (Figure A and Table A in S7 Appendix). Due to the large potentials to close yield gaps and reduce cropland, we furthermore assume that, even with an increasing future demand of agricultural commodities, cropland expansion into currently unfarmed land could initially be avoided or substantially reduced [4], contributing to prevent or decrease greenhouse gas emissions induced e.g. by carbon stock decline resulting from the conversion of natural habitats like forests, but also grassland to cropland [25, 54-58]. Moreover, especially in the context of the 2° target of the Paris Agreement [59], there's a growing interest in land based negative emission technologies to mitigate climate change [60]. By identifying new areas that could potentially be used for this purpose, the assessed land saving potentials reframe the opportunity costs of those technologies and could thus contribute to re-think and re-discuss plant-based carbon dioxide removal options like e.g. bioenergy carbon capture and storage [61, 62], but also permanent afforestation and reforestation [63, 64]. An estimation of the carbon sequestration potential of our land saving scenarios carried out with the bookkeeping model of land use emissions BLUE [65] shows that additionally between 31 Gt and 41 Gt carbon, which is equivalent to 114 Gt and 151 Gt CO_2, respectively, could potentially be sequestered on the saved land by renaturation, assuming a transformation from cropland to the respective potential secondary vegetation (see S8 Appendix).

Our results can furthermore add a quantitative perspective on the land-sparing-potential in the context of the land-sparing vs. land-sharing debate, and serve as a basis for regional research on targeted strategies to reconcile food production and biodiversity conservation [17, 66, 67]. For example, we found large land saving potentials in Sub-Saharan Africa and Central and South America. Both regions have been identified as hotspots, where biodiversity is particularly threatened by future cropland expansion [68]. Regional research on potentials for land saving could thus help to avoid or at least question cropland expansion threatening biodiversity in those regions to meet the increasing demand of agricultural commodities in the future.

On the other hand, as the assessed land saving potentials are based on an intensification of current agricultural production, supposed positive effects of land saving on ecosystems and biodiversity could be reversed by the negative impacts of agricultural intensification on the environment. Increased mechanization based on fossil fuels or the production and generally higher inputs of fertilizer can for example increase greenhouse gas emissions [19, 24, 25, 69], or threaten plant species richness [22], while pesticides, habitat homogenization and the loss of landscape elements for example reduce species diversity [21]. Also increasing irrigation can have negative environmental impacts, such as groundwater depletion [26, 27], or N_2O emissions [70, 71], but can on the other hand also reduce the overall greenhouse gas emissions of crop production, for example by increasing yields and residue returns and thereby enhancing soil carbon storage [71-73] or preventing further cropland expansion [70]. Thus, the overall environmental effects of land saving strongly depend on how agricultural intensification and the associated management practices regarding e.g. fertilizer application, cropping systems, irrigation or tillage are implemented [24, 72-79]. This highlights the importance of sustainable intensification strategies and technologies [67, 80-82] when discussing land saving and its potential positive contributions to protect ecosystems, reduce greenhouse gas emissions and conserve biodiversity.

In this context, a potential source of uncertainty in our land saving potentials is the assumption that the required economic, technological, and institutional means as well as the societal, cultural and infrastructural framework is given to optimize crop management and realize biophysical yield potentials, for example access to credits, knowledge or inputs like fertilizer [83, 84]. We partly take this limitation into account by not fully closing yield gaps and by assessing the land saving potential for different yield gap closing scenarios (S6 Appendix). However, in this context, it is a potential drawback of our approach that we only partly consider the costs of intensification in our economic model, not taking investment and research & development costs into account. Thus, a complete welfare analysis of the socio-economic impacts of land saving on individual household types is not possible within our study. Yet, from a regional perspective, we see that in particular the regions, where we identify largest land saving potentials, such as Sub-Saharan Africa, India or Former Soviet Union, currently show relatively large yield gaps (Figure F in S7 Appendix), especially for typical smallholder crops such as millet or sorghum. In Sub-Saharan Africa and India, smallholder farms represent around 80% of all farms and operate between 30% and 40% of the agricultural land [85, 86]. Thus, a realization of 80% yield gap closure and accordingly large potentials to reduce current cropland extent needs to be discussed critically: Particularly for less endowed smallholders, overcoming knowledge gaps on best practice and the financial, cultural and legal access to food production resources are main constraining factors for closing yield gaps [84, 87, 88]. Moreover, high costs of agricultural intensification combined with biophysical and socio-economic uncertainties, such as unreliable markets, weather uncertainties, plant pests and diseases or labor shortage, can be an additional barrier for farmers to adopt yield-enhancing technologies [53, 84, 89, 90]. As soon as the risk of additional inputs to close yield gaps being unprofitable is too high, it becomes unlikely that yield gaps are closed [84]. However, technological progress as well as institutional frameworks could help to reduce these uncertainties for farmers, for example information technology to monitor spatial variability of soil nutrients or institutional programs to improve the knowledge of farmers about plant pests and possibilities to control them, or the amount and timing of fertilizer application. Reducing uncertainties changes the economically optimum decision for intensification and could thus encourage farmers to invest and implement measures that close yield gaps and enable land saving [84, 91].

Regarding the large land saving potentials and the large share of smallholders in those regions, it might moreover be challenging to implement land saving without jeopardizing the livelihoods of smallholders [92, 93]. Within the BLS strategy, more than 80% of currently cultivated cropland could be taken out of production in Sub-Saharan Africa and over 50% in India. Even under the less spatially concentrated uniform land saving strategy, still 76% and 44% of cropland could be saved in Sub-Saharan Africa and India, respectively. By taking such large shares of currently cultivated land out of production, many farmers could lose main parts of their income, depending on their income diversity, and also rural population engaged in agriculture, for example as agricultural workers, could be negatively affected. Yet, the saved cropland not necessarily needs to lose its potential to create income: Innovative policies and projects could help to enable a further economic value creation on saved land and co-create environmental benefits, e.g., by economically rewarding carbon sequestration or biodiversity conservation, and support the transition into other livelihoods [93].

Moreover, it is important to mention, that population growth and dietary change are important drivers of future cropland requirements for food production [94] and the effects of climate change will strongly affect agricultural production in terms of its spatial structure and potential productivity [95-98]. As the focus of our study is on the potential contribution of optimized crop and farm management and the effect of strategic crop allocation for land saving, we assess the land saving potential under current climatic and economic conditions. This avoids an overlap with additional effects of different future development paths, such as changes in demand, production patterns and volumes or climate change. However, considering further possible contributions to reduce the pressure on land, like a dietary shift towards increased plant-based diets or food waste reduction [99-104], could help to identify combinations of different measures for reaching a more efficient land use.

Implications of land saving on food security

While our aggregation to regional households in the economic model does not allow to make any statements about distributional impacts between different household types, a view on crop prices, especially for the staple crops wheat, paddy rice and maize, gives a general idea about potential effects on food security in terms of economic access to food. Given that most poor households in developing countries are net consumers of food [105], the large drop in global agricultural prices through land saving is on one hand likely to increase food security in the short run, as the access to food for poorer households, which spend a large share of their income on staples, improves [106-109]. We find that prices for paddy rice and maize drop by up to -49% and -38%, respectively, especially in Malaysia and Indonesia, India and South East Asia, while prices for wheat fall by up to -27% especially in Russia, China and Paraguay, Argentina, Chile and Uruguay. Also in Sub-Saharan Africa prices for staples drop between -12% and -14%. However, net producers of food do not necessarily benefit from lower prices of agricultural commodities.

On the other hand, studies that looked at the medium run and adaptive responses of supply and demand especially of rural households found positive impacts of global food price shocks that increase food prices, as agricultural wages rise and smallholder farmers benefit [110, 111]. The findings of these studies would imply that the decreasing food prices in our scenarios could negatively affect smallholder farmers and the food security of the rural population. Yet, in our study, the lower prices of agricultural commodities are a result of all farmers, including smallholders, becoming more productive, not a global food price shock. Especially in regions with a large share of smallholders like Sub-Saharan Africa, India or South-East Asia [85, 86, 112], we find an increase in agricultural GDP of +7%, +23% and +44%, respectively. While this increase generally implies higher incomes for farmers, we cannot say whether this is distributed evenly among all farmers and thus whether the access to food is improved.

In terms of domestic production and food sovereignty, we see tendencies in both directions: Falling world market prices can make crop imports cheaper than domestic production and thus regionally reduce food sovereignty, e.g., wheat production in the Middle East and Northern Africa, while an increased productivity via land saving can on the other hand also decrease imports and increase domestic production, such as in Rest of Latin America. In general, our results show a larger specialization towards the widely consumed staple crops instead of increasing import pressure through cheaper crop prices. On average, the smallholder intensive regions become less dependent on food imports or can increase their exports. Sub-Saharan Africa for example can increase its maize exports by +8% and reduce rice imports by -8% and other grain imports by -62%, which make up for 85% of cereal consumption. Wheat imports on the other hand grow by +15%. India can increase its exports of rice, maize and other grains by +43%, +24% and +95%, respectively, while wheat exports decrease by -19%. The latter might by more problematic for India as wheat makes up about 40% of cereal consumption. South East Asia increases its rice exports by +53% and reduce its maize and other grain imports by -62% and -33%, respectively, whereas wheat imports increase by +22% (but only make up 8% of cereal consumption). Thus, wheat seems to be the only cereal where there is an increase in import competition due to the large production increases in regions like the USA. Nevertheless, the productivity increases in the three regions rather point to lower import competition and strengthening of domestic agricultural production.

In summary, land saving can decrease regional food sovereignty and increase dependency on imports on one hand, while on the other hand consumers can benefit from lower prices of agricultural commodities and effectively increase their available income and welfare and thereby potentially improve access to food. Due to the aggregation to regional households in the economic model, the analysis of net impacts on different types of households, such as smallholder households that produce and consume food simultaneously, goes beyond the scope of our study, since we have only one representative household per region. Further research that explicitly takes different households and their income structure into account is necessary to investigate the potential impact and contribution of land saving on food security, especially in smallholder regions.

Rebound effects and displacement of land saving effects

Earlier studies have shown that intensification does not necessarily induce a decline in cropland area [37] [41], as an increased land use efficiency creates incentives to increase production [113, 114]. We find that globally, land saving triggers an increase in production of all crops compared to statistical reference, while from a regional perspective, particularly land-scarce regions with a high input share of land, such as Malaysia and Indonesia, show large production increases induced by land saving. Since the aim of our study is to assess the economic implications of land saving under current regional production patterns, we restrict available land in the economic model by assuming that saved land is no longer available for crop production. Thus, we cannot capture the full rebound effect, where an increased agricultural production diminishes land saving potentials by taking already saved cropland back into agricultural production or even leads to an expansion of cropland into currently uncultivated land. Nevertheless, our results indicate, in which regions rebound effects would be triggered and thus policies might be required to link an implementation of land saving with cropland reduction.

In our results, we furthermore see how regional economic effects of land saving can impact spatially distant regions due to the global connectedness of regions via trade. The displacement of the induced changes is observable e.g. in the case of soy trade, where a land saving induced productivity increase in China leads to a decrease in soy production in the two main exporting regions USA and Brazil. Moreover, we observed drastic effects in Canada. Here the negative spiral of low land saving potentials as well as land abundance leads to reduction of land use, output and exports. Since production of agricultural products in Canada is now more expensive than in other regions, Canadian exports of soy decrease for example by more than -50%, while the region turns from an exporter to an importer of maize. This demonstrates the importance of a global, integrative framework to identify potentials but also possible risks of land saving induced directly or by the caused economic effects on prices, production and trade, locally as well as in spatially distant places.

3.1.6 Conclusions

In this paper, we evaluated the land saving potential of different spatial implementation strategies and their effects on agricultural markets in terms of prices, production and trade. The results confirm findings from previous studies on large potentials for cropland reduction by yield gap closing [33, 43]. Similar to Folberth et al. [33], we find that global cropland requirement could be substantially reduced to nearly half of currently cultivated land under a land saving scenario based on a biophysical optimization of land use, while 45% and 37% of current cropland could be saved under land saving strategies that maximize profit or minimize spatial concentration of land saving. The overall small difference in land saving potentials between the three strategies shows that there are large potentials to reduce cropland requirements with strategies that go beyond a purely biophysically driven implementation, accounting for the regional socio-economic framework and potential risks of land saving in terms of spatial marginalization.

By investigating the effects of land saving on agricultural markets within an integrative approach that links local, regional and global scale, we go beyond biophysical potential evaluations and extend the debate on land saving by adding an interdisciplinary quantitative perspective on impacts on and feedbacks with agricultural markets. The resulting reduction of cropland requirement to 52% to 63% of current global cropland causes crop prices globally to fall for all crop categories, which could have positive impacts on food security. However, the increased efficiency of land use and agricultural production would, on the other hand, cause global crop production to increase by around +2.8%, and thereby partly reduce current land saving potentials. Moreover, we find that the impacts of land saving on agricultural markets are non-linear, so that the strongest changes in prices, production and trade do not generally occur in regions with large cropland reduction potentials. The effects on agricultural markets are mainly determined by the value share of land in the production costs of agricultural goods, the relative relevance of a crop within a region in terms of cropland area and by global market prices and trade. Thus, our study points out the importance of an integrative, global approach as well as the consideration of trade, when land saving and its impacts on agricultural markets are analyzed. The identified regional differences in potential impacts and implications of land saving (Fig. 6) moreover show the relevance of taking global-local-global linkages into account and point to a variety of further research questions in the context of land saving, such as occurring rebound effects in the context of global trade, or social implications in different agricultural systems.

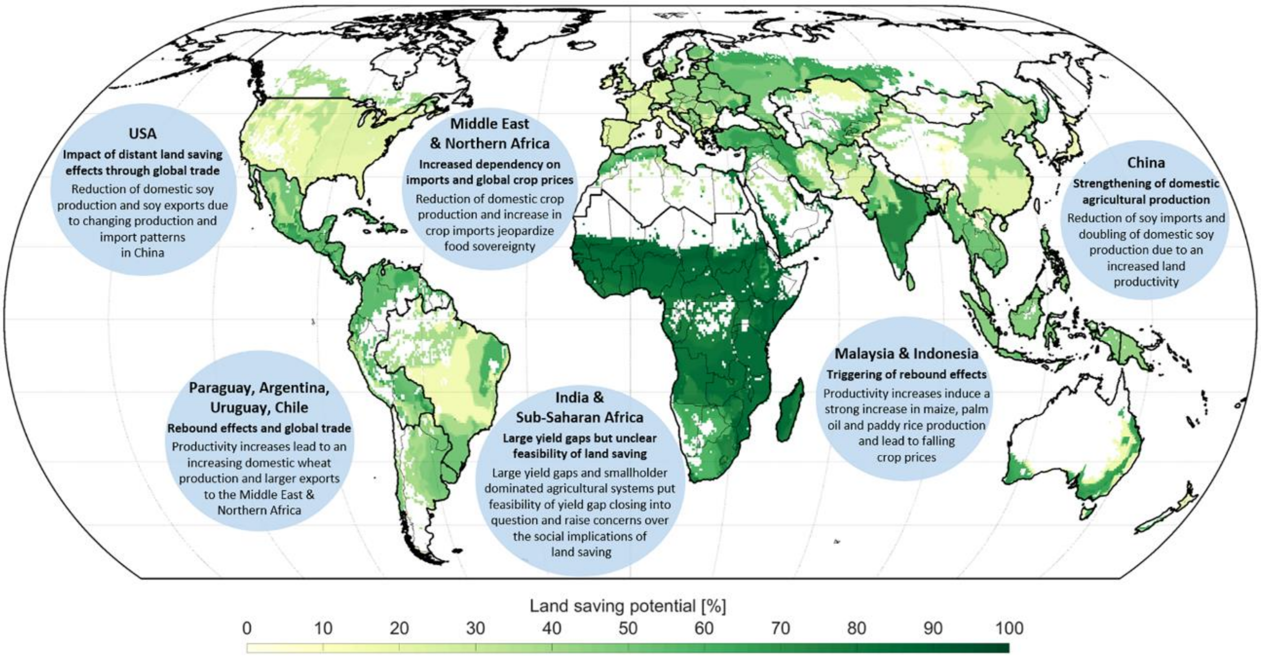

Fig 6. Graphical summary of identified regional effects and implications of land saving. *Different identified effects are displayed exemplarily for the most dynamic regions. The underlying global map shows*

the biophysical land saving potential (BLS) in percentage of total cropland (summed up over all considered crops according to Monfreda et al. [115], see S2 Appendix) for each sub-region. As land saving can only be implemented on current cropland areas, land that is currently not used as cropland is masked out. The thick region lines show the aggregated 17 study regions (see S3 Appendix), while the country boarders are displayed according to the global administrative areas of GADM version 2.8. Reprinted from GADM (https://gadm.org/) under a CC BY license, with permission from GADM, original copyright 2012.

Land saving can change the potentials and opportunity costs of further strategies to reconcile food production and environmental conservation, such as afforestation or negative emission technologies to reduce greenhouse gas emissions, or establishing protected areas to protect nature and biodiversity. The results of our study can serve as a starting point to assess the potential for different usages of the freed-up land, such as for carbon sequestration or biodiversity conservation, so that the possible contribution of those strategies to approach for example the goals of the Paris Agreement [59] or the post-2020 global biodiversity framework [115], or to reduce trade-offs between different Sustainable Development Goals [5] can quantitatively be re-assessed and re-discussed. Whether land saving can in the end contribute to reaching those goals, however, depends on how agricultural intensification is implemented and the freed-up cropland is used. Thus, further research is needed to quantitatively link the land saving potential with the entailed positive and negative environmental implications. Combining our land saving approach with simulation models to estimate carbon fluxes due to land cover conversion [65, 116] as well as investigating the effect and interplay of future scenarios of different drivers [38, 117] on land saving potentials represent interesting perspectives for future research. Overall, an interdisciplinary research framework is necessary to move beyond the theoretical construct of reducing cropland requirements, allowing to investigate measures and mechanisms that can link intensification and land saving without neglecting their social and socio-economic effects and opportunity costs, for example financial compensation and subsidies, or the provision of technology and knowledge. Together with further strategies such as dietary shifts, reduction of food waste and a sustainable intensification, land saving can contribute to reduce the pressure on land resources and play a key role in action on the main global challenges of the 21st century.

3.1.7 Acknowledgements

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3.1.8 Supporting information

The following appendix can be found at the end of this thesis in the Supplement Chapter:

S1 Appendix. Model descriptions.

S2 Appendix. Crops and crop categories.

S3 Appendix. Spatial structure of the analysis.

S4 Appendix. Yield potentials.

S5 Appendix. Coupling approach and socio-economic land saving.

S6 Appendix. Effect of different yield gap closing scenarios.

S7 Appendix. Supplementary results.

S8 Appendix. Carbon sequestration potential of land saving.

S9 Appendix. Supplementary Data: Land saving potentials.

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3.2 Publication 2: Potentially cultivable land and potentially available cropland

Julia M. Schneider, Florian Zabel, Wolfram Mauser (2022): Global inventory of suitable, cultivable and available cropland under different scenarios and policies. Scientific Data. DOI: 10.1038/s41597-022-01632-8.

Contrary to the reduction of cropland simulated in the first publication on land saving, modeling cropland expansion mostly requires information on the extent and location of land that could potentially be used as cropland, which accordingly is a common input in land use models and IAMs (Eitelberg et al. 2015). However, differing assumptions on the definition of land being potentially available for cropland use and the biophysical constraints defining this, but also differences in the underlying datasets lead to an inconsistency of this model input, which, depending on the sensitivity of the model, can have strong effects on the simulation of land use change and cropland expansion. A reference dataset on potentially cultivable land could increase the comparability between different models and simulations of cropland expansion. Publication 2 thus describes the spatially explicit data on land (1) potentially cultivable and (2) potentially available for cropland use created as input to the iLANCE model to simulate cropland expansion under two different scenarios: Without land use restrictions (1) and under the assumption of selected land use regulations (2).

Global and regional changes in the potentially cultivable area and potentially available cropland under different future climate change scenarios are analyzed and discussed. With the datasets being available globally at different spatial resolutions and for different time periods from 1980 until 2100, thereby considering also climate change, it could be a useful input for various model-types investigating land use dynamics. Thus, the data has been made available as open access data for four different time periods under two different climate change scenarios, for irrigated and rainfed conditions, and for two crop mixes (including and excluding second-generation bioenergy crops): https://doi.org/10.5281/zenodo.5993934.

Global inventory of suitable, cultivable and available cropland under different scenarios and policies

3.2.1 Abstract

Where land-use change and particularly the expansion of cropland could potentially take place in the future is a central research question to investigate emerging trade-offs between food security, climate protection and biodiversity conservation. We provide consistent global datasets of land potentially suitable, cultivable and available for agricultural use for historic and future time periods from 1980 until 2100 under RCP2.6 and RCP8.5, available at 30 arc-seconds spatial resolution and aggregated at country level. Based on the agricultural suitability of land for 23 globally important food, feed, fiber and bioenergy crops, and high-resolution land cover data, our dataset indicates where cultivation is possible and how much land could potentially be used as cropland when biophysical constraints and different assumptions on land-use regulations are taken into account. By serving as an input for land-use models, the produced data could improve the comparability of the models and their output, and thereby contribute to a better understanding of potential land-use trade-offs.

3.2.2 Introduction

Looking at the challenges of the 21st century that are addressed in the United Nations' Sustainable Development Goals (SDGs)[1], land plays a major role in various SDGs, such as in meeting the increasing demand for food and bioenergy, the conservation of ecosystems and biodiversity or taking action against climate change. However, competing needs of land and emerging trade-offs between the different usages increase the pressure on land, which is particularly apparent in the context of agricultural land-use: While expansion and shifting agriculture were identified as main drivers for biodiversity loss[2-5] and deforestation[6-8], which is moreover accompanied with carbon emissions[9-12], cropland extent is still projected to increase globally by up to 7% until 2050[13].

Thus, investigating land-use change and particularly the spatial dynamics of potential future cropland expansion is an important current research task, which can be addressed with land-use models and Integrated Assessment Models[14-19]. Thereby, information on the extent and the spatial location of potentially cultivable land resources that could be transformed into cropland is an essential input information[20]. Depending on the model, it constrains for example the spatial extent of cropland expansion[21] or impacts the costs of land conversion and land prices[20,22]. However, the spatial location and extent of land assumed to be potentially cultivable differs between models, mainly due to different assumptions on which current land-use/-cover is considered as being potentially available for cropland use[20]. Yet, a study from Eitelberg et al.[20] shows that also variations of up to 84% exist between cultivable land datasets with comparable assumptions on land availability, resulting from different underlying data and also from differences in assumed biophysical constraints for cropland use. Depending on the sensitivity of the land-use model, those differences can have large implications on the simulated results and thus complicate the comparison of model outputs and simulated land-use change projections.

Reference data on potentially cultivable land could contribute to increasing the comparability and consistency between land-use change simulations[23,24]. However, published datasets are rare, and due to their often very specific assumptions difficult to apply within different models and studies. They refer for example only to specific crops when evaluating the biophysical suitability of land for agriculture[25-27], include various social, administrative and economic constraints[28], focus only on a specific time period or region[28], or are provided in a rather coarse spatial resolution[20]. To be applicable in as many land-use models and scenarios as possible, a dataset of potentially cultivable land should (1) include a broad spectrum of agricultural crops when evaluating the suitability of land for agriculture. It is (2) ideally provided with and without universally applicable assumptions on institutional restrictions constraining the availability of land for agricultural use, and is (3) available in a high spatial resolution on a global scale and for different time periods, considering also climate change.

Here, we provide two spatially explicit global datasets: An updated version of the agricultural suitability[29], and a new dataset on potentially cultivable and available land for agricultural use[30] for past and future time periods from 1980 until 2100[29,30]. While biophysical and climatic constraints determine the potential suitability for agriculture, the potentially cultivable land is defined by its agricultural suitability and the (technical) feasibility of crop cultivation. The potentially available cropland additionally takes selected existing and potential nature protection policies into account (Fig. 1).

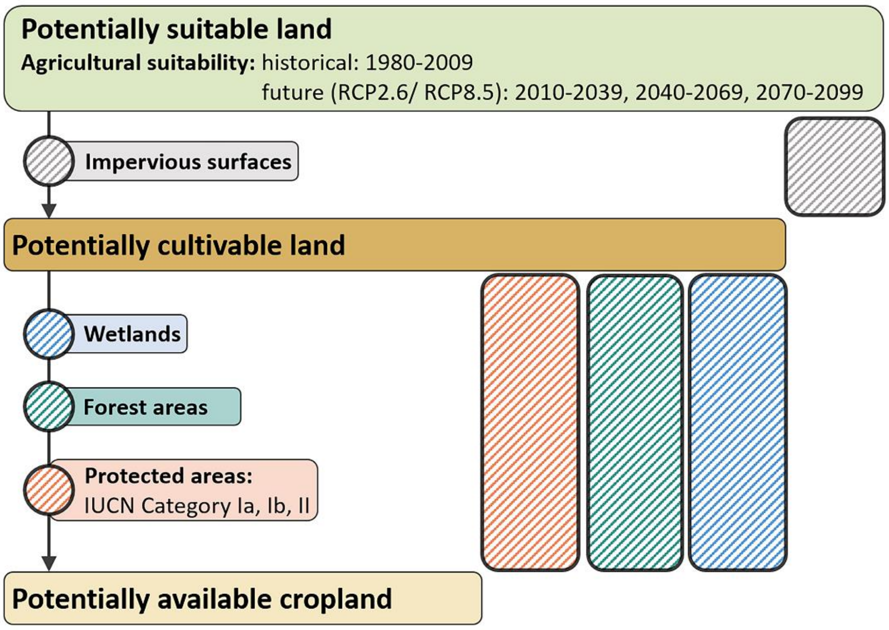

Figure 1: Overview of the analysis framework. *The agricultural suitability refers to land that is suitable for crop cultivation under the environmental conditions of each time period and climate scenario. The potentially*

cultivable land excludes impervious areas that are agriculturally suitable, such as settlements or roads. The potentially available cropland additionally accounts for a subset of institutional restrictions, regulations and (potential) nature protection policies on the agricultural use of land. Thereby, we assume strictly protected areas, forests and wetlands to be not available for cropland use, and thus exclude those areas in the potentially available cropland.

The assessment of potentially cultivable land is based on the historic and future agricultural suitability for 23 food, feed, fiber, and first- and second-generation bioenergy crops[31,32] considered as globally important with respect to their cultivation area and production volumes (Table 1). By using a fuzzy logic land suitability model[32], the approach accounts for crop-specific characteristics and requirements during the growing period with regard to climate, soil and topography, and considers the effects of climate change on the agricultural suitability for two representative concentration pathways, RCP2.6 and RCP8.5[33]. The impact of irrigation on the suitability is taken into account by referring to current irrigation patterns[34], which we assume constant also for future time periods. This results in a dataset on land potentially suitable for agricultural use (for details see Methods). We use high resolution data on man-made impervious areas[35] to exclude settlements and infrastructure, which we assume to be technically difficult or unlikely to be cultivated or converted into cropland. The resulting dataset displays the potentially cultivable land. Thereupon, the potentially available cropland dataset is created by considering the most strictly protected areas[36], designated with the International Union for Conservation of Nature (IUCN) Category Ia, Ib and II, as not available for cropland use. Moreover, we exclude forests[37] and agriculturally suitable, but not yet cultivated wetlands[38] from the potentially available land due to their importance for carbon sequestration and biodiversity conservation. Thus, the dataset accounts for a subset of selected (institutional) restrictions, regulations and (potential future) policies on cropland expansion and nature protection, thereby reflecting key aims of the Sustainable Development goals[1] and recent efforts to stop deforestation[39], protect the climate[40] and preserve biodiversity[41] (Fig. 1). Yet, it is important to note that the term 'potentially available cropland' does not imply that the identified land can unrestrictedly be used for crop cultivation without potentially arising conflicts and trade-offs with other land-uses (see the Discussion section for details).

Table 1: Overview of the considered crops within the agricultural suitability*. Included are staple crops of global importance, such as maize, wheat and rice, that provide more than half of global calorie intake, but also more regionally important food crops, such as millet or cassava. Furthermore, we include the main first- and second-generation bioenergy crops to capture the trends in political support of biofuels and the emerging bioeconomy.*

Food, feed, fiber and first-generation bioenergy crops			**Second-generation bioenergy crops**
Barley	Potato	Sugarbeet	Jatropha

Cassava	Rapeseed	Sugarcane	Miscanthus
Groundnut	Rice	Sunflower	Switchgrass
Maize	Rye	Summer wheat	Reed canary grass
Millet	Sorghum	Winter wheat	Eucalyptus
Oilpalm	Soy		Willow

All resulting global datasets on potentially suitable, cultivable and available land are available for historic (1980-2009) and three different future time periods (2010-2039, 2040-2069, 2070-2099) under RCP2.6 and RCP8.5 at 30 arc-seconds (approximately 1km at the equator) spatial resolution, and thus allow for historic and future land-use change analysis under different climate change scenarios. By including first- and second-generation bioenergy crops into our suitability assessment, also land-use change and cropland expansion in the context of an emerging bioeconomy can be investigated. Moreover, the datasets are available for rainfed and irrigated conditions separately to enable the investigation of land-use change under changing irrigation patterns. Since the information of potentially cultivable land resources could also be of interest for models that use aggregated data, such as many economic models[42], all datasets are available also in aggregated form at country level. The provided data could thus contribute to increase also the consistency within interdisciplinary research and integrated model coupling approaches investigating land-use change and arising trade-offs.

3.2.3 Results

Historic potentially cultivable land and potentially available cropland

For the historic time period (1980-2009), around 78.1 million km^2 are potentially suitable for agricultural use under current irrigation patterns. Of this potentially suitable land, around 390,000 km^2 (0.5%) are impervious surfaces such as human settlements or infrastructure, and thus considered as being not cultivable. Accordingly, globally around 77.7 million km^2 are potentially cultivable in terms of biophysical characteristics regarding soil, climate, topography and the current surface cover (Fig. 2a). Of this area, 3% is designated as strictly protected area, mainly covered with forests (64%), while additionally 36% of the potentially cultivable land is covered with forests and 1% with wetlands not classified as strictly protected, resulting in a potentially available cropland of around 46.3 million km^2 (Fig. 2b).

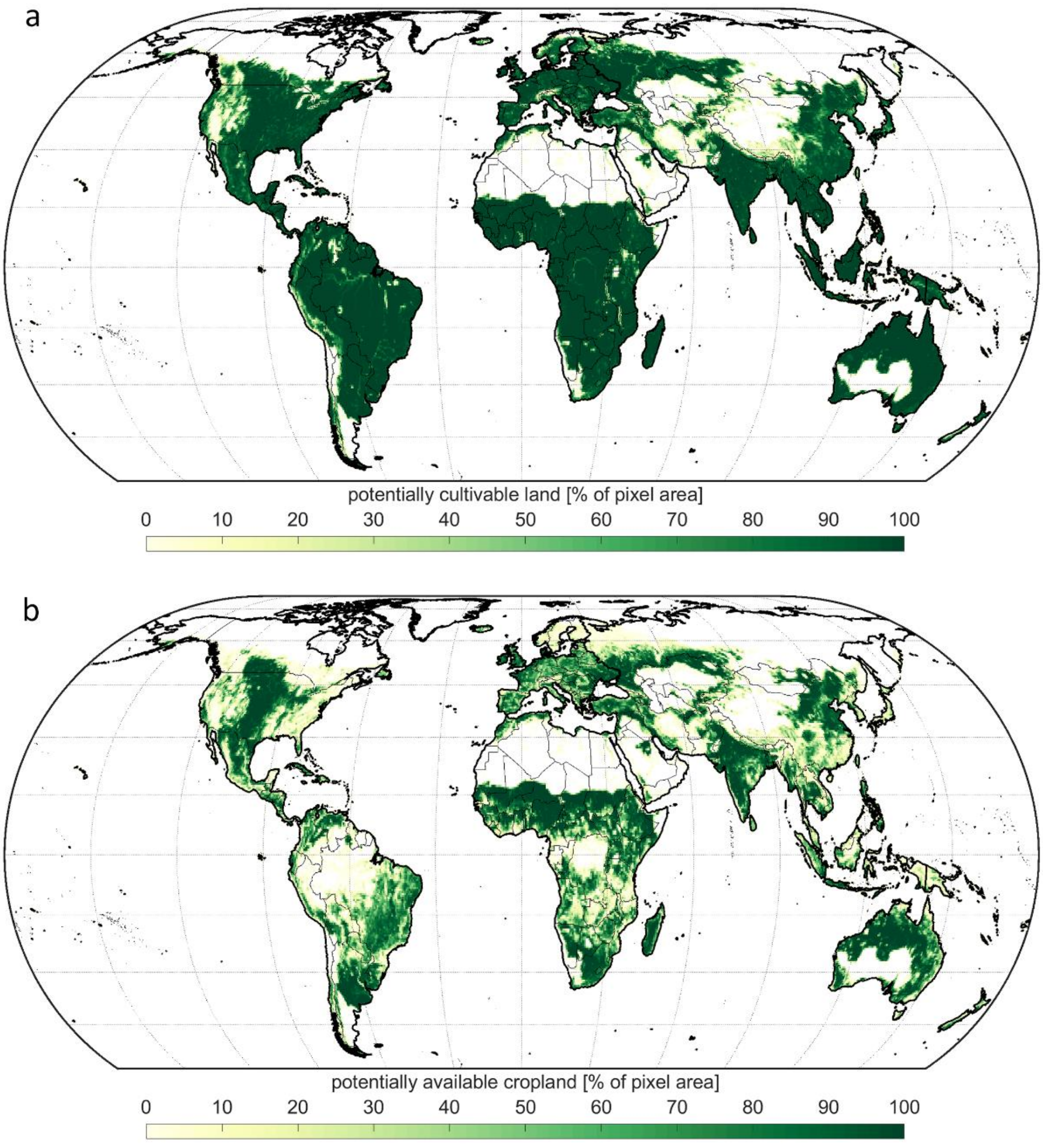

Figure 2: Global potentially cultivable land (a) and potentially available cropland (b) for historic time period. *The maps display (a) the share of potentially cultivable land on the total area of each 1km pixel [%], taking only biophysical restrictions for cultivation into account and (b) the share of potentially available cropland on the total pixel area [%] additionally considering restricted agricultural use of forests, wetlands and protected areas. The country borders are displayed according to the global administrative areas of GADM version 3.6.*

Around 10% of the potentially cultivable land is highly suitable for agriculture (suitability values: 75-100), while the major part of it (58%) is moderately suitable (suitability values: 33-74) and around one third (32%) is marginally suitable (suitability values: 1-32) for agriculture (Fig. 3). By excluding land currently covered with forest, wetlands and protected areas to assess the potentially available cropland, mainly marginally (35%) and moderately (60%) suitable areas are excluded. Yet, around 1/3 (33%) of the 46.3 million km^2 of potentially available cropland is currently already used as cropland[37]. Since current cropland is mainly located in highly and moderately suitable areas, 35% of the potentially available cropland not yet under cultivation is marginally suitable for agriculture (Fig. 3).

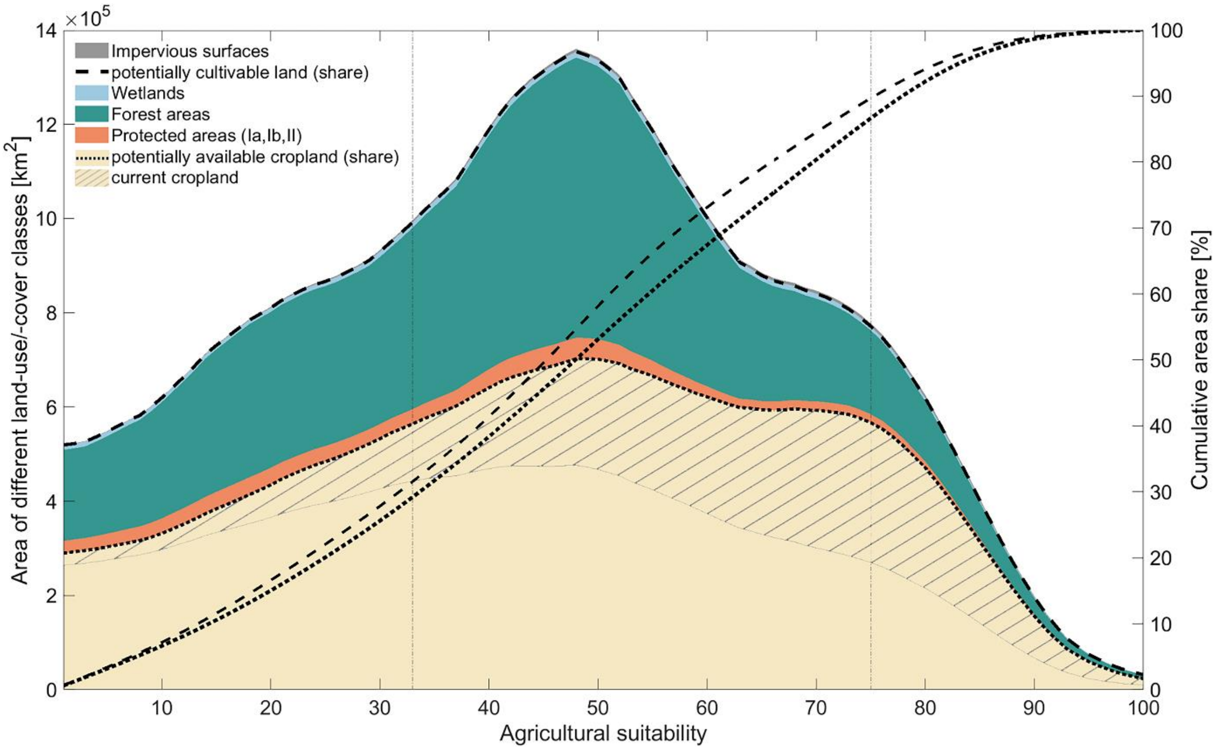

Figure 3: Suitability and land-use/-cover of the potentially cultivable land and potentially available cropland. *The area graph shows the potentially suitable area [km^2] and the different land-use/-cover classes (displayed as moving average) considered to distinguish between the potentially cultivable land and the potentially available cropland dependent on the agricultural suitability. Hatched areas indicate the parts of the potentially available cropland already under cultivation. The potentially cultivable land and potentially available cropland area [km^2] for each suitability value is indicated with the dashed and dotted line inserted in the area graph. The two additional line graphs display the cumulative distribution function of the potentially cultivable land (dashed line) and potentially available cropland (dotted line), respectively. They thus visualize the cumulative area share in the total area potentially cultivable and available [%] across the agricultural suitability.*

Regarding the regional potentially cultivable land resources, South America shows with around 81% globally the largest share of cultivable land in total land area. It is followed by Europe (68%) and Africa (62%), while in North America and Asia & Russia less than half of the total land area is potentially cultivable (Fig. 4). Yet, especially in South America, Europe and North America, large shares of the total land area are covered with forests: For example, in South America, 46% of the land area is covered with forests, of which 94% is potentially suitable for agriculture. Accordingly, when excluding forests, wetlands and protected areas to assess the potentially available cropland, the potentially cultivable land is more than halved to 35% of total land area being potentially available for cropland. In Europe, North America and Asia & Russia, the regions with the globally second, third and fourth largest share of forested land in total land area, 85%, 62% and 48% of the forest areas are potentially suitable for agriculture. Excluding forest areas together with wetlands and protected areas thus reduces the potentially cultivable land by around 37%, 45% and 35%, respectively, to a share of potentially available cropland in total land area of 43% in Europe, 22% in North America and 26% in Asia & Russia. Due to the generally small area of forests and protected areas in Oceania, the share of potentially cultivable land (61%) is only marginally reduced and 44% of the total land area is potentially available for cropland use (Fig. 4).

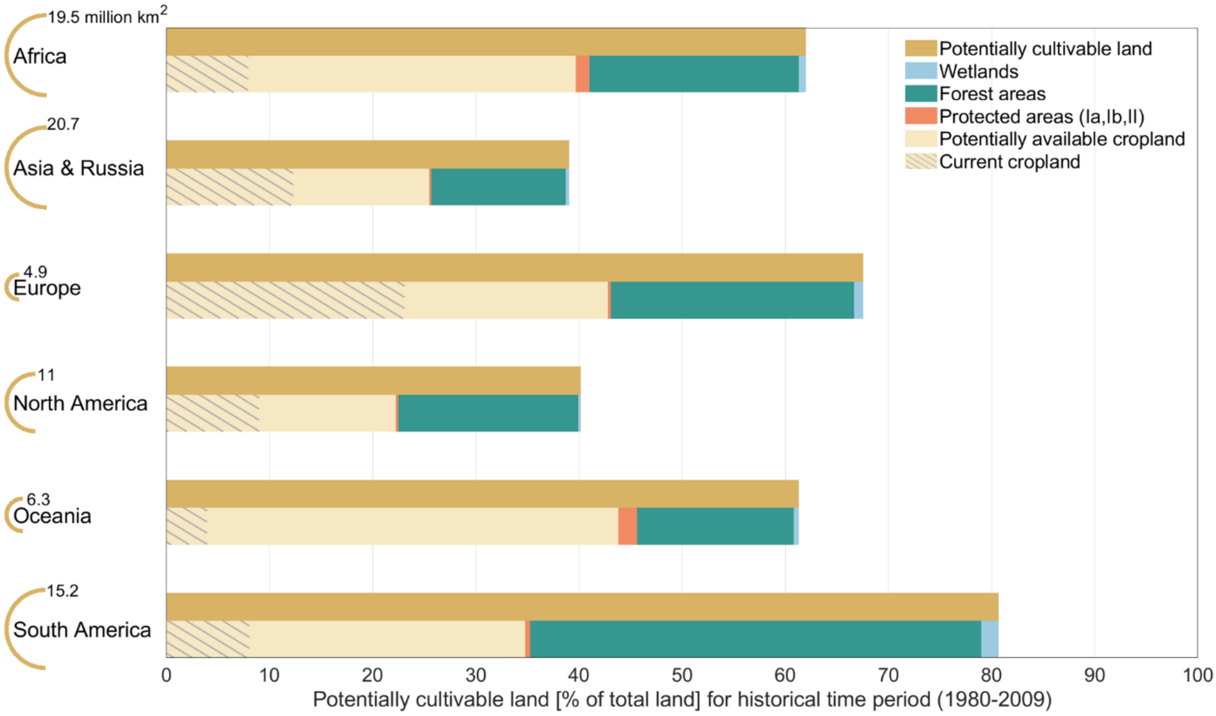

Figure 4: Regional potentially cultivable land [% of total land] for the historic time period. *The bars display the share of potentially cultivable land in total land area [%], the shares of protected areas, forested areas and wetlands and the resulting potentially available cropland. The hatched parts of the bars indicate the potentially available cropland currently already cultivated. The absolute area of potentially cultivable land is displayed in million km² for each world region within the legend of the y-axis. The region mapping is displayed in the Methods section (Fig. 7).*

The potentially cultivable land as well as the potentially available cropland entail land currently already under agricultural use. Particularly in Europe, Asia & Russia and North America, large parts of the potentially available cropland are already used as cropland: 54% in Europe, 48% in Asia & Russia and 40% in North America (Fig. 4). In South America, Africa or Oceania on the other hand, only about 23%, 20% and 9% of potentially available cropland is currently in use. Accordingly, especially in Africa and South America, but regarding absolute land resources also in Asia & Russia, large areas of approximately 10 million km² (Africa), 5 million km² (South America) and 7 million km² (Asia & Russia) would potentially remain for a transformation into cropland. Yet, regarding the suitability of the potentially available cropland that is not yet agriculturally used, highly suitable remaining land resources are mainly located in Africa (1.28 million km²), Asia & Russia (768,000 km²) and North America (454,000 km²), where around 11% to 13% of the potentially available cropland not yet under cultivation is highly suitable for agriculture. In South America and Oceania on the other hand, large parts of the potentially available cropland not yet under cultivation, 40% and 39%, respectively, are marginally suitable.

Change of potentially cultivable land over time until future time period 2070-2099

Until 2100, the potentially cultivable area globally increases compared to the historic time period by 5% and 13% under RCP2.6 and RCP8.5, respectively, resulting in a potentially cultivable land area between 82 million and 88 million km^2. The largest increases in cultivable land compared to the historic time period can be found in North America and Asia & Russia with +11% and +12%, under RCP2.6, and with +34% and +30%, respectively, under RCP8.5 (Fig. 5a, 5b). This increase mainly results from a northwards shift of the agricultural frontier due to global warming. Thus, large areas in the northern hemisphere become at least marginally suitable for agriculture. Large parts of these areas are currently covered with forests, leading to an increase of forest areas being assessed as potentially cultivable from around 29.8 million km^2 in historic time period by +7% to 31.7 million km^2 under RCP2.6, and by +18% to 35 million km^2 under RCP8.5 until 2100. Mainly in North America and Asia & Russia, forest areas being potentially cultivable increase by +16% in both regions under RCP2.6 and by +49% in Asia & Russia and by +40% in North America under RCP8.5. Moreover, also areas currently covered with wetlands become suitable for cultivation until 2100. Compared to historic time period, the area of current wetlands potentially cultivable globally increases by 25% until 2100 under RCP2.6 and by almost 70% under RCP8.5. Similar to the observed changes in forest suitability, the area of potentially cultivable wetlands increases mainly in the northern latitudes of Asia & Russia (+272%) and North America (+114%). Overall, the additional agriculturally suitable areas in the north outweigh the areas that become unsuitable in the future, e.g. by becoming too hot or too dry for agriculture. The potentially cultivable land area remains widely constant in Africa and South America under both climate change scenarios, while it decreases until 2100 between -6% and -8% in Oceania under RCP2.6 and RCP8.5 (Fig. 5a, 5b).

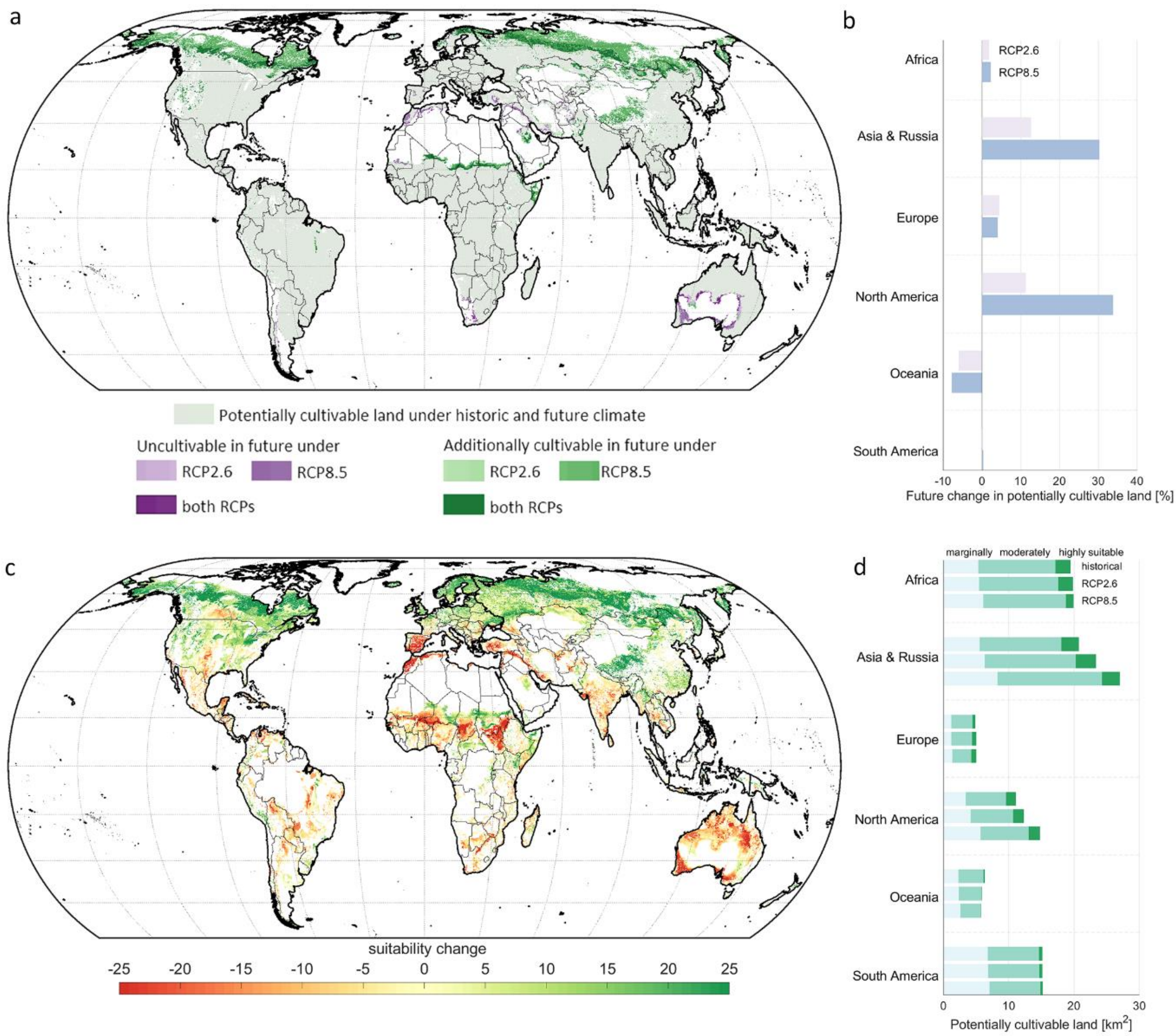

Figure 5: Future changes in potentially cultivable land extent and its suitability until the end of the century (2070-2099) compared to the historic time period (1980-2009). *Map (a) indicates regions that become potentially cultivable in the future under RCP2.6, RCP8.5 or under both scenarios, as well as regions that lose their suitability for agriculture under future climate and thus are not cultivable anymore under one or both climate change scenarios. Graph (b) displays the percentage change [%] of potentially cultivable land between the historic and the future time period (2070-2099) under both RCPs within each world region. Map (c) shows the underlying change in agricultural suitability from historic time period until 2100 exemplarily for potentially cultivable land under RCP8.5. Graph (d) displays the absolute potentially cultivable land area [million km²] for historic and both future time periods, subdivided into marginally suitable (light green), moderately suitable (green) and highly suitable land (dark green).*

Beside changes in the extent of the potentially cultivable land, also its agricultural suitability changes due to changing future climate conditions (Fig. 5c, 5d). Under RCP8.5, we find an increase in potentially cultivable land that is marginally suitable (+26%), while highly suitable land decreases by -11%. This decrease can particularly be observed in Africa, where the potentially cultivable land highly suitable for agriculture halves (-51%), whereas marginally suitable land increases by +14%. Accordingly, the share of highly suitable land on the potentially cultivable land in Africa decreases from 12% in 1980-2009 to 6% in 2070-2099 under RCP8.5. In Europe on the other hand, the contrary is the case: Even though the total potentially cultivable land increases by only +4% compared to historic time period, the share of highly suitable land increases from 9% to 16%, leading to an increase in highly suitable land area of +82% especially in northern Europe. Yet, also marginally suitable land area increases by +16%, for example in the Mediterranean, so that in total the share of moderately suitable land on potentially cultivable land in Europe decreases by 9 percentage points (pp) from 66% (1980-2009) to 57% (2079-2099). In North America, where potentially cultivable land increases by +34%, mostly marginally suitable land in Canada becomes cultivable, while the agricultural suitability of large areas decrease in the south of the United States of America and Mexico. Accordingly, the share of marginally suitable land in potentially cultivable land area rises by 7pp to 38%, while the share of moderately and highly suitable land decreases by 5pp and 2pp to 50% and 12% of potentially cultivable land. Under RCP2.6, on the other hand, where the potentially cultivable land globally increases by +5%, the shares of marginally, moderately and highly suitable land remain nearly constant on a global scale and vary only slightly on regional scale.

Our results thus show that especially for investigating future land-use change, the impact of different climate change scenarios on agricultural suitability needs to be taken into account to include land that will become suitable for agriculture in the future. Moreover, we see that due to the fact that particularly forest areas in the northern hemisphere become potentially cultivable under future climate, the assumption on forests being potentially available for cropland use or not is becoming more relevant, as its effect on the total extent of potentially available cropland increases.

3.2.4 Discussion

An important question causing large differences in the estimations of potentially cultivable land is the question *'how suitable is suitable enough?'*[20]. By determining at each pixel the maximum suitability across all crops included in our agricultural suitability, our potentially cultivable land includes all areas that are agriculturally suitable for at least one of the 23 considered crops (Table 1). Thus, we consider also marginally suitable land for a specific crop as potentially cultivable. Since areas with a low suitability for agriculture might not be transformed into cropland, as the attainable crop yields could be too low or unstable, the attained potentially cultivable land and available cropland provide rather an upper benchmark estimate. However, within regions that are generally rather marginally suitable for agriculture, also land with a rather low suitability can be considered as suitable and thus be of interest for agricultural use. Further, a potential conversion of land into cropland is, beyond its agricultural suitability, mostly influenced by the potentially attainable yields (of specific crops) on the cultivable land. Those yields do not solely depend on the agricultural suitability in terms of soil properties, climate and topography, but might to a large extent also be influenced by soil-, crop- and farm-management measures, which are only partly considered in this suitability approach. Additionally, also the political and socio-economic framework drives land-use dynamics[43-45]: For example, depending on the scarcity of land and achievable crop prices, it might even be profitable to transform marginally suitable land into cropland, for example for the cultivation of bioenergy crops[46]. Therefore, we consider it useful to be least restrictive in our assumptions on the agricultural suitability of potentially cultivable land and thus have not applied a suitability threshold (see Methods). Model- or study-specific further biophysical limitations for cultivation can either be applied directly to our spatially explicit datasets, be implemented with a suitability threshold, or could also result from a land-use modeling framework, e.g. through simulated crop yields or economic factors such as demand or prices.

By maintaining the current irrigation patterns[34], we avoid assuming an expansion of irrigation into areas where water might not be (sustainably) available or an implementation of irrigation infrastructure not feasible, for example due to a lack of technology, knowledge or required investments[47]. Nonetheless, as an expansion of irrigation infrastructure would substantially change global patterns of potentially cultivable land, a corresponding dataset of available cropland under irrigation provides an interesting input into land-use change models to investigate the effects and land-use dynamics of an expansion of irrigation. Therefore, we provide each dataset of potentially cultivable land and available cropland also under rainfed and irrigated conditions separately. This allows users to apply own assumptions on the expansion of irrigated areas.

Another central question is the definition of '*availability for cropland use'*. To provide a basis dataset that leaves aside institutional, socio-economic or policy-driven assumptions on the issue of accessibility and availability, we applied only biophysical restrictions to derive the potentially cultivable land**.** We thereby assume that man-made impervious surfaces are difficult and unlikely to be used as cropland due to, the associated uncertainty regarding their transformability to cropland, arising costs for their transformation into cropland and potentially resulting conflicts of use. For the assessment of the potentially available cropland, we assume that the most strictly protected areas, forests and not yet agriculturally used wetlands are not considered as available for cultivation. We have chosen these restrictions for several reasons: First, those land-use/-cover types play a key role in biodiversity conservation[48-51] and climate change mitigation due to their large potential for carbon sequestration[52-55] and thus in the context of the SDGs, while at the same time the conversion of forests and wetlands are land-use/-cover changes of major importance in the context of agricultural development[56,57]. Second, the applied restrictions reflect efforts of current policies and institutional regulations. Particularly a stop of deforestation until 2030 was recently declared as an important goal at the 26th UN Climate Change Conference of the Parties[39], while possibilities for agricultural activities in protected areas are regulated within the IUCN categorization of protected areas. Accordingly, assuming their unavailability for the conversion into cropland creates a dataset that reflects the importance of those land-use/-cover types and the (declared) ambitions to protect them.

However, it needs to be noted that there are concepts for the cultivation of wetlands and forests which for example go beyond drainage-based agriculture and deforestation, such as Paludiculture[58] or Agroforestry[59], and thus enable an agricultural use that is less conflicting with aims of climate protection and biodiversity conservation. Finally, the study of Eitelberg et al.[20] shows that in many of the reviewed studies and land-use models, forests are excluded from estimations of potentially available land[26-28], suggesting that these restrictions might be most commonly applied across different models and studies. Nonetheless, further political, social, cultural and economic factors, such as land tenure issues or conversion costs of land to cropland[28], as well as current uses of the land, e.g. as pastures or idle land, can additionally restrict or conflict its availability for crop cultivation. Thus, it strongly depends on the land-use model, the research question and the spatial scale of investigation whether, how and at which spatial level further restricting factors are exogenously or endogenously implemented[60]. Due to the spatial explicitness and the high spatial resolution of our generated datasets, further exogenous restrictions that might be needed for specific land-use models or research questions can be applied by overlaying and masking our datasets with corresponding spatial data. Users could for example extend the assumptions on potential nature protection policies and additionally exclude grasslands or specific high-biodiversity areas from the potentially available cropland, or use the potentially cultivable land data to apply own restrictions that for example only exclude currently already protected wetlands or forests.

Overall, it is important to note that the term ‘potentially available cropland’ does not imply that the identified areas are unrestrictedly available for agricultural use without any trade-offs or potential land-use conflicts. Large parts of the identified land suitable for crop production are recently not cultivated, but covered for example with grassland or shrubland, or used as pasture (for details see Fig. 6 in the Methods section). Changing the land-cover and –use of these areas by cultivating them can have various negative implications, for example destroy valuable ecosystems and thereby the habitat of species, or reduce the carbon sequestration potential of these areas and lead to carbon emissions. Depending on the current land-use, a conversion into cropland can moreover impact the local population by taking away their livelihoods and thus force migration. A conversion into cropland can thus lead to social conflicts and compromise important action for example towards climate protection and biodiversity conservation. Moreover, further practical issues associated with land-use and cropland conversion, such as land tenure, social or cultural functions of the current land-use, the political framework and land-use regulations, or the availability of capital and labor to cultivate this land, are not considered in our approach. Yet, by providing information on land potentially cultivable or available and its agricultural suitability, our datasets can be used to identify possible conflicting areas where land is under a high risk of being transformed into cropland. The dataset can thus contribute to analyze where trade-offs between crop cultivation and other land-use and land functions could occur, and thereby point to regions where an implementation of land-use regulations might be of particular importance, especially in the context of projections on future cropland expansion. Besides that, it might be necessary to think about a change in the terminology to describe land potentially available for crop production towards a term that reflects also the potentially arising trade-offs and land-use conflicts that can come along with cultivating this land.

Assessing the potentially cultivable land for future time periods enables to include also land currently not yet suitable for agricultural use in assessments of land-use dynamics, and thus allows for consistently investigating future land-use dynamics and potential cropland expansion under a changing climate by providing realistic boundary conditions. Yet, it is important to note that future scenarios of urbanization and changes in man-made impervious surface as well as future changes in forest cover and wetlands, e.g. due to forest degradation, deforestation or afforestation or the drainage of wetlands, as well as the expansion or reallocation of protected areas could not be considered in this approach, but could also be applied upon the provided datasets.

We conclude that by providing information on potentially cultivable land and potentially available cropland for historic and different future time periods, spatially explicit and additionally aggregated to country level, our datasets could serve as basic input datasets for different types of models investigating land-use dynamics. This could improve the comparability in land-use change modeling[23,24], which is crucial for a better understanding of land-use dynamics, feedbacks and potentially emerging trade-offs between crop production and other land-uses and functions.

3.2.5 Methods

Agricultural suitability

To identify the land that is potentially suitable for agricultural use, we refer to an updated version (v3.0) of the data on agricultural suitability by Zabel et al.[32], in which updated data on soil, irrigated areas and climate were applied, and an increased range of crops was considered. The suitability of land for crop production was assessed with a fuzzy logic land suitability model[32] at 30 arc-seconds spatial resolution for 23 globally important crops in terms of their cultivation area and production volume (Table 1). Among those 23 crops, the 17 food, feed, fiber and first-generation bioenergy crops currently represent around 67% of global harvested area and 73% of the global production volume according to FAOSTAT[61], while jatropha, miscanthus, switchgrass, reed canary grass, eucalyptus and willow represent six important second-generation bioenergy crops.

The land suitability model accounts for crop-specific characteristics and requirements during the growing period with regard to climate, soil and topographic conditions. To account for uncertainties in future climate projections, daily data for temperature, precipitation and solar radiation is based on five CMIP5 climate models (GFDL, HadGEM2, IPSL, MIROC and NorESM1), representing a range of temperature and precipitation changes seen in the full CMIP5 model ensemble[62]. The climate data was statistically downscaled from 30 arc-minutes to 30 arc-seconds (approximately 1km at the equator) spatial resolution and bias corrected. Soil data is derived from the Harmonized World Soil Database (HWSD)[63] v1.21, considering the following soil properties: soil texture, proportion of coarse fragments and gypsum, base saturation, pH content, organic carbon content, salinity and sodicity. Soil depth is considered as an additional constraint[64]. Topography data was applied from the Shuttle Radar Topography Mission (SRTM)[65]. The determinant factors are contrasted with the crop-specific requirements taken from literature[66]. The suitability is assessed by comparing the growing condition at each grid cell in terms of temperature, precipitation, solar radiation, soil properties and topography with the crop-specific requirements during the growing period. Thereby, daily climate data is used to identify an optimal growing period in the time period under consideration. Thus, the suitability approach accounts for an adaptation to changing climatic conditions. The agricultural suitability is simulated for each crop under rainfed and irrigated conditions for four different time periods, 1980-2009, 2010-2039, 2040-2069 and 2070-2099.For future time periods, we applied two climate change scenarios, RCP2.6 and RCP8.5, thereby representing the range between lower and higher emission pathways[33]. For further information on the methodology of the suitability assessment, see Zabel et al.[32] and Cronin et al.[31]. A detailed description on the methodological improvements of the updated agricultural suitability v3.0 compared to the previous version v2.0 is provided in the description of the dataset[29].

For our analysis, we use the maximum suitability across all considered 23 crops for each time period in order to represent a more general agricultural suitability. Besides the maximum suitability across all crops, also the agricultural suitability of each crop as well as data on the most suitable crop at each pixel are additionally provided for download[29]. We assume that current irrigation is not expanded. Therefore, we combine rainfed and irrigated suitability datasets for each time period referring to current irrigation patterns[34].

Of the globally 78.1 million km^2 potentially suitable for agricultural use for historic time period and under current irrigation patterns, 30% are marginally suitable (suitability values: 1-32), 59% moderately suitable (suitability values: 33-74) and 11% highly suitable (suitability values: 75-100) for crop cultivation. Since the agricultural suitability describes a general opportunity for crop cultivation and does not imply which crop is cultivated, the data does not include any assumptions on current and future (potentially shifting) production patterns. Looking at the current land-use/-cover of the suitable land according to HILDA+ land-use data[37] for the year 2010 (Fig. 6), we see that marginally and moderately suitable land is currently mainly covered with forest and pasture/rangeland, while current croplands and urban areas are mainly located in highly suitable areas. The higher the agricultural suitability, the larger the share of cropland, which is mainly irrigated in highly suitable areas. Altogether, about half of the suitable land is under agricultural use (as cropland, pasture or rangeland) today. Urban areas are more frequently located on land highly suitable for agriculture, since in many regions humans historically preferred to cultivate fertile areas first[67], in which they settled. Furthermore, it can be seen that the share of forests under protection decreases with higher suitability, resulting in larger areas of forests under protection on marginally suitable than on highly suitable land. Overall, the figure illustrates by how far anthropogenic dominated forms of land-use (urban areas, cropland, pasture) have already encroached on forests and natural grass- and shrublands, and it indicates that especially ecosystems on highly suitable land, mainly forests, are under higher pressure for land-use/-cover change, as a large proportion of this land has already been put under anthropogenic use.

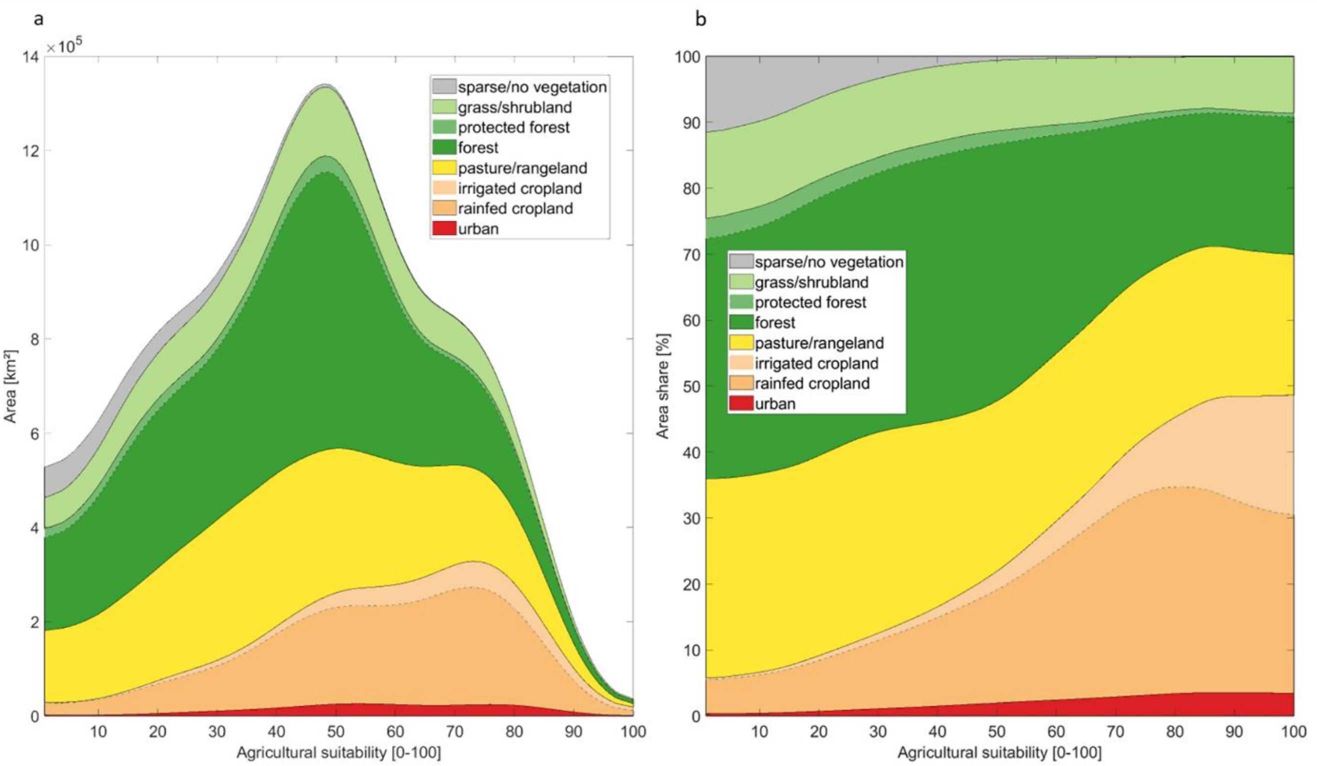

Figure 6: Land-use/-cover of the global agriculturally suitable areas. *(a) displays the absolute area [km²] of each land-cover class for each agricultural suitability value, while (b) shows the relative area share of each land-cover class. A moving average was applied in both figures. The land-use/-cover refers to HILDA+ data[37] for the year 2010.*

Suitability threshold

When referring to the agricultural suitability for our assessment of potentially cultivable land and potentially available cropland, we decided to apply no suitability threshold below which areas are excluded from our cultivable land potential. Thereby, we consider the possibility to cultivate marginally suitable land as well as the potential influence of further socio-economic factors on decisions on the agricultural use of land (see also Discussion). If a suitability threshold of e.g. 10, 20 or 30 would be applied to exclude less suitable areas, potentially suitable and potentially cultivable land would be reduced by 6%, 15% and 27% (Fig. 3) and exclude 1.6%, 4.7% and 10% of the current cropland areas (Fig. 7). Excluding land defined as marginally suitable (suitability < 33) would neglect 30% of the potentially suitable and potentially cultivable land and more than 10% of current cropland.

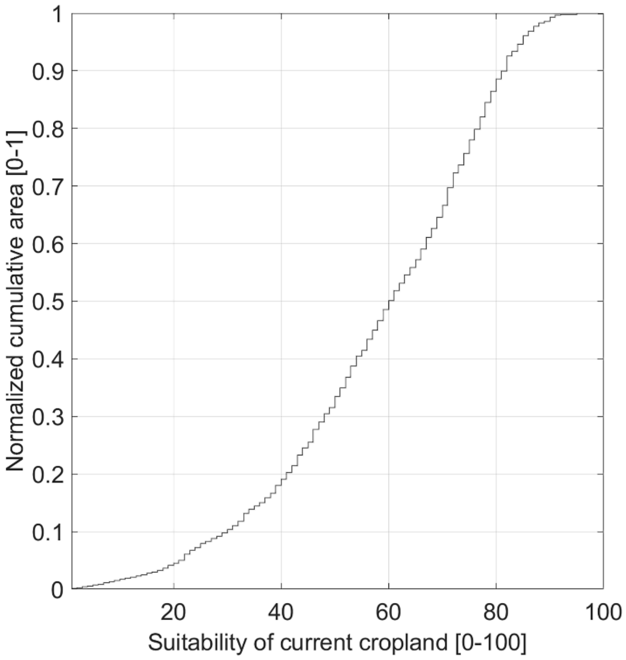

Figure 7: Normalized cumulative distribution function of global suitability values on current cropland area. *The graph displays for each agricultural suitability value the normalized cumulative current cropland area.*

Land-use and land-cover

Besides the agricultural suitability dataset, various further land-use/-cover datasets are used to calculate the potentially cultivable land and potentially available cropland (Table 2): For information on current land-cover, we refer to ESA CCI Land Cover Maps - v2.0.7[38] for the year 2010 as baseline with 300m spatial resolution, resampled to 1km spatial resolution. We omit agriculturally suitable pixels that are classified as water bodies (210) or permanent snow and ice (220) to ensure consistency between the land cover and agricultural suitability. Around 598,000 km^2 (0.76% of the global agriculturally suitable land) is thereby excluded. Moreover, wetlands, defined as shrub or herbaceous cover, flooded with fresh, saline or brackish water (180), are excluded from the potentially available cropland due to their large contribution to carbon sequestration and thus their importance for climate protection and climate change mitigation. Yet, wetlands currently already cultivated (base year 2010) are classified as cropland within the ESA CCI dataset and accordingly, for example already drained wetlands currently used as cropland are not excluded from the potentially available cropland in our approach.

To identify forest areas, we refer to the latest dataset on land-use/-cover from the HIstoric Land Dynamics Assessment + (HILDA+) by Winkler et al.[37]. Created by harmonizing different spatially explicit land-use/-cover information with statistical data at national scale, the forest areas for example correspond well with the Global Forest Resources Assessment (FRA) of the Food and Agriculture Organization of the United Nations (R^2= 0.99). This increases the applicability of our dataset in models that are calibrated with or refer to statistical forest data, such as economic models on global forest products[68]. An uncertainty assessment of the HILDA+ data can be found in Winkler et al.[37].

We address the often-stated issue of underestimating infrastructure and settlements due to subpixel heterogeneity[20,25,27] by using the Global Man-made Impervious Surface dataset[35], a high spatial resolution dataset which describes the impervious cover for the year 2010 at 30m spatial resolution. Thereby, we aim to minimize potential errors due to subpixel heterogeneity that often occur with urban areas and infrastructure[20]. For our analysis, we refer to an aggregated version of the dataset displaying the percentage of impervious cover at 1km spatial resolution.

To consider protected areas, we refer to the IUCN and UNEP-WCMC world database on protected areas (WDPA)[36]. We exclude the most strictly protected areas, namely strict nature reserves, wilderness areas and national parks (IUCN categories Ia, Ib and II), that explicitly or implicitly do not allow for agricultural use. We assume a pixel to be not available for cropland use, if 50% or more of the pixel area is protected.

Table 2: Overview of the considered data to calculate the potentially cultivable land and the potentially available cropland.

Dataset	Reference	Spatial resolution	Reference Year(s)
Suitability	Zabel, F. Global Agricultural Land Resources – A High Resolution Suitability Evaluation and Its Perspectives until 2100 under Climate Change Conditions. Zenodo **https://doi.org/10.5281/zenodo.5982577** (2022)[29] Zabel et al. 2014[32], Cronin et al. 2020[31]	30 arc-seconds (~1 km)	1980 -2009 2010 -2039 2040 - 2069 2070 - 2099
ESA CCI land cover classification	ESA. Land Cover CCI Product User Guide Version 2. Tech. Rep. (2017). Available at: maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf	300m	2010
Global Man-made Impervious Surface	Brown de Colstoun, E. C., C. Huang, P. Wang, J. C. Tilton, B. Tan. J. Phillips, S. Niemczura, P.-Y. Ling, and R. E. Wolfe. 2017. Global Man-made Impervious Surface (GMIS) Dataset from Landsat. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4P55KKF. Accessed 20 05 2020.	30m	2010
Protected areas	IUCN and UNEP-WCMC (2019), The World Database on Protected Areas (WDPA) [On-line], [05/2019]. Cambridge, UK: UNEP-WCMC. Available at: www.protectedplanet.net.	Vectors	2019
HIstoric Land Dynamics	Winkler, Karina; Fuchs, Richard; Rounsevell, Mark D A; Herold, Martin (2020): HILDA+ Global Land Use Change	0.00998837° (~1 km)	2010

Assessment + (HILDA+).	between 1960 and 2019. PANGAEA, **https://doi.org/10.1594/PANGAEA.921846** [37]		

To evaluate the representation of current cropland, we refer to the HILDA+ land-use/-cover dataset from Winkler et al.[37]. We identify 97% of current cropland as potentially cultivable land. Globally aggregated, around 1/5th of the potentially cultivable land and 1/3rd of the potentially available cropland is currently already under cultivation.

Spatial structure of the result analysis

To present and discuss our data within this study, we aggregate our results to six large world regions: Africa, Asia & Russia, Oceania, Europe, North America and South America (Fig. 8).

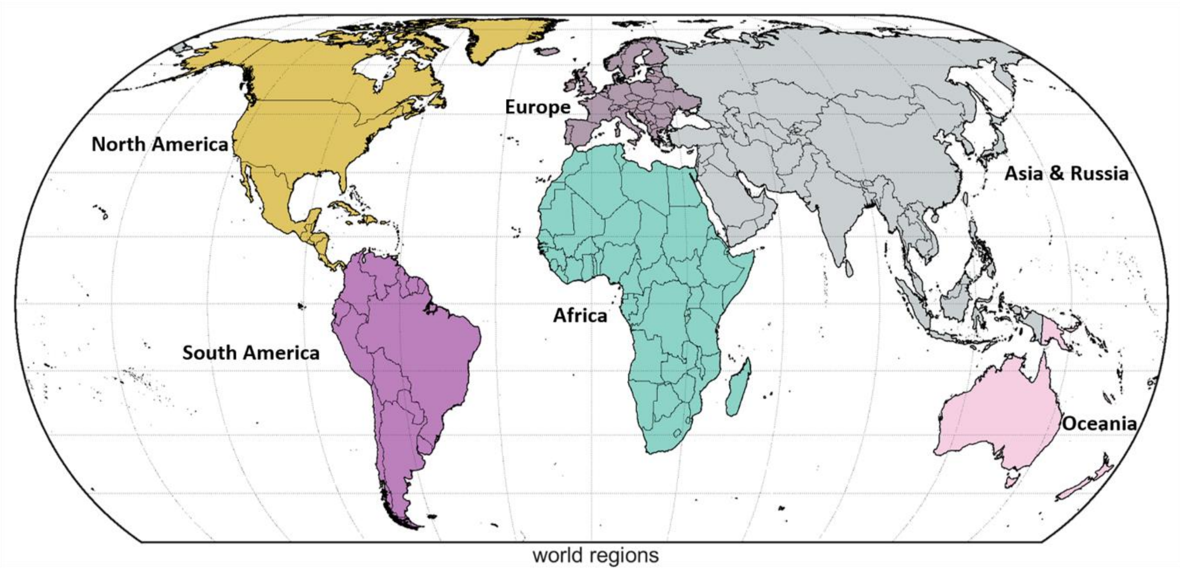

Figure 8: Overview of the regions referred to in the analysis of our results: Africa, Asia & Russia, Europe, North America, Oceania and South America. *Regions are aggregated based on the displayed country borders according to the global administrative areas of GADM version 3.6 (https://gadm.org/).*

Comparison to existing dataset of available cropland

Even though different datasets on potentially cultivable land are hardly comparable due to their different assumptions on availability of land for cultivation, different underlying data and differences in their spatial resolution, we can compare our datasets with the estimates of available cropland from Eitelberg et al.[20], available at 5 arc-minutes spatial resolution. The 'high estimate' of available cropland from Eitelberg et al.[20] includes croplands, mosaics of cropland and natural vegetation, open shrublands, savannas, grassland, closed shrublands and woody savannas, forests, barren or sparsely vegetated areas and also protected areas as potentially cultivable. These assumptions most closely resemble our definition of potentially cultivable land. A rather fundamental difference in the datasets is the general assumption of Eitelberg et al.[20] that on average 15% of a raster cell is occupied by nonproductive uses.

Comparing our potentially cultivable land for historic time period with the ‘high estimate’ from Eitelberg et al.[20], we see that our potentially cultivable area is with 77.7 million km^2 around +48% larger than the ‘high estimate’ of 53.3 million km^2 potentially cultivable land. More than half of this additionally included land (53%; around 12 million km^2) can be considered as only marginally suitable for agriculture. Yet, 42.5% is moderately suitable and 4.5% are even highly suitable areas, altogether leaving around 10 million km^2 of land relatively well suitable for cultivation excluded in the estimate by Eitelberg et al.[20] The largest additional area, around 7 million km^2, can be found in Africa, where our approach additionally includes mainly marginally suitable land in the Sahel and the east and south of Africa, such as parts of Niger, Sudan, Somalia Angola, Namibia or Botswana. However, around 45% of the additionally included potentially cultivable land is moderately or highly suitable, for example areas in the Democratic Republic of the Congo, Ethiopia or Zambia. In Oceania, our potentially cultivable land is more than twice as large as the estimate from Eitelberg et al.[20]: 3.2 million km^2 are additionally included, of which around 48% are moderately or highly suitable. Thereof, 80% is located in Australia, where our approach identifies around 2.8 million km^2 of additionally potentially cultivable land, of which 45% are moderately or highly suitable. In Asia & Russia, we additionally include 5.3 million km^2, of which 8% are highly and 46% moderately suitable for agriculture. Applying a suitability threshold to our potentially cultivable land would reduce its extent and might bring it closer to the estimate from Eitelberg et al.[20], but would on the other hand also exclude areas which are currently already used as cropland.

3.2.6 Data and code availability

Data availability: The datasets on potentially cultivable land and potentially available cropland are available under: Schneider, J.M., Zabel, F., Mauser, W. Global inventory of potentially cultivable land and potentially available cropland under different scenarios and policies. *Zenodo* **https://doi.org/10.5281/zenodo.5993934** (2022)[30].

The potentially cultivable land and the potentially available cropland are both available for historic (1980-2009) and future (2010-2039, 2040-2069 and 2070-2099) time period under RCP2.6 and RCP8.5, and under current irrigation patterns as well as for rainfed and irrigated conditions separately. Thus, different assumptions on the expansion of irrigation patterns could be applied by users. All datasets are available referring to the agricultural suitability of all considered 23 crops, as well as referring only to the agricultural suitability of the 17 food, feed, fiber and first-generation bioenergy crops, thereby excluding land that is solely suitable for second-generation bioenergy crops (see Table 1). The datasets provide the potentially cultivable land and the potentially available cropland in km^2 at 30 arc-seconds and 30 arc-minutes spatial resolution and aggregated to country level according to the global administrative areas of GADM version 3.6.

Time period	Climate change	Irrigation	Considered crops

historic	1980-2009	----	▪ Rainfed ▪ Irrigated ▪ Current irrigation patterns	▪ All 23 crops ▪ 17 crops excluding second-generation bioenergy crops
future	2010-2039	▪ RCP 2.6 ▪ RCP 8.5	▪ Rainfed ▪ Irrigated ▪ Current irrigation patterns	▪ All 23 crops ▪ 17 crops excluding second-generation bioenergy crops
	2040-2069	▪ RCP 2.6 ▪ RCP 8.5	▪ Rainfed ▪ Irrigated ▪ Current irrigation patterns	▪ All 23 crops ▪ 17 crops excluding second-generation bioenergy crops
	2070-2099	▪ RCP 2.6 ▪ RCP 8.5	▪ Rainfed ▪ Irrigated ▪ Current irrigation patterns	▪ All 23 crops ▪ 17 crops excluding second-generation bioenergy crops

The suitability data (version 3.0) is available for all crops, climate change scenarios, irrigation assumptions and time periods under: Zabel, F. Global Agricultural Land Resources – A High Resolution Suitability Evaluation and Its Perspectives until 2100 under Climate Change Conditions. *Zenodo* **https://doi.org/10.5281/zenodo.5982577** (2022)[29].

Code availability: The MATLAB code for calculation and creation of the dataset is available as supplementary information file.

3.2.7 Acknowledgements

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3.3 Publication 3: Profit-driven cropland expansion and its economic and environmental effects

Julia M. Schneider, Ruth Delzeit, Christian Neumann, Tobias Heimann, Ralf Seppelt, Franziska Schuenemann, Mareike Söder, Wolfram Mauser, Florian Zabel (2024): Environmental and socio-economic effects of profit-driven cropland expansion and conservation policies. Nature Sustainability *(Submitted: August 2023; Accepted: May 2024).*

Despite expansion conflicting with important goals of the 21st century, such as to protect climate and biodiversity (United Nations 2015a, United Nations 2015b, UNEP Convention on Biological Diversity 2020), cropland is still being expanded in many regions to increase agricultural production. The third publication thus investigates where land is under the highest pressure of profit-driven cropland expansion and which environmental and socio-economic effects would be associated with a conversion of these areas into cropland. Therefore, an additional module to simulate cropland expansion has been developed and integrated into iLANCE. Using the dataset of the second publication on land potentially cultivable as an input into the iLANCE model, the areas globally under the highest pressure of being converted into cropland up to an increase in current cropland by +30% can be assessed.

The study analyzes the spatial pattern of a global cropland expansion scenario of 3.6% until 2030, as projected by the latest FAO and OECD agricultural outlook (OECD/FAO 2023), and evaluates the potentially arising effects of this cropland expansion on agricultural markets within the iLANCE modeling framework. To investigate potential effects on biodiversity and potentially generated carbon emissions, the iLANCE model output is applied within algorithms to assess biodiversity intactness and the carbon storage potential of different land use/ covers. Finally, the study analyzes how the spatial distribution of expansion pressure and its socio-economic and environmental effects change under implementing a global conservation policy that prevents forests, wetlands and currently protected areas from being converted into cropland. From a methodological point of view, the third study demonstrates (1) the application of iLANCE for modeling land use change on previously uncultivated land, and (2) the applicability of the model output in other research disciplines, e.g. as input into biodiversity models, and thus the potential of an integration of the model into larger interdisciplinary research contexts.

Environmental and socio-economic effects of profit-driven cropland expansion and conservation policies

3.3.1 Abstract

Protecting biodiversity and mitigating climate change globally requires an in-depth understanding of possible future cropland expansion and potentially resulting trade-offs. In this study, we identify the top 30% areas under the globally highest pressure for future cropland expansion by applying an interdisciplinary coupled modeling approach. Based on these results, we investigate a 3.6% expansion scenario until 2030 and integratively analyze potential impacts on agricultural markets, biodiversity and CO_2 emissions. Moreover, we assess how global conservation policies could shift expansion pressure and alter the resulting environmental and socio-economic effects. Our results show that recent expansion hotspots remain, with areas under pressure being located mainly in the tropics. A cropland expansion of 3.6% increases global agricultural production by +2%. The associated land-use change generates 17.1 Gt CO_2 emissions and leads to a further decline in biodiversity intactness by -25% in the expanded areas. Conservation policies restricting the expansion into forests, wetlands, and existing protected areas, could substantially reduce the induced land-use change emissions without compromising global agricultural productivity, but might have contradictory effects on biodiversity. The results highlight the potential of strategic land-use planning to reconcile agricultural production with environmental protection. The provided output data on areas under expansion pressure could serve as basis for further impact assessments and contribute to improving the spatial planning of conservation measures.

3.3.2 Introduction

Despite large potentials to close current yield gaps[1-4] and even to reduce the globally cultivated area[5,6], cropland is still expanded in many regions[7], most notably in Africa and South America. Future projections indicate that this expansion is likely to continue[8-10] despite a range of associated negative effects[11,12]: The loss and fragmentation of natural habitat[13], particularly through deforestation, threatens biodiversity[14,15], with the tropics being a hotspot of this development[16,17]. In the past decades, more than half of the new cropland and pasture area was created at the expense of intact forests[17] and natural vegetation[7], with cropland encroaching even in already protected areas[18]. Carbon emissions induced by deforestation largely contribute to climate change[19-24], and cropland expansion might undermine natural climate solutions for mitigation[25,26]. Cropland expansion is thus conflicting with important goals of the 21st century, such as to protect climate and biodiversity[27-29]. Yet, limiting cropland expansion and supporting further (conventional) intensification of current land-use, on the other hand, might even further lead to a decline in biodiversity[30-32]. Targeted land-use regulations could contribute to reducing these conflicts between agricultural production and environmental protection. Therefore, identifying those areas that are under the highest pressure of being converted into cropland in the future is essential to identify hotspots where resulting trade-offs might be strongest.

While past dynamics of cropland expansion and relevant drivers are well investigated[7,8,33], there is uncertainty about future dynamics[34,35]. Besides environmental conditions determining the crop growth potential, socio-economic factors strongly affect expansion dynamics[36]. Population growth and consumption preferences, for instance, are among the most influential determinants for future cropland extent[35], and deforestation in the first decades of the 21st century was found to be mainly commodity driven[37,38]. Moreover, international trade can spatially shift the effects of socio-economic drivers over large distances[39]. Accordingly, integrated research frameworks are required that capture this cross-scale interplay of environmental and economic factors that determines the profitability of land to be agriculturally used. At the same time, spatially explicit approaches are needed to assess the environmental impacts of cropland expansion and potentially arising trade-offs[40]. Yet, while various studies on future expansion exist[8,10,15], only a few capture the interdisciplinary context of the drivers and trade-offs in a global, spatially explicit research framework that links global and local dynamics[11,12,41,42]. Moreover, most studies explore expansion dynamics by referring to one single future cropland extent resulting either endogenous from the scenario, or exogeneous as a predefined assumption[11,12,42,43]. Spatial data on potential future expansion areas is rarely provided[15], and mostly refers to one specific expansion scenario investigated. Accordingly, impact assessments that require such input data on future expansion areas are often limited to the provided data for specific expansion scenarios and cannot independently set the extent of future cropland expansion. Quantitative and spatial data on the expansion pressure would enable impact assessments with individual and varying assumptions on future cropland extents, thereby making them less dependent on the few existing future cropland projections.

To combine these different requirements, we developed an integrative, spatially explicit and quantitative approach to simulate future profit-driven cropland expansion based on relative marginal profits of agricultural crop production. It assesses the relative profitability of expansion across different crops on a 0.5° grid to identify the globally most profitable expansion areas, which we assume to be under the highest pressure to be converted into cropland. Thus, the aim of this study is not to investigate to which extent cropland might expand under a certain socio-economic scenario in the future, but to investigate which areas are under the globally highest expansion pressure considering future socio-economic and environmental conditions. The quantitative profitability ranking approach enables the exploration of areas under expansion pressure in various future scenarios of cropland expansion.

In this study, we use this approach to identify the land under the globally highest expansion pressure until 2030, thereby considering socio-economic business-as-usual conditions carrying forward current trends (Methods 1). As a first step, we map the spatial location and regional distribution of up to 4.27 million km^2 under expansion pressure, which is equivalent to an increase in global current cropland by up to 30%. The results can form the basis for expansion scenario analysis from 1% up to an upper boundary assessment of 30% cropland expansion. Thus, as a second step, referring to expansion projections from the most recent agricultural outlook of the Food and Agriculture Organization (FAO) of the UN and the Organization for Economic Co-operation and Development (OECD) (2023)[44], we then investigate a global cropland expansion scenario of 3.6%, corresponding to an expanded area of 515,000 km^2 (EXP scenario; Extended Data Fig. 1). For this scenario, we identify the areas under expansion pressure and evaluate the resulting environmental and socio-economic effects of converting them into cropland on agricultural markets, biodiversity and CO_2 emissions to investigate the environmental and socio-economic effects compared to a reference future without expansion (REF scenario). In the context of current political targets to stop deforestation[45,46], mitigate climate change[28] and protect biodiversity[27,29], we moreover analyze the impact of global conservation policies on expansion dynamics and resulting trade-offs. Therefore, we implement a second expansion scenario in which we assume forests[33], wetlands[47] and protected areas[48] to be protected from cropland conversion (CON scenario; Extended Data Fig. 1) under otherwise identical scenario conditions (for details on the scenario design, see Methods 1). Considering the conservation areas, we again analyze the spatial distribution of expansion pressure for an area of 4.27 million km^2 to generally map how expansion pressure might be spatially shifted by conservation policies, and then analyze the 3.6% expansion scenario to assess how socio-economic and environmental impacts might be affected.

Within our integrative land-use change model iLANCE, profit-driven cropland expansion is modelled by combining environmental conditions and simulated crop yields with socio-economic drivers of land-use change and regional economic conditions. Therefore, the biophysical crop model PROMET is coupled with the economic computable general equilibrium model DART-BIO (Extended Data Fig. 2). PROMET is applied to simulate crop growth globally for a future time period around 2030 (2016 to 2045, SSP585), providing crop yields under current crop management (Methods 2). Socio-economic dynamics driving agri-food demand and supply, such as trends in demography or income, serve as input for DART-BIO to model future changes in crop prices, production and trade patterns until 2030. The model provides marginal profits to land of different crops in different regions, which describe the economic profitability of cultivating a crop on one unit of land at a certain location (Methods 3). Based on the interplay of the simulated crop yields from PROMET describing the biophysical productivity, and the relative marginal profits of crops derived from DART-BIO, the iLANCE expansion module evaluates the relative profitability of cropland expansion at each pixel. Thus, the globally most profitable areas for cropland expansion can be identified taking data on potentially cultivable land[49] and current cropland areas[50] into account (Methods 4). Due to this quantitative profitability ranking approach, the created output data on areas under expansion pressure can be used to investigate various scenarios of an increase in future cropland extent by extracting the assumed top share of the globally most profitable areas, for example for the 3.6% expansion scenarios. The effects of cropland expansion on agricultural markets are explored by feeding back the changes in cropland extent and agricultural productivity resulting from iLANCE as exogenous changes into DART-BIO (Methods 3). To assess the effects on biodiversity, we calculate the Biodiversity Intactness Index (BII)[51], thereby referring to data on current land-use[33,52] and cropping intensity[50,53], and evaluate its changes under expansion. Additionally, we analyze how the world's most threatened biodiversity hotspots[54] are quantitatively affected by expansion pressure as well as regarding their biodiversity intactness (Methods 5). Based on carbon storage data[55,56] and spatial land-use/-cover data[33,52,57], we analyze the potentially affected land covers and estimate the land-use change induced CO_2 emissions (Methods 6). The results are analyzed at 0.5° spatial resolution or at aggregated regional level (Methods 1, Extended Data Fig. 3). Gridded data on areas under expansion pressure and their profitability ranking is provided for download at 0.5° spatial resolution and aggregated at country level for a global cropland expansion from 1% up to 30% (see Data availability statement).

3.3.3 Results

1. Unrestricted cropland expansion

1.1 Global spatial patterns of expansion pressure (top 30% areas)

We find more than one-third of the globally investigated 4.27 million km^2 most profitable areas for cropland expansion in Africa (36%), followed by Asia & Russia (24%) and South America (15%). Assuming that the globally most profitable areas for cropland expansion are also under the highest pressure of being converted into cropland, particular large areas under expansion pressure are located in Central African countries, with the globally largest area in Angola (585,000 km^2), and large areas in Cameroon and Gabon (Fig.1; Extended Data Fig. 4). In South America, the area under expansion pressure is particularly large in Brazil and Argentina, while areas under expansion pressure in Asia & Russia are mainly located in India, China, countries in the Middle East and Russia. Despite the rather small share of Australia & Oceania in the globally identified most profitable expansion area (9%), the relative increase in cropland induced by their conversion would be the highest globally with +72%, and Australia shows globally the fourth largest area of profitable land for expansion (313,000 km^2) after Angola, the USA and Brazil. Australia, Brazil and Angola are moreover among the global future expansion hotspots, which are already under expansion pressure in less severe scenarios of future global cropland increase, e.g., of +3%, +5% or +10% (Fig. 1, Supplementary Note 1.1).

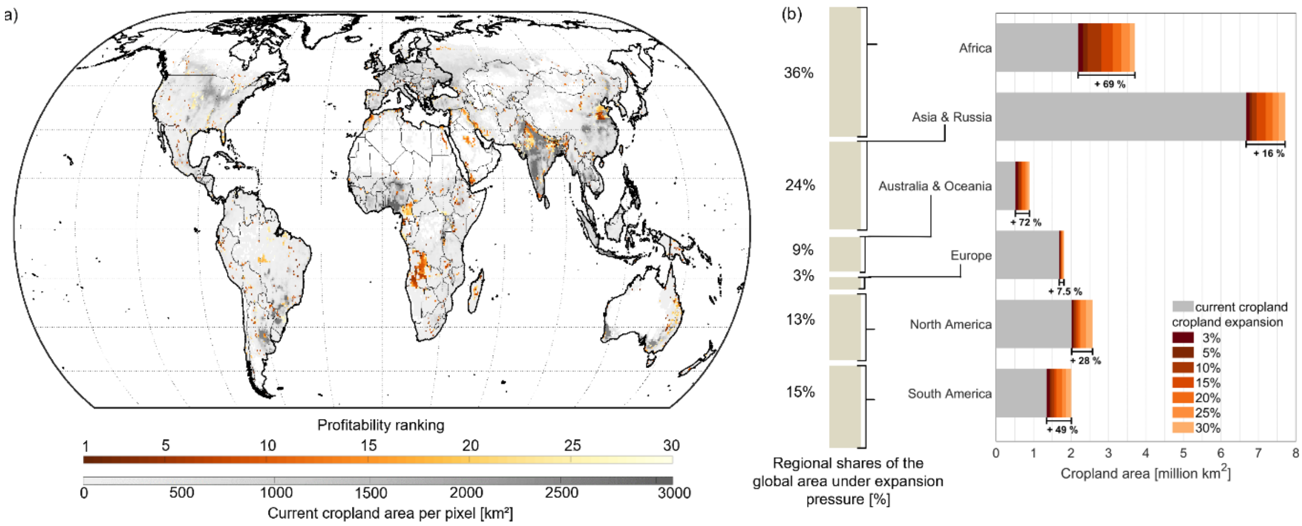

Figure 1: Areas under expansion pressure up to a potential increase in current cropland of 30% without conservation policies. *(a) Pixel-based profitability ranking of expansion areas, indicating under which global cropland expansion (1% to 30%) a pixel is among the globally most profitable ones to be transformed into cropland. Grey areas display current cropland. (b) Regional distribution of the most profitable expansion areas by displaying the regional area shares and the potential relative cropland expansion of current cropland within each region up to 30% global expansion.*

In Asia and Europe, the areas under expansion pressure are mainly located at the frontiers of current cropland on pixels that are to a large extent already agriculturally used, while in Africa, South America and Russia they are located in pixels currently not or barely used for crop cultivation. Globally, around 70% of the most profitable expansion areas are located at pixels with 10% or less cropland cover, 8% even at pixels considered as not or barely used for crop cultivation (0.1% or less cropland cover) (for details, see Supplementary Note 1.2).

1.2 EXP scenario (3.6% global cropland expansion)

Areas under expansion pressure

Extracting the globally most profitable expansion areas for the projected 3.6% cropland increase of the FAO and OECD[44], we find the identified 515,000 km^2 under globally highest expansion pressure to be similarly distributed across the continents as the 4.27 million km^2: Around one third of the area under highest expansion pressure is located in Africa (165,500 km^2), 22% (117,000 km^2) in Asia & Russia and around 18% (91,000 km^2) in South America (Fig. 2a). As visible in Fig.1a, the most profitable areas for cropland expansion (displayed in dark red) identified are mainly located in Australia, Brazil, China and India and various African countries, such as Angola, Ethiopia, South Africa or the Democratic Republic of Congo. Globally, around 34% of the most profitable expansion areas are located in pixels not or barely used for crop cultivation (0.1% or less cropland cover) (Fig. 2b). The share of areas under expansion pressure at already cultivated locations is particularly high in Asia, e.g. Eastern Asia (100%) and India (91%). While in Brazil, the areas under highest expansion pressure are mainly (75%) located at the frontiers of current cropland in pixels already cultivated, more than half of the most profitable land for expansion in Paraguay, Argentina, Chile & Uruguay (56%) and in Sub-Saharan Africa (59%) is located in currently not or barely cultivated pixels (Extended Data Fig. 5).

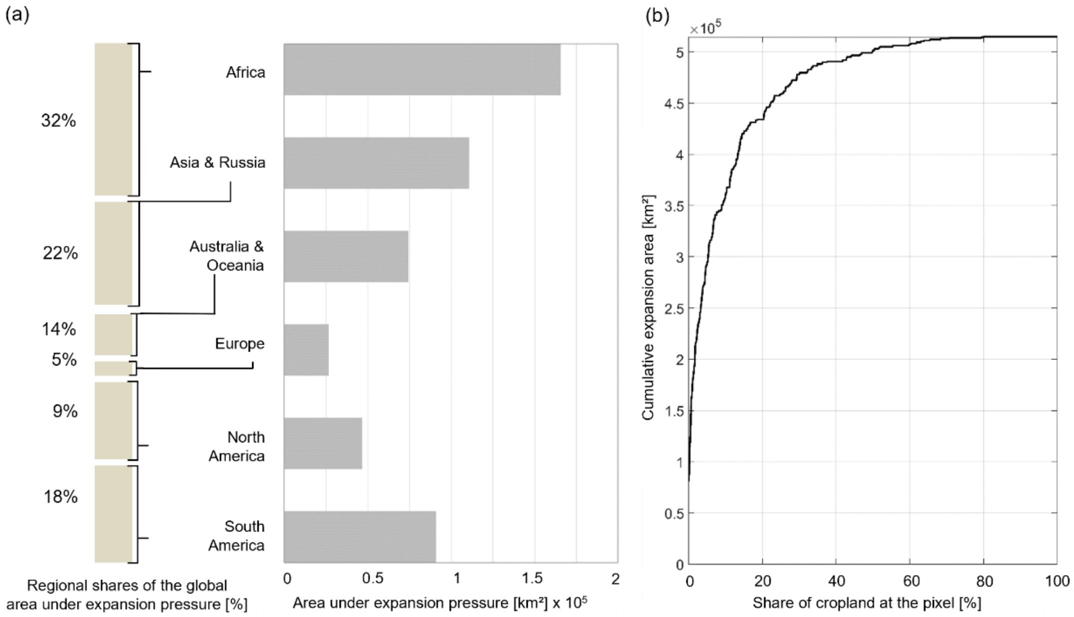

__Figure 2: Areas under expansion pressure in the 3.6% EXP__ scenario (a) Regional distribution of areas under expansion pressure and their global shares in the total area under pressure. (b) Global cumulative distribution of area under expansion pressure [%] at pixels with shares from 0% to 100% currently covered with cropland.

Impacts on agricultural markets

Implementing the 3.6% cropland increase of the EXP scenario in the economic model raises global agricultural production until 2030 by +2% compared to a reference future without cropland expansion (REF scenario). Particularly the production of cash crops like sugar cane/ sugar beet and soy increases (+2.8% and +2.7%, respectively), which are mainly cultivated in regions highly profitable for cropland conversion. On average, crop prices are -7% lower than in the REF scenario, leading to generally higher consumption levels and lower producers' income due to falling prices in all regions. The global volume of imports and exports increases by 4%. Especially regions with high relative cropland expansion, such as Australia & Oceania, South America or Africa, exhibit strong production increases (Fig. 3a) that are often accompanied by higher net-exports, for example wheat in Australia & Oceania (+32% production increase, +53% net-exports). In Brazil, mainly the production of maize (+3%) and cash crops like soy (+2%) and sugar cane (+2%) increases, contributing to an increase in overall regional export of +3%. In Sub-Saharan Africa, in particular the production of food crops, such as various grains (wheat +11%, maize +3%, other grains +3%)

increases. Three-quarters of this production increase is used to satisfy domestic consumption, while the rest is exported, leading to an increase in exports of +7%. In Asia & Russia, overall production increases only slightly by +1%, with regions like India and China increasing their net-imports by +10% and +6.6%, respectively, rather than their production (+0.7% and +1%, respectively).

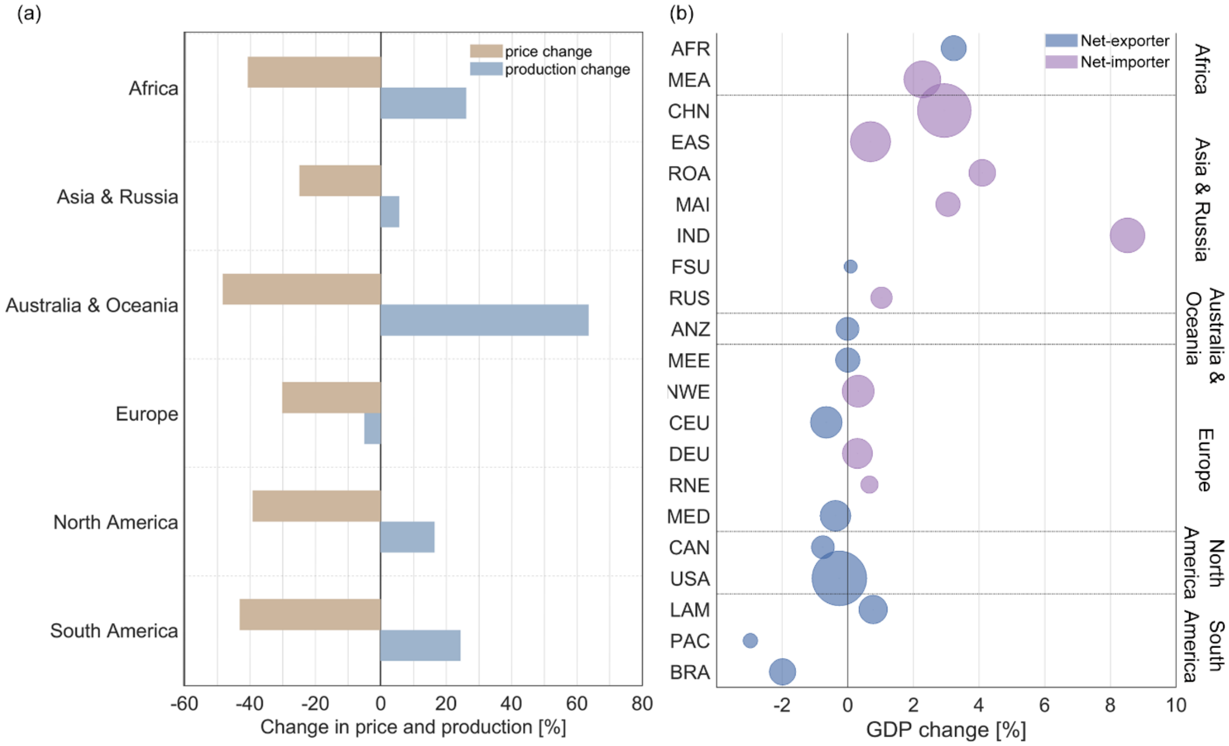

Figure 3: Economic impacts of converting the areas under expansion pressure in the 3.6% EXP scenario into cropland until 2030 compared to the REF scenario. *(a) Relative changes in producer prices and production [%] per region. (b) Relative changes in the Gross Domestic Product (GDP) [%] for the 21 economic regions, distinguishing between net-exporters and net-importers. The size of the dots represents the absolute GDP of the regions under the EXP scenario in 2030. The region mapping and abbreviations of the economic regions can be found in the Extended Data Fig. 3*

Looking at the Gross Domestic Product (GDP) as a welfare indicator, the possibility to increase domestic production with cropland expansion and to import at lower prices generally increases the GDP especially in net-importing regions in Asia, such as India (+1.2%), Malaysia and Indonesia (+0.8%), and China (+0.7%) (Fig. 3b). For most net-exporters, on the other hand, the EXP scenario leads, despite increased production, to a decline in GDP due to lower world market prices. In South America, the GDP drops for example by -0.4% in Brazil and by -0.3% in Paraguay, Argentina, Chile and Uruguay, while it also declines in North America and parts of Europe. In a few exporting regions, the lower prices can be compensated, for example by an increased export quantity in Australia, New Zealand and Oceania, and by additional increases in total consumption resulting from lower domestic food prices due to a rise in cultivation of food crops in Sub-Saharan Africa and the Rest of Latin America.

Impacts on CO_2 emissions from land use change and biodiversity

Expanding current cropland extent by around 3.6% in the EXP scenario would generate 17.1 Gt CO_2 emissions and reduce the biodiversity intactness index (BII) across these areas by -25%.

The areas under expansion pressure in the EXP scenario are currently mainly covered with secondary vegetation (53%) or used as pasture (39%) (Fig. 4a). Since a major part (71%) of the identified potential expansion area is located in the tropics, almost half (42%) of the associated global emissions are generated by the conversion of land with tropical moist and seasonal forest as potential natural vegetation (PNV) (Fig. 4a), of which 88% and 61%, respectively, are primary or secondary forests. Additionally, more than 75% of the temperate and boreal forest PNV under expansion pressure is considered as primary or secondary vegetation. Overall, the regions with the largest areas under expansion pressure show the highest CO_2 emissions potentially generated by cropland conversion (Fig. 4b). While in Africa, those emissions are generated almost equally by the conversion of areas with grass- and shrubland PNV (52%) and forest PNV (48%), in Asia & Russia and South America around two thirds of the emissions come from a conversion of forest PNV (69% and 63%, respectively). Globally, the highest share of emissions generated from a conversion of tropical forests can be found in South America (54%), followed by Africa (48%), while emissions in Europe and North America are mainly generated by converting areas with temperate and boreal forest PNV (87% and 36% of the regionally generated CO_2 emissions).

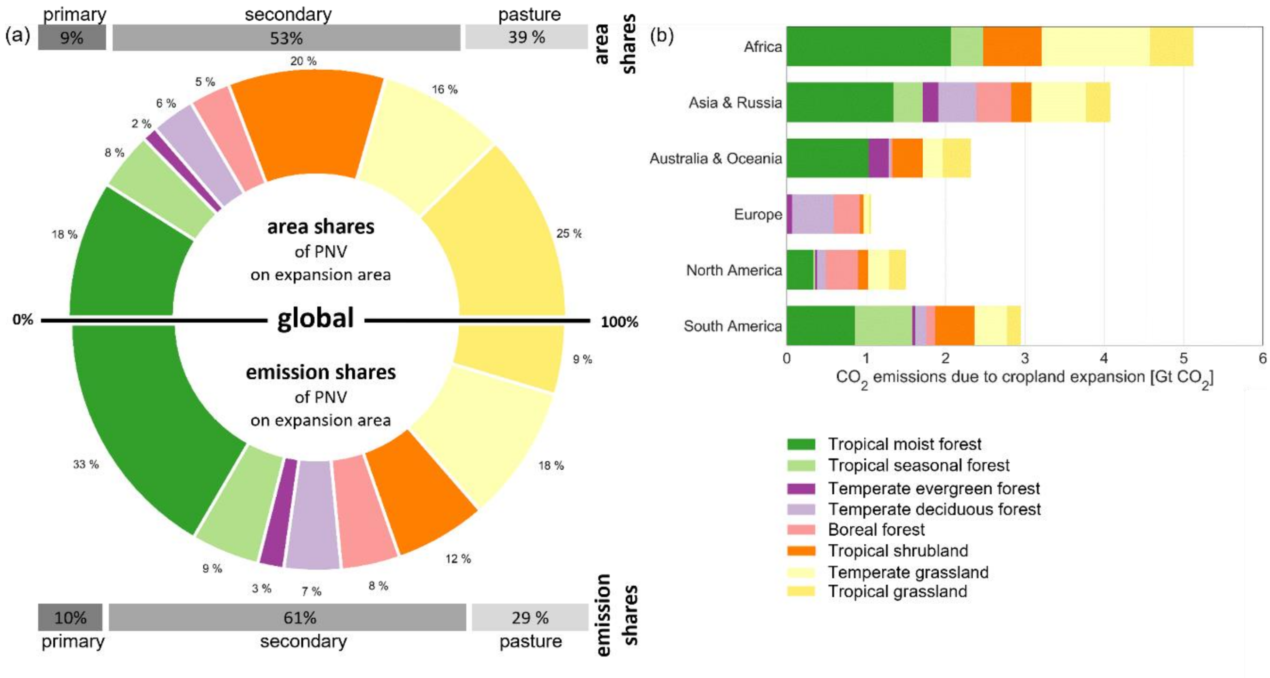

Figure 4: CO_2 emissions generated by converting the areas under expansion pressure in the 3.6% EXP scenario into cropland *(a) Shares of the different cover types (primary, secondary, pasture) and potential*

natural vegetation (PNV) types on the global area under expansion pressure (top) and the generated CO_2 emissions (bottom). (b) Regional distribution of the generated CO_2 emissions in absolute terms [Gt CO_2].

The reduction in biodiversity intactness across the areas under expansion pressure is with -34% strongest in Australia & Oceania (Fig. 5a), where around 25% of the potentially converted areas are currently covered with primary vegetation. The second strongest BII decrease can be found in South America (-30%), where biodiversity intactness would be particularly reduced across the areas under expansion pressure in Brazil (-32%) and Paraguay, Argentina, Chile and Uruguay (-29%) (Supplementary Fig. 21). The BII decline in North America (-26%) is especially strong in Canada (-38%), where almost one-third of the areas under expansion pressure are currently still covered with primary vegetation, of which 10% are even classified as being under minimal human influence. In Africa and Asia & Russia, the BII drops by around -21% across the areas under expansion pressure. In Russia (-32%), areas under pressure are to large parts currently covered with secondary vegetation (49%) or used as pastureland (41%), and only 18% of the areas under pressure are located in pixels currently already under cultivation (>5% cropland at the pixel). In other countries in Asia & Russia, such as in China or India, on the other hand, large parts (47% and 91%, respectively) of the areas under pressure are located at the frontiers of current cropland and correspondingly less primary and also secondary vegetation is potentially converted into cropland in these regions. The BII decrease across these areas is with -17% and -16%, respectively, among the lowest globally. Globally, areas under expansion pressure are particularly located in the world's most threatened biodiversity hotspots of the Eastern Afromontane (42.000 km^2), Indo-Burma (23.000 km^2), the Tropical Andes and the Cerrado (both 17.000 km^2 each), and the Horn of Africa (15.000 km^2) (Fig. 5b).

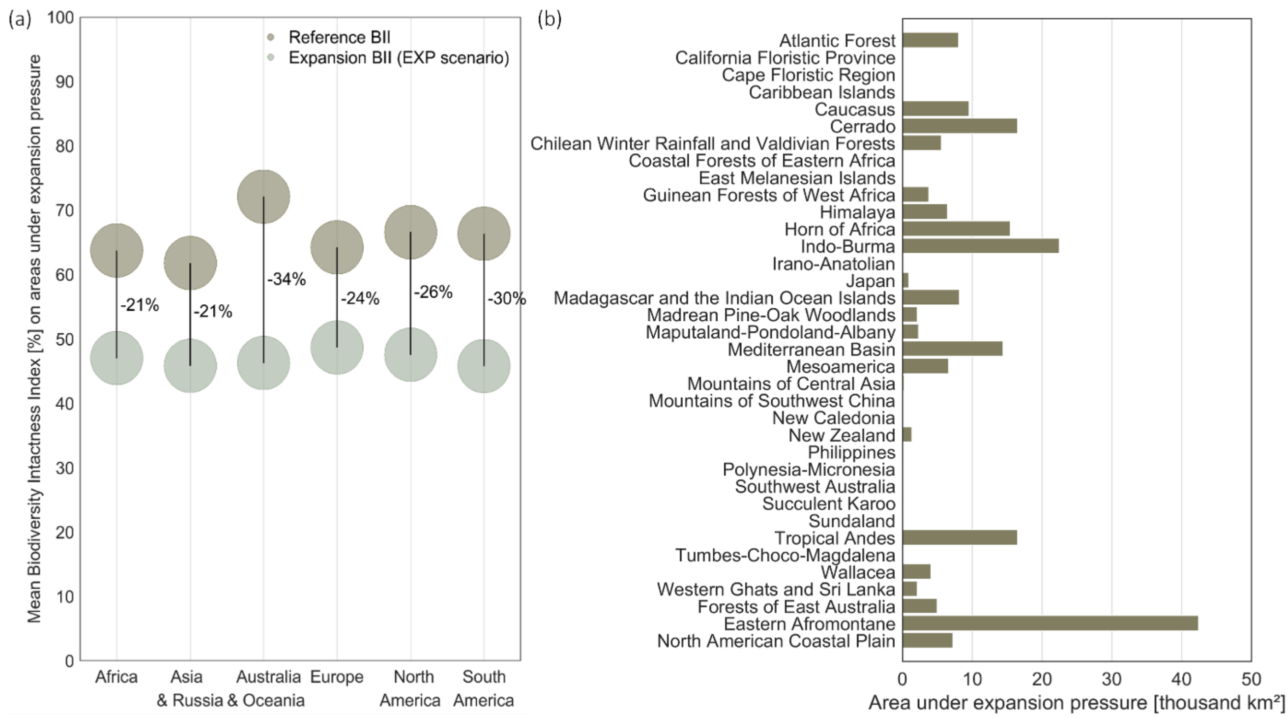

Figure 5: Regional impacts of the transformation of the areas under expansion pressure into cropland on biodiversity in the 3.6% EXP scenario. *(a) Regional biodiversity intactness and its changes due to cropland expansion. The dots display the reference BII across the areas under expansion pressure under current land-use (Reference BII) and under their use as cropland (Expansion BII). Moreover, the regional change in BII [%] from the reference to the respective scenario is displayed as a percentage. (b) Area [thousand km²] identified to be under expansion pressure in the world's most threatened biodiversity hotspots[54] under the 3.6% EXP scenario.*

2. Impacts of global conservation policies

Implementing a global policy that prohibits the conversion of forests, wetlands and protected areas into cropland spatially shifts expansion pressure into other locations. In the following, we first analyze the global shift of the top 30% areas globally under expansion pressure (2.1), and then analyze the effects within the 3.6% CON scenario (2.2).

2.1 Global area shift (top 30% areas)

We find that the introduced conservation policy puts 47% of the 4.27 million km^2 previously identified as globally most profitable areas for expansion (see Results 1.1) under protection. Around 17% of these areas are currently already classified as protected[48]. Identifying the next most profitable areas not protected by the conservation policies (until again 4.27 million km^2 under expansion pressure are identified) displays the potential spatial shift of expansion pressure induced by conservation policies (Fig. 6a). Even though the expansion pressure does not strongly shift between the large world regions (Extended Data Fig. 6), there are strong spatial shifts within those regions. In South America, for instance, the total area under expansion pressure decreases in Brazil (-14%) and shifts from the central part in the Amazon to the south, southwest and the Cerrado region (Fig. 6a). On the other hand, more land is under expansion pressure in the southern part of the continent in Paraguay, Argentina, Chile and Uruguay (+36%), mainly in the Gran Chaco region. Globally, the share of areas under expansion pressure being located at pixels with less than 10% cropland cover is reduced from 70% to 55% and less area currently not or barely used for crop cultivation is under expansion pressure (for details, see Supplementary Note 1.2).

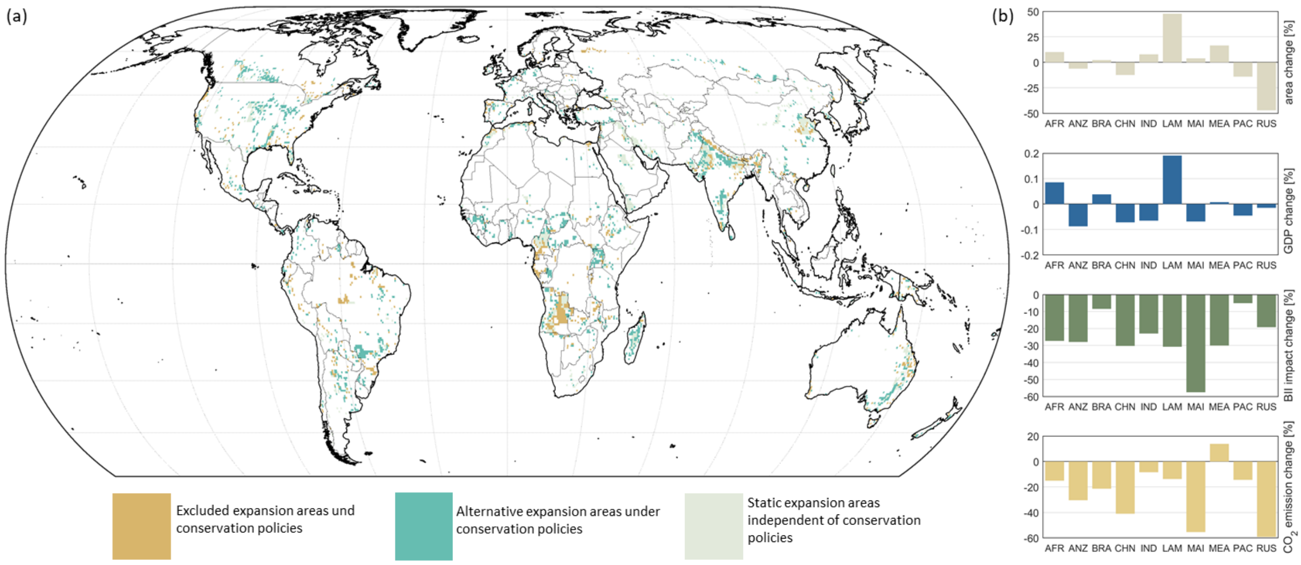

Figure 6: Changes in the spatial patterns of expansion pressure and the socio-economic and environmental impacts under the implementation of conservation policies. *(a) shows the spatial shift of areas under expansion pressure for the identified areas up to an increase of current cropland by 30% (4.27 million km²) as a defined upper boundary. Brown areas have been identified to be under expansion pressure without the consideration of conservation policies, but are protected by the assumed conservation policy; Green areas are the areas into which expansion pressure shifts under conservation policies; Grey areas are under expansion pressure with and without conservation policies. (b) displays the relative changes in area under expansion pressure [%], GDP [%], BII impact [%] and CO_2 land-use emissions [%] between the expansion scenarios with (CON scenario) and without (EXP scenario) conservation policies under a global expansion of 3.6%, exemplary for selected economic regions (see Extended Data Fig. 3 for region mapping).*

2.2 CON scenario (3.6% global cropland expansion under conservation policies)

The introduction of conservation policies within a 3.6% expansion scenario in the CON scenario particularly reduces the area under expansion pressure in Europe (-42%, -11,300 km²) and Asia & Russia (-9%, -10,200 km²), here especially in Russia (-47%) and China (-12%). Less area is also under expansion pressure in Australia & Oceania and North America (both -6%). In Africa and South America on the other hand, the total area under expansion pressure increases by +10% and +11%, respectively (Extended Data Fig. 7). In South America, expansion pressure shifts mainly from Paraguay, Argentina, Chile and Uruguay (-14%) to the Rest of Latin America (+48%), but also to Brazil (+2%) (Fig 6b). Overall, however, the countries with the globally largest area under expansion pressure remain similar to the EXP scenario: Australia, Brazil, Angola, Ethiopia, South Africa and

Madagascar, China and India. Particularly in Malaysia and Indonesia and Sub-Saharan Africa, expansion pressure is strongly shifted to locations already cultivated, with the share of area under expansion pressure in pixels currently cultivated rising from 29% to 57% in Malaysia and Indonesia and from 41% to 55% in Sub-Saharan Africa. On the other hand, a higher share of area under expansion pressure is located in not or barely cultivated pixels in South America in Brazil (from 25% to 32%) and also Paraguay, Argentina, Chile and Uruguay (from 56% to 80%).

Agricultural production is only marginally reduced by -0.1% and regionally shifts according to the changes in area under expansion pressure. It is mainly reduced in Australia, New Zealand and Oceania (-3%), Paraguay, Argentina, Chile and Uruguay (-1%), and the USA (-1%) and shifted in particular to the Rest of Latin America (+3%), Sub-Saharan Africa (+0.5%), and the Middle East and Northern Africa (+0.5%). The impacts on the GDP, however, are marginally (< +/-0.1%) in most regions (Fig 6b), indicating that the introduction of conservation policies may cause only marginal economic costs in a 3.6% expansion scenario. Strongest impacts on the GDP can be observed particularly in the regions in which the area under expansion pressure is mainly shifted to, namely the Rest of Latin America and Sub-Saharan Africa, where the GDP increases by +0.2% and +0.1%, respectively, and the Rest of Asia, where a decrease in agricultural production (-0.5%) and higher import prices contribute to a decline in GDP by -0.2%.

The spatial shift of expansion pressure away from forests, wetlands and protected areas in the CON scenario reduces the global CO_2 emissions associated with converting the areas under expansion pressure into cropland by almost -25% to 13 Gt CO_2. Areas with tropical grass- and shrubland PNV account for more than half (54%) of the global area under expansion pressure, while 21% of the areas are located at land with temperate grassland PNV. Compared to the EXP scenario, where 9% of the area under pressure is primary vegetation and 53% secondary vegetation, the pressure on primary and secondary vegetation decreases under the CON scenario by -4 and -21 percentage points, respectively. Yet, more pastureland is under expansion pressure, with almost two-thirds (63%) of the areas under expansion pressure being currently used as pasture. Regionally, the decline in area under expansion pressure more than halves the potential CO_2 emissions in Europe (-58%) and reduces them by -30% in Asia & Russia and Australia & Oceania. In Asia & Russia, the drop in CO_2 emissions is particularly strong in Russia (-59%), Malaysia and Indonesia (-55%) and China (-41%) (Fig 6b), while they increase in Eastern Asia (+15%), where also the area under expansion pressure increases in the CON scenario (+8%). Despite the increased area under expansion pressure in Africa and South America, the CO_2 emissions associated with a conversion of these areas into cropland nonetheless drop by -20% in South America and by -15% in Africa, resulting mainly from a shift from tropical forests into tropical and temperate grass- and shrublands.

In both regions, Africa and South America, the introduction of conservation policies moreover leads to a reduced decline of biodiversity intactness across the areas under expansion pressure: The BII declines by -24% and -16% in the CON scenario instead of -30% and -21% in the EXP scenario in South America and Africa, respectively (Supplementary Fig. 18). The impact on biodiversity intactness is reduced strongest in Australia & Oceania (by almost 10 percentage points to -25%), mainly resulting from a shift of expansion pressure away from primary vegetation into managed pastureland. The BII across the areas under expansion pressure in Asia & Russia drops by -15% in the CON scenario (instead of -21% in the EXP scenario). Strongest effects can be observed in Malaysia and Indonesia (Fig. 6b), where the expansion pressure shifts away from primary and secondary vegetation into pastureland, while rather moderate changes can be observed in the rest of Asia & Russia, e.g., in China (-12% instead of -17%), India (-12% instead of -16%) and Russia (-26.1% instead of -32.3%). Globally, the BII decline across the identified areas under pressure is with -19.4% instead of 25.2% around 24% (5.8 percentage points) lower than in the EXP scenario. Regarding the world's most threatened biodiversity hotspots, introducing conservation policies shifts expansion pressure away from hotspots such as the Indo-Burma hotspot, the Chilean Winter Rainfall and Valdivian Forests, Mesoamerica or the Atlantic Forest to the biodiversity hotspot of Madagascar and the Indian Ocean Islands (+200%), the New Zealand hotspot (+100%) and the hotspot of the Horn of Africa (+ 46%) (Supplementary Figure 23).

3.3.4 Discussion

Spatial patterns of expansion pressure

The location of regions we find under expansion pressure in the future tie in with the spatial patterns of recent and past expansion dynamics[7], and are in line with projections that locate future expansion mainly in the tropics in Sub-Saharan Africa and Central and South America[11,58], in the Middle East and Northern Africa[42,58] and Australia[11]. Particularly Angola, Brazil and Ethiopia, countries we identified to be under a high expansion pressure under a global cropland expansion scenario of 3.6% and beyond up to a 30% expansion, show already a rapid cropland increase in the recent past (Angola, Brazil[7]) or are identified as future expansion hotspots in other studies (Brazil, Ethiopia[41,42]).

Economic and environmental impacts

The higher production of globally traded cash crops like sugar cane/ sugar beet and soy under the 3.6% EXP scenario and the resulting reduction in global agricultural prices could change the relative wealth of regions differently, depending also on their exports and imports: Net-importing regions in Asia and the Middle East and Northern Africa economically benefit from falling world market prices and higher gross domestic output, while the GDP of net-exporting regions whose agricultural sector is strongly dependent on cash crop exports, especially in Brazil and the southern part of South America, are negatively affected. These findings corroborate the strong impact of global market interactions on the regional economic implications of expansion, thus highlighting the importance of global approaches to investigate such effects.

Our results on the global patterns of expansion pressure and the potential impacts on biodiversity intactness agree with previous global studies[41,42] that identify South America and the tropics in general as hotspots (Supplementary Note 1.4). Yet, we find biodiversity intactness to be also particularly threatened on areas under expansion pressure in Canada and Russia. Here, the underrepresentation of observational data in northern latitudes in the underlying database used to assess the BII[59,60] can even lead to an underestimation of expansion effects on the BII (see paragraph on limitations of the BII further below). The 17.1 Gt CO_2 global emissions associated with the land-use change in the 3.6% EXP scenario are almost half the current global annual total emissions[61], with around one-third of the emissions being generated by converting land with primary and secondary tropical forest PNV.

Comparing the location of the most profitable expansion areas under the globally highest expansion pressure identified in the 3.6% EXP scenario with the location of all 4.27 million km^2 identified to be under expansion pressure under a 30% cropland increase, the most profitable areas within the 3.6% scenario are more often located in pixels currently not or barely used for crop cultivation (35% in the 3.6% EXP scenario instead of 8% under a 30% expansion without conservation policies; see Supplementary Note 1.2). The emissions induced by converting the areas under expansion pressure into cropland in the 3.6% EXP scenario are proportionally reduced and around 10% of the emissions generated when converting all 4.27 million km^2 of a 30% cropland increase (Supplementary Note 1.3). The relative reduction of the BII across the potentially expanded areas, however, is very similar (-25% under the 3.6% EXP scenario and -27% under a 30% expansion without conservation policies; see Supplementary Note 1.4). Thus, we see that already comparatively small increases in cropland affect land where biodiversity intactness is reduced in the same relative magnitude as in more severe expansion scenarios. Further analysis of different global expansion targets and the resulting socio-economic and environmental impacts could provide further information about the correlations, the sensitivity of the impacts and reveal also potential non-linearities.

Effects of conservation policies

The introduction of conservation policies in the 3.6% CON scenario shifts the expansion pressure to Africa and South America, CO_2 emissions and the decline of the biodiversity intactness across the potentially expanded regions are globally reduced by around -25%, while only marginally reducing agricultural production (-0.1%) and marginal changes (< +/-0.1%) in GDP in most regions. Given this reduction in environmental impacts, even in regions where the area under expansion pressure is stable or increases compared to the EXP scenario, the assumed conservation policies could substantially contribute to reconcile agricultural production with environmental protection without compromising global agricultural productivity. This underlines the potential of existing political agreements for reducing deforestation and protecting forests[45,46], as well as the importance of informed, strategic land-use planning. However, the following limitations need to be considered.

Potentials and limitations

The expansion module in iLANCE takes biophysical growing conditions, agricultural management, various socio-economic drivers and the resulting economic conditions into account. We refrained from considering further factors, such as proximity to historic expansion[34,62,63], infrastructure[38], market influence[64] or extreme poverty[16], amongst others because of the lacking knowledge[34,35] and data[34] on their quantitative impact on the economic profitability of a pixel for cropland expansion (for a detailed discussion, see Methods 4). Due to the spatial explicitness of our approach, however, further factors and constraints of expansion can individually be applied in the post-processing by masking specific pixels that do not meet defined criteria for expansion according to the research question. Yet, the need remains for an improved global, but spatially differentiated understanding of drivers and predictors of future agricultural expansion[34,65] and their quantitative impact. This holds particularly for expansion at the frontiers of current cropland, which is relatively poorly explained by existing data on drivers[34], and thus might be insufficiently captured in our profit-driven approach, with which we identify mainly currently uncultivated or barely cultivated locations to be under expansion pressure.

To focus on the potential dynamics of future agricultural expansion, we assume the potentially expanded areas to be cultivated with the same intensity as the current cropland in the corresponding Agro-ecological Zone[66] of the economic study region (see Methods 2). Accordingly, potential additional impacts of future agricultural intensification on expansion dynamics[67-70] are not considered in this study. Yet, contrasting and comparing the effects of expansion with potential socio-economic and environmental effects of intensification is an important aspect, particularly in the context of biodiversity conservation[30-32,68,71-76], which can be addressed with the presented modeling framework in future studies. Moreover, the regional implementation of conservation policies and investigation of potential leakage effects[77] could be an interesting potential application area of the presented approach. A sensitivity analysis of the identified areas under expansion pressure to different assumptions on agricultural intensification can be found in Supplementary Note 3.

Beyond that, the assessment of potential future expansion areas is based on a global profitability ranking and the assumption, that the globally most profitable areas for cropland expansion are under the highest pressure of being converted into cropland. The approach thus does not capture other national or regional conditions that, for instance, could additionally cause cropland expansion in the respective region on areas with a lower profitability relative to the global ranking. It is moreover important to note that, as the profitability ranking is, inter alia, based on static economic trends, also the economic outcomes are highly dependent on the assumed continuation of these trends with regard to land expansion. Accordingly, the economic results are also likely to change under changing political or socio-economic conditions as well as relative to exogenous shocks, for example geopolitical developments.

Applying the BII allows for assessing the potential reduction of biodiversity intactness if currently uncultivated land is transformed into cropland. While the index takes species abundance and compositional similarity into account (see Methods 5 and Supplementary Note 2), it does not provide information on whether endangered species might be affected. Additionally, the BII does not capture lagged responses of biodiversity to pressure over time (so called extinction debt), as the database refers to the current point in time, assuming the full impact on biodiversity has already been achieved for the land-use intensity classes[78,79]. As a relative measure describing the biodiversity intactness compared to a pristine ecosystem state of the area (primary vegetation areas with minimal use intensity), the BII moreover does not reflect the biodiversity in absolute terms. The focus on pristine ecosystems and the BII being a relative measure moreover might lead to an underestimation of the impacts on biodiversity in areas with other habitat types and of substantial biodiversity importance, such as global biodiversity hotspots that have already lost 70 % of primary vegetation, while hosting at least 1,500 vascular plant species[54]. Moreover, threatened species located in areas already degraded or with lower biodiversity intactness might be overseen. Yet, combining the BII with further diversity metrics and data, such as the included analysis focusing on the world's most threatened biodiversity hotspots[54], provides additional information regarding for example impacts on threatened species or species loss, the biodiversity impacts in endangered ecosystems or in areas with a particularly high biodiversity. [54]Overall, the BII is a suitable index for this analysis of biodiversity impacts resulting from cropland expansion, as it is, to our knowledge, the only global biodiversity indicator that is able to connect land-use intensity to its impact on biodiversity at pixel level on a global scale. It builds on the vast PREDICTS database, the largest database containing information on land use and its intensity across a wide range of taxa[60].

In the design of the CON scenario, we exclude forests, wetlands, and protected areas from cropland expansion. We have chosen this scenario design (1) due to the high relevance of forests and wetlands for biodiversity protection and carbon sequestration[19,22,57,80,81], (2) to take into account that those land-covers were highly affected by past and recent cropland expansion[13,17,18,82] and (3) to reflect current global political conservation efforts, such as the Glasgow Leaders' Declaration on Forests and Land Use[45] or the EU Regulation on deforestation-free supply chains[46]. Yet, it is important to mention that also further land-covers, e.g. native grassland, are important ecosystems[83,84] and of relevance for biodiversity conservation and carbon sequestration[85]. As shown in the previous paragraph, globally uniform protection of certain ecosystems, such as forests, might cause environmental trade-offs in certain regions by shifting expansion pressure to other highly biodiverse ecosystems. Grasslands, for instance, are well known to make an important contribution to biodiversity[86-88], with the Cerrado being the world's most biodiverse tropical savannah[89] that, however, is already highly threatened by land-use conversion and resulting habitat loss[90-92]. Its protection and restoration could play an important role in reducing the risk of extinction and conserving threatened species[90,93,94]. Thus, further research on which areas should be prioritized for conservation measures is needed for more strategic conservation planning. Thereby, it is important to identify also areas, where the potential negative effects of agriculture on the environment are lowest and trade-offs between agricultural production and environmental protection are smallest.

Finally, our impact assessment focuses on the potential effects of expansion on agricultural markets, biodiversity and generated CO_2 emissions. Yet, we aim to make the output of our analysis on areas under expansion pressure as applicable as possible for further impact assessments. We therefore provide the data on the identified areas globally at 0.5° spatial resolution and aggregated at country level for both scenarios and for any global expansion rate from 1% up to 30%. It could be used in future studies to investigate additional environmental impacts of cropland expansion, for instance on the hydrological cycle[97,98], potentially arising social conflicts, such as land tenure issues, or land-use changes coinciding with or being induced by expansion, such as shifting agriculture[37] or land-use spillover effects[99].

3.3.5 Conclusion

Our study identifies the areas under the highest pressure of profit-driven cropland expansion and evaluates the economic and environmental impacts of their conversion. This information might be useful for example in the context of political efforts on global nature and biodiversity conservation, such as the Kunming-Montreal Global Biodiversity Framework[100], assuring that alongside areas with high conservation value also areas under high expansion pressure or areas in which biodiversity might be threatened most by cropland expansion are taken into account. This could improve the effectiveness of conservation strategies substantially and contribute to a more holistic approach by considering also the economic impacts of environmental protection and their potential social implications.

The study moreover gives a first outlook on the potential environmental benefits and associated economic impacts of an implementation of global policies protecting forests, wetlands and protected areas from cropland conversion. The results demonstrate the high potential of global conservation policies to reduce the environmental effects of cropland expansion without compromising agricultural production and thus the potential contribution of strategic land-use planning to reconcile food security and economic interests with the protection of climate and biodiversity. Yet, particularly in the context of biodiversity conservation, globally uniform conservation policies protecting certain ecosystems, such as forests or wetlands, might lead to trade-offs threatening other highly biodiverse ecosystems. This points to the importance of considering regional particularities in global conservation policies and to the need for research frameworks that integrate the global and local scale.

By providing the data on areas under high expansion pressure at 0.5° spatial resolution and aggregated at country-level for future global cropland expansion from 1% up to 30%, it can be distinguished between areas already under pressure in low future expansion scenarios and areas that are under pressure only in more severe expansion scenarios. The created output data allows for flexible assumptions on the extent of expansion from 1% up to 30% for thereon based further impact assessments. Further research on the drivers of cropland expansion, their quantitative impact and spatial and temporal distribution is needed to improve the simulation of land-use change dynamics in integrative models. An in-depth understanding of potential future dynamics is necessary to identify not only potentially arising trade-offs, but also possibilities to create co-benefits between the different land-use interests that need to be balanced with global climate protection and biodiversity conservation goals.

3.3.6 Methods

1. Analysis Framework

The globally most profitable land for cropland expansion is identified by applying the integrative land-allocation sequencer iLANCE. iLANCE is a land-use model based on an established coupling approach of the biophysical crop growth model PROMET (Methods 2) and the Computable General Equilibrium (CGE) model DART-BIO (Methods 3), which has previously been used in other interdisciplinary studies[2,49]. The iLANCE model allows for integratively simulating crop allocation and land-use change on current cropland based on biophysical and socio-economic drivers globally at 0.5° spatial resolution. For this study, we extended the iLANCE model by an expansion module to investigate the spatial allocation of cropland expansion (Methods 4). The models are described in the Methods sections 2,3 and 4.

Within this study, we investigate the spatial patterns of expansion pressure up to an hypothetical increase in current cropland by 30% until 2030 with and without conservation policies. This upper threshold of 30% (approximately 4.27 million km^2) until 2030 is set to take the high uncertainty of future cropland projections into account[101], ranging from 0.7 million km^2 and 1.8 million km^2 up to 5.9 million km^2 until 2050[8-10]. The large spread originates from uncertainty around various factors, such as the regional effects of climate change on yields[102], technological development and its potential to increase production on current cropland[2], future dietary changes and consumption patterns[9], the impact of an increasing demand of agricultural goods for bioenergy and the bioeconomy, and potential decreases in food waste. The assessments can be seen as upper thresholds that shows a broader picture of how expansion pressure is distributed spatially on a regional and global level. As the approach allows for ranking the areas according to their relative profitability for cropland expansion (marginal profits to land), the relatively most profitable expansion areas can be extracted for any global area threshold and thus any predefined global expansion rate up to the 30% upper threshold assumed in this study can be investigated. It is important to note that we do not assess the absolute profitability for global cropland expansion, but investigate the areas that can be assumed to be under the highest expansion pressure due to their relatively highest profitability for cropland expansion within an exogenously defined global expansion scenario.

Both spatial datasets on areas under expansion pressure, with and without conservation policies, serve as a basis for the scenario analysis described in the following.

Scenario design

Based on the created spatial data on expansion pressure, the areas of a potential cropland expansion of 3.6% are investigated for two scenarios, cropland expansion with conservation policies (CON scenario) and without conservation policies (EXP scenario). The potential environmental and socio-economic effects are analyzed and compared with a future reference scenario without expansion dynamics (Extended Data Fig. 1).

All three scenarios (REF, EXP and CON scenario) assume a socio-economic business-as-usual development until 2030. For its calibration in DART-BIO, we adjust the labor productivity to match annual growth rates of regional GDP projections of the OECD[103]. The capital stock available for the next period is updated with the current period's investments and depreciation, while labor supply changes according to regional workforce and population dynamics taken from the OECD[103]. Other important assumptions that drive the baseline are policies, e.g. commodity tax rates or subsidies, which we take from the GTAP database[53]. These assumptions and calibrated parameters are not changed across the three different scenarios. Further assumptions implemented in the economic model are described in the Methods section 3.

The three scenarios differ in their assumption on future expansion dynamics and land-use regulations: Within the reference scenario (REF), we assume that the sum of managed land area (cropland, pastureland, managed forests) is constant until 2030, implying that there is no expansion into unmanaged land.

For the assessment of expansion pressure without conservation policies (the EXP scenario), we do not assume particular land-use regulations for cropland expansion. Accordingly, the profitability of land for expansion is assessed without any restrictions to investigate areas under expansion pressure independently of current or future potential conservation or protection policies. This takes into account (1) that established protected areas can change as well as conservation interests and (2) that cropland already encroaches into protected areas[18].

To investigate, on the other hand, how conservation policies impact profit-driven cropland expansion, we introduce the second future expansion scenario, the conservation policy scenario (CON scenario), in which we assume global policies prohibiting expansion into forests[33], wetlands[47] and strictly protected areas[48]. We decided to select those restrictions for several reasons: First, due to the comparatively high relevance of forests and wetlands for carbon sequestration and biodiversity conservation. Despite their globally rather small area, the high carbon sequestration potential of peatlands[81] and their potential to remain a net CO_2 source in the 21st century makes their protection essential for climate change mitigation[80]. Also, the carbon storage potential of primary forests for example is on average substantially higher than the storage potential of primary grasslands[56,57] and food-related deforestation was the single largest emission source on agricultural land over the past three decades[19]. Moreover, forests are the habitat for the majority of terrestrial plant and animal species[104] and thus play an important role in the global protection of biodiversity. Secondly, those land-covers were highly affected by past and current cropland expansion and land conversion processes[7,8,105]: Studies show that across tropical regions, more than 80% of the new agricultural land from 1980-2000 was derived from forests and particularly the relative amount of expansion from clearing intact forests increased in this time period[17]. We explicitly also excluded designated protected areas from cropland expansion, since they are however often agriculturally used despite their status[106]. Furthermore, the expansion rate in protected areas increased 58-fold from 2003-2007 to 2015-2019[18]. With our scenario design, we finally also aim to reflect current global political conservation efforts, for example the Glasgow Leaders' Declaration on Forests and Land Use[45] or the EU Regulation on deforestation-free supply chains[46] that both aim to halt deforestation. The CON scenario is based on the same assumptions as the EXP scenario with respect to the socio-economic development (business-as-usual) and the cropland expansion magnitude (3.6%), but excludes forests, protected areas and wetlands when assessing the most profitable land for expansion. This is done by referring to the potentially available cropland dataset[49] (2010-2039; RCP8.5) that provides information on land that is potentially cultivable but not covered with wetland, forest or classified as currently strictly protected area according to the International Union for Conservation of Nature (IUCN) classification (category Ia, Ib, II). Excluding those areas results in a protection of around 40% of the global land resources considered as potentially cultivable[49] in terms of biophysical characteristics regarding soil, climate, topography and the current surface cover.

Spatial analysis level and region mapping

iLANCE bridges the scale between the PROMET simulations at 0.5° spatial resolution and the 187 Agro-Ecological Sub-regions (AES) into which DART-BIO is structured. The definition of the AES can be found in the Methods section 3, while the model coupling and bridging of scales in iLANCE is described in Methods section 4. The resulting land-use maps of iLANCE are available at 0.5° spatial resolution.

In this study, the results are analyzed (1) at grid cell level with 0.5° spatial resolution, (2) at the level of the 21 economic regions defined in DART-BIO (Methods 3), or (3) aggregated to 6 world regions to provide a more aggregated perspective on the results (Extended Data Fig. 3). When aggregating the economic data to the 6 world regions, two economic regions, ‚Rest of Latin America' (LAM) and ‚Middle East and Northern Africa' (MEA), span across the borders of two world regions (North and South America, and Africa and Asia & Russia, respectively). We allocated LAM to South America and MEA to Africa.

2. Agricultural production potentials: Crop modeling

The crop yields referred to in this study are simulated with the biophysical land surface process model PROMET[107], which has been extended by a biophysical dynamic vegetation component to model crop growth and yield formation[2,108]. PROMET uses first order physical and physiological principles to determine net primary production and respiration based on approaches from Farquhar et al.[109] and Ball et al.[110], combined with a phenology and a two-layer canopy architecture component of Yin and van Laar[111]. It considers the interdependency of net primary production and phenological development, leaf temperature, water availability and environmental conditions including meteorology, CO_2 concentration, as well as water and temperature stress. PROMET has been used in global[2,6,11,112] and regional studies[113]. Moreover, it takes part in the Global Gridded Crop Model Initiative within the Agricultural Model Intercomparison and Improvement Project [114-116], which is connected to the Inter-Sectoral Impact Model Intercomparison Project.

Crop growth is simulated globally on around 170,000 sample locations representative of the agriculturally suitable area[117] within a 0.5° grid. This allows to capture the spatial heterogeneity of environmental factors within a pixel, such as the topography and climatic conditions. Using high resolution global data on climate[118], soil data obtained from the Harmonized World Soil Database[119] and topography derived from the Shuttle Radar Topography Mission[120], PROMET simulates crop growth at an hourly time step for each year of the considered 30-year time period around the economic target year 2030 (2016 to 2045). Climate change is considered under the SSP585 to refer to a business-as-usual scenario regarding the projected emissions until 2030[121]. Similar to Jägermeyr et al.[112], this is done by applying perturbation factors on the ERA5 reanalysis data for 1981-2010, which are derived by the median changes of five bias-corrected CMIP6 climate models ('GFDL-ESM4', 'IPSL-CM6A-LR', 'MPI-ESM1-2-HR', 'MRI-ESM2-0', 'UKESM1-0-LL') from ISIMIP[122]. The impact of climate change on the simulated crop yields in PROMET and for an ensemble of different crop models is analyzed and discussed in Jägermeyr et al.[102].

Yields are simulated for 18 agricultural food and energy crops (Extended Data Table 1), which we consider as globally important regarding their cultivation area and economic relevance, as they represent around 67% of global harvested area and 73% of the global production volume according to FAOSTAT (all listed crops, average for 1981-2010[123]). They include staple crops of global importance, such as maize, wheat and rice, as well as rather regionally important food crops, such as millet or cassava. To capture the trends in the political support of biofuels, also the predominant bioenergy crops, such as oil palm, sugarcane and rapeseed, are also considered.

For the simulation of potential yields, we assume an optimized crop management considering nutrient supply, and no harvest losses, for example due to pests and diseases. The yields are simulated under irrigated and rainfed conditions separately, assuming perfect irrigation management and no water stress under irrigation. Assuming that the potential expansion areas are managed similarly to the current cropland at each pixel, we combine irrigated and rainfed yields based on spatial data on current irrigation patterns[124] to obtain potential yields under current irrigation. This is based on the assumption that the irrigation of current cropland at a pixel indicates that irrigation is an established and profitable agricultural management practice at this location, for which knowledge and infrastructure already exists. While we do not evaluate whether enough water is available for the additional irrigation and if its use can be considered sustainable, we, however, prohibit irrigation of expansion areas at pixels not yet irrigated or cultivated. Accordingly, we see expansion areas in Angola or Brazil being mostly rainfed, while the most profitable expansion areas in Saudi Arabia or the Middle East are almost exclusively irrigated. However, the separate simulation of irrigated and rainfed yields and the design of our research approach allows for varying assumptions on irrigation on the expanded areas, such as the irrigation of certain crops or only rainfed agricultural expansion, which could be explored in further studies.

The simulated yields are aggregated to 30-year averages (1) to avoid bias from selecting a single year yield caused by annual variabilities and (2) to refer to yields that represent a timespan on which land-use decisions are made.

For this study, in which we focus on agricultural expansion without an additional increase in agricultural intensification, we assume that expansion areas are cultivated at the same agricultural intensification level as regional current cropland. Similar to other studies[102], we therefore apply a bias-adjustment based on statistical yields at AES level[53], while conserving yield changes induced by climate change. This results in spatial crop yields reflecting the current statistical intensification level. Yet, our approach permits various assumptions to be made on the degree of agricultural intensification at current cropland and expansion areas. We evaluated the sensitivity of the spatial location of expansion areas to the level of agricultural intensification. The sensitivity analysis can be found in the Supplementary Note 3.

In a final step, the simulated 18 crops are aggregated to the 10 crop categories considered in DART-BIO (Extended Data Table 1) to be consistent with the representation of crops in the economic model, which is necessary for the coupling within iLANCE. While some crop categories in DART-BIO include more than one crop (cb, gron, osdn and agr; see Extended Data Table 1), not all crops included in a crop category in the economic model can be simulated with the crop growth model PROMET for computational reasons. Therefore, each economic crop category is represented by selected representative crops simulated with PROMET. To match this difference in the crops representing a crop category in the economic model versus in our model framework, weighting factors are calculated for each crop category on AES level. The factors refer to GTAP 9 data[53] on cropland area and production and indicate the ratio between the statistical yield of a crop category based on the crops included in the economic model versus based on the crops simulated with PROMET to represent the crop category. For example, in the case of the crop category ‘gron’, these crops are barley, millet, rye and sorghum, while in the economic model ‘gron’ contains 12 different crops, including for instance buckwheat, fonio, oats and quinoa. The weighting factor is used in the aggregation process to scale the simulated yield level of a crop category to match the yield level of the crop category including all crops represented in DART-BIO.

3. Economic modeling

To assess the impacts of cropland expansion on prices, production and trade-patterns, we employ a computable general equilibrium (CGE) model. CGE models are widely used for economic analysis to assess feedback effects of policy measures across sectors and regions[125]. The CGE model DART-BIO is a multi-regional and multisectoral model of the world economy, which has been developed to investigate implications of climate policies[126] and further developed to capture midterm scenarios for agricultural markets taking into account biofuel policies, dietary patterns, cropland expansion and yield changes[127,128]. In its current version, it is calibrated to the GTAP 9 database[53], aggregated to 21 regions (Extended Data Fig. 3), within which homogeneous economic conditions are assumed, and 53 sectors. The GTAP database also provides the land-use to which the economic model is calibrated in the base year. The agricultural sector is represented by 10 crop categories (Extended Data Table 1), two livestock sectors, and 20 sectors including processed food and biofuels. In the case of crops, we have split rapeseed, soybeans, palm fruit and maize as separate sectors from the original database using information from FAOSTAT. Each of the 21 regions feature a representative household that interacts with producers at product and factor markets where flexible prices and market balance conditions ensure general equilibrium on all markets (see Delzeit et al.[129] for a detailed technical description of the model). To assess the sectoral competition for land in a more differentiated way, the production factor land in DART-BIO is disaggregated within the 21 regions into Agro-Ecological Zones[66], which are defined by parameters relevant for land-use and agricultural productivity, such as the climatic zone and the length of the growing period[130]. Dividing the 21 economic regions by Agro-Ecological Zones[131] results globally in 187 Agro-Ecological sub-regions (AES).

Following Laborde & Valin[132], land-use change is governed by a Constant Elasticity of Transformation (CET) function. Applying a three-level nesting, land is first allocated between land for agriculture and managed forest. Then, agricultural land is allocated between pasture and crops. In the next level, cropland is allocated between rice, palm, sugar cane/beet and annual crops (wheat, maize, rapeseed, soybeans, other grains, other oilseeds and other annual crops). At each level, the elasticity of transformation increases, reflecting that land is more mobile between different crops than between forestry and agriculture (for a discussion of the approach see Calzadilla et al.[133]). In the REF scenario, we assume that the land endowment available for agricultural and forest activities does not change over time. Hence, land-use change is only an endogenous result of a change in managed land-uses, e.g. more land is used for the production of cropland at the cost of pastureland. In contrast, in the EXP and CON scenarios, we exogenously add additional land endowment to the model, which is equivalent to expanding crop production to previously unmanaged land. Practically, we increase the available land in each AES according to the information from iLANCE on where land expansion is spatially happening, but make no assumption on allocation to crops, forest and pasture. Land allocation to different production sectors is then the endogenous decision of producers. Following Zabel et al.[11], for both expansion scenarios, no additional costs for reclaiming this land are considered in DART-BIO, due to a lack of global data on expansion costs and the fact that it is still subject to research, how such costs can be taken explicitly into account in global models. This is because these costs inter alia strongly depend on how expansion is implemented in terms of management practices, related input requirements and the efficiency of their usage. Hence, for consistency and comparability of the two scenarios, we assume no additional costs for both options. However, this challenges welfare analyses on household or farm level with our research approach, and can lead to a potential overestimation of the cropland expansion impacts on GDP compared to a reference scenario.

The recursive-dynamic character of the model is a result of solving for a sequence of static one-period equilibria for future time periods, which are connected through capital accumulation and changes in labor supply. For the calibration of the baseline period (2011-2030), we adjust the labor productivity to match annual growth rates of regional GDP projections of the OECD[103]. The capital stock available for the next period is updated with the current period's investments and depreciation, while labor supply changes according to regional workforce and population dynamics taken from the OECD[103]. Other important assumptions that drive the baseline are policies, e.g. commodity tax rates or subsidies, which we take from the GTAP database[53].

Marginal profit functions

DART-BIO provides sub-regional and crop-specific marginal profit functions with respect to land that are derived from the market equilibrium and depend i.a. on the productivity of land in relation to other factor inputs (capital, labor, energy). The marginal profit determines the achievable profit for allocating a certain crop category on an additional unit of land as a function of the already allocated area to this crop category within an AES, and is thus a key input into iLANCE. Let Θ_{Lc} be defined as the factor income share of land for each crop category and each AES, Θ_{KLEc} the factor income share of capital, labor and energy, and ρ the elasticity of substitution, the marginal profit [$/hectare (ha)] attainable by allocating a cropland area L is calculated as follows:

Marginal profit function (Equation 1):

$$\text{MP}\left[\frac{\$}{\text{ha}}\right] = \left[\Theta_{KLEc} + \sum_{B \neq A} \Theta_{Lc} + \Theta_{Lc}^{1-\rho} * L_{Lc}^{\rho}\right]^{\frac{1-\rho}{\rho}} * \Theta_{Lc}{}^{1-\rho} * L_{Lc}^{\rho-1} - 1$$

The marginal profits to land depend on market interactions, which in the model may dynamically change depending on scenario assumptions. Therefore, the relative profitability of different crop categories not only varies between different AES, but may shift depending also on the scenario. For details on how marginal profit functions are determined, see Mauser et al.[2]. We use the marginal profit function in the iLANCE model to globally rank all crop categories in all AES according to their profitability when allocating an additional unit of cropland within the AES (explained below in Methods section 4).

4. Integrative assessment of profit-driven cropland expansion

The expansion module within the iLANCE model assesses the globally most profitable pixels for a predefined extent of cropland expansion by combining two main inputs from the PROMET and the DART-BIO model, thereby accounting for (1) the biophysical and (2) the socio-economic drivers of cropland expansion and land-use change: (1) The simulated crop yields, aggregated as described according to current irrigation patterns and to the 10 considered crop categories, and (2) marginal profit functions for each crop category and each AES, describing the relative marginal profits to land of different crops under expansion scenarios (Extended Data Fig. 2). We assume that the attainable marginal profit is highest for the first cultivated hectare of a crop category and decreases the more cropland is allocated, until it approaches zero, when the area to be allocated within an AES is reached.

For the allocation of cropland, iLANCE considers current land-use constraints, such as urban and impervious surface and open water bodies[49], within a 0.5° grid cell. Thus, corresponding further essential inputs into the expansion module are information on (3) the land that could potentially be cultivated under the given scenario assumptions as well as (4) currently already cultivated land. For (3), we refer to the potentially cultivable land and the potentially available cropland datasets[49] (for the time period 2010-39 under RCP8.5). The potentially cultivable land data provides information on land that is agriculturally suitable but not covered by water bodies, permanent snow and ice or impervious surfaces such as infrastructure or urban areas. Since the spatial information on current cropland extent (4) must be consistent with the cropland areas in the economic model derived from the GTAP 9 database[53], we spatialize the GTAP data for each AES. This is done by using the crop-specific spatial data on cropland, production and yields from Monfreda et al.[50] and the MIRCA2000 dataset[134] to obtain a crop-specific relative spatial distribution of cropland, to which we then refer to distribute the crop-specific absolute cropland area from GTAP. If the GTAP cropland within an AES exceeds the cropland of the spatial data, the additional area is distributed across the AES by taking information about the potentially cultivable land at each pixel[135] into account. Thereby, we create a spatial dataset of the GTAP 9 cropland areas, representing approximately 99.7% of the original GTAP cropland.

By combining the marginal profitability of cropland allocation derived from DART-BIO with the simulated crop yields from PROMET and the spatial information on potentially cultivable land and current cropland, we are able to model profit-driven cropland allocation by calculating the potentially attainable profit for cropland allocation and expansion per unit area at each pixel and relatively compare them. Thereby, different assumptions on the crop diversification can be made: For example, monocultures can be assumed by allocating only the crop category with the highest potential marginal profit at each pixel. To account for risk aversion of farmers and a potential implementation of crop rotation, we assume the highest crop diversification possible at each pixel within this study. Accordingly, we allocate all crops at the expansion area of a pixel for which a yield can be attained, with their area shares reflecting their relative profitability. Hence, more profitable crops with high attainable yields receive a higher share of the available land, while less profitable crops with lower yields are assumed to receive only a small area share. This creates a diversified, but profit-oriented crop mix on the expanded land.

Based on the calculated profitability value for each pixel, we are able to successively select the globally relatively most profitable pixels for crop cultivation until the defined upper boundary of global cropland expansion, here 30%, is reached.

Further drivers of cropland expansion

Besides the profitability of an area to be used cropland, determined by the agricultural yield potential and the attainable profit of crop cultivation in that area, there are further factors that can have an influence on expansion dynamics. Regarding for example past expansion, studies show that it disproportionately occurred near areas with historic expansion[34,62,63], and natural environments are most intensively modified in areas with high market influence[64]. Moreover, extreme poverty[16] and the building of infrastructure, such as roads[38], can spatially be associated with agricultural expansion and could thus be considered as drivers of cropland expansion. However, we decided to focus solely on profit-driven agriculture, and thus do not include these further factors into our expansion module for various reasons: A main issue is that there is still a lack of knowledge on the relevance and the magnitude of impact of these drivers and also on how both, relevance and magnitude of impact, varies across space and time[34,35]. Market density, for example, has less impact on cropland expansion dynamics in South Asia and Africa, where large parts of agriculture are focused on subsistence[64], and a high profitability of land-use often provides an economic impetus, for example for road constructions[16]. In some cases, large scale actors might even be able to impact the conditions for cropland expansion, such as accessibility, infrastructure or even policies[136]. Moreover, a recent study shows that the distance to markets explains current cropland extent, but not current expansion dynamics[34]. Including those factors would thus be associated with large uncertainties. Further limiting factors are the availability of such data at a sufficient spatial resolution on global scale[34], and the lack of knowledge on how the factor quantitatively impact the economic profitability of a pixel for cropland expansion. The latter is necessary to maintain the quantitative approach in the iLANCE model that allows for investigating the profitability of cropland use. To our knowledge, such data is not yet available on a global scale, which would make further assumptions necessary, for example on the monetary effect of the spatial proximity of an area to roads on the attainable marginal profit on this land when transformed into cropland.

Finally, our spatially explicit approach allows for applying further constraints of cropland expansion in the post-processing by masking certain pixels that do not meet the defined criteria for cropland expansion, such as a certain proximity to roads or markets. The identified expansion areas could for example be masked with global datasets on distance to markets, while agglomeration effects could be considered by taking current cropland into account. Drivers or restricting factors can thus be applied and thresholds set according to the needs of the research question or study requirements.

Accordingly, due to these uncertainties and lack of quantitative global data on the one hand, and the possibility to include restrictions in the post processing on the other hand, we decided to include only the described biophysical and socio-economic drivers as input into our expansion module. This also improves the applicability of the expansion area data derived from this study for various research questions.

5. Impact assessment on biodiversity

To assess the impact of cropland expansion on biodiversity, we calculate the Biodiversity Intactness Index (BII), which describes the change in species richness and species abundance compared to a pristine natural ecosystem state in response to land-use[51]. Therefore, we adapt and extend the PREDICTS modeling approach[137] used by Newbold et al.[78] and methods described in De Palma et al.[59,79]. The BII is calculated as a result of community composition and species abundance in a pristine ecosystem compared to the impact of land-use and additional pressure variables we include, such as human population density[138], distance to the nearest road[139], and environmental similarity[59,78]. The biodiversity input is based on the PREDICTS database[60], and its extension[140]. We include in our analysis abundance data of 3,319,467 records, covering 26,788 sites worldwide and 23,472 species. This includes 63.5% animals (vertebrates and invertebrates), 2.5% fungi, and 32.6% plants.

The assessment of the biodiversity intactness and its change under cropland expansion requires spatial information on land-use/-cover and intensity, distinguishing between 8 land-use intensity classes: Primary vegetation under minimal use intensity, primary vegetation, secondary vegetation, cropland with different use intensities, pasture and urban areas. This data is created referring to the input data and output of the iLANCE model on cropland and cropland use intensity based on Monfreda et al.[50] and the GTAP 9 database[53], the HILDA+ land-use/-cover data[33] to identify primary and secondary vegetation land-cover, the GMIS database[141] for urban areas and the ESACCI land-use/ -cover dataset[47] to exclude areas with permanent snow/ice cover. Moreover, we use the human influence dataset from Riggio et al.[52] to further distinguish between primary vegetation (under minimal use) and secondary vegetation (for details see Supplementary Note 5.1). The created spatial dataset with the required eight land-use intensity classes is used to link the PREDICTS dataset to the expansion output of iLANCE. Thereby, primary vegetation with minimal use intensity represents the reference, a pristine ecosystem state with minimal human influence.

Calculation of the Biodiversity Intactness Index

To simulate the impact of land-use on biodiversity, two linear-mixed effects models are constructed (for details, see Supplementary Note 5.2): The abundance model and the compositional similarity model. The first model simulates species abundance on local sites by simulating the alpha diversity, while the second model simulates compositional similarity among local sites by simulating the beta diversity, therefore calculating the balanced Bray-Curtis Index[142] as a measure for the response variable. All pressures are included in both models, except for geographic distance between the sites and environmental similarity, which are only used in the compositional similarity model (calculated as Gowers dissimilarity using Bioclim variables[143]).

The resulting predictions of abundance and compositional similarity for each land-use intensity class were multiplied with the fractional land-use raster data for each land-use intensity class and then divided by the primary vegetation with minimal use intensity representing a pristine ecosystem state. Based on this, the BII is calculated by multiplying the resulting abundance and compositional similarity raster (Supplementary Note 5.2, Eq. 3)[59].

Assessment of impacts on the world's biodiversity hotspots

To add an additional perspective on the assessment of biodiversity impacts of cropland expansion that takes into account whether biodiversity is currently already particularly threatened, we also quantify the area under expansion pressure within the 3.6% EXP and CON scenario that is located in the world's most threatened biodiversity hotspots, defined as biodiversity hotspots that have already lost 70% of primary vegetation, while hosting at least 1,500 vascular plant species[54]. Moreover, we assess how biodiversity intactness changes across these biodiversity hotspots when the identified areas are converted from their current land-use into cropland.

6. Evaluation of generated CO_2 land-use change emissions

To estimate the CO_2 emissions induced by converting the identified areas under expansion pressure into cropland, we assess the change in carbon stocks based on the potential natural vegetation cover and the current land-use state compared to a use as cropland. For our calculations, we use data on the average carbon stocks in biomass and soil of 11 different types of potential natural vegetation (PNV) depending on their land-use states (cover type) as primary land, secondary land, pastureland or cropland, based on Hansis et al.[55].

While the spatial distribution of the different PNV types is provided by Pongratz et al.[57,144], the spatial distribution of primary land, secondary land and pastureland is assessed in the same way as for the biodiversity impact assessment on a 1 km spatial resolution referring to HILDA+ land-use data[33] and the integrative global dataset on human influence[52]. Primary land is defined as forests, unmanaged grass-/ shrubland or land with sparse vegetation (HILDA+ classes 44, 55, 66) under low or very low human influence, which distinguishes it from secondary land as well as from pastureland (Supplementary Note 5.1).

Due to a lack of data on PNV-specific land-use states, we assume that within a 0.5° pixel each PNV type is used as primary land, secondary land and pastureland according to the area ratio between the three land-use states at the pixel. Accordingly, similar to other studies[55], we assume expansion in all specified PNV and land-use types proportionally to their area share at the pixel in the unrestricted expansion scenario. Within the conservation policy scenario CON, on the other hand, expansion into forests is prohibited, which is why we assume cropland to be expanded primarily into non-forest PNV types and forest PNVA types currently used as pasture.

On this basis, we assess the carbon stocks on the expansion areas for all existing PNV types under the current land-use states as well as under a potential use as cropland. The difference between the two carbon storage potentials describes the carbon emissions caused by land-use change through cropland expansion. They are transformed to CO_2 emissions by multiplying the emissions with the ratio of the molecular weight of carbon dioxide to that of carbon. This approach does not take temporal dynamics into account, but attributes all (instantaneous and delayed) emissions related to the cropland expansion to the time when the transformation into cropland occurs, assuming that carbon stocks before and after an LULCC event are at equilibrium[55]. We find this method to be sufficient for the purpose of our study, since no temporal attribution of carbon fluxes is required.

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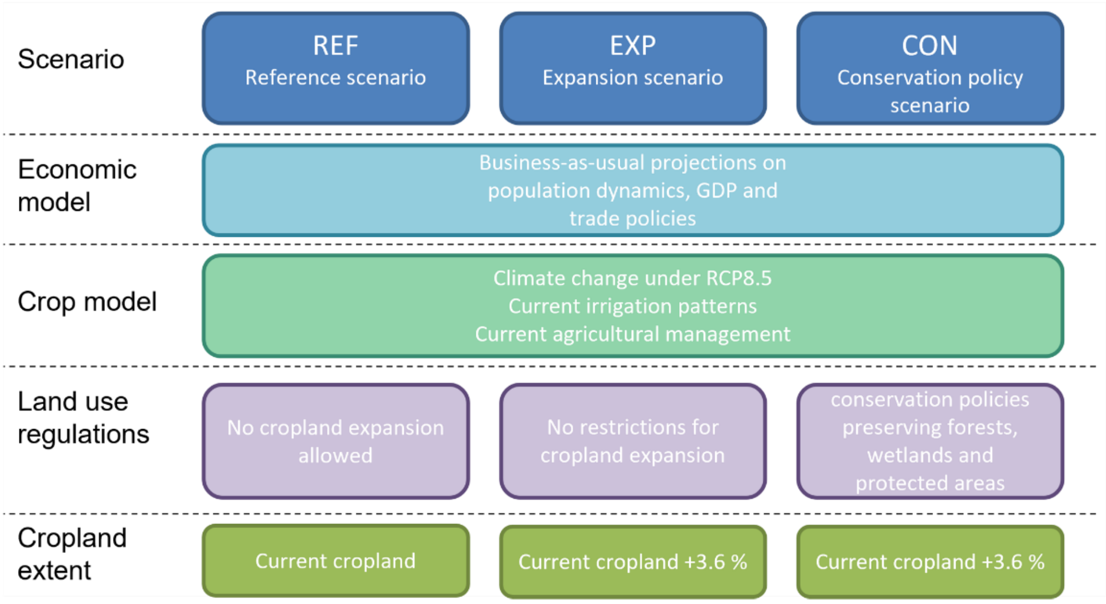
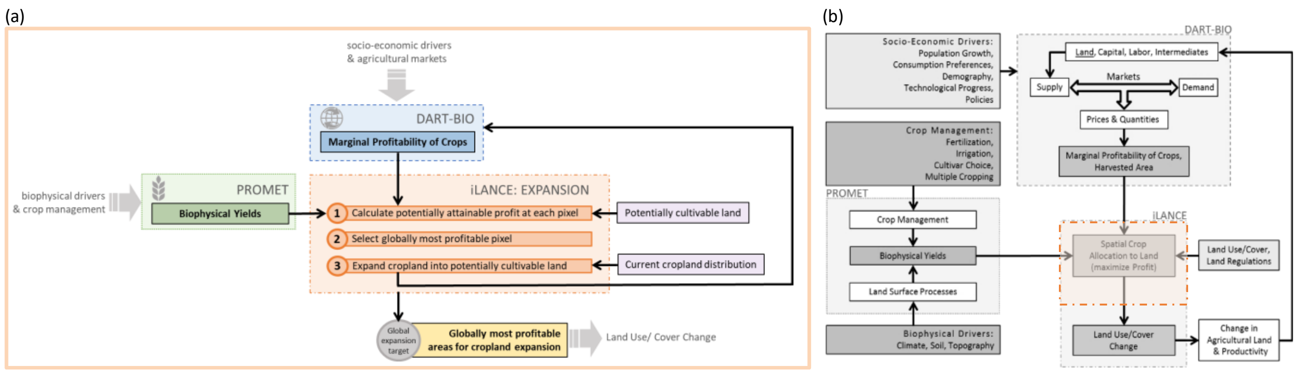
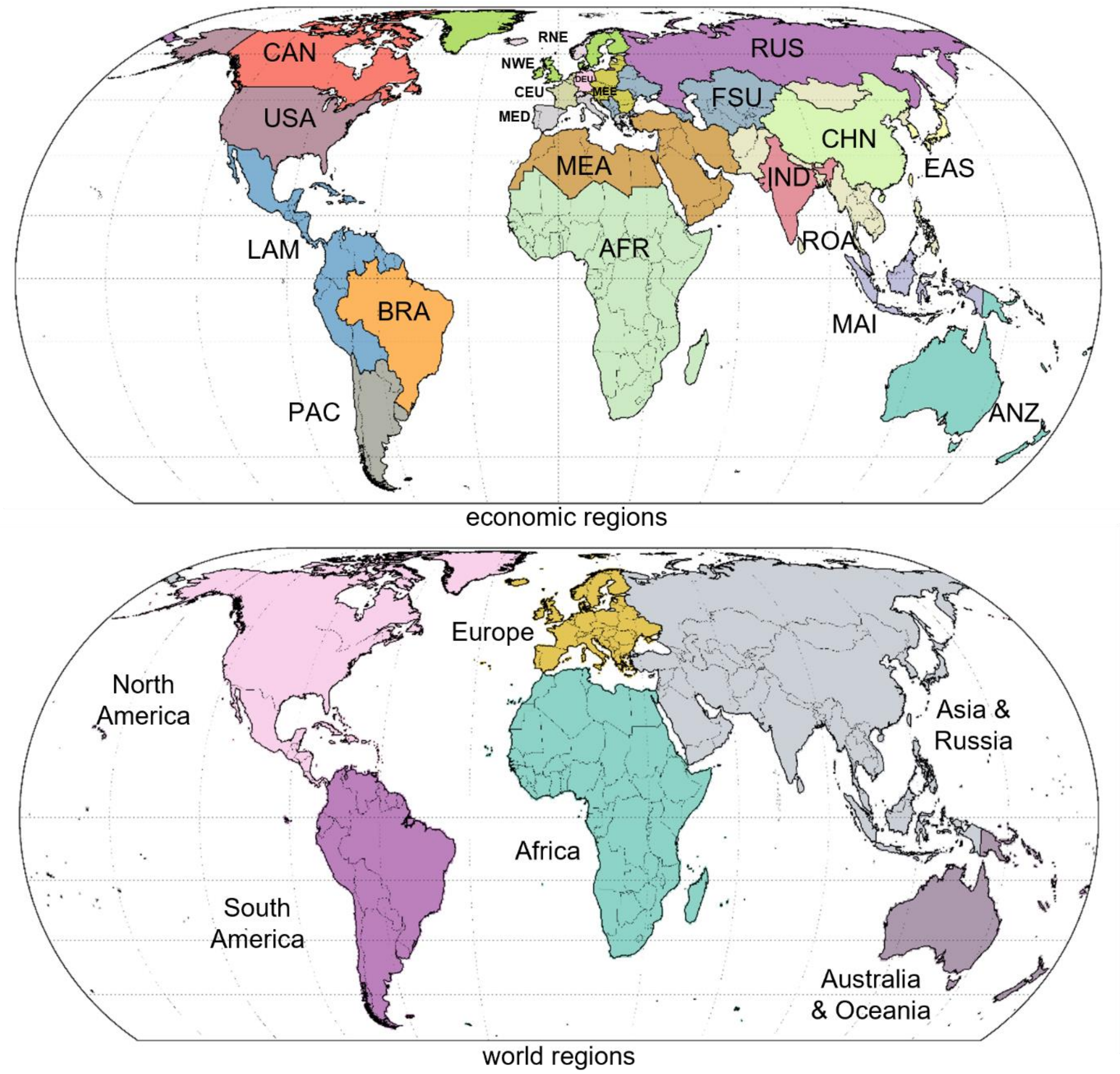
3.3.8 Extended Data Figures



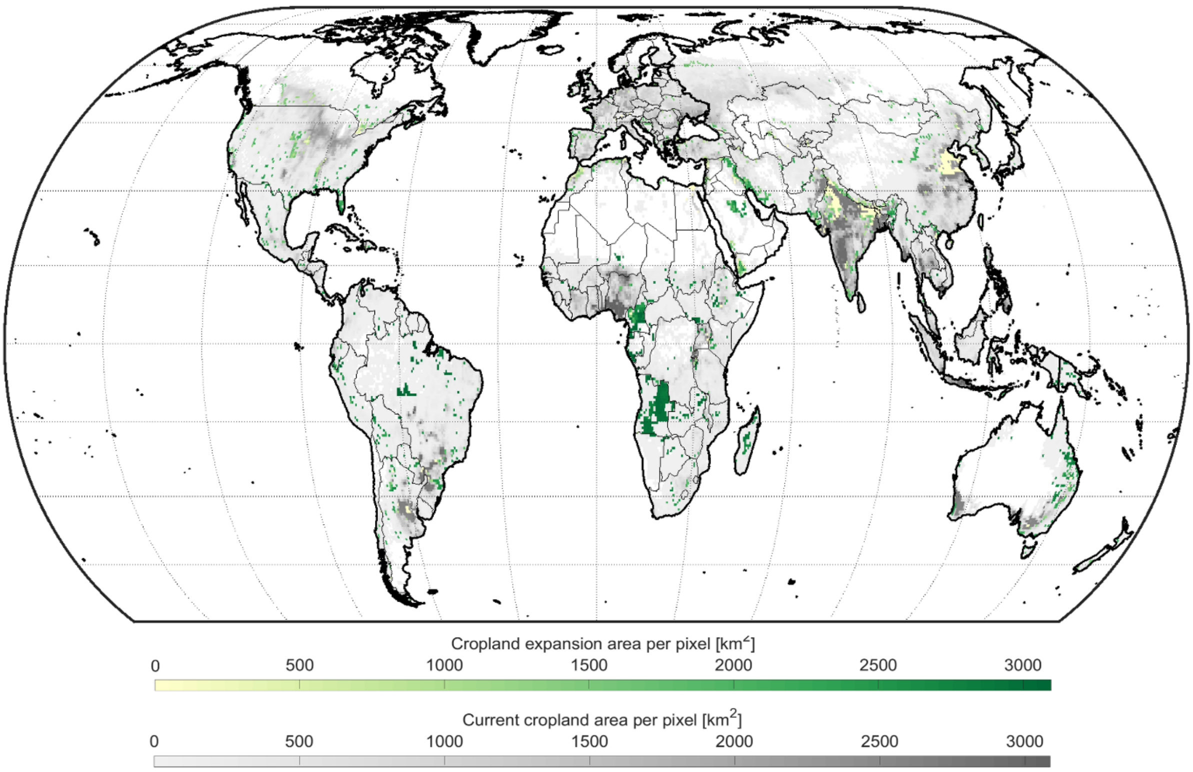
Extended Data Figure 1: Overview of the scenario design. *To evaluate the economic impact of cropland expansion on prices, production and trade patterns, the expansion scenario (EXP) is compared to a reference scenario without cropland expansion (REF) until 2030. The impacts of conservation policies are assessed by comparing two identical future expansion scenarios that only differ in the presence (CON scenario) or absence (EXP scenario) of conservation policies protecting forests, wetlands and already protected areas from a conversion into cropland. A detailed description on the scenario design is provided in Methods 1.*



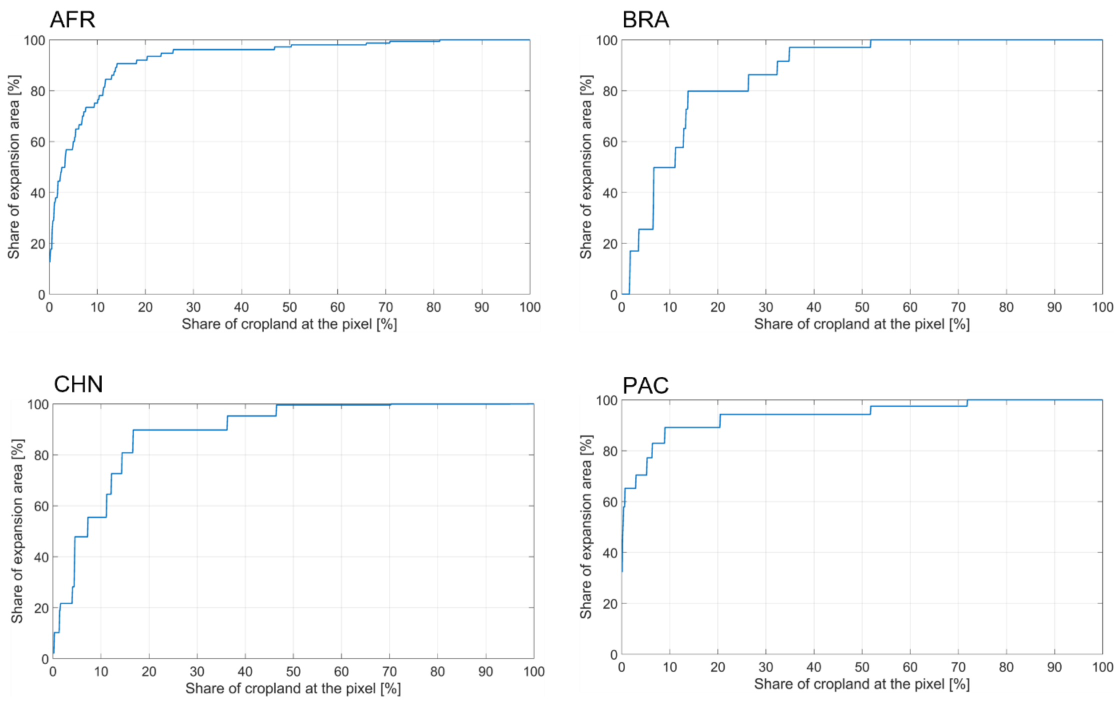
Extended Data Figure 2: Overview of the applied research framework *(a) displays the developed expansion module in iLANCE and the various inputs from the biophysical and economic model as well as land-use information. (b) locates the expansion module in the integrative coupling framework of the land-use model iLANCE and provides a wider context of the model structure.*



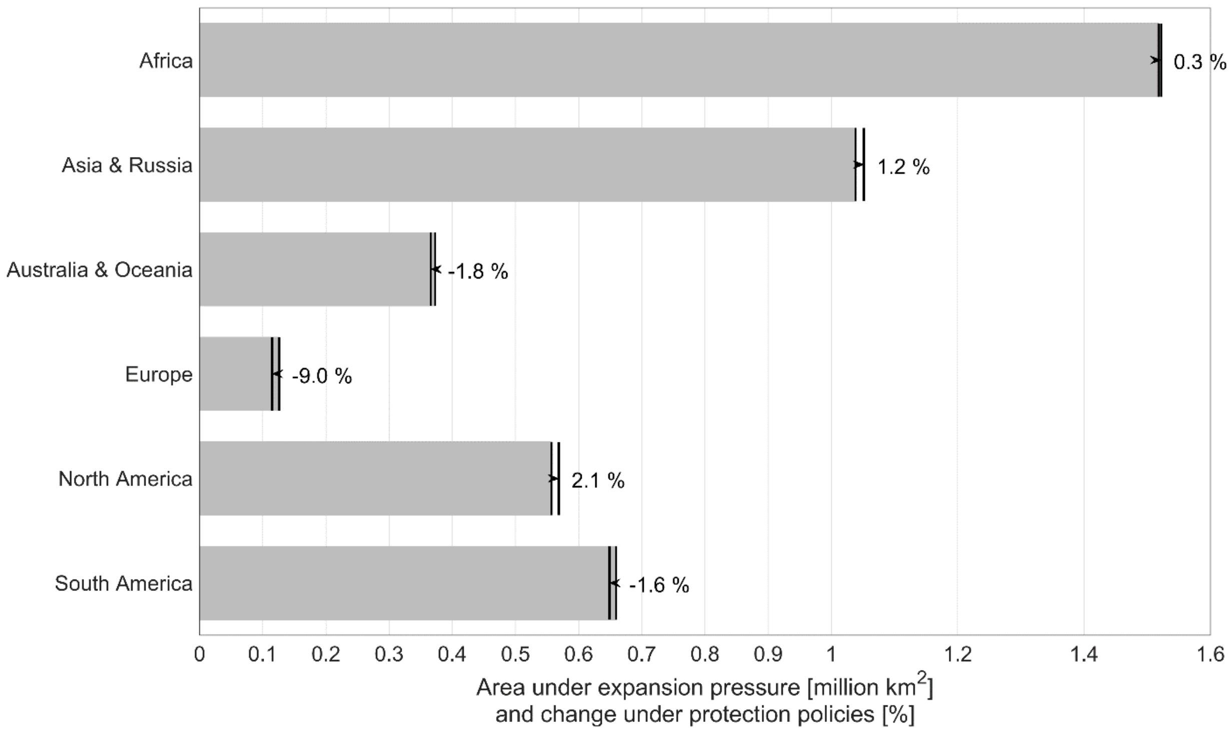
Extended Data Figure 3: Region mapping for the analysis of the results. (*a) Region mapping of the 21 economic study regions: AFR (Sub-Saharan Africa), ANZ (Australia, New Zealand and Oceania), BRA (Brazil), CAN (Canada), CEU (Central Europe), CHN (China), DEU (Germany), EAS (Eastern Asia), FSU (Rest of Former Soviet Union), IND (India), LAM (Rest of Latin America), MAI (Malaysia and Indonesia), MEA (Middle East and Northern Africa), MED (Mediterranean), MEE (Middle Eastern Europe), NWE (North Western Europe), PAC (Paraguay, Argentina, Chile, Uruguay), RNE (Rest of Northern Europe), ROA (Rest of Asia), RUS (Russia), USA (United States of America). (b) Region mapping of the 6 aggregated ‚world regions': Africa, Australia & Oceania, Asia & Russia, Europe, North America and South America. The region borders of both maps show the aggregated country borders according to the global administrative areas of GADM version 3.6. (https://gadm.org/).*



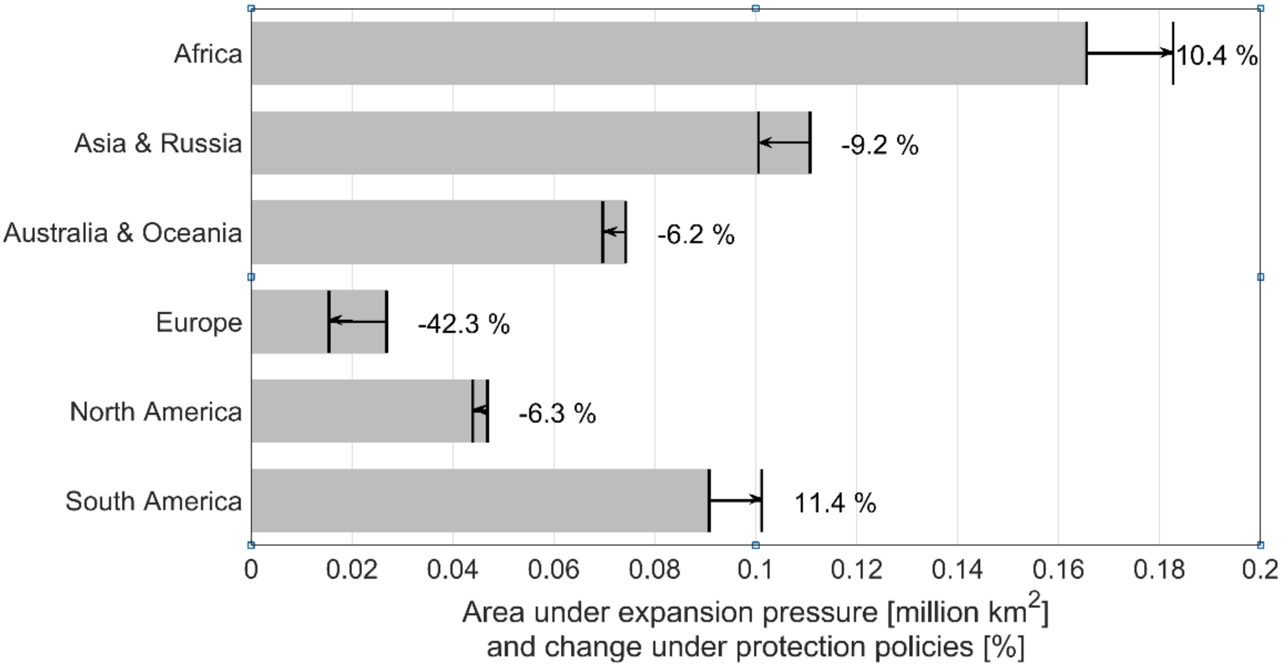
Extended Data Figure 4: Area under expansion pressure per pixel [km²] under a global cropland expansion of 30%. The grey areas display the current cropland distribution [km²].



Extended Data Figure 5: Cumulative share of the regionally most profitable expansion area [%] under the 3.6% EXP scenario located at pixels with shares from 0% to 100% currently covered with cropland exemplarily for the four regions Sub-Saharan Africa (AFR), Brazil (BRA), China (CHN) and Paraguay, Argentina, Chile & Uruguay (PAC).



Extended Data Figure 6: Regional distribution of the identified profitable area for cropland expansion [million km²] under an increase in current cropland by 30% without conservation policies, and the relative changes [%] under the introduction of conservation policies for each world region.



Extended Data Figure 7: Regional distribution of the identified profitable area for cropland expansion [million km²] under an increase in current cropland by 3.6% without conservation policies, and the relative changes [%] under the introduction of conservation policies for each world region.

4 CONCLUSION AND OUTLOOK

This thesis and the associated publications provide an overview of the iLANCE model, its development and functions, and examples of its applications. It is demonstrated, how the integrative modeling approach can be applied to investigate profit-driven changes in cropping patterns and land use and how potentially resulting effects on agricultural markets and the environment can be assessed.

With iLANCE, cropping patterns and land use change can be simulated at 0.5° spatial resolution under various scenario assumptions, such as on agricultural management, land use regulations, socio-economic changes and climate change. Within the three associated publications, different aspects to reduce trade-offs between the various SDGs related to agricultural production have been investigated: (1) The global potential to reduce the current cropland extent without compromising agricultural production in order to provide land for biodiversity and carbon sequestration (2) the spatial distribution of land that is potentially cultivable or available for cropland use currently and under a changing climate and (3) where areas are under highest expansion pressure, and the potential environmental and socio-economic implications of their conversion into cropland. Besides providing new scientific findings on the imposed research questions and thus offering an insight into the global effects of agricultural intensification and cropland expansion and potential trade-offs in the context of the SDGs, the application of the iLANCE model in these studies revealed its methodological advantages as well as challenges and limitations of the created interdisciplinary modeling framework:

Firstly, the studies demonstrate how considering socio-economic drivers adds an important additional perspective to biophysical assessments. This becomes particularly apparent in the first publication when comparing the global land saving potential of the different saving strategies: The potential to reduce current cropland extent based solely on biophysical criteria is with -48% slightly higher than the land saving potential achievable by additionally taking economic interests of farmers to simultaneously maximize their economic profit into account (-45%). Strict land use regulations that support a uniform reduction of current cropland across regions (to avoid a spatial concentration of agricultural production on high yielding locations) reduce the land saving potential to -37%. This range of results contributes to an improved, quantitative understanding on, for instance, the biophysical potential of biodiversity conservation measures like land sparing, and how they are influenced by the societal context or policies. Thereby, particularly quantitative information can support the balancing of objectives and the reduction of trade-offs. Reducing current cropland in a way that simultaneously maximizes the potentially attainable profit of crop cultivation, for example, only marginally reduces the global land saving potential (by 3 percentage points). An increase in global cropland by 3.6%, as a further example, would increase agricultural production by only 2%, but reduce biodiversity intactness across the converted areas by -25% and generate additional CO_2

emissions of around 17 Gt CO_2. Such quantitative information could further be used to evaluate opportunity costs for different stakeholders and thus might contribute to a policy design that keeps various interests and sustainability goals simultaneously in consideration.

In this context, the iLANCE framework is moreover useful for assessing the effects of specific agricultural policies and land use regulations. The third publication, for example, also investigates the effects of a conservation policy that prevents forests, wetlands, and protected areas from being converted into cropland, thereby reflecting current global political conservation efforts, such as the Glasgow Leaders' Declaration on Forests and Land Use (United Nations Climate Change Conference of the Parties 2021) or the EU Regulation on deforestation-free supply chains (European Commission & Directorate-General for Environment 2023). The results show that such a policy could reduce the impact of cropland expansion on biodiversity intactness and the generated CO_2 emissions without compromising agricultural production. Yet, in some regions, such as in South America, this policy shifts expansion pressure away from forests to other highly biodiverse ecosystems, such as grasslands like the Cerrado (Beuchle et al. 2015, Salazar et al. 2015, Strassburg et al. 2017, Colli et al. 2020). With their interdisciplinary perspective, integrative models like iLANCE can evaluate global conservation measures and identify potentially arising trade-offs, for example in the context of the Kunming-Montreal Global Biodiversity Framework (UNEP Convention on Biological Diversity 2022) or the Half Earth Project (Wilson 2017), thereby taking also future scenarios into account, e.g., changes in consumption patterns, demography or climate.

Particularly the spatial explicitness of the iLANCE model improves the comparability of the created results with the outputs from other models and supports the application of the model output in other research disciplines. The spatial information on land potentially cultivable (publication 2) or on areas potentially under future expansion pressure (publication 3), for example, could be used as input to Integrated Assessment Models or discipline-specific models, e.g., biodiversity models or carbon storage models, to enable further, more detailed analysis on the potential impacts of different expansion scenarios. Publication 3 on cropland expansion, for instance, demonstrates how the assessed areas under highest expansion pressure are used within an algorithm that evaluates the biodiversity intactness under this potential land use change. Moreover, it shows how the spatially explicit data can be used to assess the CO_2 emissions generated by the land use change associated with the simulated cropland expansion. These examples suggest the potential of integrating the iLANCE model into larger interdisciplinary research contexts, evaluating for example the impacts of land use change on biodiversity in more detail or using the created data in the context of farmer's land use decision-making (Mialhe et al. 2012, Githinji et al. 2023) (see also further below).

Finally, throughout the different studies in which iLANCE is applied, the importance of simulating at a global scale and locally at the grid cell level and the linking of processes from global-to-local-to-global becomes apparent. Particularly due to the globalization of agricultural markets, the consideration of global trade within the global CGE model DART-BIO is essential to simulate agricultural land use change and its global and regional economic impacts, including potential spillover effects (Hertel et al. 2019, Meyfroidt et al. 2020, Baldos et al. 2023, Hertel et al. 2023). The results of the first publication, for instance, show that (1) the regional economic effects of land saving are also strongly influenced by global market prices and trade, and (2) reveal a strong non-linearity of land saving impacts, with the strongest changes in prices, production and trade not generally occurring in regions with large land saving potentials. (3), telecoupling effects became apparent, with the results demonstrating how global markets can shift impacts of regional changes in land use and agricultural production to spatially distant regions via trade and global crop prices, for example in the case of soy trade. Thus, the integration of the CGE model in the spatially explicit approach created a multi-scale approach that allows for analyzing and mapping the relations and feedbacks between global dynamics and local processes in more detail. With the high regional resolution of DART-BIO, referring to 21 economic regions and further 178 Agro-Ecological Subregions, at which the economic input into the iLANCE model is generated, iLANCE additionally captures the 'meso-scale' between the local and global level, which is reflecting regional economic conditions such as demand patterns (Hertel et al. 2023) as well as the subregion-specific relevance of land as an economic input factor (Figure 4). Finally, the application of a CGE model offers the advantage that it takes into account the linkages and interdependencies between different economic sectors. It is thus able to capture, for example, the broad economic effects of changes in agriculture and land use, which is particularly relevant in the context of research on the SDGs that address various economic sectors.

However, bridging differences in the spatial and temporal levels of analysis between different research disciplines remains one of the main challenges in creating an interdisciplinary land use model. While the differences in the spatial resolution of the economic model and the crop model have been harmonized in iLANCE, the difference in the analyzed time period, for instance, can be challenging depending on the research question. Economic simulations, for example, are driven by political and societal changes, and accordingly projections into distant futures are rarely conducted due to the very high uncertainties. Crop growth and particularly climate change impacts on agricultural yields, on the other hand, are frequently investigated until the end of the century (Jägermeyr et al. 2020). Finally, assessments of carbon fluxes from land use and land cover change, as a third example, often reach back to 1700 or 1850 in order to account for historical legacy fluxes (Houghton et al. 2012, Houghton et al. 2017). Hence, defining a common modeling reference time period can be challenging for certain research questions. Yet, the continuously increasing availability of data can either bridge these gaps directly, such as in the case of land use data reaching back to the 19th century, or contribute to creating assumptions that help to bridge these gaps, such as regarding assumptions on the societal development until the end of the century.

Another challenge is the selection of further drivers of land use change and their introduction into the iLANCE model. Regarding, for example, the simulation of cropland expansion, various additional aspects influencing expansion dynamics could be included in the currently existing approach, for example historic patterns of expansion (Garrett et al. 2013, Meyfroidt et al. 2018, Eigenbrod et al. 2020), the building and existence of infrastructure (Geist et al. 2002), political and cultural aspects such as land tenure issues, or further socio-economic drivers, e.g. extreme poverty (Laurance et al. 2014) or the market influence of a region (Verburg et al. 2011). Yet, their inclusion is, on one hand, limited by the availability of such data at a sufficient spatial or temporal resolution and at global scale, and, on the other hand, by the difficulty of translating the impact of drivers on land use dynamics into a quantitative effect that can be considered within the quantitative profitability approach in iLANCE. Here, further research on the drivers of agricultural land use dynamics and improvements in their data availability might substantially improve land use change simulations with iLANCE. Moving beyond economically driven land use simulations and profit-optimized reallocation strategies would moreover allow to capture also subsistence farming, which makes an important contribution to food security particularly in rural areas in developing countries (FAO et al. 2023).

Beyond this, also the integration and coupling with further models that describe specific processes in more detail could be an interesting field for future research. For instance, integrating an agent-based model into the framework could contribute to a more differentiated representation of farmers' decision-making processes (Mialhe et al. 2012). National CGE models, as a further example, could help to represent national or region-specific economic processes, policies, or sectors in more detail, and thus support the often "missing middle" (Hertel et al. 2023) within global-to-local-to-global research frameworks. Furthermore, additional models to improve the impact assessment of the simulated changes could be integrated into the iLANCE research framework: Climate models could, for instance, capture the resulting feedbacks of land use change on the climate system, e.g., changing matter- and energy fluxes, changing albedo and surface roughness, and resulting carbon emissions (Pongratz et al. 2010). Hydrological models, as a further example, could be used to simulate the impact of land use change on the hydrological cycle (Jayawickreme et al. 2011, Lamparter et al. 2018), and, if water is considered in more detail in the crop growth model and the economic model, the competition for water within the agricultural sector between various crops as well as the competition between different economic sectors could be taken into account and modeled. This could enable the investigation of further interesting research questions, e.g., how cropping patterns, land saving or cropland expansion dynamics might be influenced if (additionally to profit-maximizing) water-saving objectives are pursued, or how water prices impact land use change. Carbon storage models could simulate the induced changes in the carbon storage in more detail (Obermeier et al. 2021, Pongratz et al. 2021), and thus investigate not only potentially resulting carbon emissions but also the impact of afforestation/ reforestation measures, for example in a land saving scenario.

Yet, also the current iLANCE framework with the already established model links offers the opportunity to investigate various further research questions: Regarding the crop diversification at landscape level, for example, it would be interesting to investigate how different cultivation systems (from monocultures to highly diversified cropping patterns) impact regional agricultural production potentials and attainable profits, or in which way changes in cropping patterns could serve for climate change adaptation. In the context of land use change, a follow-up study on land saving, for instance, could look into the potentially arising rebound effects of a more efficient cropland use in more detail. Moreover, iLANCE could be applied to conduct an integrative study on cropland expansion versus agricultural intensification, in which the regional potential of both strategies to increase or maintain agricultural production is investigated, and the associated socio-economic and environmental impacts are evaluated to regionally assess the strategy with the smallest trade-offs. Finally, currently discussed conservation policies and their potential impacts could be investigated with iLANCE in more detail: The effects of protecting 30% (UNEP Convention on Biological Diversity 2022) or half of the earth's surface (Wilson 2017) on agricultural markets and the potential environment benefits could be quantified and located. Building up on the results from publication 3, areas could be identified that are not only under high pressure for agricultural expansion, but at the same time highly relevant in terms of biodiversity intactness or carbon storage, and thus potential key areas for protection policies.

Despite the discussed issues and challenges, integrative modeling approaches and interdisciplinary assessments play a crucial role in exploring ways towards an agriculture, land use and a food system that reconciles the defined sustainability goals in the different fields. The constantly increasing availability of global data at high spatial resolution

The increasing awareness of the relevance of interdisciplinary work in the fields of agriculture and land use change research (Ruane et al. 2017) and the continuously improving availability of global data, also due to major advances in remote sensing (both in terms of data and its interpretation), suggest that integrative modeling approaches will continue to improve within the following years, enabling to simulate agriculture and land use change, their drivers and various effects in increasing detail. The thereby generated knowledge can contribute to a more efficient policy design that might even create co-benefits and simultaneously support social, economic and environmental sustainability, the cornerstones of the SDGs and the transformation towards a sustainable future.

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6 SUPPLEMENT

6.1 Supplementary Information of Publication 1

The following chapters contain the Supplementary Information of publication 1 on the global land saving potential under different saving strategies and their effects on agricultural markets. The references to the individual appendices are included in each chapter.

6.1.1 S1 Appendix: Model descriptions

For our analysis, we refer to biophysical yield potentials from Mauser et al. 2015 [1], which are simulated with PROMET. The socio-economic context is considered by simulations with DART-BIO. Both models, PROMET and DART-BIO, are briefly described below.

PROMET

PROMET is a biophysical and hydrological land surface process model [2], which has been extended by a biophysical dynamic vegetation component to model crop growth and yield formation [1, 3]. It uses first order physical and physiological principles to determine net primary production and respiration based on approaches from Farquhar et al. [4] and Ball et al. [5], combined with a phenology and a two-layer canopy architecture component of Yin and van Laar [6]. PROMET takes into account the interdependency of net primary production and phenological development, leaf temperature, water availability and environmental conditions including meteorology, CO_2 concentration for C3 and C4 pathways, as well as water and temperature stress. Further details on the PROMET model can be found in Mauser et al. [1].

PROMET has been used in global [1, 7, 8] and regional studies [9]. Moreover, it is used in the Global Gridded Crop Model Initiative (GGCMI) within the Agricultural Model Intercomparison and Improvement Project (AgMIP) [10-12], which is connected to the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP).

The framework and model setup of PROMET for the simulations of the biophysical yield potentials referred to in this study are described in S4 Appendix and Mauser et al. 2015 [1].

DART-BIO

The DART-BIO model is a recursive-dynamic computable general equilibrium (CGE) model of the world economy disaggregated into 23 regions. The model depicts the functioning of regional economies through a system of non-linear equations based on economic theory that are calibrated to an extended version of the Global Trade Analysis Project (GTAP) 9 database [13] with a focus on the production and processing of agricultural commodities and other sectors based on biomass. 40 of the 52 economic sectors in DART-BIO are involved bioeconomy activities. The model features 21 production factors including 18 land types based on the GTAP-AEZs (Agro-Ecological Zones).

In each of the 23 world regions representative consumers interact with producers at commodity and factor markets. Behavior of economic agents is governed by maximization of utility and profit. Consumer maximize their utility according to a Stone-Geary utility function that gives rise to a linear expenditure system. This is calibrated to empirical income and price elasticities for all commodities, which describe the consumers' preferences and govern how demand reacts to income and price changes. Flexible prices and market balance conditions lead to equilibrium of demand and supply on all markets (see [14] for a technical description of the model). Multi-nested constant elasticity of substitution (CES) functions determine sectoral production and ensure imperfect substitution between production factors, which are combined with intermediate inputs through fixed input-output coefficients in Leontief functions. Similarly, bilateral trade is governed by the Armington assumption of imperfect substitutes of domestic and foreign goods and depict with CES functions for imports and CET functions for exports. Consistency of microeconomic behavior and macroeconomic aggregates is ensured through savings driven investment and fixed current account balances (with the United States of America as flexible numeraire region). The model is solved annually. Long-term dynamics are depicted through updating essential parameters (capital stocks, productivity, labor force and population growth).

Table. Value share of land in production costs [%] for each crop category within each region.

region / crop category	cb	gron	mze	osdn	pdr	plm	rsd	soy	wht
Sub-Saharan Africa	8.40	11.00	10.80	9.80	11.60	12.20	8.20	11.20	7.60
Australia & New Zealand	14.50	9.50	8.70	14.90	11.30	--	14.90	15.20	14.20
Belgium, Netherlands, Luxemburg	9.40	9.50	8.40	20.00	--	--	18.10	--	8.40
Brazil	12.20	11.10	9.90	11.60	10.80	11.70	11.70	10.90	11.00
Canada	11.80	8.30	8.10	10.20	--	--	9.90	9.90	9.20
China	26.80	30.00	23.90	37.50	27.60	38.00	37.70	37.20	23.10
France	10.00	9.90	9.90	10.40	--	--	10.40	11.00	10.20
Former Soviet Union	13.30	16.90	17.70	17.80	3.20	--	17.30	19.30	13.30
Great Britain	12.00	12.60	--	12.80	--	--	12.30	--	11.30
Germany	13.40	14.60	14.70	--	--	--	13.90	--	13.70
India	30.20	28.40	28.60	31.10	34.70	--	32.20	31.80	18.70
Japan	11.00	10.10	--	--	25.30	--	--	8.20	10.80
Rest of Latin America	21.60	21.50	20.00	20.60	20.20	23.80	--	18.70	15.10

Malaysia & Indonesia	38.70	--	44.30	39.30	39.90	37.00	--	40.60	--
Middle East & Northern Africa	7.60	7.70	8.10	8.30	9.60	--	7.80	8.30	6.80
Mediterranean (Italy, Spain, Portugal, Greece, Malta, Cyprus)	24.80	13.20	14.80	12.80	30.30	--	12.60	--	13.80
Paraguay, Argentina, Chile & Uruguay	17.40	15.80	16.20	18.10	18.40	23.00	16.60	17.50	16.60
Rest of Europe (Austria, Estonia, Latvia, Lithuania, Poland, Hungary, Slovakia, Slovenia, Czech Republic, Romania, Bulgaria)	30.20	25.50	26.30	19.10	35.60	--	24.60	23.40	25.80
Rest of the world	30.40	27.50	36.30	33.10	38.00	40.00	25.50	39.10	31.70
Russia	24.60	24.60	24.60	22.30	23.30	--	24.30	21.70	22.80
Scandinavia (Denmark, Finland, Sweden)	15.50	20.80	11.80	10.10	--	--	17.00	--	14.50
South East Asia	30.80	35.00	36.20	28.80	32.50	30.30	15.00	26.20	10.80
United States of America	22.70	18.90	18.50	21.00	18.30	--	21.30	20.00	21.10

The table displays the within DART-BIO assumed value share of land in the production costs of crops relative to all other inputs, i.e. labor, capital and intermediate goods such as fertilizer. For the different crop categories, the following abbreviations are used (for details see also Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat. For further information on the spatial structure and regions of the analysis, see S3 Appendix.

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6.1.2 S2 Appendix: Crops and crop categories

Within our study, we consider 15 globally important crops with respect to area and economic relevance, as they represent 70% of global cropland area and 65% of global crop production according to FAOSTAT (all listed crops, average for 1981-2010 [1]). We include staple crops of global importance, such as maize, wheat, rice and soy, that provide 2/3 of global calorie production, but also consider more regionally important food crops, such as millet or cassava. Furthermore, we capture the main bioenergy crops, such as oil palm, maize, soy, sugarcane and rapeseed, to capture the trends in political support of biofuels. To be consistent with the representation of crops in the economic model, the 15 crops are aggregated to 9 crop categories that are considered in DART-BIO (see Table below).

Table. Considered crops for simulations of biophysical yield potentials with PROMET and their grouping to crop categories considered in DART-BIO.

Crops	Crop Category	
Sugar cane Sugar beet	cb	Sugar cane & sugar beet
Barley Millet Rye Sorghum	gron	Rest of cereal grains
Maize	mze	Maize
Groundnut Sunflower	osdn	Rest of oil seeds
Paddy rice	pdr	Paddy rice
Oil palm	plm	Oil palm fruit
Rapeseed	rsd	Rapeseed
Soy	soy	Soybean
Summer wheat Winter wheat	wht	Wheat

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6.1.3 S3 Appendix: Spatial structure of the analysis

Our global analysis is structured in 23 regions, that are again divided by Agro-Ecological Zones (AEZ) [1] into sub-regions, resulting globally in 216 sub-regions. Subdividing regions into AEZ enables to better assess the sectoral competition for land. The different AEZ are defined by the length of the growing period (0 to 59 days, 60 to 119 days, 120 to 179 days, 180 to 239 days, 240 to 299 days and more than 300 days) and the climatic zone (tropical, temperate and boreal), described by absolute minimum temperature and Growing Degree Days [2]. To ensure a sufficient number of locations for a robust assessment of the land saving potential, we excluded sub-regions with less than 10 sample locations. As a result, 139 sub-regions, representing 95% of global cropland

and crop production of the considered crop categories, are considered within our study. Land saving potentials and impacts on agricultural markets are investigated at sub-region level. For the evaluation and discussion of our results, we aggregated the regions BEN (Belgium, Netherlands, Luxemburg), FRA (France), GBR (Great Britain), GER (Germany), MED (Italy, Spain, Portugal, Greece, Malta, Cyprus), SCA (Denmark, Finland, Sweden), and REU (Austria, Estonia, Latvia, Lithuania, Poland, Hungary, Slovakia, Slovenia, Czech Republic, Romania, Bulgaria) to the Region Europe (EUR), resulting in a total of 17 study regions globally (see Figure A).

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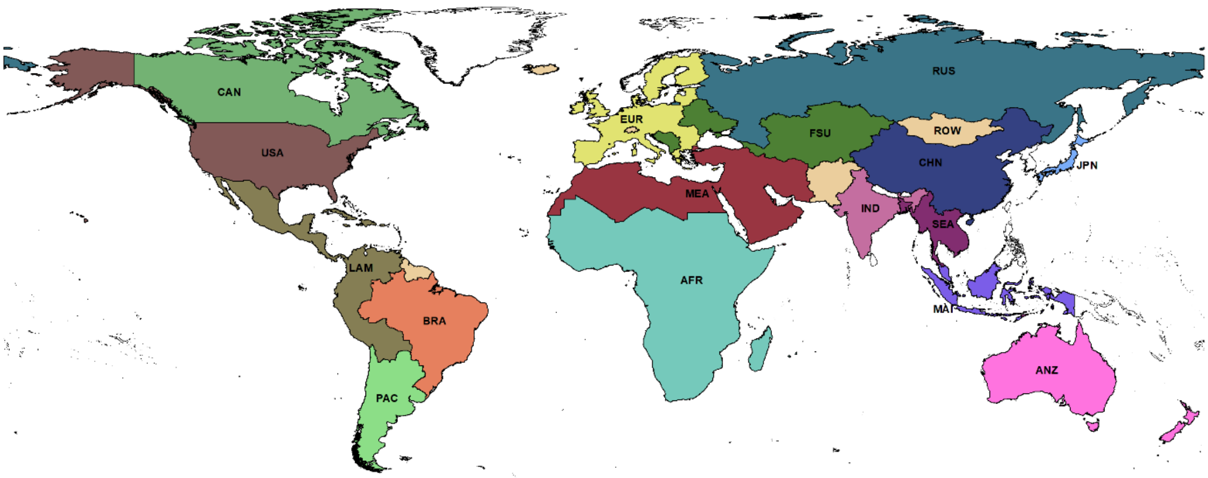

Figure A. Region mapping of the 17 study regions. AFR (Sub-Saharan Africa), ANZ (Australia, New Zealand), BRA (Brazil), CAN (Canada), CHN (China), EUR (Austria, Belgium, Bulgaria, Czech Republic, Cyprus, Denmark, Estonia, France, Finland, Germany, Great Britain, Greece, Hungary, Italy, Latvia, Lithuania, Luxemburg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden), FSU (Rest of Former Soviet Union and Rest of Europe), IND (India), JPN (Japan), LAM (Rest of Latin America), MAI (Malaysia, Indonesia), MEA (Middle East and Northern Africa), PAC (Paraguay, Argentina, Chile, Uruguay), ROW (Rest of the World), RUS (Russia), SEA (South East Asia: Cambodia, Bangladesh, Laos, Myanmar, Thailand, Vietnam), USA (United States of America). The region lines show the aggregated country boarders according to the global administrative areas of GADM version 2.8. Reprinted from GADM (https://gadm.org/) under a CC BY license, with permission from GADM, original copyright 2012.

6.1.4 S4 Appendix: Yield potentials

Biophysical yield potentials

A global dataset of biophysical yield potentials for the 15 crops included in this study is provided by Mauser et al. [1]. The potential yields are based on simulations with PROMET on 246,000 representative sample locations on the agriculturally suitable area [2]. Crop growth is simulated hourly for 30 years (1981 to 2010), using high-resolution (30 arcsec) global data on climate from the output of the general circulation model ECHAM5 [3], soil data obtained from the Harmonized World Soil Database [4] and topography derived from the Shuttle Radar Topography Mission [5]. The yield potentials include optimal crop management considering nutrient supply, sowing and harvest dates, as well as realizing multiple harvests and no harvest losses due to pests and diseases. For the simulation of irrigated yield potentials, we furthermore assume that no water stress occurs. The yields are aggregated to 30-year means to avoid bias from selecting a single year, and to crop categories to be consistent with the crop representation in DART-BIO for the model coupling (for details on the sampling approach, input data and model setup see Mauser et al. [1]).

Mauser et al. [1] show that the conducted PROMET simulations provide similar results to existing studies on biophysical production potentials. For example, compared with the FAO-GAEZ [6] global simulations of potential yields and production, significantly similar distributions, means and standard-deviations occur.

Yield gap closing

Biophysical yield potentials are helpful to explore natural potentials and limits as upper benchmarks. However, to account for several constraints limiting the realization of potential yields, such as (socio-)economic or technological factors [7, 8], we do not assume full yield gap closing. In literature, it is often referred to 80% of the potential yield being considered as an 'attainable yield potential' [8-10]. However, assuming a proportion of the biophysical yield potentials would lead to yields that solely depend on the current biophysical production potentials (and thus environmental conditions), while current yield gaps, that strongly depend on the socio-economic conditions, are neglected and regional differences in current yields are not taken into account. We thus decided to assume that yield gaps are closed by 80%, leading to yields that depend on the biophysical yield potential but also on currently achieved yields and yield gaps. This approach was also evaluated as realistic and consistent by stakeholders within a co-design process for scenario-development [11]. Therefore, we calculate the mean yield gap for each crop category within a sub-region as the difference between the area-weighted mean potential yield under current irrigation and cropping patterns [12] and our statistical reference yield from the GTAP 9 database [13]. Closing this mean yield gap by 80% enables to calculate a mean potential yield share for the sub-region, that is applied to the modelled potential yields at each location to simulate an 80% yield gap closing scenario. If the mean yield gap of a crop category is negative, so that current statistical yields of a crop exceed the simulated potential yields, we refer to the current statistical yields of the crop and do not close the yield gap.

To evaluate the impact of yield gap closing on the land saving potential, we simulated different scenarios from 50% to 100% yield gap closing. The effect on the global land saving potential is shown in S6 Appendix.

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6.1.5 S5 Appendix: Coupling approach and socio-economic land saving

Marginal Profit Functions

For the coupling, DART-BIO provides sub-region and crop-specific marginal profit functions that are derived from the market equilibrium and depend i.a. on the productivity of land in relation to other factor inputs (capital, labor, energy). They determine the achievable profit for allocating a certain crop category on an additional unit of land as a function of the already allocated area to this crop category. The attainable marginal profit [$/hectare (ha)] is highest for the first cultivated hectare of a crop category and decreases, the more cropland is allocated, until it approaches zero when current cropland area of the crop is reached (Figure A). Within a sub-region, the marginal profit functions can rank the crop categories according to the profitability of allocating an additional unit of its cropland. For details on how marginal profit functions are determined, see Mauser et al. [1].

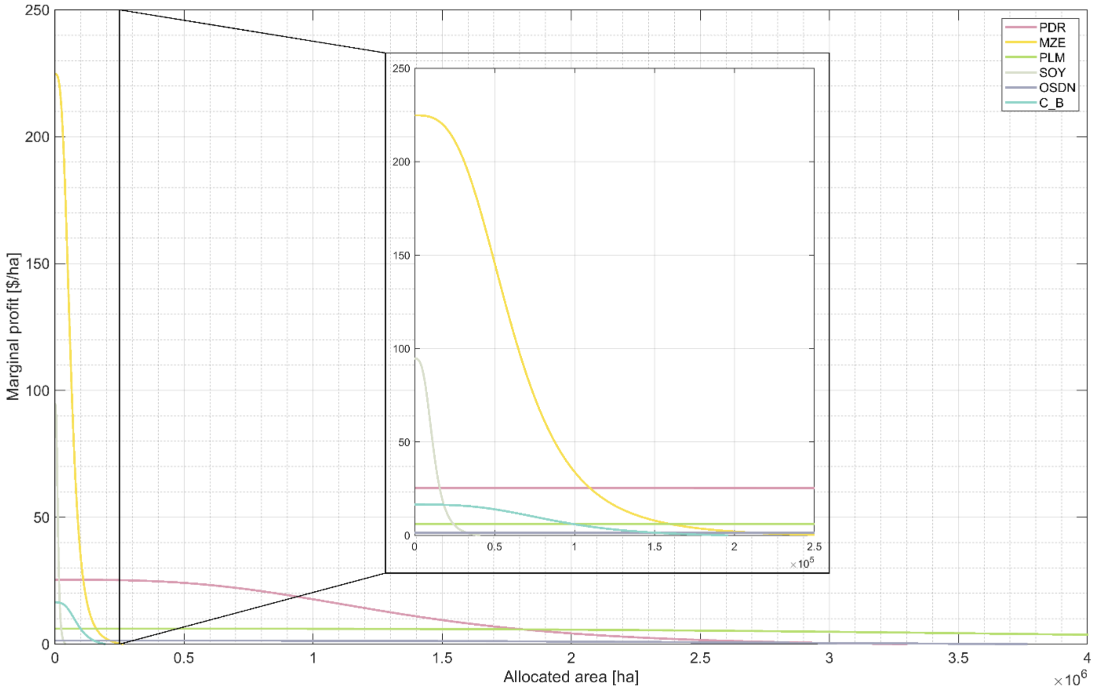

Figure A. Exemplary marginal profit function for the sub-region in AEZ 6 in Malaysia and Indonesia. The x-axis displays the allocatable cropland [hectare (ha)] for each crop category within the sub-region, while the y-axis shows the attainable marginal profit [$/ha] for the allocation of one additional hectare cropland. Marginal profit functions are attainable for all crop categories cultivated within the sub-region.

Coupling PROMET and DART-BIO

Based on the marginal profit functions from DART-BIO and the resulting marginal profitability per production unit [$/t], we can calculate the potential marginal profit per hectare [$/ha] attainable under the potential yields derived from PROMET. It defines the attainable marginal profit by allocating one unit of cropland of a specific crop category. The potential marginal profit per hectare [$/ha] differs between the sample locations within a sub-region due to spatially differing environmental conditions and thus biophysical yield potentials. A maximum achievable total potential profit [$] could be derived by allocating the crop category with the highest potential marginal profit per hectare at each location. However, to account for risk aversion of farmers and the implementation of crop rotation, all profitable crops at a location are allocated, with their cropland ratio reflecting the ratio of the potential marginal profits per hectare. This results in profit-maximized but diversified cropping patterns at each location. Within our coupling algorithm, cropland is then allocated at the most profitable location with the highest achievable total potential profit [$]. Since the attainable marginal profit per hectare changes with the ratio of allocated and total cultivated area of a crop category (Figure A), also the achievable total potential profit at the remaining locations changes after the allocation of cropland at the most profitable location. Thus, the cropland allocation and the thereupon calculated achievable total profit needs to be recalculated for all remaining locations after each allocation at the next most profitable location. These steps are sequentially repeated until current statistical production is reached for all crop categories within the sub-region (for details see Mauser et al. [1]).

When current cropping patterns change to more profitable ones, it is possible that less profitable crops are reallocated to locations with relatively lower production potential, resulting in a larger cropland requirement compared to current statistics for those crops. However, if the statistical acreage has been reached, the marginal profitability of additional cropland allocation is not yet defined so that the attainable marginal profit is zero, and thus the crop is by definition no longer profitable to allocate. To maintain current crop production, we assume that the crop is nonetheless allocated by a fixed area share, determined by the number of crops that can be allocated at each location. Thus, we allow the expansion of cropland into saved cropland of other crops, if it is necessary to maintain current statistical production, and as long as current statistical cropland over all crops is not expanded. If within a sub-region, profit-maximized reallocation and the resulting cropping patterns are not able to meet the current statistical production targets, we assume that current cropping patterns are maintained and land saving is not implementable within this sub-region.

Iteration

As soon as current statistical production is reached, the allocation is stopped, and the resulting new cropland requirements for each crop category are fed back into DART-BIO (Figure B). Even though the total production of each crop category remains constant, the decreased cropland requirements change the productivity of land as primary production factor and thus affect the marginal profitability of crops, leading to new marginal profit functions. Thus, for the SLS, those changes are again fed back and serve as input for the coupling approach with the socio-economic land saving algorithm, resulting in new profit-optimized cropping patterns and land saving potentials. The iteration hence allows to account for the interplay of land use decision making and resulting cropping patterns and the socio-economic context (demand, prices, trade flows). It is carried out until a stable crop-allocation is established in all sub-regions, which is defined as changes in required cropland and resulting cropland productivity between two iteration-steps are below 1% (Figure C). For this evaluation, we include all crops that are sufficiently relevant within their sub-region, defined by their cropland share on total cropland area in the sub-region and their absolute cropland area that needs to be greater than 1% and 250 hectares, respectively, and for which land is a relevant production factor and thus the proportion of land in factor input is above 5%.

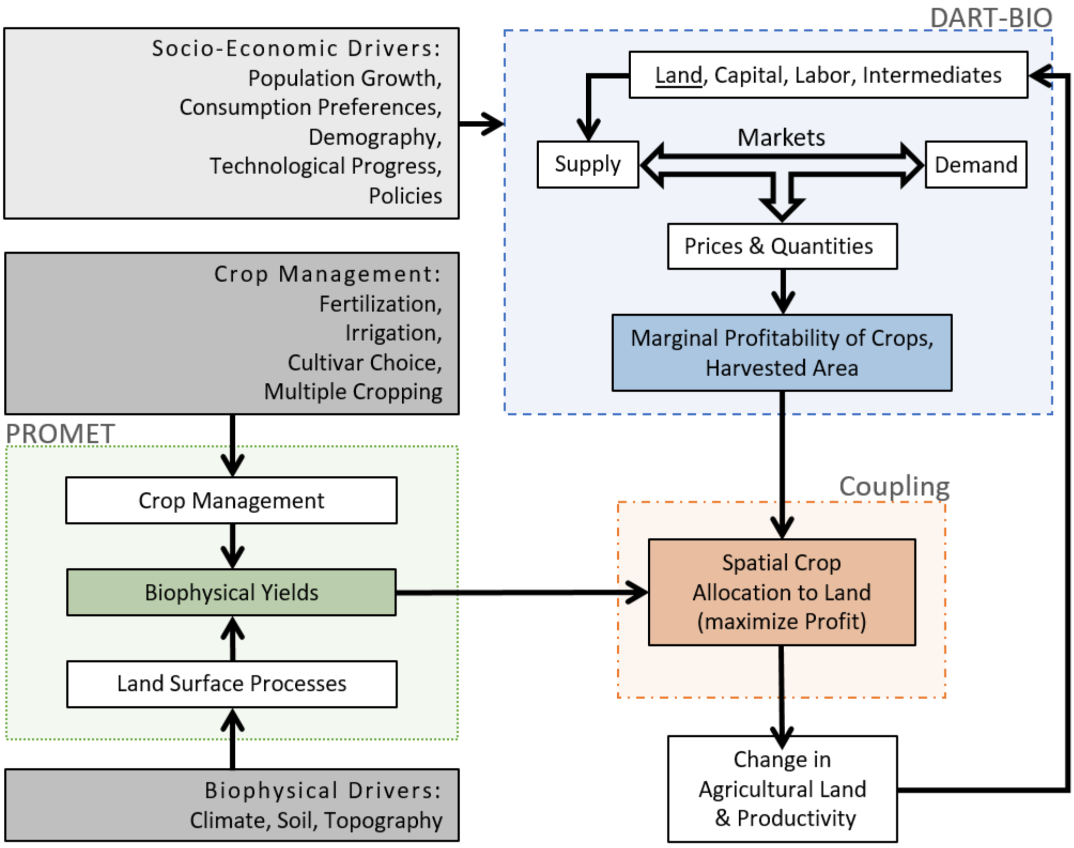

Figure B. Modified coupling approach of PROMET and DART-BIO to integratively assess the effect of land saving on agricultural markets and the resulting feedbacks on land saving.

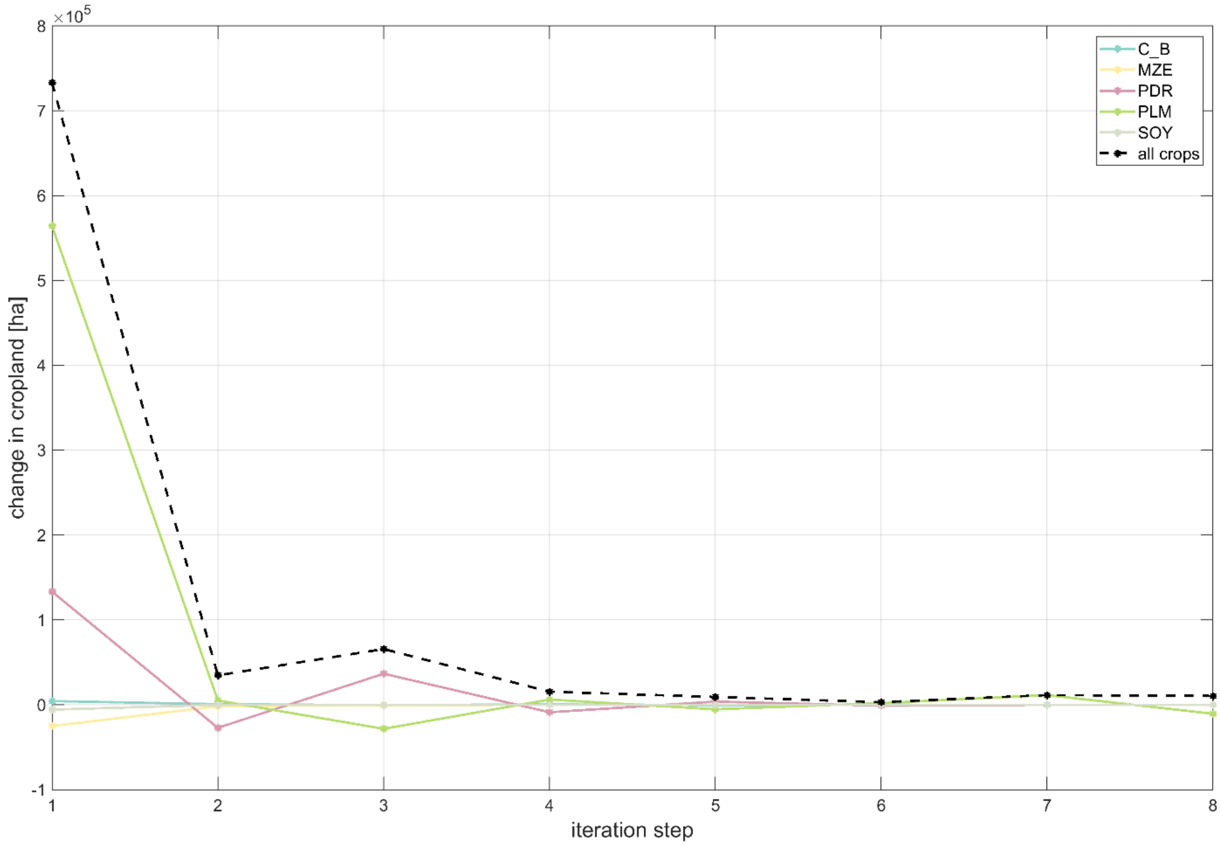

Figure C. Change in allocated cropland [hectare] per crop category and accumulated over all crops within the exemplary sub-region AEZ 6 in Malaysia and Indonesia. For each sub-region, a stable cropland allocation can be achieved after a different iteration step. However, iteration is carried out until a stable allocation is reached globally in all sub-regions.

References

1. Mauser W, Klepper G, Zabel F, Delzeit R, Hank T, Putzenlechner B, et al. Global biomass production potentials exceed expected future demand without the need for cropland expansion. Nat Commun. 2015;6. doi: 10.1038/ncomms9946.

6.1.6 S6 Appendix: Effect of different yield gap closing scenarios

We assessed the land saving potential for different yield gap closing scenarios from 50% to 100% yield gap closing. When yield gaps are closed by 50% instead of 80%, land saving potentials decrease for all land saving strategies by around -7 pp, resulting in global land saving potentials of 41% (BLS) to 29% (ULS). Assuming full yield gap closing (100%), on the other hand, increases the global land saving potential only by +3 pp to +4 pp compared to an 80% yield gap closing, so that globally, 51% (BLS) to 40% (ULS) of current cropland could be taken out of production. Since for all strategies the global land saving potential increases only by around 10 percentage points when yield gaps are fully closed instead of a 50% yield gap closing (Table A), our results suggest that the large potentials for land saving are not strictly tied to a highly-intensified agriculture, but persist also within lower yield gap closing scenarios.

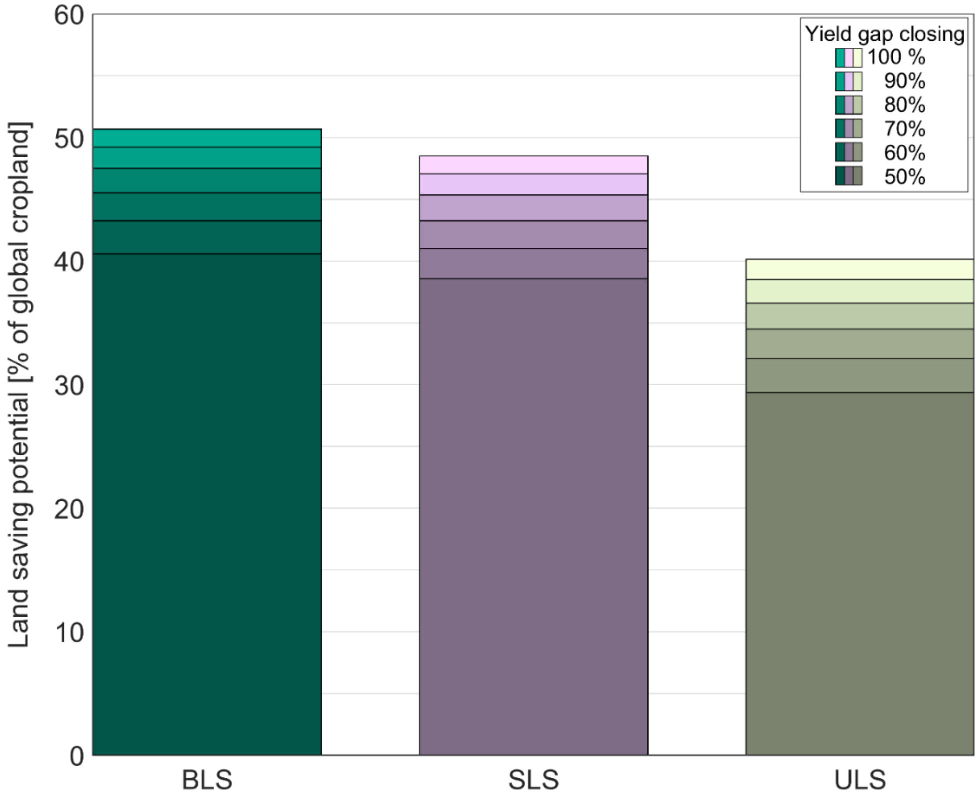

Figure. Land saving potentials for biophysical land saving (BLS), socio-economic land saving (SLS) and uniform land saving (ULS) for 50%, 60%, 70%, 80%, 90% and full (100%) yield gap closing. The land saving potentials displayed for the SLS are obtained with direct coupling without iteration.

Table A. Global land saving potentials [% of global cropland] for the three different land saving strategies biophysical land saving (BLS), socio-economic land saving (SLS) and uniform land saving (ULS) under different yield gap closing scenarios.

yield gap closing	BLS	SLS	ULS
50%	40.59	38.59	29.38
60%	43.27	41.03	32.11
70%	45.54	43.26	34.49
80%	47.50	45.36	36.60
90%	49.21	47.06	38.48
100%	50.69	48.51	40.15

Analyzing the sensitivity of global impacts on agricultural markets, our results show that the global average changes in production and prices due to the implementation of land saving are very robust against different yield gap closing scenarios. Looking at the BLS and the ULS strategies as an upper and lower boundary, we see that the changes between 50% and 100% yield gap closing scenarios are around 0.1% for crop production and between 0.4% and 0.6% for crop prices (Table B). This result is to be expected, as the correlation between yield gap closing and land saving is rather strong, so that there's less land available in the economic model by the degree by which we close yield gaps.

Table B. Global average changes of crop production and prices [%] compared to a baseline without land saving for the biophysical land saving (BLS) and the uniform land saving (ULS) strategy under different yield gap closing scenarios.

	Change in global crop production		Global average change of crop prices	
yield gap closing	BLS	ULS	BLS	ULS
50%	+2.87	+2.99	-8.53	-9.14
80%	+2.84	+2.90	-8.24	-8.73
100%	+2.84	+2.87	-8.12	-8.52

6.1.7 S7 Appendix: Supplementary results

Land saving potentials

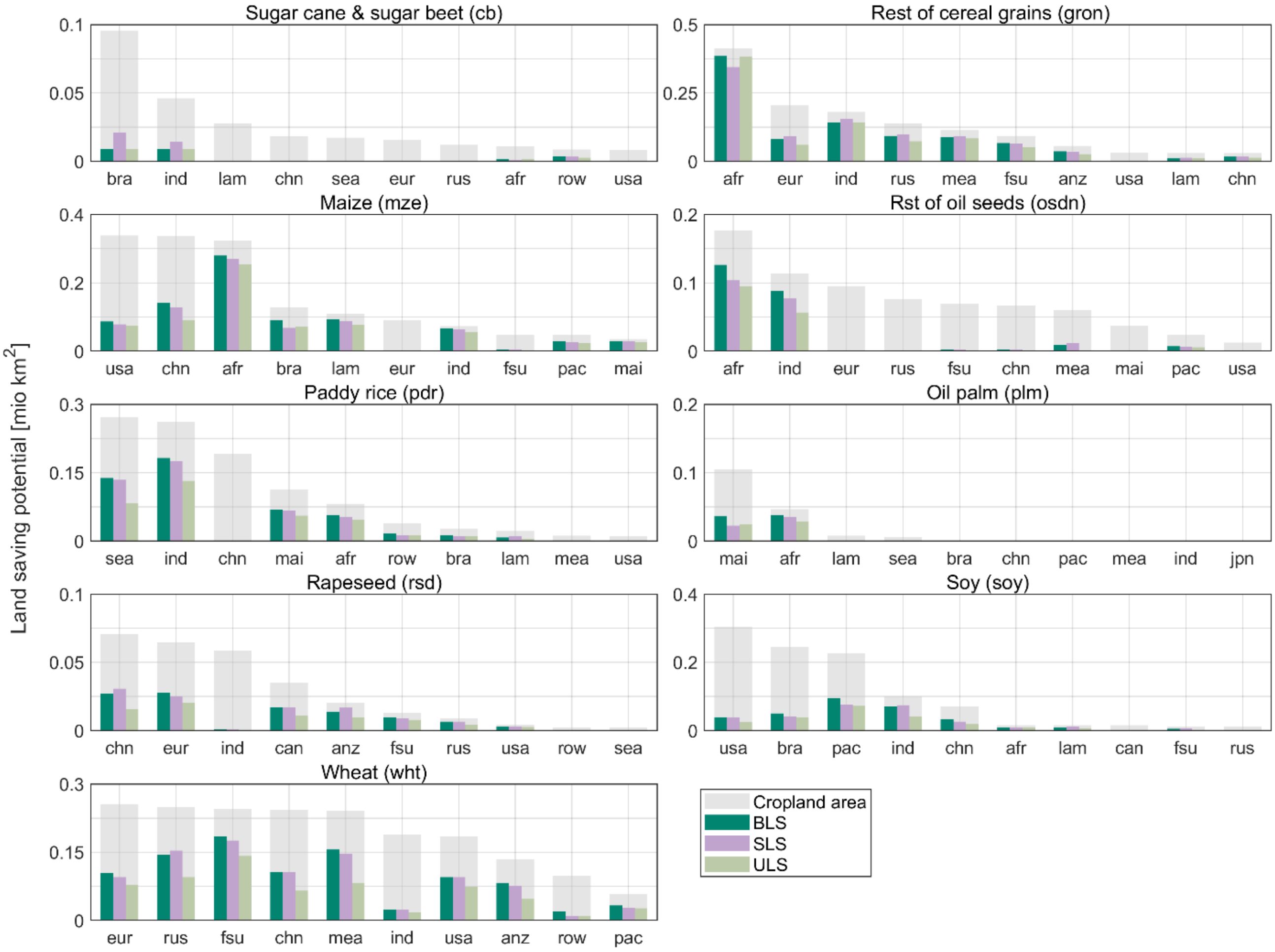

Figure A. Absolute land saving potential [million km^2] for the top 10 growing regions of each crop category. Grey bars show the current cropland extent, colored bars the area that could be saved under biophysical land saving (BLS), socio-economic land saving (SLS) and uniform land saving (ULS). Top growing regions are defined as the 10 regions with the largest statistical growing area of the crop category.

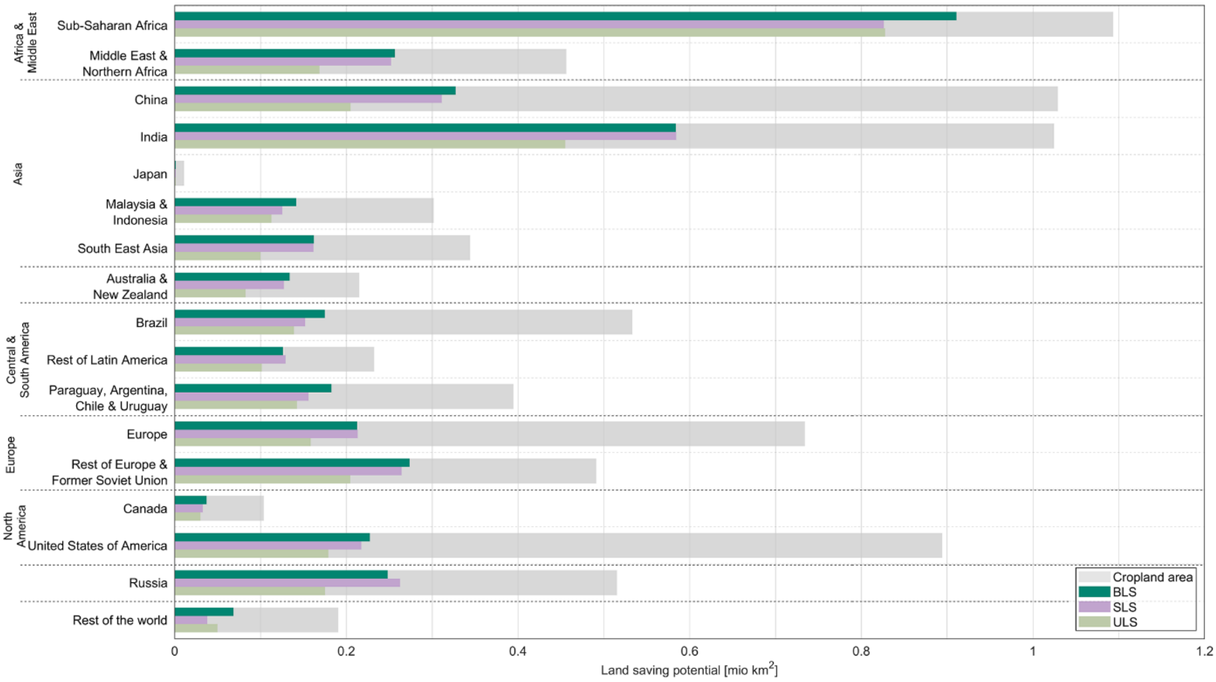

Figure B. Absolute land saving potential [million km^2] for the 17 study regions under biophysical land saving (BLS), socio-economic land saving (SLS) and uniform land saving (ULS). Grey bars show the current cropland extent, colored bars the area that could be saved under the three different land saving strategies within each region accumulated over all crops.

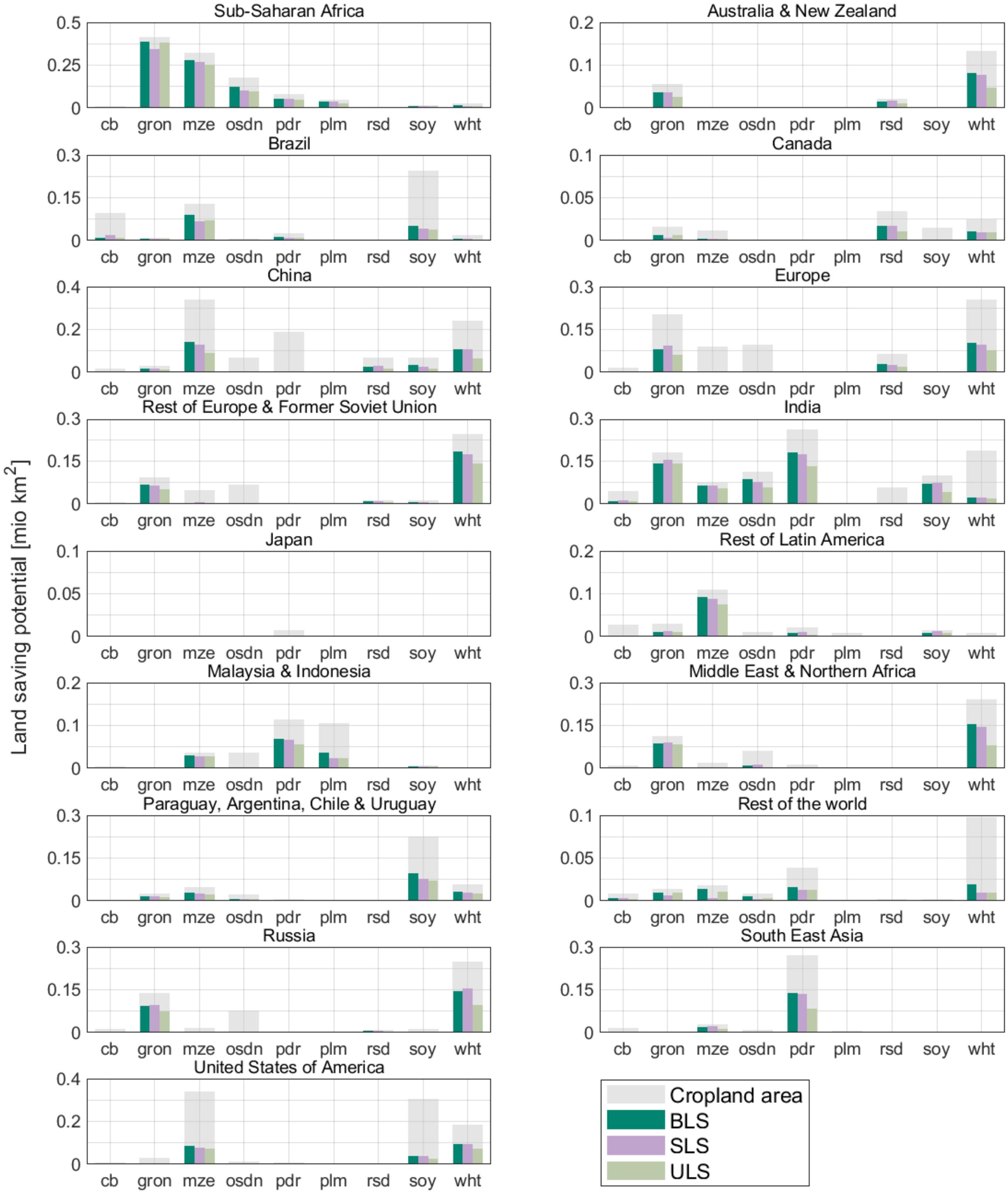

Figure C. Absolute land saving potential [million km^2] for each crop category in each of the 17 study regions under biophysical land saving (BLS), socio-economic land saving (SLS) and uniform land saving (ULS). Grey bars show the current cropland extent, colored bars the area that could be saved under the three different land saving strategies.

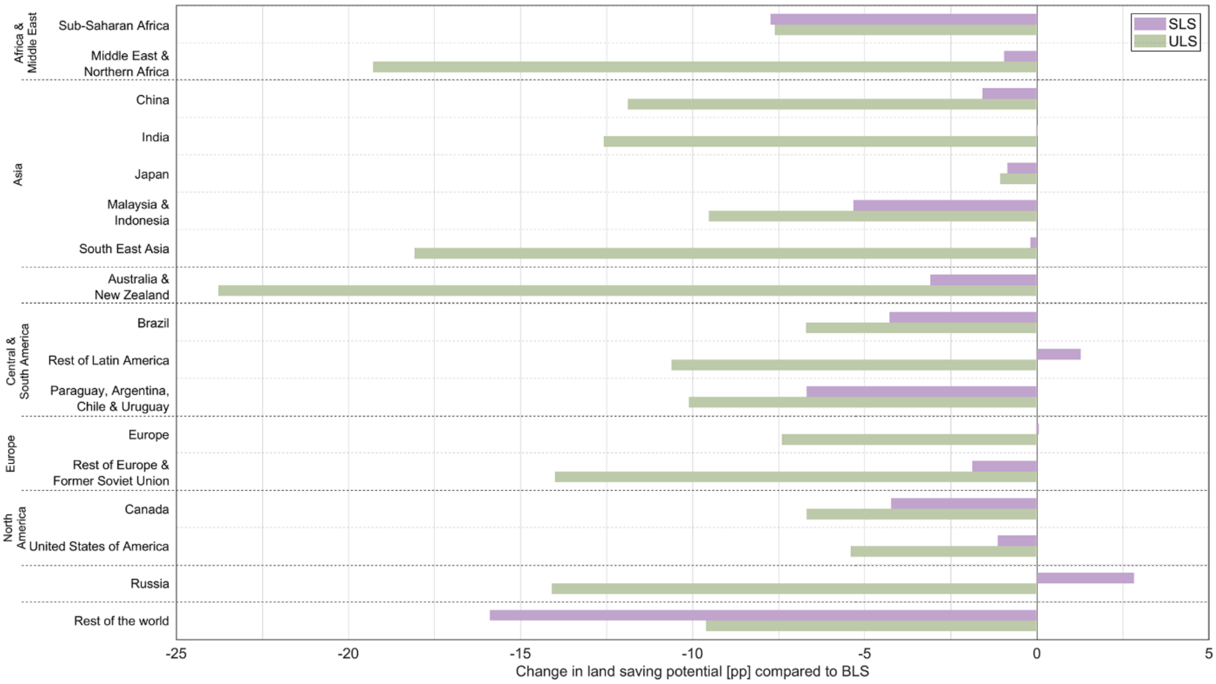

Figure D. Change in the regional land saving potential in percentage points [pp] compared to the biophysical land saving (BLS) as upper benchmark for realizable land saving.

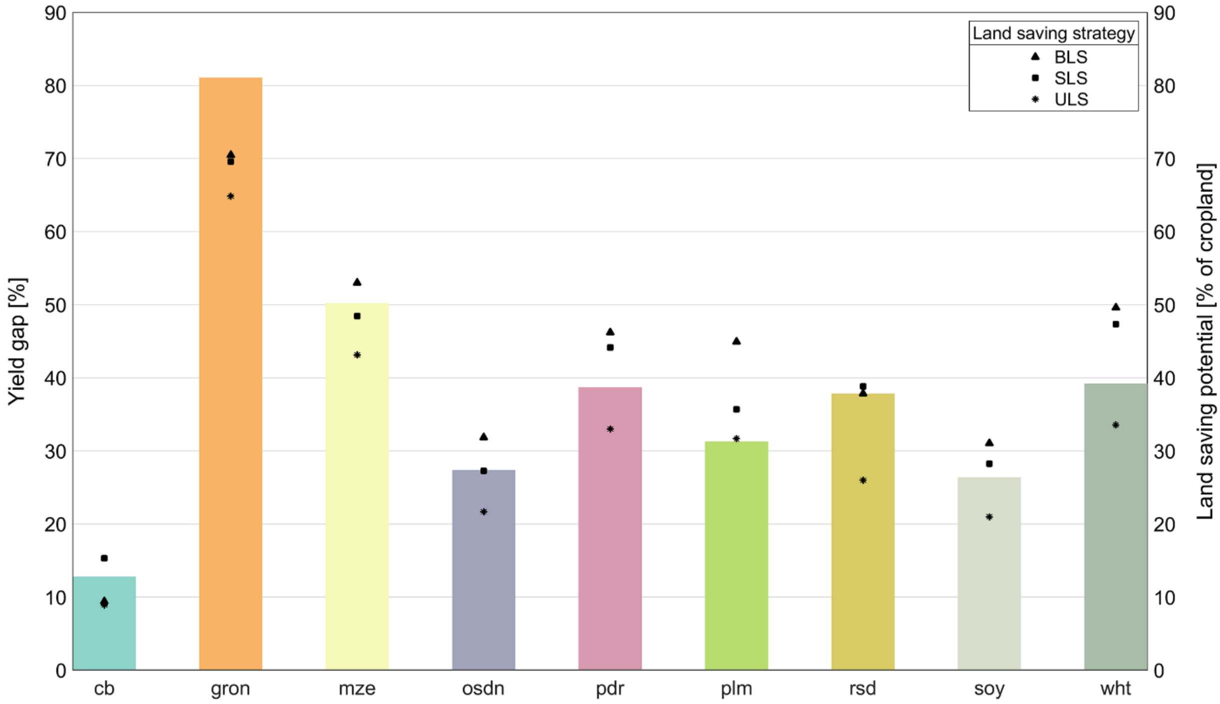

Figure E. Global area-weighted yield gap [%] and land saving potential [% of global cropland] per crop category for the three land saving strategies biophysical land saving (BLS), socio-economic land saving (SLS) and uniform land saving (ULS). Yield gaps are displayed with bars and land saving potentials with markers. The yield gap is defined as the percentage difference between statistical and potential yields (1-statistical yield/ potential yield).

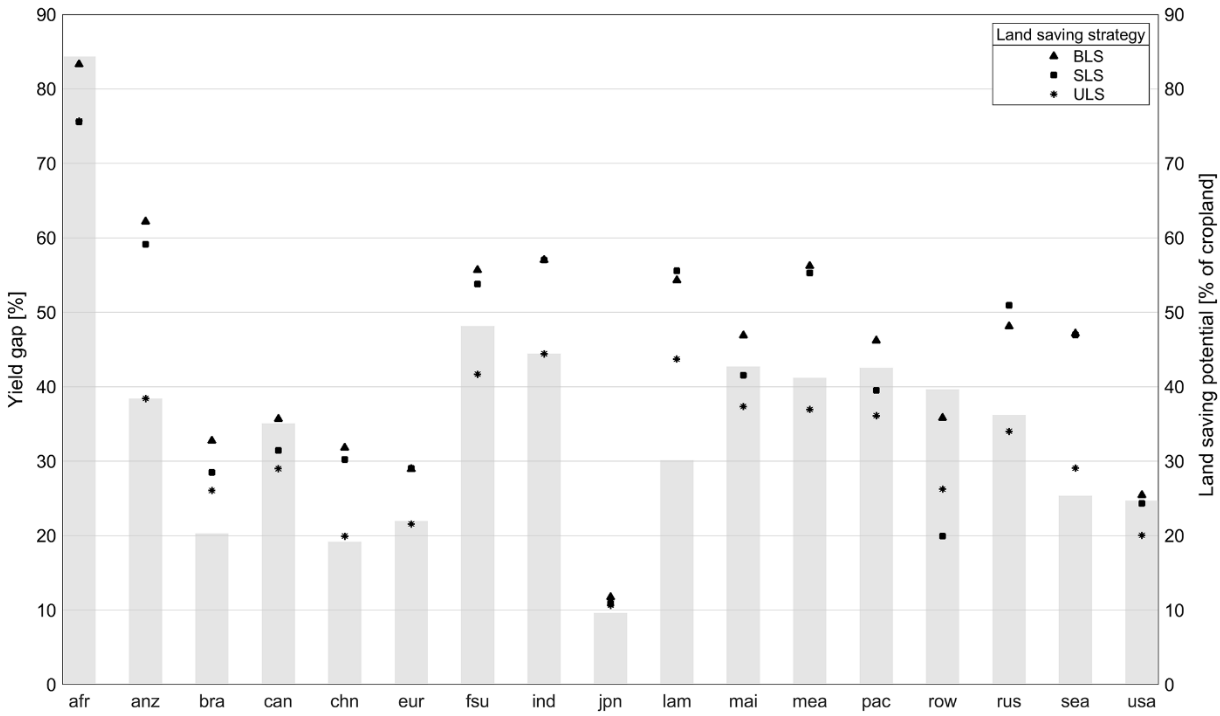

Figure F. Regional yield gap [%] area-weighted across all crop categories and potential for land saving with the three different land saving strategies. Yield gaps are displayed with bars and land saving potentials with markers. The yield gap is defined as the percentage difference between statistical and potential yields (1-statistical yield/ potential yield).

Table A. Relative land saving potentials [% of cropland] under the biophysical land saving (BLS) strategy.

region / crop category	cb	gron	mze	osdn	pdr	plm	rsd	soy	wht	overall
Sub-Saharan Africa	13.65	93.18	86.38	71.38	68.94	81.8	46.6	63.61	58.83	83.32
Australia & New Zealand	0	65.73	22.95	11.52	0	0	68.1	43.29	61.67	62.21
Brazil	9.25	49.84	70.2	5.26	49.28	0.96	22.86	20.6	32.21	32.77
Canada	0	41.77	21.04	23.7	0	0	48.72	0	43.02	35.67
China	0.92	54.37	41.91	3.36	0.12	0	38.52	46.69	43.85	31.81
Europe	0	39.41	0.15	0.1	0	0	42.92	8.51	40.67	28.97
Rest of Europe & Former Soviet Union	3.54	71.22	8.69	2.82	57.58	0	74.31	42.19	75.07	55.7
India	19.37	78.89	88.72	77.99	69.58	0	1.39	70.71	12.76	57.02
Japan	0	77.75	0	0	0	0	0	5.27	43.12	11.73
Rest of Latin America	0	33.23	85.86	27.18	36.68	10.29	0	61.14	14.58	54.31
Malaysia & Indonesia	42.92	0	81.93	0	61.18	34.27	0	82.53	0	46.88
Middle East & Northern Africa	11.43	76.74	10.89	15.88	0	0	45.99	0.04	64.69	56.24
Paraguay, Argentina, Chile & Uruguay	13.92	56.15	60.44	32.16	1.36	58.81	40.11	42.48	56.94	46.22
Rest of the world	42.35	73.14	73.2	62.8	42.75	0	0	0.02	19.87	35.84
Russia	0	67.5	24.07	0	17.14	0	73.29	0	57.64	48.11
South East Asia	0	56.6	72.45	0.14	51	0	0	39.1	23.32	47.14
United States of America	0.68	9.39	25.82	0	0	0	69.91	12.95	51.33	25.45
global	9.42	70.49	53.02	31.85	46.21	44.94	37.87	31.05	49.62	47.5

The potential is displayed for each region and each crop category, as well as per region accumulated over all crop categories (overall) and globally accumulated over all regions (global). For the different crop categories, the following abbreviations are used (for details see also Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat.

Table B. Relative land saving potentials [% of cropland] under the socio-economic land saving (SLS) strategy.

region / crop category	cb	gron	mze	osdn	pdr	plm	rsd	soy	wht	overall
Sub-Saharan Africa	9.62	83.36	83.43	58.77	65.31	76.96	33.85	57.11	36.59	75.59
Australia & New Zealand	0	63.98	-298.89	25.77	0	0	81.58	-18.04	57.11	59.11
Brazil	21.85	53.47	53.18	5.25	36.46	1.33	6.24	16.93	27.7	28.49
Canada	0	23.13	16.6	3.84	0	0	48.88	0	40	31.44
China	-0.68	55.82	38.04	3.11	0.28	0	43.49	37.57	43.6	30.24
Europe	0	45.09	0.05	0.32	0	0	38.64	8.37	37.35	29.03
Rest of Europe & Former Soviet Union	13.93	69.76	10.18	3.06	51.75	0	68.77	46.12	71.36	53.81
India	30.5	86.1	86.08	67.63	66.81	0	1.73	74.21	12.36	57.04
Japan	0	77.99	0	0	0	0	0	30.86	18.49	10.88
Rest of Latin America	0	42.47	80.99	24.26	48.07	11.76	0	78.4	19.88	55.58
Malaysia & Indonesia	53.61	0	80.8	0	58.77	21.6	0	79.06	0	41.56
Middle East & Northern Africa	-0.79	80.08	8.44	20.42	0	0	37.09	0.03	60.86	55.29
Paraguay, Argentina, Chile & Uruguay	14.73	57.14	56.73	29.37	1.49	55.9	46.85	34.12	47.62	39.53
Rest of the world	38.89	45.86	20.37	23.21	32.36	0	0	0.02	10.41	19.95
Russia	0	70.61	24.99	0	17.14	0	74.06	0	61.66	50.94
South East Asia	0	86.24	75.97	1.25	49.57	0	0	72.16	26.99	46.96
United States of America	7.62	8.94	23.09	0	0	0	68.52	12.32	51.64	24.31
global	15.31	69.6	48.45	27.25	44.15	35.69	38.83	28.22	47.34	45.01

The potential is displayed for each region and each crop category, as well as per region accumulated over all crop categories (overall) and globally accumulated over all regions (global). For the different crop categories, the following abbreviations are used (for details see also Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat. Within a SLS, negative land saving potentials can occur when less profitable crops are shifted to locations with less optimal growing conditions and accordingly lower yield potentials.

Table C. Relative land saving potentials [% of cropland] under the uniform land saving (ULS) strategy.

region / crop category	cb	gron	mze	osdn	pdr	plm	rsd	soy	wht	overall
Sub-Saharan Africa	13.65	92.85	78.28	53.56	57.94	61.53	30.24	52.79	42.75	75.71
Australia & New Zealand	0	46.16	6.88	8.19	0	0	47.51	23.25	34.99	38.43
Brazil	9.25	49.84	56.17	3.92	36.68	0.96	15.27	15.38	24.68	26.07
Canada	0	41.77	18.23	23.7	0	0	31.65	0	40.36	28.98
China	0.45	44.72	26.66	1.9	0.02	0	22.16	26.7	26.98	19.93
Europe	0	29.4	0.08	0.1	0	0	31.24	5.65	30.42	21.57
Rest of Europe & Former Soviet Union	3.54	55.74	0.65	1.08	45.74	0	61.09	7.87	57.61	41.7
India	19.37	78.89	75.14	49.91	50.31	0	0.97	40.79	9.53	44.44
Japan	0	77.75	0	0	0	0	0	0.24	38.28	10.67
Rest of Latin America	0	32.67	69.9	20.44	20.11	2	0	50.49	9.55	43.7
Malaysia & Indonesia	42.92	0	75.14	0	49.1	22.82	0	71.28	0	37.35
Middle East & Northern Africa	7.66	73.25	4.23	1.86	0	0	45.79	0.03	33.93	36.95
Paraguay, Argentina, Chile & Uruguay	13.92	49.46	46.85	25.49	1.13	45.87	21.26	32.13	46	36.11
Rest of the world	30.84	73.14	58.92	41.33	34.17	0	0	0.02	10.07	26.24
Russia	0	52.84	12.78	0	12.7	0	51.48	0	38.2	34.02
South East Asia	0	56.11	49.5	0.11	30.76	0	0	25.04	12.79	29.07
United States of America	0.68	8.15	22.21	0	0	0	62.84	8.2	39.96	20.04
global	8.93	64.86	43.14	21.68	33	31.68	25.98	21.01	33.54	36.6

The potential is displayed for each region and each crop category, as well as per region accumulated over all crop categories (overall) and globally accumulated over all regions (global). For the different crop categories, the following abbreviations are used (for details see also Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat.

Impacts on agricultural markets

Table D. Relative changes [%] in crop production compared to statistical reference production under biophysical land saving (BLS) for each crop category within each region and accumulated over all crop categories (overall).

region / crop category	cb	gron	mze	osdn	pdr	plm	rsd	soy	wht	overall
Sub-Saharan Africa	-3.96	9.95	7.93	5.1	6.6	3.29	-7.68	1.29	-22.83	1.49
Australia & New Zealand	-6.41	-9.34	-5.45	-3.46	-3.64	0	28.36	3.26	10.07	1.5
Brazil	23.31	5.38	6.54	-1.21	2.31	-34.34	-1.63	-16.01	-5.34	2.39
Canada	-1.26	-6.21	-12.6	-6.16	0	0	-14.31	-25.77	-17.35	-7.49
China	-0.19	24.15	10.59	1.09	-2.88	-21.17	29.71	107.87	16.79	4.13
Europe	-2.51	1.4	-11.76	-12.5	-7.55	0	1.2	-32.12	-3.3	-2.09
Rest of Europe & Former Soviet Union	-0.35	21.64	-1.44	-9.35	-0.99	0	62.23	-8.83	12.06	2.92
India	5.91	23.07	28.58	30.31	8.65	0	8.17	22.35	3.49	4.37
Japan	-5.58	-20.31	0	0	-0.17	0	0	-41.17	-32.1	-1.88
Rest of Latin America	-0.46	11.77	64.5	3.99	6.46	-4.48	0	37.03	-32.88	4.02
Malaysia & Indonesia	55.99	0	82.49	6.05	13.19	22.15	0	940.92	0	14.25
Middle East & Northern Africa	-1.41	-3.86	-39.75	-4.46	-0.4	0	-9.72	-59.88	-10.16	-4.62
Paraguay, Argentina, Chile & Uruguay	1.91	11.2	8.79	31.36	-2.51	13.03	6.12	16.18	15.58	10.48
Rest of the world	8.17	7.82	-27.07	12.77	2.56	-18.14	-26.07	-58.76	41.7	3.37
Russia	-3.81	26.93	3.52	-8.38	0.52	0	20.5	-60.07	32.63	5.71
South East Asia	-1.97	23.6	51.27	-31.67	14.59	-12.99	-54.63	192.74	-35.03	6.02
United States of America	1.37	0.82	5.94	-2.55	-5.25	0	44.27	-5.48	19.45	6.15

For the different crop categories, the following abbreviations are used (for details see also Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat.

Table E. Relative changes [%] in crop production compared to statistical reference production under socio-economic land saving (SLS) for each crop category within each region and accumulated over all crop categories (overall).

region / crop category	cb	gron	mze	osdn	pdr	plm	rsd	soy	wht	overall
Sub-Saharan Africa	-3.6	8.34	7.92	4.06	6.55	3.55	-8.87	0.99	-30.9	1.46
Australia & New Zealand	-7.2	-9.97	-6.11	2.1	-3.59	0	41.57	4.83	12.9	2.95
Brazil	22.73	5.45	5.72	-1.15	2.35	-35.56	-1.71	-16.01	-2.67	2.27
Canada	-1.21	-6.98	-12.12	-4.75	0	0	-14.27	-26.28	-16.25	-7.32
China	0.05	25.06	10.65	1.78	-2.8	-21.46	28.35	100.15	17.15	4.22
Europe	-2.43	1.71	-11.12	-12.34	-7.32	0	0.01	-31.78	-3.29	-2.2
Rest of Europe & Former Soviet Union	-0.33	21.37	-0.86	-9.35	-0.97	0	54.99	-7.96	11.39	2.75
India	5.8	27.18	25.68	26.28	8.51	0	7.69	24.8	3.43	4.17
Japan	-5.39	-23.19	0	0	-0.15	0	0	-39.71	-34.28	-2
Rest of Latin America	-0.53	20.02	55.7	0.3	6.58	-4.74	0	75.17	-28.89	3.54
Malaysia & Indonesia	56.28	0	81.75	8.43	13.23	23.08	0	968.44	0	14.77
Middle East & Northern Africa	-1.08	-1.33	-38.53	-3.13	-0.3	0	-10.3	-59.66	-10.85	-4.5
Paraguay, Argentina, Chile & Uruguay	2.41	10.39	11.78	33.4	-2.32	12.16	9.25	15.61	14.6	11.07
Rest of the world	6.73	-19.51	-33.25	14.4	1.74	-18.56	-21.57	-50.43	30.63	2.18
Russia	-3.73	27.67	2.92	-8.92	0.52	0	20.84	-62.47	36.53	6.13
South East Asia	-1.88	37.06	51.9	-35.67	14.7	-13.31	-62.77	612.07	-38	6.81
United States of America	1.5	0.04	6.4	-1.83	-4.63	0	43.62	-6.19	21.43	6.38

For the different crop categories, the following abbreviations are used (for details see also Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat.

Table F. Relative changes [%] in crop production compared to statistical reference production under uniform land saving (ULS) for each crop category within each region and accumulated over all crop categories (overall).

region / crop category	cb	gron	mze	osdn	pdr	plm	rsd	soy	wht	overall
Sub-Saharan Africa	-3.82	10.08	7.19	3.74	6.3	2.46	-12.99	1.02	-25.45	1.42
Australia & New Zealand	-5.66	-10.53	-3.3	1.88	-3.4	0	24.47	6.36	9.24	2.01
Brazil	23.45	5.67	5.84	-1.1	2.3	-35.73	-1.59	-15.1	-1.44	2.56
Canada	-1.24	-6.47	-11.01	-5.74	0	0	-14.44	-24.36	-15.47	-7.29
China	0.25	23.83	10.65	3.11	-2.43	-21.06	28.68	94.6	15.92	4.49
Europe	-2.51	0.91	-9.9	-11.95	-7.58	0	0.96	-28.69	-2.74	-2.23
Rest of Europe & Former Soviet Union	-0.11	17.73	0.85	-7.62	-0.95	0	50.51	-16.1	10.17	2.81
India	6.23	24.44	22.64	21.39	8.61	0	7.86	17.31	3.67	4.1
Japan	-5.95	-20.35	0	0	-0.22	0	0	-39.8	-30.26	-2.38
Rest of Latin America	-0.29	14.14	47.48	3.38	6.5	-4.48	0	27.2	-30.21	2.7
Malaysia & Indonesia	57.22	0	77.42	9.45	13.19	23.04	0	710.43	0	14.12
Middle East & Northern Africa	-1.49	-2.74	-35.44	-4.78	-0.29	0	-5	-54.8	-11.01	-4.42
Paraguay, Argentina, Chile & Uruguay	2.32	10.74	9.5	32.29	-2.26	12.81	3.57	17.87	15.59	11.65
Rest of the world	8.39	8.79	-24.66	12.22	2.62	-18.49	-22.52	-55.83	41.94	3.55
Russia	-3.25	22.99	4.99	-6.33	0.68	0	15.14	-50.82	28.86	5.7
South East Asia	-0.92	26.27	31.54	-19.5	15.64	-12.49	-48.69	171.74	-30.4	6.68
United States of America	1.42	0.47	6.95	-1.12	-5.23	0	47.06	-3.72	18.94	6.62

For the different crop categories, the following abbreviations are used (for details see also Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat.

Table G. Relative changes [%] in crop prices under biophysical land saving (BLS) for each crop category within each region and accumulated over all crop categories (overall).

region / crop category	cb	gron	mze	osdn	pdr	plm	rsd	soy	wht	overall
Sub-Saharan Africa	-3.22	-17.66	-15.96	-13.41	-13.98	-12.51	-9.07	-12.32	-12.52	-6.13
Australia & New Zealand	-3.64	-7.3	-5.71	-9.9	-1.7	-22.12	-20.33	-13.73	-16.48	-6.73
Brazil	-11.71	-13.69	-14.17	-9.11	-12.5	-14.35	-9.51	-3.94	-13.99	-8.77
Canada	-5.28	-7.27	-10.01	-10.61	-7.45	-18.78	-7.79	-7.73	-3.96	-7.62
China	-1.88	-24.8	-23.28	-8.78	-4.22	-17.51	-20.96	-14.97	-20.2	-7.69
Europe	-2.02	-11.32	-4.64	-3.93	-4.35	0	-11.54	-7	-10.95	-4.95
Rest of Europe & Former Soviet Union	-3.95	-18.41	-6.82	-5.5	-2.9	-19.87	-20.76	-12.73	-17.8	-7.06
India	-13.6	-29.31	-34.33	-36.78	-37.32	-17.36	-7.76	-24.47	-0.41	-9.77
Japan	-2.93	-12.51	-15.8	-10.44	-0.7	-17.13	-10.31	-12.26	-13.21	-1.45
Rest of Latin America	-2.17	-15.1	-22.64	-11.69	-17.35	-11.02	-10.42	-14.49	-11.47	-7.41
Malaysia & Indonesia	-19.94	-13.4	-37.73	7.27	-48.66	-35.63	-10.6	-27.35	-13.6	-23.03
Middle East & Northern Africa	-5.51	-10.78	-10.61	-7.87	-1.91	-18.33	-9.86	-13.1	-11.32	-3.95
Paraguay, Argentina, Chile & Uruguay	-7.52	-17.32	-17.21	-15.71	-3	-19.08	-14.38	-15.83	-20.06	-13.29
Rest of the world	-15.58	-13.29	-15.44	-13.52	-6.87	-24.92	-6.14	-12.62	-16.95	-6.57
Russia	-3.21	-21.88	-10.15	-2.23	-7.63	-19.11	-20.94	-10.24	-25.86	-7.91
South East Asia	-3.88	-27.39	-37.31	-7.81	-25.81	-14.81	-6.51	-13.95	-12.69	-13.58
United States of America	-8.9	-12.53	-12.92	-9.4	-6.78	-15.87	-12.85	-13.95	-20.34	-10.39

For the different crop categories, the following abbreviations are used (for details see also Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat.

Table H. Relative changes [%] in crop prices under socio-economic land saving (SLS) for each crop category within each region and accumulated over all crop categories (overall).

region / crop category	cb	gron	mze	osdn	pdr	plm	rsd	soy	wht	overall
Sub-Saharan Africa	-3.56	-15.58	-15.81	-12.28	-13.87	-13.09	-9.32	-12.07	-12.25	-6.18
Australia & New Zealand	-4.45	-7.46	-5.75	-13.01	-1.99	-22.68	-24.67	-15.44	-17.1	-7.43
Brazil	-11.47	-13.88	-13.27	-9.25	-12.82	-14.29	-9.11	-4.17	-13.9	-8.79
Canada	-5.38	-7.05	-9.77	-10.51	-7.09	-19.24	-7.95	-7.84	-4.39	-7.71
China	-2	-25.47	-23.31	-9.53	-4.42	-17.82	-20.46	-15	-20.5	-7.99
Europe	-2.05	-11.63	-4.81	-4.08	-4.32	0	-10.93	-7.44	-10.8	-5.01
Rest of Europe & Former Soviet Union	-3.93	-18.46	-7.08	-5.66	-2.89	-20.36	-19.45	-13.33	-17.38	-7
India	-13.38	-32.52	-32.56	-33.11	-36.95	-17.84	-7.81	-27.69	-0.31	-9.64
Japan	-2.9	-12.92	-15.37	-10.43	-0.75	-17.55	-10.51	-12.48	-13.14	-1.56
Rest of Latin America	-1.99	-17.38	-21.05	-10.18	-17.47	-10.97	-10.55	-15.75	-11.59	-7.15
Malaysia & Indonesia	-19.89	-12.68	-37.01	7.81	-48.7	-36.57	-10.61	-28.35	-13.5	-23.34
Middle East & Northern Africa	-5.73	-11.04	-10.39	-8.07	-1.99	-18.76	-9.87	-13.29	-11.24	-4.07
Paraguay, Argentina, Chile & Uruguay	-7.86	-17.79	-17.86	-16.49	-3.63	-19.06	-16.1	-15.88	-19.55	-13.63
Rest of the world	-13.95	-10.98	-14.95	-13.45	-5.7	-25.57	-6.95	-12.83	-15.57	-5.99
Russia	-3.07	-22.34	-9.88	-1.71	-7.54	-19.41	-20.89	-10.3	-27.01	-8.15
South East Asia	-3.83	-38.69	-37.23	-5.44	-25.82	-15.17	-6.13	-16.99	-12.42	-13.87
United States of America	-8.87	-12.43	-13.02	-9.57	-6.82	-16.18	-12.98	-13.87	-20.86	-10.49

For the different crop categories, the following abbreviations are used (for details see also Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat.

Table I. Relative changes [%] in crop prices under uniform land saving (ULS) strategy for each crop category within each region and accumulated over all crop categories (overall).

region / crop category	cb	gron	mze	osdn	pdr	plm	rsd	soy	wht	overall
Sub-Saharan Africa	-3.72	-17.87	-14.93	-12.16	-13.64	-11.22	-8.49	-11.73	-12.08	-6.32
Australia & New Zealand	-5.04	-6.9	-6.81	-12.28	-2.77	-22.87	-19.4	-14.54	-15.86	-7.72
Brazil	-11.84	-13.96	-13.46	-9.33	-12.71	-14.49	-9.11	-4.57	-13.97	-9.02
Canada	-5.72	-7.46	-9.92	-10.95	-7.95	-19.26	-7.85	-8.09	-4.91	-7.98
China	-2.38	-24.43	-22.99	-11.48	-4.79	-17.93	-20.21	-14.69	-19.71	-8.63
Europe	-2.32	-11.17	-5.47	-4.57	-4.69	0	-10.95	-7.69	-10.75	-5.34
Rest of Europe & Former Soviet Union	-4.47	-16.97	-8.02	-6.89	-3.07	-20.19	-18.69	-11.07	-16.35	-7.4
India	-14.27	-30.61	-30.29	-29.67	-36.86	-17.42	-10.71	-21.61	-1.54	-10.06
Japan	-3.24	-12.66	-15.14	-10.8	-0.93	-17.14	-10.26	-12.25	-12.88	-1.87
Rest of Latin America	-2.78	-15.82	-19.7	-11.68	-17.88	-11.72	-10.4	-14.2	-11.29	-7.36
Malaysia & Indonesia	-20.47	-13.78	-34.1	7.62	-49.03	-36.82	-10.88	-21.48	-13.21	-23.36
Middle East & Northern Africa	-5.92	-10.91	-10.37	-7.95	-2.5	-18.36	-10.01	-13.12	-10.76	-4.43
Paraguay, Argentina, Chile & Uruguay	-8.19	-17.42	-16.95	-16.08	-3.99	-19.2	-12.41	-16.19	-19.84	-13.75
Rest of the world	-16.14	-13.62	-14.75	-12.84	-7.51	-25.7	-6.58	-12.6	-16.7	-7.15
Russia	-3.63	-20.36	-11.03	-4.7	-8.2	-19.41	-18.18	-10.83	-24.12	-8.09
South East Asia	-4.82	-29.36	-30.45	-7.8	-27.38	-15.72	-7.14	-13.81	-12.4	-14.69
United States of America	-9.47	-12.73	-13.36	-9.78	-7.22	-16.36	-13.01	-14.7	-19.93	-10.79

For the different crop categories, the following abbreviations are used (for details see also Table in S2 Appendix): cb: sugar cane & sugar beet; gron: rest of cereal grains; mze: maize; osdn: rest of oil seeds; pdr: paddy rice; plm: oil palm; rsd: rapeseed; soy: soy; wht: wheat.

Land saving potential: Global maps

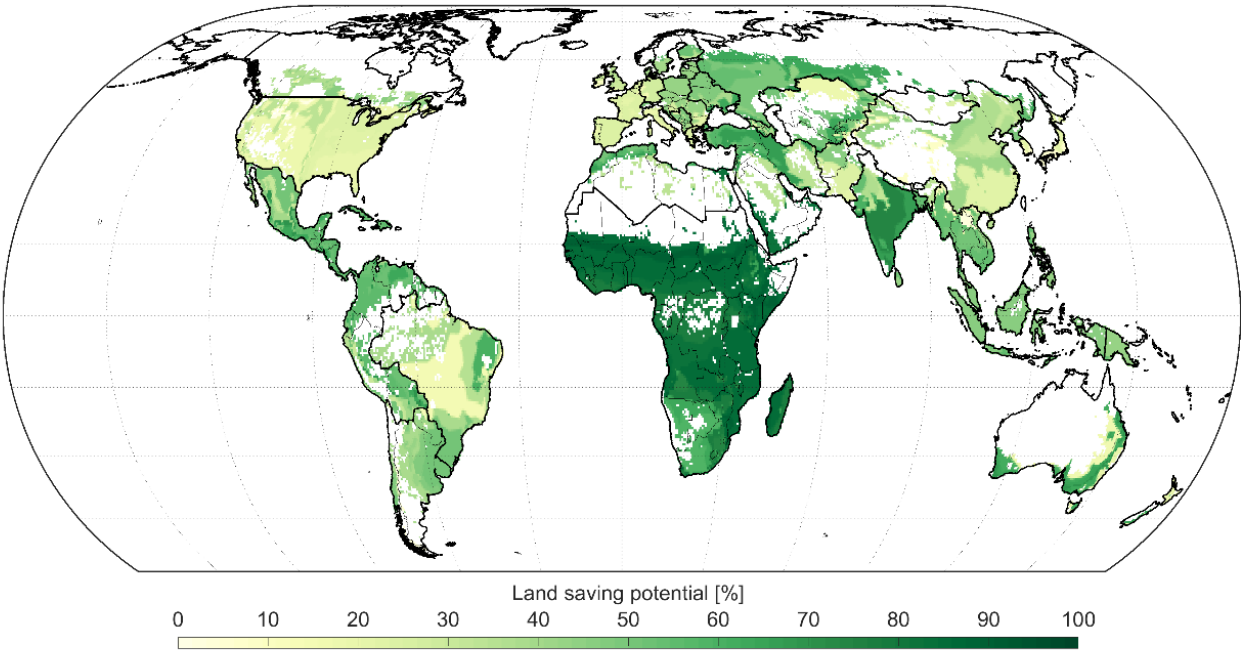

Figure G. Global map of the biophysical land saving potential (BLS). The potential describes the percentage share of total cropland (summed up over all considered crops according to Monfreda et al.[1], see S2 Appendix) that can be taken out of production within the sub-region. As land saving can only be implemented on current cropland areas, land that is currently not used as cropland is masked out. The thick region lines show the aggregated 17 study regions (see S3 Appendix), while the country boarders are displayed according to the global administrative areas of GADM version 2.8. Reprinted from GADM (https://gadm.org/) under a CC BY license, with permission from GADM, original copyright 2012.

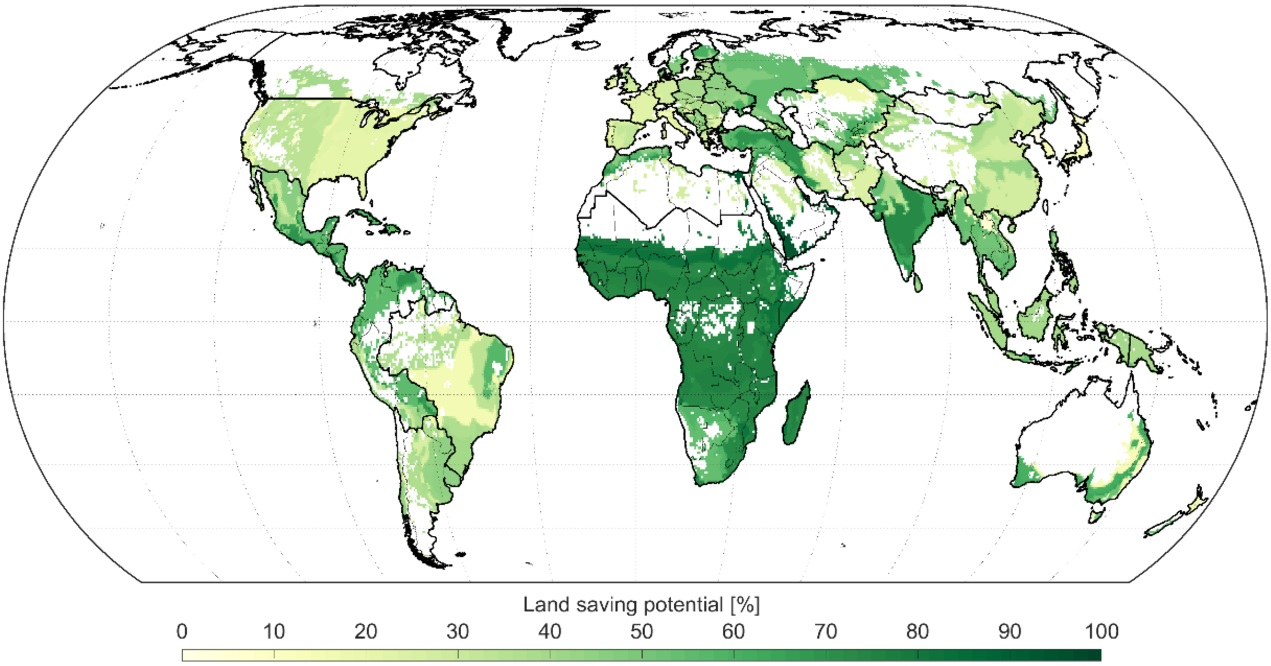

Figure H. Global map of the socio-economic land saving potential (SLS). The potential describes the percentage share of total cropland (summed up over all considered crops according to Monfreda et al.[1], see S2 Appendix) that can be taken out of production within the sub-region. As land saving can only be implemented on current cropland areas, land that is currently not used as cropland is masked out. The thick region lines show the aggregated 17 study regions (see S3 Appendix), while the country boarders are displayed according to the global administrative areas of GADM version 2.8. Reprinted from GADM (https://gadm.org/) under a CC BY license, with permission from GADM, original copyright 2012.

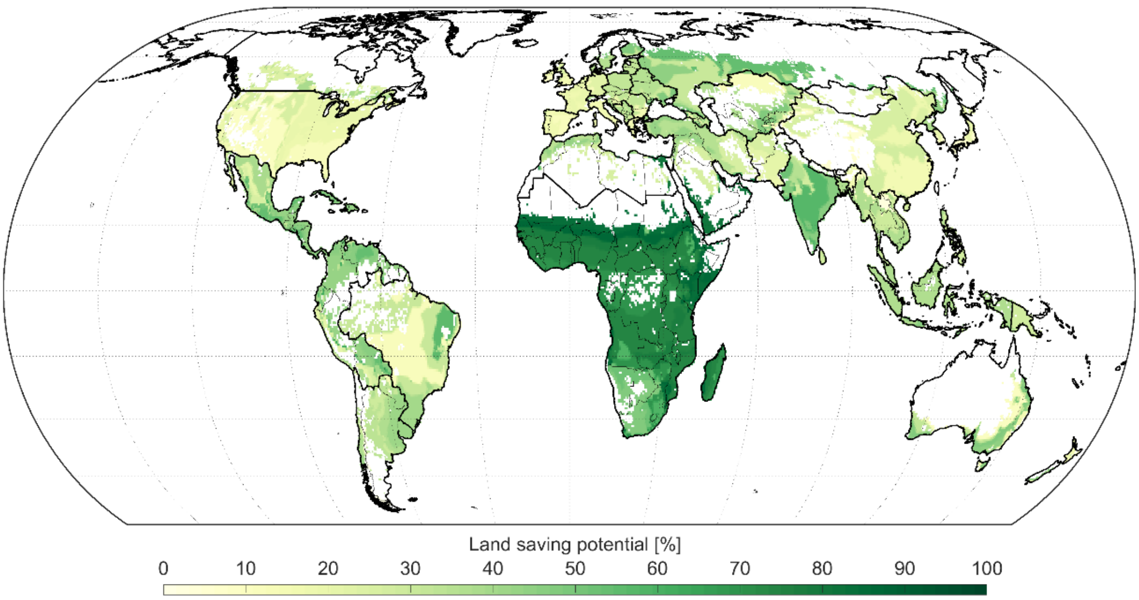

Figure I. Global map of the uniform land saving potential (ULS). The potential describes the percentage share of total cropland (summed up over all considered crops according to Monfreda et al.[1], see S2 Appendix) that can be taken out of production within the sub-region. As land saving can only be implemented on current cropland areas, land that is currently not used as cropland is masked out. The thick region lines show the aggregated 17 study regions (see S3 Appendix), while the country boarders are displayed according to the global administrative areas of GADM version 2.8. Reprinted from GADM (https://gadm.org/) under a CC BY license, with permission from GADM, original copyright 2012.

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6.1.8 S8 Appendix: Carbon sequestration and land saving potential

Saved land that has been taken out of agricultural use could potentially be used to sequester carbon by the recovery of natural vegetation. Studies have shown that e.g. forest recovery can play an important role for climate change mitigation [1]. To roughly estimate the sequestration potential by the recovery of natural vegetation on saved land, we assume that the potential natural vegetation type reestablishes as secondary vegetation, which has a reduced capacity for carbon storage in comparison to the original primary vegetation. Thus, the results of this calculation refer to the additionally saved carbon in the vegetation and soil layer after the time it takes to transform cropland to fully recovered potential secondary vegetation.

Therefore, we apply the spatially explicit bookkeeping model of land use emissions BLUE [2], in which the average carbon storage of 11 different primary and secondary vegetation types including their soils as well as the spatial distribution of the potential natural vegetation are deposited.

To obtain the additional carbon storage by the recovery of natural vegetation, the carbon sequestration of the potential secondary vegetation (including soils) is subtracted with the previous carbon sequestered by croplands (including soils), that are also deposited in the BLUE model. Current cropland areas used for the carbon sequestration calculation refer to the spatial distribution of harvested area according to Monfreda et al. [3] for the considered crops (see S2 Appendix) that are scaled to the area used in the GTAP database 9 [4] to be consistent with the economic model. Harvested areas are converted to (physical) growing area in order to avoid double counting of an area in case of more than one harvest per year by using a multiple cropping factor (harvested area/growing area) derived from the MIRCA dataset [5]. The calculation of the carbon balance takes place at 0.5° degree spatial resolution and is based on the sub-regional land saving potential of all crops across the sub-region.

We find that a recovery of natural vegetation on saved land of the investigated crops could globally sequester between 31 to 41 Gt more carbon than current cropland on the same area, which is equivalent to 114 Gt to 151 Gt CO_2. The considered crops in this study in total account for around 9 million km² globally. Table A shows the result of the carbon saving by recovery of the natural vegetation on saved land according to the different strategies for the considered crops, while Table B relates the results to the entire global cropland area by assuming that the land saving potential results of the considered crops can be transferred in general to all crops and the total global cropland, that globally accounts for approx. 15 million km².

Table A. Carbon sequestration potential of land saving by the recovery of natural vegetation in Gt C and Gt CO_2 and the corresponding globally recovered area in km² for the three different saving strategies for the considered crops (see S2 Appendix).

	Area [million km²]	Additional carbon sequestration potential by land saving [Gt C]	Additional carbon sequestration potential by land saving [Gt CO_2]
BLS	4.0	41	151
SLS	3.8	39	144
ULS	3.1	31	114

Table B. Carbon sequestration potential of land saving by the recovery of natural vegetation in Gt C and Gt CO_2 and the corresponding globally recovered area in km² for the three different saving strategies, assuming that the considered crops are representative for the entire global cropland area.

	Area [million km²]	Additional carbon sequestration potential by land saving [Gt C]	Additional carbon sequestration potential by land saving [Gt CO_2]
BLS	6.3	66	242
SLS	3.1	63	231
ULS	4.9	50	185

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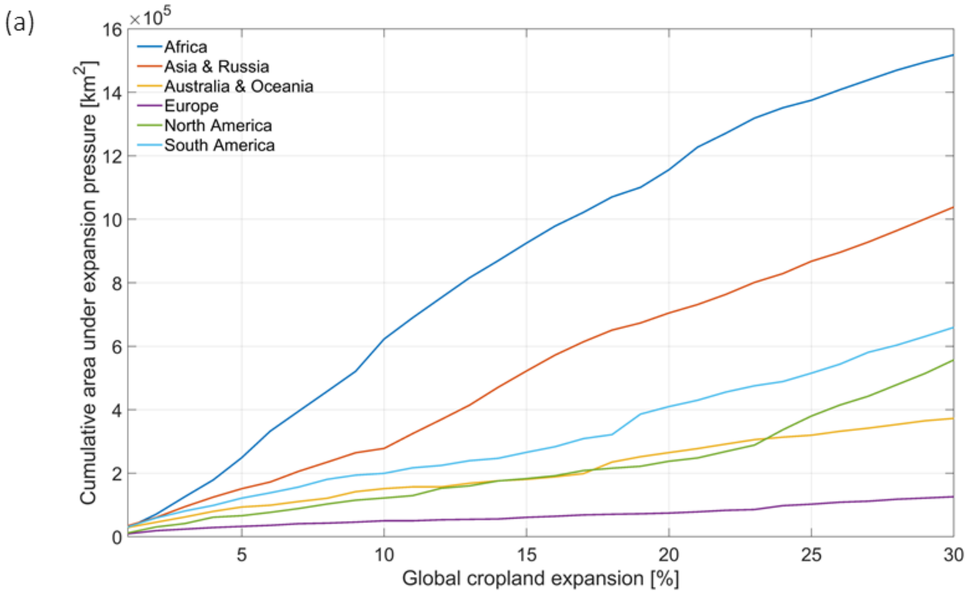
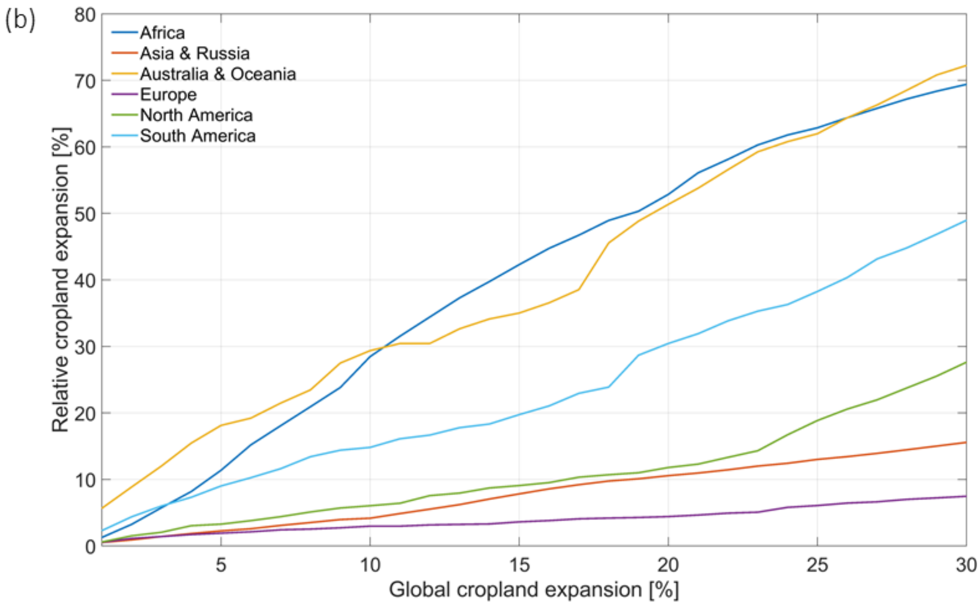
6.2 Supplementary Information of Publication 3

6.2.1 Supplementary Note 1: Global areas under expansion pressure (top 30%)

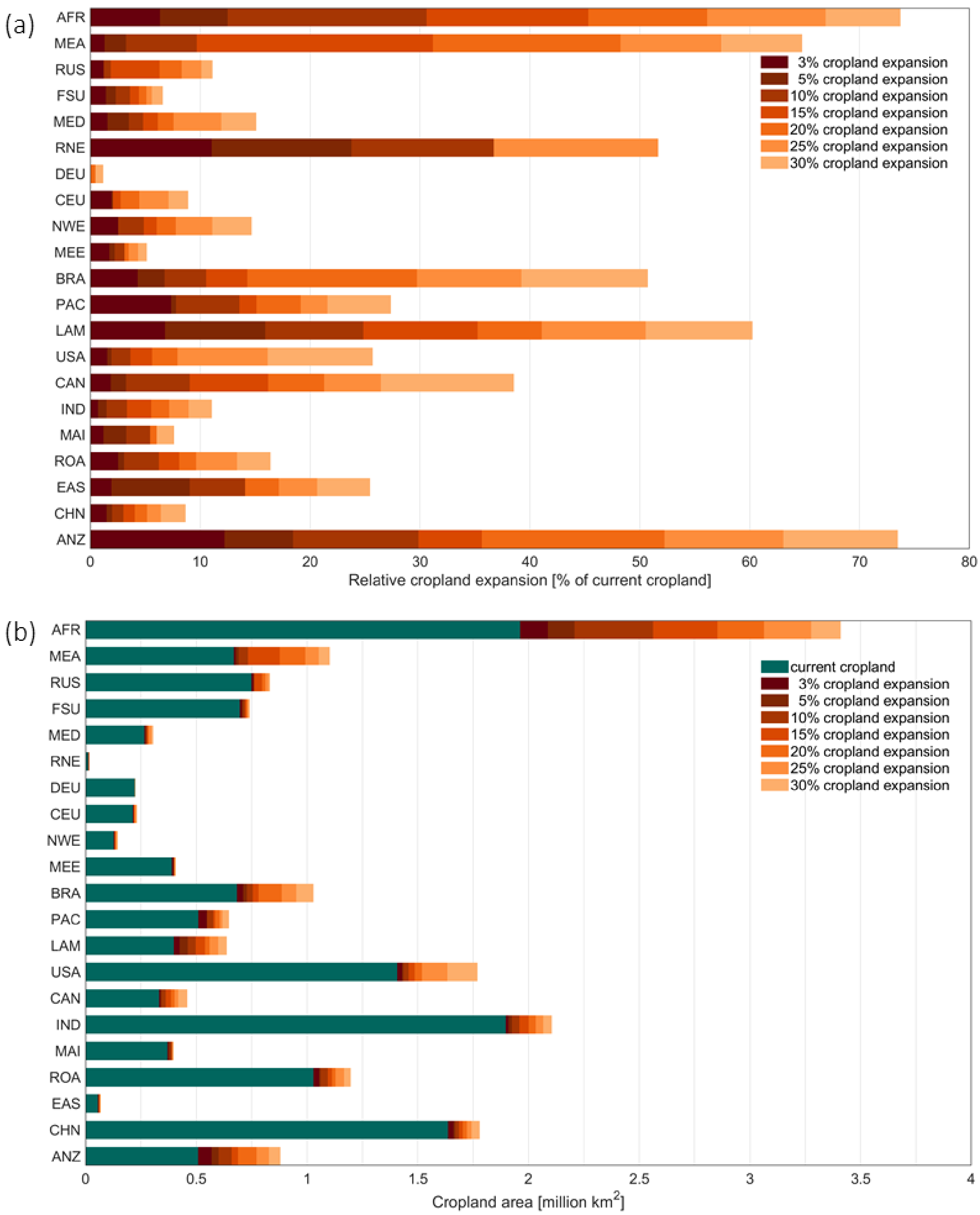
1.1 Regional details on areas under expansion pressure

The following figures provide a more detailed view on the spatial distribution of 4.27 million km^2 (an area equivalent to a global cropland expansion of up to 30%) that we identify to be relatively most profitable for cropland expansion. Ranking the identified areas according to their profitability and assuming that areas with relatively higher profitability are under a higher pressure of being converted into cropland, we can look at various global expansion targets, for example at a global expansion of current cropland by 3.6%, which is the projected cropland expansion until 2030 from the most recent FAO and OECD agricultural outlook[1]. The results show that particularly Australia, Brazil, China, Angola and Ethiopia are the five countries with the globally largest area under expansion pressure in this scenario, and moreover remain hotspots under a global cropland expansion of 5% and 10% (Supplementary Data). Additional information at country level and for further expansion targets is also provided in the dataset published with the article.





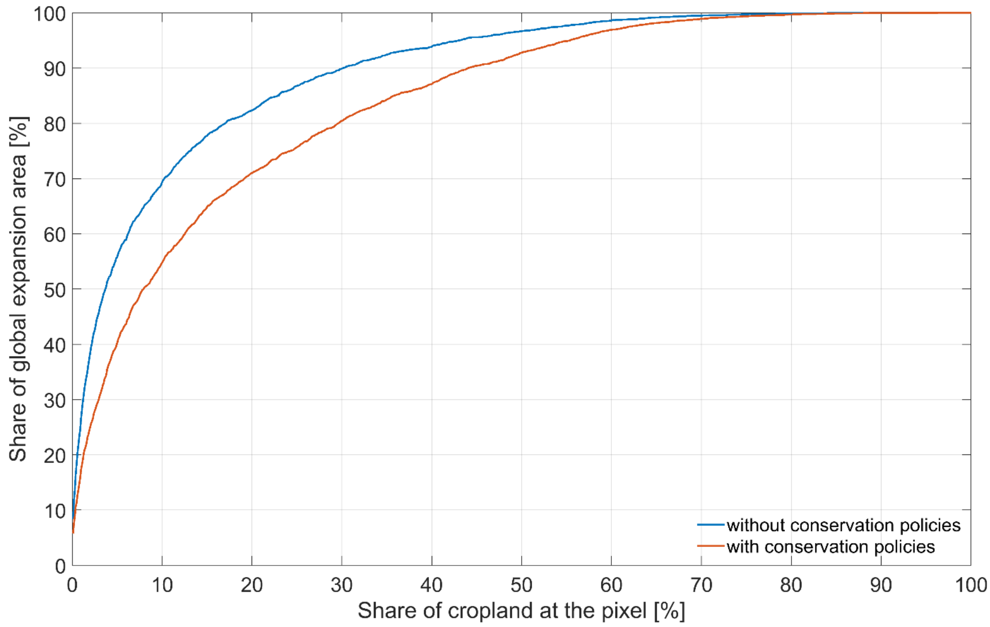
Supplementary Figure 1: Regional distribution of expansion pressure for global cropland expansion from 1% to 30% until 2030 without conservation policies. (a) displays the identified area of profitable land for expansion [km^2] for each world region under the different global cropland expansion scenarios. (b) shows the potentially induced relative expansion of current cropland [%] within each world region, if the identified profitable expansion areas were converted into cropland.



Supplementary Figure 2: Regional distribution of the globally most profitable areas for cropland expansion for a global cropland increase from 3% to 30% without conservation policies. (a) shows the resulting potential relative expansion of current cropland within each region, while (b) displays the absolute regional distribution of current cropland and the assessed profitable expansion areas under different global expansion targets up to 30%. The region mapping and abbreviations are displayed and explained in the Extended Data Figure 3.

1.2 Expansion pressure on already cultivated pixels

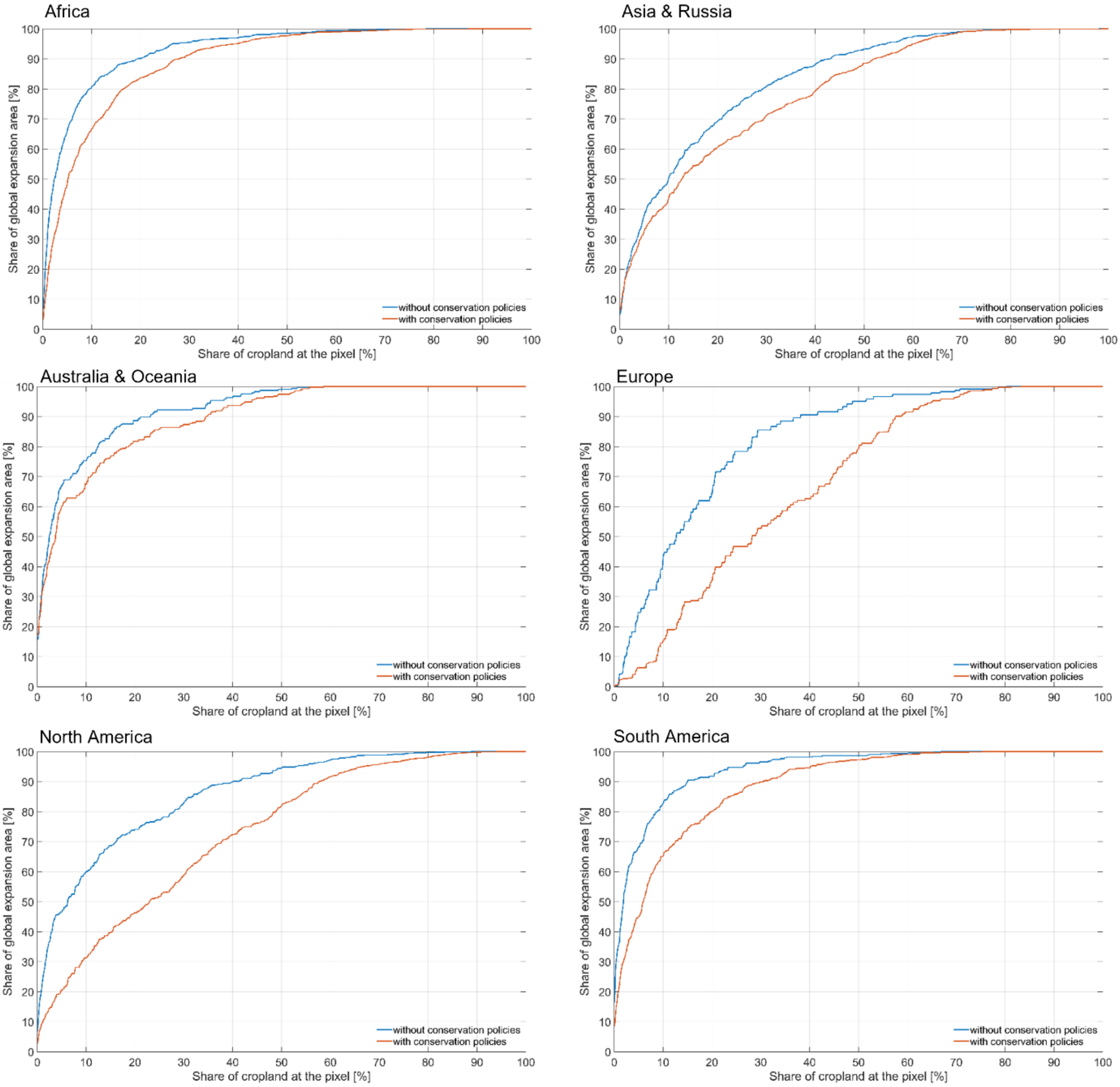
Due to the spatial explicitness of our approach, it is possible to investigate whether the areas under the highest expansion pressure are rather located at pixels that are already cultivated or not yet under agricultural use. Globally, more than two-third (70%) of the 4.27 million km^2 under expansion pressure is located at pixels with 10% or less cropland cover, and around 8% of the area is even located at cultivated pixels with a cropland cover share below 0.1% (Supplementary Fig. 3, blue graph). Looking at the expansion pressure from a 30% cropland increase with conservation policies, the most profitable expansion areas shift towards locations already under agricultural use. This reduces the global share of areas under expansion pressure being located at pixels with less than 10% cropland cover from 70% to 55%. Moreover, 6% of the global area under expansion pressure is located at pixels with a cropland cover share below 0.1% (Supplementary Fig. 3, red graph).



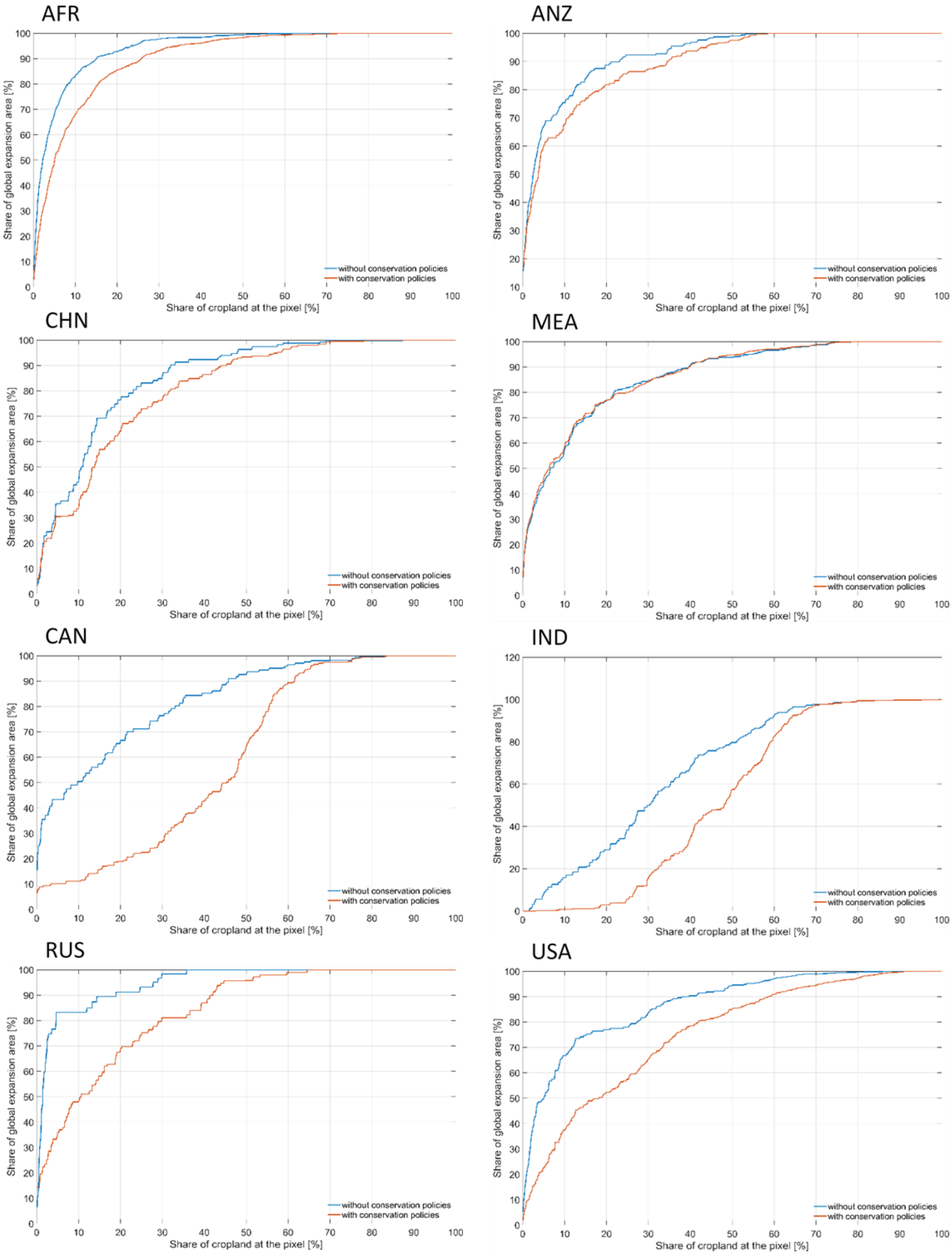
Supplementary Figure 3: Global cumulative share of the total area under expansion pressure [%] at pixels with shares from 0% to 100% currently covered with cropland, with (red graph) and without (blue graph) conservation policies, for a global cropland expansion of 30%.

Regional differences

Analyzing the regional differences in the profitability of current cropland frontiers without conservation policies, we see that the most profitable expansion areas are particularly located at the frontiers of current cropland in Regions in Asia and Europe, for example in China, India or the Mediterranean. In Russia, Sub-Saharan Africa and Regions in South America like Brazil or the Rest of Latin America, on the other hand, at least 80% or more of the regionally most profitable expansion areas are located at pixel with 10% or less cropland cover. The implementation of conservation policies shifts the expansion pressure to areas already under cultivation particularly in Canada, India, Russia and the United States of America (Supplementary Fig. 4 and 5). Detailed country wise information on the share of area under expansion pressure at pixels already cultivated can be found in the provided datasets of this study.



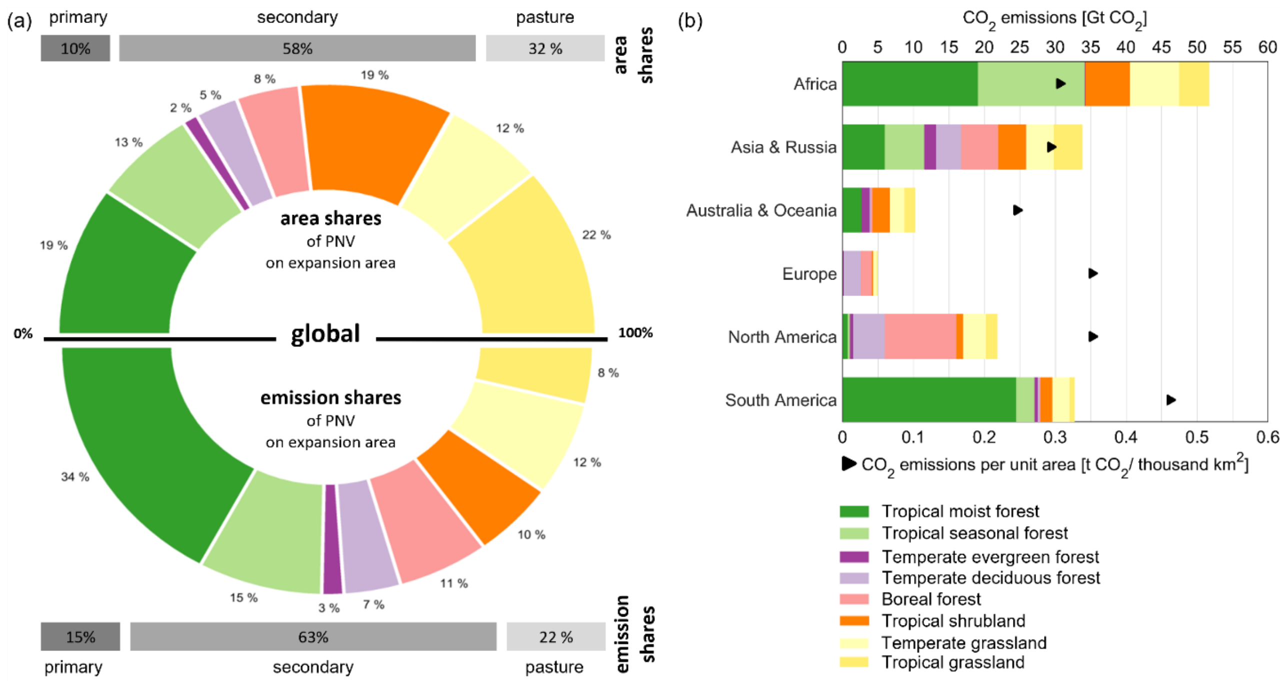
Supplementary Figure 4: Cumulative share of the regionally most profitable expansion area [%] located at pixels with shares from 0% to 100% currently covered with cropland for the six aggregated world regions. Results are displayed for cropland expansion with (red graph) and without (blue graph) conservation policies for a global cropland expansion of 30%.



Supplementary Figure 5: Cumulative share of the regionally most profitable expansion area [%] located at pixels with shares from 0% to 100% currently covered with cropland exemplarily for eight of the 21 economic study regions: Sub-Saharan Africa (AFR), Australia, New Zealand and Oceania (ANZ), China (CHN), Middle East and Northern Africa (MEA), Canada (CAN), India (IND), Russia (RUS) and the United States of America (USA). Results are displayed for cropland expansion with (red graph) and without (blue graph) conservation policies for a global cropland expansion of 30%.

1.3 Land-use change induced CO_2 emissions

Our results show that the majority of the most profitable areas for expansion we identify assuming an unrestricted expansion without conservation policies are located in the tropics. Accordingly, an expansion of current cropland of up to 30% mainly threatens land with tropical potential natural vegetation (PNV), such as tropical moist and seasonal forests, which cover around 19% and 13% of the identified global area under expansion pressure, respectively, tropical grasslands (22%) and tropical shrublands (19%). 15% of the expansion area is located on land with temperate and boreal forest PNV and 12% on temperate grassland PNV (Supplementary Fig. 6).

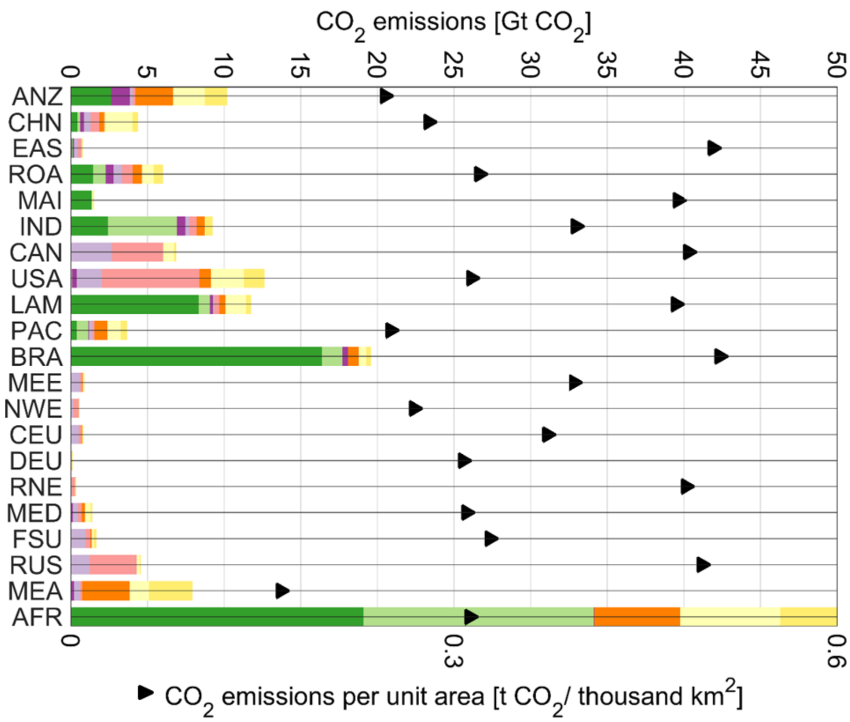


Supplementary Figure 6: CO_2 emissions potentially generated by converting the identified areas under expansion pressure up to a global cropland expansion of 30% into cropland (a) Shares of the different cover types (primary, secondary, pasture) and potential natural vegetation (PNV) types on the global area under expansion pressure (top) and the generated CO_2 emissions (bottom). (b) Regional distribution of the generated CO_2 emissions in absolute terms [Gt CO_2] and per unit area [t CO_2/ thousand km^2].

Of the emissions potentially generated by converting all identified areas under expansion pressure (4.27 million km^2) into cropland (around 156 Gt CO_2), 49% of the emissions would be generated by expansion into tropical forest PNV, mainly into primary moist tropical forest (11%) and secondary moist (23%) and seasonal (12%) tropical forests. 21% of the emissions would be induced by expanding into mostly secondary (79%) temperate or boreal forest PNV. The potential expansion into tropical and temperate grass- and shrubland PNV, of which half of it is currently used as pasture, would account for 30% of the global carbon emissions.

Regionally, the highest absolute emissions would be generated in the regions with the highest potentially expanded area: In Africa (51.6 Gt CO_2), CO_2 emissions would mainly be generated (66%)

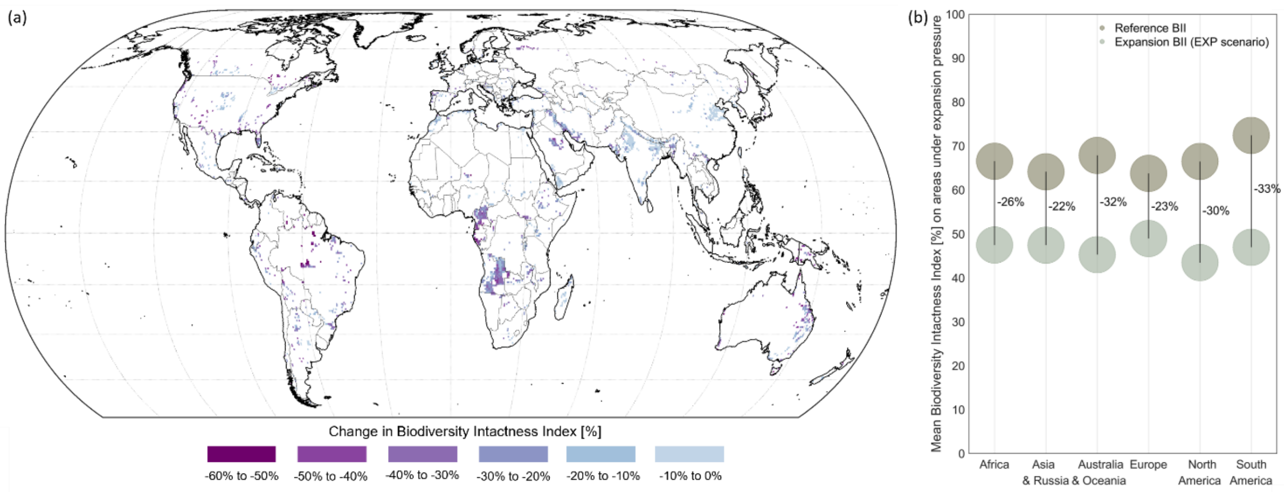
due to the conversion of tropical moist and seasonal forest PNV, whereas in Asia & Russia (33.8 Gt CO_2) around one-third of the emissions would be generated by the conversion of areas located in tropical (moist or seasonal) forests, one-third by the conversion of temperate and boreal forest PNV and the other third by the transformation of shrub- and grassland PNV. Similarly high total emissions would be generated in South America (33.2 Gt CO_2), where mainly tropical moist forest (75%) and tropical seasonal forests (8%) PNV is identified to be under expansion pressure, mainly in Brazil and the Rest of Latin America (Supplementary Fig. 7). This also explains the high level of carbon emissions per unit area in South America, as the share of (mainly tropical) forest PNV being potentially converted into cropland is particularly high (68% of total area under expansion pressure). The carbon emissions per unit area are also relatively high in Europe and North America due to the large shares of (exclusively and mainly temperate and boreal) forest PNV (76% and 53%, respectively) under expansion pressure. However, due to the small total area under expansion pressure in Europe, the induced total emissions of their conversion into cropland would be rather small (4.9 Gt CO_2). The also rather small total profitable expansion area in Australia & Oceania combined with 80% of the areas under pressure being located in grass- and shrubland PNVs leads to comparatively small total and per unit area carbon emissions associated with the conversion of the areas under pressure (10.2 Gt CO_2).



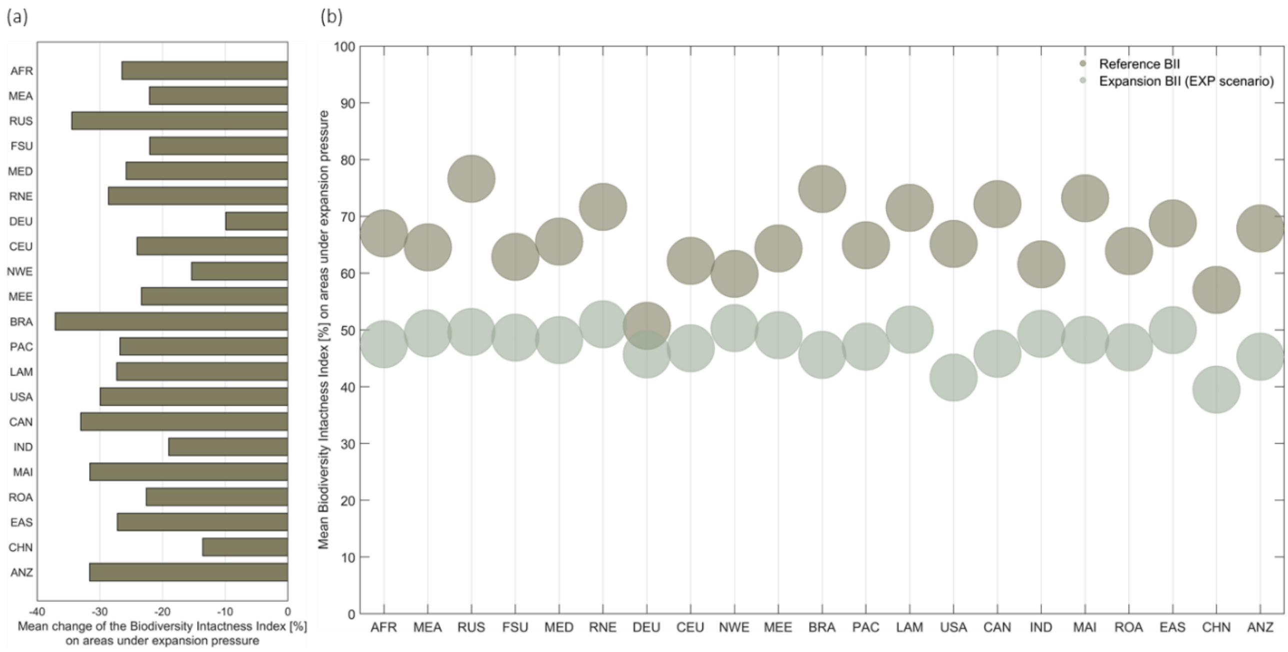
Supplementary Figure 7: Regional distribution of the CO_2 emissions induced by the conversion of the identified profitable expansion areas under a +30% cropland expansion without conservation policies in absolute terms [Gt CO_2], displayed in bar charts, and per unit area [t CO_2/ thousand km^2], displayed with the triangle. The region mapping and abbreviations are displayed and explained in the Extended Data Figure 3.

1.4 Assessment of biodiversity intactness

A conversion of the areas identified to be under expansion pressure under a cropland expansion of up to 30% without the assumption of conservation policies effects biodiversity intactness particularly in South America (Supplementary Fig. 8) with a BII decline across the areas by one-third (-33%). Here, biodiversity intactness is particularly endangered across the identified areas under expansion pressure in Brazil (-37%; Supplementary Figure 9), where these areas are mainly (89%) located on uncultivated pixels and around one-quarter of the identified area is currently covered with primary vegetation, 4% are even pristine ecosystems under very low human influence. High shares of primary vegetation under expansion pressure can be found in Malaysia and Indonesia, in Canada and in Russia, where the BII would decline by -32%, -33% and -34% across the areas, respectively, if converted into cropland. The BII would decrease less strongly in regions where the profitable expansion areas are mainly identified in locations currently already agriculturally used, such as in China (-14%) or parts of Europe, e.g. Germany (-10%) and North Western Europe (-15%).



Supplementary Figure 8: Impact of transforming the areas identified to be under expansion pressure for a global cropland expansion of up to 30% without conservation policies on the biodiversity intactness. (a) Percentage change of the Biodiversity Intactness Index (BII) compared to the reference biodiversity intactness on the pixels under expansion pressure. (b) Regional impacts on the BII. The dots display the reference BII on the areas under expansion pressure under current land-use (Reference BII) and under their use as cropland (Expansion BII). Moreover, the regional change in BII [%] is given as a percentage.



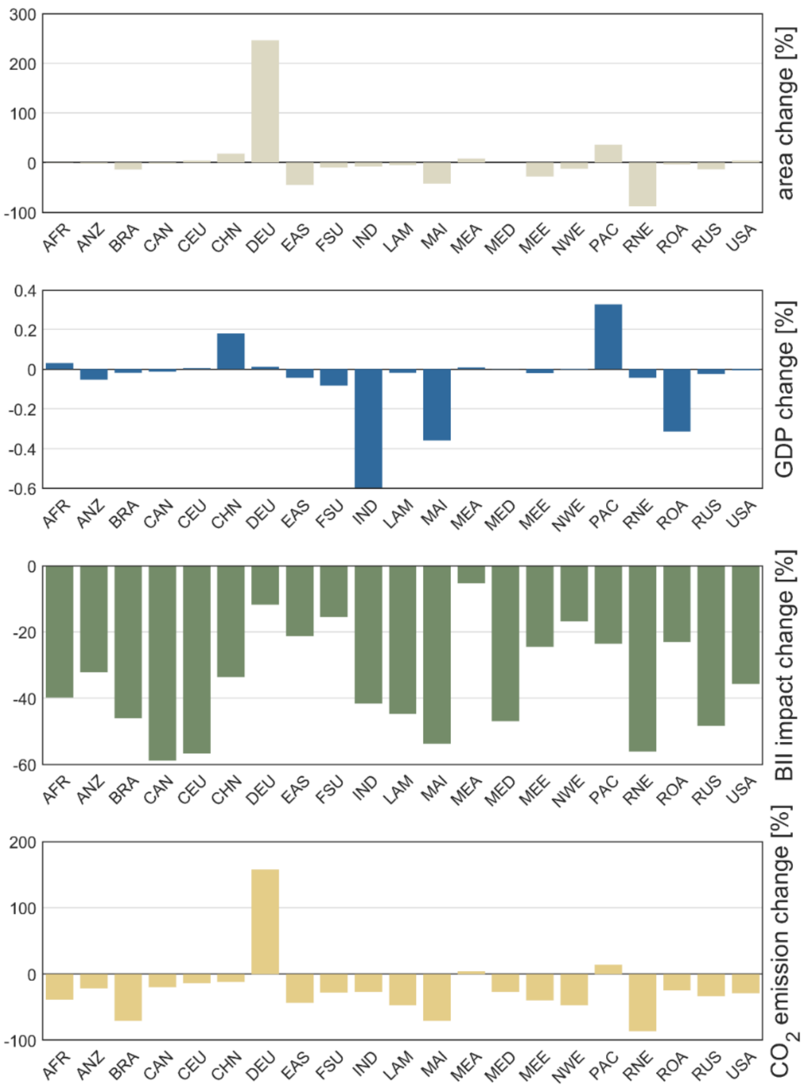
Supplementary Figure 9: Regional change in the Biodiversity Intactness Index (BII) [%] across the identified profitable expansion areas due to their conversion into cropland under the unrestricted expansion scenario with a global cropland expansion of 30%. (a) displays the mean percentage change of the BII [%], while (b) shows the mean Biodiversity Intactness Index [%] across the identified most profitable expansion areas under the EXP scenario before and after their conversion into cropland. The region mapping and abbreviations are displayed and explained in the Extended Data Figure 3.

1.5 Impact of conservation policies

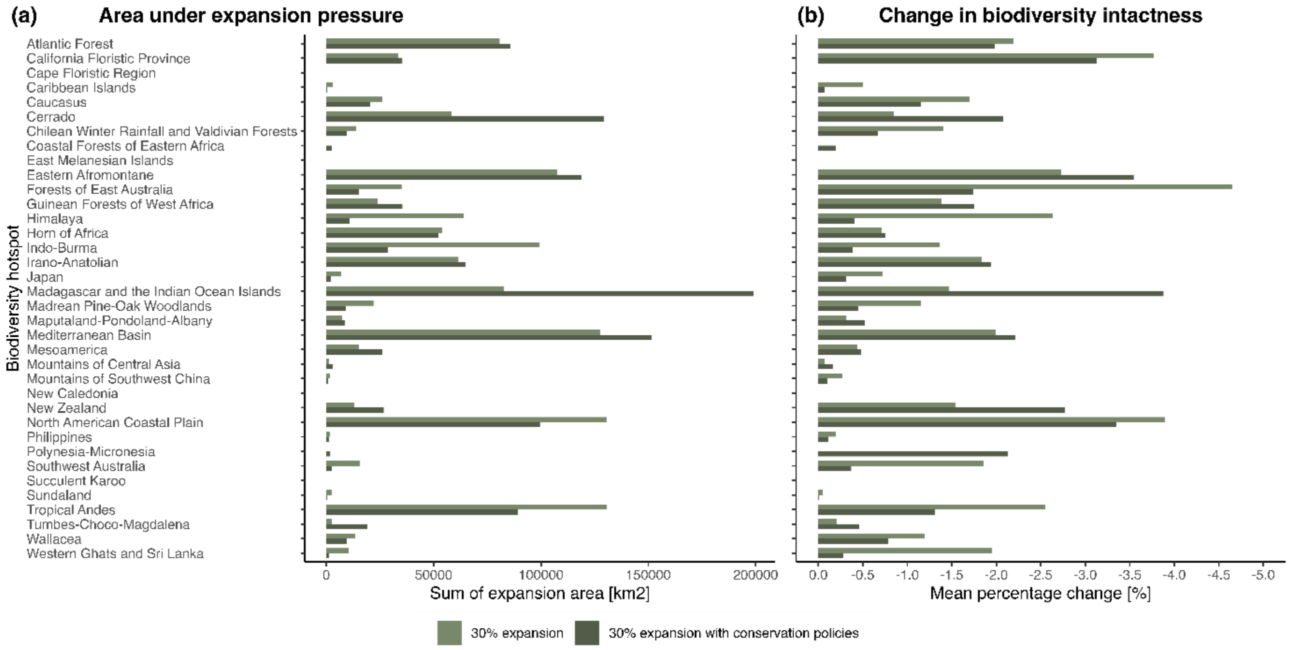
The following figures provide a more detailed overview of the spatial changes in the areas identified to be most profitable for cropland expansion up to +30% as well as the changes in the resulting effects of their conversion into cropland on generated carbon emissions and impacts on biodiversity intactness with conservation policies compared to without restrictions for cropland expansion.

Generally, we see that in some regions, the reduction in the area under expansion pressure due to the introduction of conservation policies decreases also the carbon emissions and the impacts on the BII associated with their conversion into cropland. The decreased area under expansion pressure in Brazil, for example, and its spatial shift away from mainly tropical forest PNV into pastureland and grass- and shrubland reduces the potential CO_2 emissions by more than two-third, and also the potential BII decline would be less strong (-20% instead of -37%). Interestingly, the environmental impacts of expansion are also reduced in regions where the total area under expansion pressure is unchanged. In Sub-Saharan Africa, for example, the area under expansion pressure remains nearly stable (+0.5%), but the spatial shift reduces both, the potential land-use change induced CO_2 emissions (-39%), and the decline of the BII (from -27% to -16%). On the other hand, the area under expansion pressure also increases under the implementation of conservation policies in some regions, such as in China, Paraguay, Argentina, Uruguay & Chile, or the Middle East and North

Africa. Yet, due to the concurrent spatial shift away from forests, wetlands and protected areas, this does not necessarily lead to increased potential environmental impacts: While in Paraguay, Argentina, Uruguay & Chile the area under expansion pressure increases by +36% and the CO_2 emissions associated with their conversion into cropland rise by +14%, the induced CO_2 emissions in China would be reduced by -12% despite an increase of the potential expansion area by +18%. The impacts on the BII would be less severe in both regions, with a BII decline reduced by -24% in Paraguay, Argentina, Uruguay & Chile and -34% in China (Supplementary Fig. 10). Exploring the expansion pressure on the worlds most threatened biodiversity hotspots[2] shows that while the introduction of conservation policies reduces the area under expansion pressure in hotspots such as for example the Forests of East Australia, Indo-Burma, the Irano-Anatolian hotspot, Southwest Australia or the Tropical Andes, the expansion pressure increases particularly in the Cerrado, the Madagascar and Indian Ocean Islands hotspot, the Eastern Afromontane and the New Zealand Hotspot (Supplementary Fig. 11).

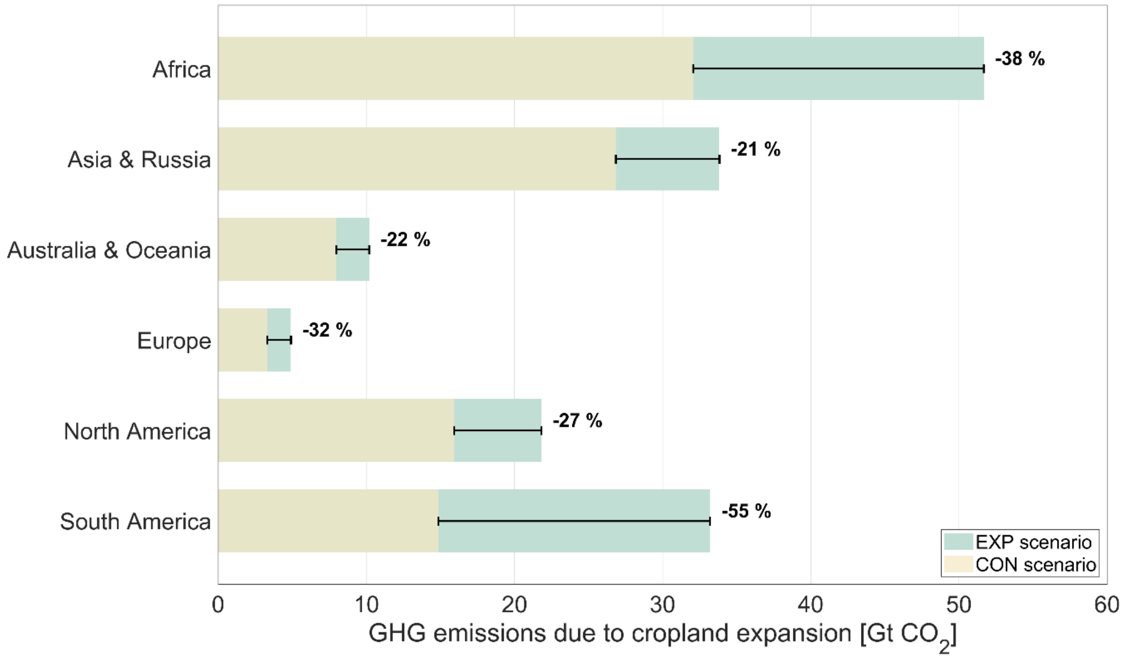


Supplementary Figure 10: Relative changes [%] between the areas under expansion pressure with and without conservation policies for an increase in current cropland of up to 30%, and changes in the BII [%] and the induced CO_2 emissions [%] resulting from the introduction of conservation policies, displayed for the 21 economic study regions. The region mapping and abbreviations are displayed and explained in the Extended Data Figure 3.

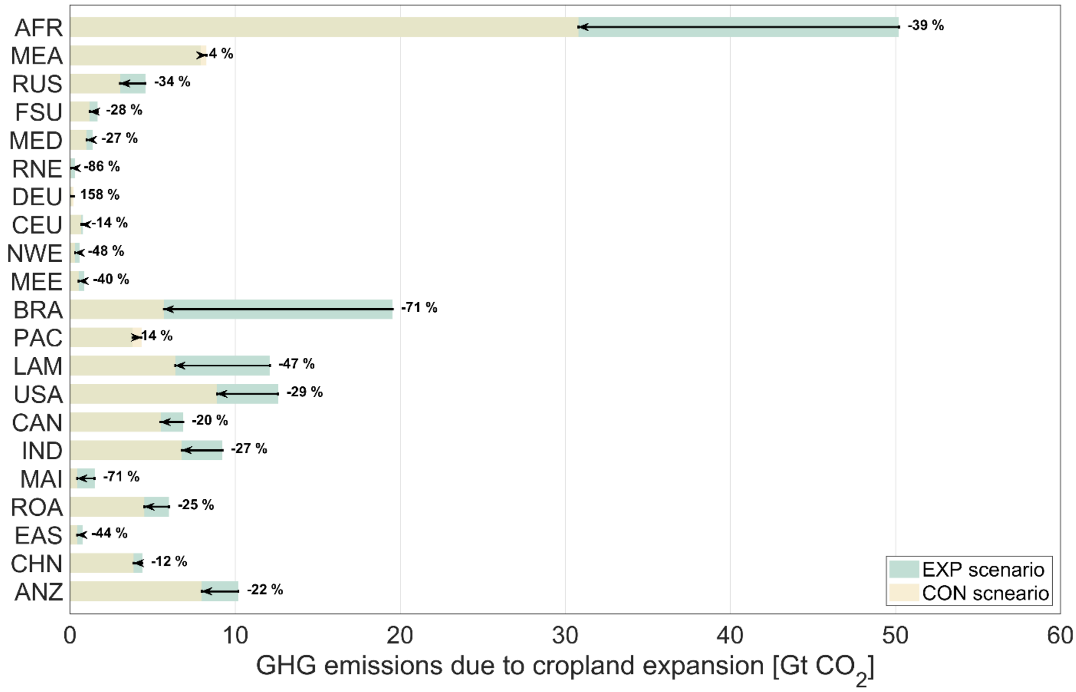


Supplementary Figure 11: Expansion pressure and changes in the biodiversity intactness in different Biodiversity Hotspots[2] for a global increase in current cropland by up to 30% with and without the consideration of conservation policies. (a) displays the area that is under expansion pressure in each Biodiversity hotspot (b) shows the resulting changes of transforming these areas under pressure into cropland in the Biodiversity Intactness Index.

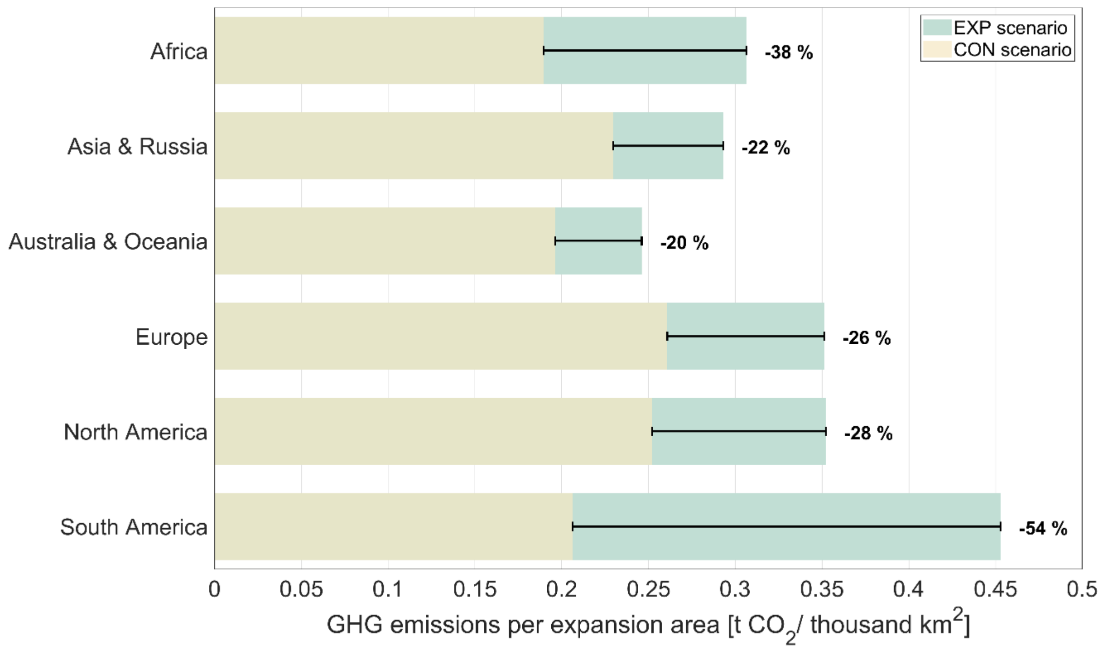
Impact of conservation policies: Supplementary Figures



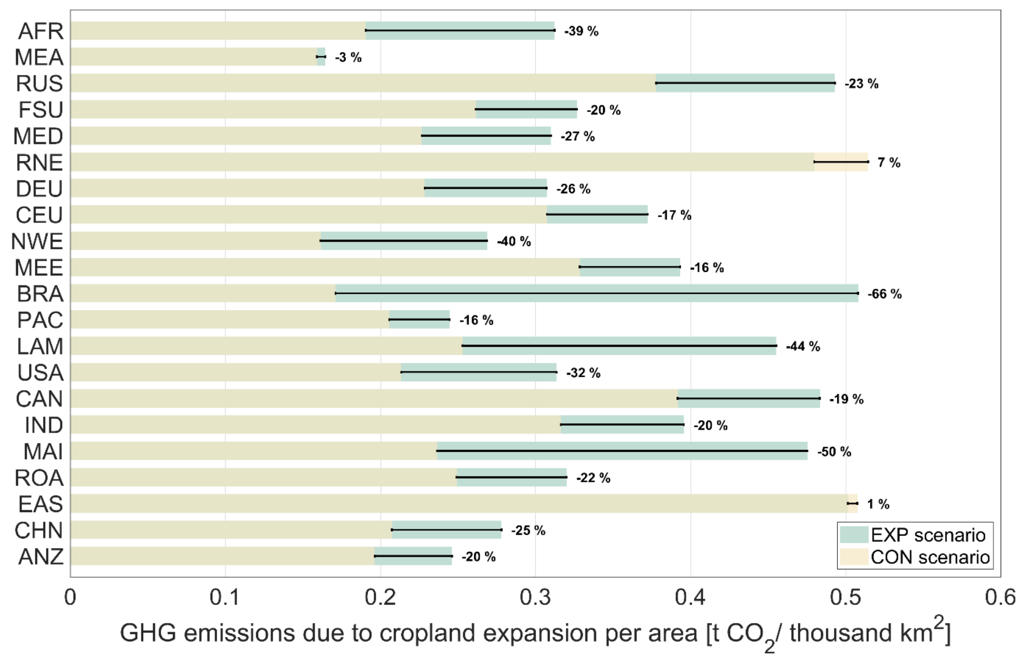
Supplementary Figure 12: Greenhouse emissions [Gt CO2] generated under an increase in current cropland by 30% without conservation policies and the relative changes [%] under the introduction of conservation policies for the aggregated world regions.



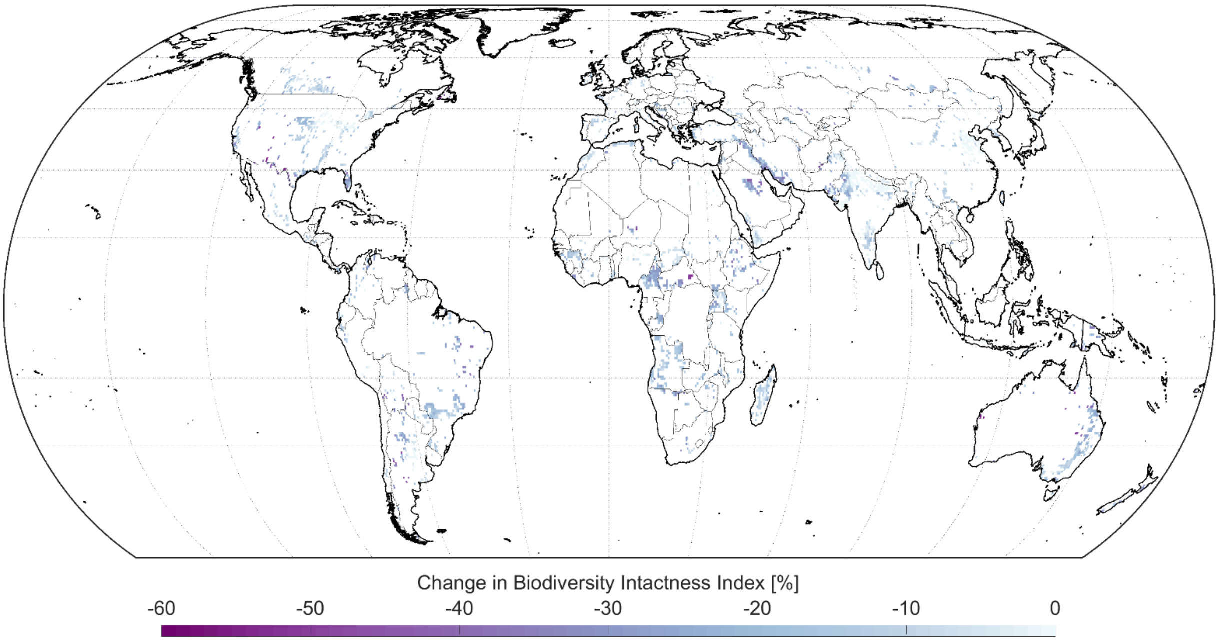
Supplementary Figure 13: Greenhouse emissions [Gt CO2] generated under an increase in current cropland by 30% without conservation policies and the relative changes [%] under the introduction of conservation policies for each of the 21 economic study regions. The region mapping and abbreviations are displayed and explained in the Extended Data Figure 3.



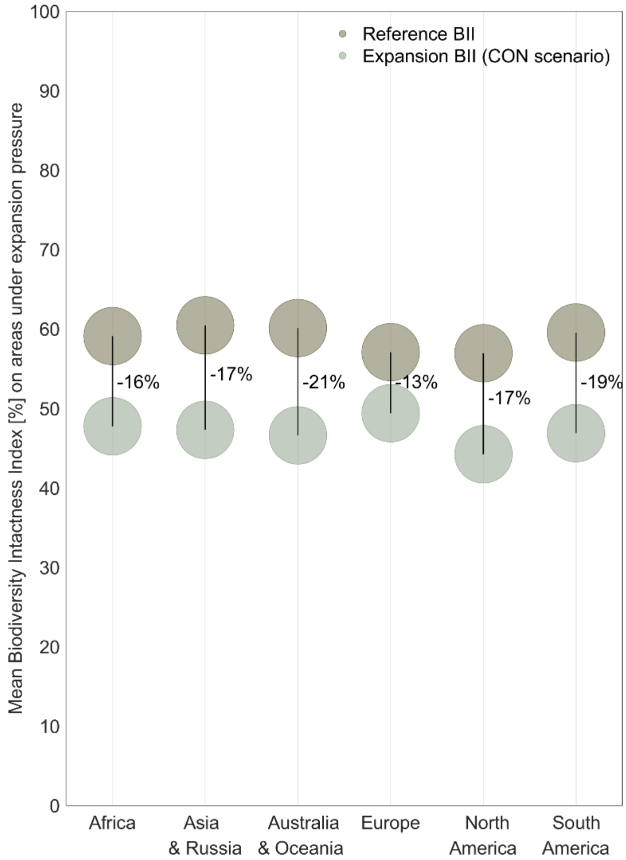
Supplementary Figure 14: Greenhouse emissions per area [t CO_2/ thousand km^2] generated under an increase in current cropland by 30% without conservation policies and the relative changes [%] under the introduction of conservation policies for the aggregated world regions.



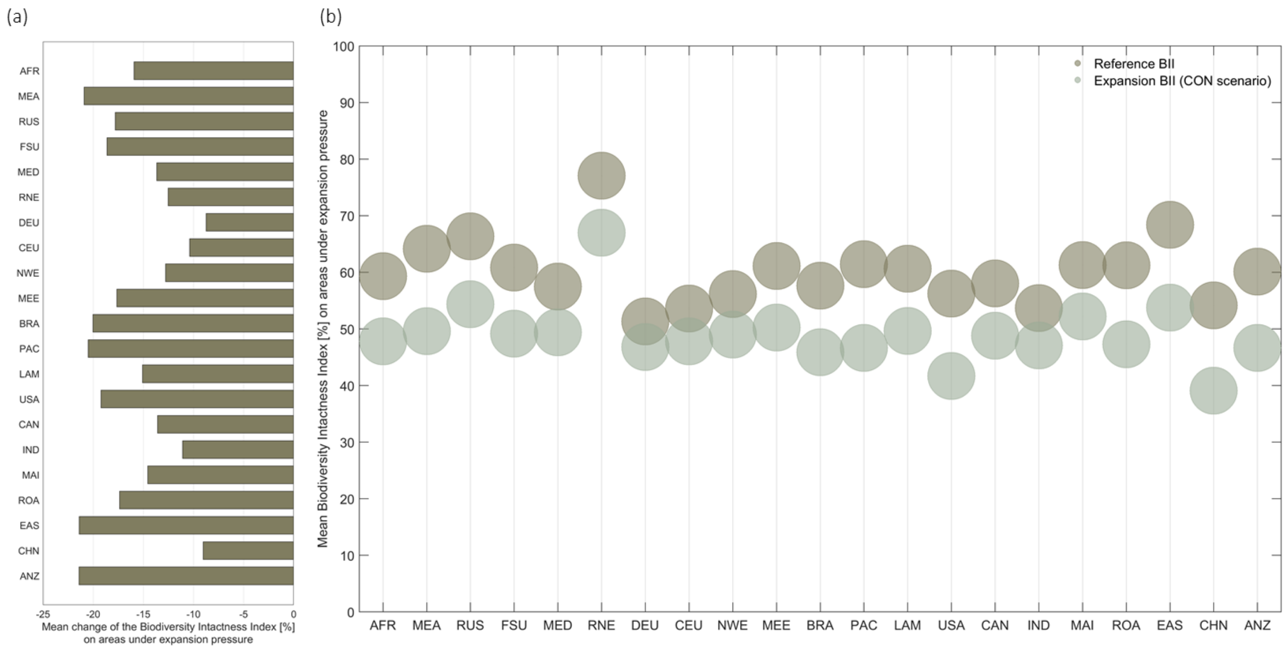
Supplementary Figure 15: Greenhouse emissions per area [t CO2/ thousand km2] generated under an increase in current cropland by 30% without conservation policies and the relative changes [%] under the introduction of conservation policies for each of the 21 economic study regions. The region mapping and abbreviations are displayed and explained in the Extended Data Figure 3.



Supplementary Figure 16: Percentage change map of the Biodiversity Intactness Index [%] under an increase in current cropland by 30% with conservation policies compared to the reference BII on the expanded pixels.



Supplementary Figure 17: Mean Biodiversity Intactness Index [%] across the identified most profitable expansion areas under a cropland area increase of up to 30% considering conservation policies before and after their conversion into cropland. This regional change in BII [%] before and after the conversion is displayed also as a percentage change [%].



Supplementary Figure 18: Regional change in the Biodiversity Intactness Index (BII) [%] across the identified profitable expansion areas due to their conversion into cropland under the expansion scenario with conservation policies (CON) with a global cropland expansion of 30%. (a) displays the mean percentage change of the BII [%], while (b) shows the mean Biodiversity Intactness Index [%] across the identified most profitable expansion areas under the CON scenario before and after their conversion into cropland. The region mapping and abbreviations are displayed and explained in the Extended Data Figure 3.

6.2.2 Supplementary Note 2: Biodiversity Intactness Assessment

2.1 Biodiversity Intactness Index: Data Preprocessing

The workflow to calculate the Biodiversity Intactness Index is adapted from the methods used in De Palma et al.[3] and the publicly available R-script of De Palma et al.[4]. We have modified the original script to include additional pressure variables and the extension dataset for the PREDICTS database[5].

To simulate the effects of different land-use classes and intensities, and to link the PREDICTS dataset to the land-use output of iLANCE, we created eight land use intensity classes (Primary vegetation with minimal use intensity, primary vegetation, secondary vegetation, cropland with minimal use intensity, cropland with light use intensity, cropland with intense use intensity, pasture and urban). We use the HILDA+ land-use/-cover data[6] to identify areas not used as cropland, pasture or urban areas and accordingly covered with potential primary or secondary vegetation, such as forests, unmanaged grass/shrubland or areas with sparse or no vegetation. To then differentiate between primary and secondary vegetation, we refer to the human influence dataset from Riggio et al.[7], which combines four spatial global datasets of human influence and their agreement on areas under low and very low human influence, taking various aspects into account, e.g. human population densities, anthropogenic forest cover change, roads and night-time lights. Primary vegetation and primary vegetation under minimal use are defined as forests, grass and shrublands or sparsely vegetated areas (HILDA+ classes 44, 55, 66) which are classified with a full agreement of all datasets considered by Riggio et al. to be under 'low human influence' and under a 'very low human influence', respectively. We consider remaining forests, grass and shrublands or sparsely vegetated areas not classified as being under (very) low human influence as secondary vegetation. The cropland areas are based on the iLANCE simulation results and thus based on Monfreda et al.[8] data scaled to the GTAP 9 database[9] (see Methods 2) and the assessed expansion areas. To distinguish between different land-use intensities, we refer to the current intensification level of agriculture, assessed by comparing the attained yields under the current agricultural intensification level with the simulated biophysical yield potentials at 0.5° spatial resolution. If less than 30% of the biophysical yield potential is attained, we assume low land-use intensity. Areas where yields range between 30% and 55% of the potentially attainable yield are considered as light use, while areas where 55% or more of the biophysical yield potential is attained are classified as intensively used cropland. Pasture areas derive from the HILDA+ land-use/ -cover dataset[6], while urban areas are based on the GMIS database[10]. To exclude areas with permanent snow/ice cover, we refer to the ESACCI land-use/ -cover dataset[11].

We use the information on land-use and intensity for each observation within the PREDICTS dataset[12]. The primary vegetation with minimal use intensity represents the reference, a pristine ecosystem state with minimal human influence. For simulating additional anthropogenic pressure, we use a 30 arc-second human population density (HPD) grid for 2020[13] and the global road vector dataset from the GRIP global roads database[14]. The human population density is log+1 transformed. The global roads dataset is reprojected to an equal-area Behrmann projection before calculating the distance to the nearest road (RD) for each location in the PREDICTS database, using the proximity to nearest feature function in QGIS version 3.30. Afterwards, the data is reprojected to a WGS84 projection and log+1 transformed. Both variables are standardized prior to modeling.

To account for environmental conditions for the compositional similarity model, the average bioclimatic variables (1970 - 2000) maximum temperature of warmest month (Bio5), minimum temperature of coldest month (Bio6), precipitation of wettest month (Bio13), precipitation of driest month (Bio14), as well as altitude[15] are used to calculate environmental similarity as Gower's distance for the environmental data between sites[16] with the gower package, version 1.0.1[17]. Afterwards environmental similarity is cube-root transformed. Finally, the geographical distance between sites is calculated and divided by the median maximum linear extent of the biodiversity dataset[3] before log+1 transforming using the geosphere package, version 1.5-18[15].

2.2 Modeling the Biodiversity Intactness Index

To simulate the impact of land use on biodiversity, two linear-mixed effects models are run, using lme4, version 1.1.32[18] following the general procedure described in De Palma et al.[3,4]: (1) The abundance model, which simulates the alpha diversity on local sites. For this purpose, the model considers the impact of land use, HPD, RD, and their two-way interactions as fixed-effects, and studies, as well as study blocks as random intercept. Following De Palma et al.[4], total abundance is calculated as the summarized abundance of all species on a local site, corrected by the sampling effort and rescaled to a zero to one scale. (2) The compositional similarity model, which simulates beta-diversity among local sites[3,4]. Therefore, all study sites containing more than one species, and at least one site with primary vegetation minimal use intensity (serving as reference) are selected to create a new dataset of site comparisons (Land use intensity class (comparison site) vs. reference). For all site comparisons the Bray-Curtis index is calculated[4,19]. Results are log+1 transformed. To incorporate the pressure of RD and HPD on sites, the difference between reference and comparison sites is calculated ($HPD_{Difference}$, $RD_{Difference}$). The resulting site-comparisons dataset is used to model the impact of each pressure (land use intensity, HPD, RD, geographic distance, environmental similarity), and their two-way interactions as fixed effects, studies and the land use intensity sites as random intercept to deal with the non-independence of the data[20] on compositional similarity. The mixed-effects structure of both models is adopted by De Palma et al.[4]. As described in De Palma et al.[3,4] we further extend the fixed effects by $HPD_{Difference}$ and $RD_{Difference}$, HPD and RD on the comparison site, as well as, environmental similarity between the sites. Collinearity is assessed using the car package[21] calculating generalized variance inflation factors (GVIF^(1/2*DF) < 3 in both models, indicating acceptable values of collinearity[20]). The final effect structure of the abundance and the compositional similarity model is shown below:

Abundance model (Eq. 1):

$$lmer\left(Abundance \sim LandUse_{Intensity} + HPD + RD + LandUse_{Intensity}{:}HPD + LandUse_{Intensity}{:}RD + (1|Study) + (1|Study_{Blocks})\right)$$

Compositional similarity model (Eq. 2):

$$\begin{aligned} lmer(&CompositionalSimilarity \sim \text{Geographic}_{\text{Distance}} + Environmental_{Similarity} + LandUse_{Contrast} \\ &+ HPD_{Difference} + RD_{Difference} + HPD_{ComparisonSite} + RD_{ComparisonSite} \\ &+ Geographic_{Distance}{:}LandUse_{Contrast} + Environmental_{Similarity}{:}LandUse_{Contrast} \\ &+ LandUse_{Contrast}{:}RD_{Difference} + LandUse_{Contrast}{:}HPD_{Difference} \\ &+ LandUse_{Contrast}{:}HPD_{ComparisonSite} + LandUse_{Contrast}{:}RD_{ComparisonSite} \\ &+ (1|Study) + \left(1\middle|LandUse_{ComparisonSite}\right)) \end{aligned}$$

The final estimates of the coefficients, the confidence interval, and the p-values of the abundance model are illustrated in Supplementary Table 1 below, while the final estimates of the coefficients and the confidence interval of the compositional similarity model are illustrated in Supplementary

Table 2. Results are bootstrapped with 1000 bootstrap replications using the sjPlot package, version 2.8.14[22].

Supplementary Table 1: Bootstrapped estimates, confidence intervals, and p-values of the abundance model.

	Abundance Model		
Predictors	*Estimates*	*Confidence interval*	*p-Value*
(Intercept)	0.65	0.63 – 0.67	<0.001
Cropland intense	-0.09	-0.12 – -0.06	<0.001
Cropland medium	-0.02	-0.05 – 0.01	0.210
Cropland minimal	-0.04	-0.07 – -0.01	0.018
Pasture	-0.04	-0.05 – -0.02	<0.001
Primary vegetation	0.02	0.01 – 0.04	0.006
Secondary vegetation	-0.02	-0.04 – -0.01	<0.001
Urban	0.07	0.03 – 0.10	<0.001
Human Population Density (HPD)	0.00	-0.00 – 0.01	0.422
Distance to the next road (RD)	-0.02	-0.02 – -0.01	<0.001
Cropland intense × HPD	-0.03	-0.04 – -0.01	0.008
Cropland medium × HPD	-0.05	-0.07 – -0.03	<0.001
Cropland minimal × HPD	-0.00	-0.02 – 0.01	0.686
Pasture × HPD	0.02	0.01 – 0.03	<0.001
Primary vegetation × HPD	-0.01	-0.02 – -0.00	0.022
Secondary vegetation × HPD	-0.01	-0.02 – -0.00	0.008
Urban × HPD	-0.04	-0.05 – -0.02	<0.001
Cropland intense × RD	0.01	-0.01 – 0.03	0.258
Cropland medium × RD	0.01	-0.01 – 0.03	0.466
Cropland minimal × RD	0.01	-0.01 – 0.03	0.564
Pasture × RD	0.03	0.02 – 0.04	<0.001
Primary vegetation × RD	0.00	-0.01 – 0.01	0.920
Secondary vegetation × RD	0.01	-0.00 – 0.02	0.254
Urban × RD	0.02	0.00 – 0.04	0.018
Random Effects			

σ^2	0.03
$\tau_{00\ SSB}$	0.01
$\tau_{00\ SS}$	0.03
ICC	0.52
N_{SS}	668
N_{SSB}	4014
Marginal R^2 / Conditional R^2	0.021 / 0.527

Supplementary Table 2: Bootstrapped estimates and confidence intervals of the compositional similarity model.

	Compositional Similarity	
Predictors	*Estimates*	*CI*
Intercept	0.50	0.48 – 0.53
Geographic distance	-0.02	-0.02 – -0.02
Environmental similarity	-0.04	-0.05 – -0.03
Land use contrast [Primary minimal vs. Cropland intense]	-0.19	-0.23 – -0.15
Land use contrast [Primary minimal vs. Cropland light]	-0.16	-0.22 – -0.08
Land use contrast [Primary minimal vs. Cropland minimal]	-0.16	-0.19 – -0.12
Land use contrast [Primary minimal vs. Pasture]	-0.19	-0.20 – -0.17
Land use contrast [Primary minimal vs. Primary vegetation]	-0.02	-0.03 – -0.01
Land use contrast [Primary minimal vs. Secondary vegetation]	-0.08	-0.09 – -0.07
Land use contrast [Primary minimal vs. Urban]	-0.11	-0.15 – -0.08
HPD, comparison site	-0.00	-0.01 – 0.00
HPD difference	-0.02	-0.02 – -0.02
RD, comparison site	0.01	0.01 – 0.01
RD difference between sites	0.01	0.00 – 0.01
Geographic distance x Land use contrast [Primary minimal vs. Cropland intense]	0.02	0.01 – 0.02
Geographic distance x Land use contrast [Primary minimal vs. Cropland light]	0.02	0.01 – 0.03
Geographic distance x Land use contrast [Primary minimal vs. Cropland minimal]	0.03	0.02 – 0.03

Geographic distance x Land use contrast [Primary minimal vs. Pasture]	0.02	0.01 – 0.02
Geographic distance x Land use contrast [Primary minimal vs. Primary vegetation]	0.00	0.00 – 0.01
Geographic distance x Land use contrast [Primary minimal vs. Secondary vegetation]	0.01	0.01 – 0.01
Geographic distance x Land use contrast [Primary minimal vs. Urban]	0.02	0.01 – 0.02
Environmental similarity x Land use contrast [Primary minimal vs. Cropland intense]	0.04	-0.02 – 0.10
Environmental similarity x Land use contrast [Primary minimal vs. Cropland light]	-0.33	-0.48 – -0.17
Environmental similarity x Land use contrast [Primary minimal vs. Cropland minimal]	-0.35	-0.43 – -0.26
Environmental similarity x Land use contrast [Primary minimal vs. Pasture]	-0.24	-0.27 – -0.20
Environmental similarity x Land use contrast [Primary minimal vs. Primary vegetation]	-0.16	-0.2 – -0.13
Environmental similarity x Land use contrast [Primary minimal vs. Secondary vegetation]	-0.03	-0.05 – -0.01
Environmental similarity x Land use contrast [Primary minimal vs. Urban]	-0.21	-0.31 – -0.11
Land use contrast [Primary minimal vs. Cropland intense] x HPD, comparison site	-0.03	-0.06 – -0.01
Land use contrast [Primary minimal vs. Cropland light] x HPD, comparison site	-0.01	-0.06 – -0.03
Land use contrast [Primary minimal vs. Cropland minimal] x HPD, comparison site	-0.04	-0.06 – -0.02
Land use contrast [Primary minimal vs. Pasture] x HPD, comparison site	-0.07	-0.08 – -0.06
Land use contrast [Primary minimal vs. Primary vegetation] x HPD, comparison site	-0.00	-0.01 – 0.01
Land use contrast [Primary minimal vs. Secondary vegetation] x HPD, comparison site	-0.02	-0.02 – -0.01
Land use contrast [Primary minimal vs. Urban] x HPD, comparison site	-0.01	-0.02 – -0.01
Land use contrast [Primary minimal vs. Cropland intense] x RD, comparison site	-0.08	-0.12 – -0.05

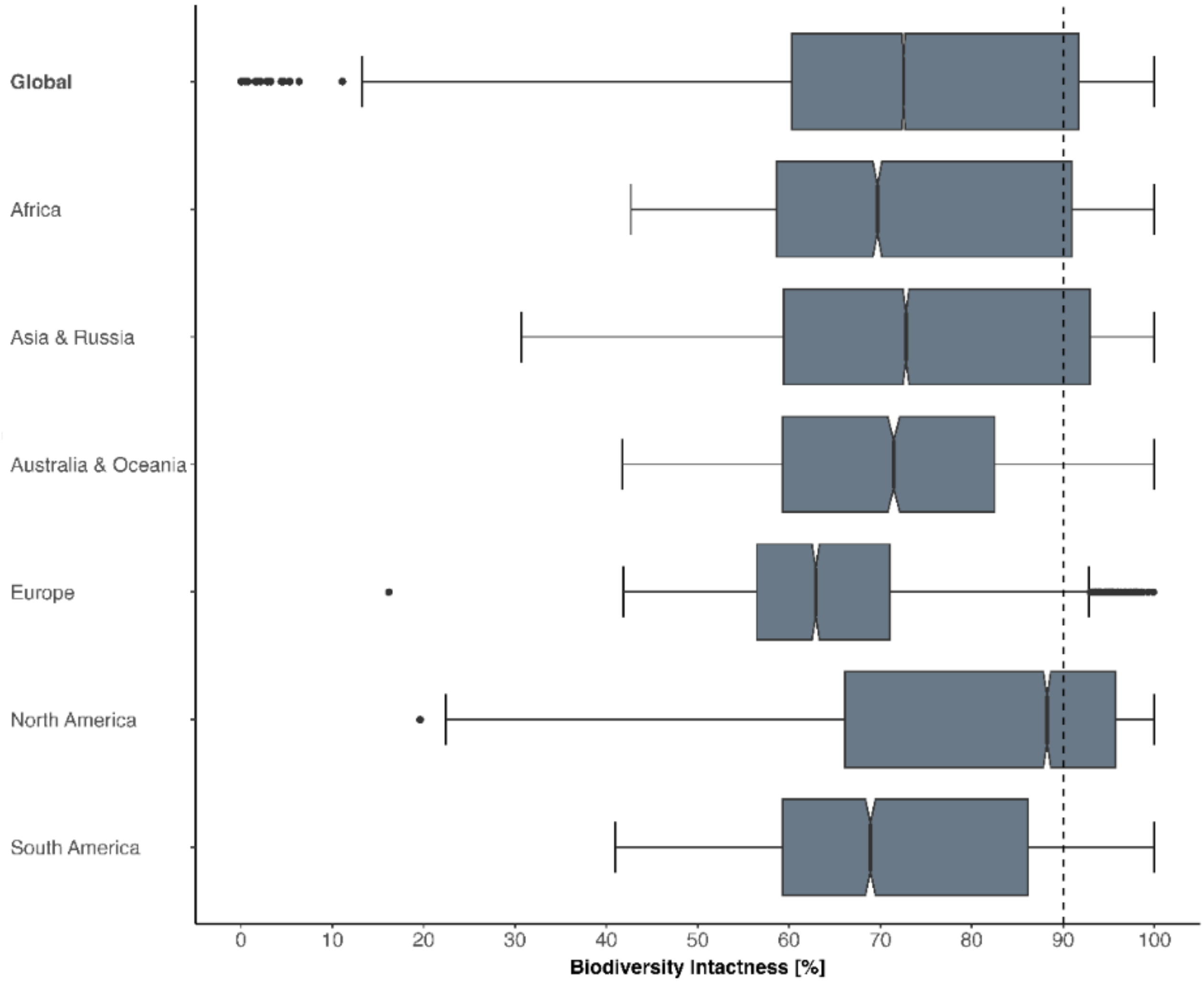
Land use contrast [Primary minimal vs. Cropland light] x RD, comparison site	0.01	-0.02 – 0.04
Land use contrast [Primary minimal vs. Cropland minimal] x RD, comparison site	-0.03	-0.05 – -0.02
Land use contrast [Primary minimal vs. Pasture] x RD, comparison site	-0.03	-0.03 – -0.02
Land use contrast [Primary minimal vs. Primary vegetation] x RD, comparison site	-0.02	-0.03 – -0.01
Land use contrast [Primary minimal vs. Secondary vegetation] x RD, comparison site	-0.02	-0.03 – -0.02
Land use contrast [Primary minimal vs. Urban] x RD, comparison site	-0.02	-0.03 – -0.00
Land use contrast [Primary minimal vs. Cropland intense] x HPD difference	0.02	0.01 – 0.04
Land use contrast [Primary minimal vs. Cropland light] x HPD difference	0.02	-0.05 – 0.10
Land use contrast [Primary minimal vs. Cropland minimal] x HPD difference	0.06	0.04 – 0.08
Land use contrast [Primary minimal vs. Pasture] x HPD difference	0.00	-0.01 – 0.01
Land use contrast [Primary minimal vs. Primary vegetation] x HPD difference	0.02	0.02 – 0.03
Land use contrast [Primary minimal vs. Secondary vegetation] x HPD difference	0.02	0.01 – 0.02
Land use contrast [Primary minimal vs. Urban] x HPD difference	0.03	0.02 – 0.03
Land use contrast [Primary minimal vs. Cropland intense] x RD difference	-0.06	-0.08 – -0.05
Land use contrast [Primary minimal vs. Cropland light] x RD difference	-0.01	-0.03 – 0.00
Land use contrast [Primary minimal vs. Cropland minimal] x RD difference	-0.02	-0.03 – -0.01
Land use contrast [Primary minimal vs. Pasture] x RD difference	-0.01	-0.01 – -0.01
Land use contrast [Primary minimal vs. Primary vegetation] x RD difference	-0.02	-0.02 – -0.01
Land use contrast [Primary minimal vs. Secondary vegetation] x RD difference	-0.02	-0.02 – -0.02

Land use contrast [Primary minimal vs. Urban] x RD difference	-0.02	-0.03 – -0.02
Random Effects		
σ^2	0.02	
$\tau_{00\ s2}$	0.01	
$\tau_{00\ SS}$	0.03	
ICC	0.65	
N_{SS}	225	
N_{s2}	8321	
Observations	544920	
Marginal R^2 / Conditional R^2	0.071 / 0.673	

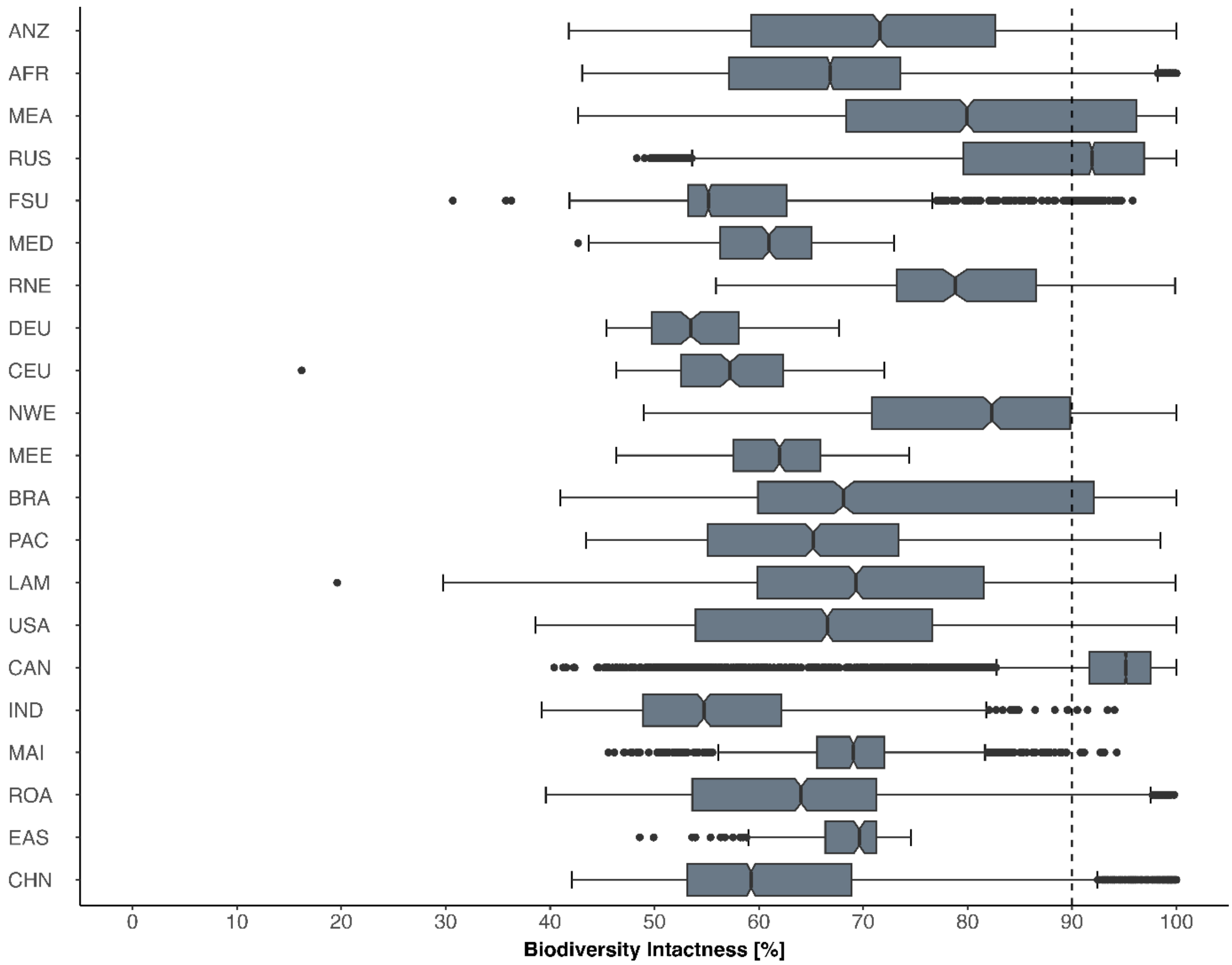
Predictions of abundance and compositional similarity for each land use intensity class are performed using lme4 package, version 1.1.32[18]. Before predictions, the square root transformation of total abundance, as well as, the logarithm of the compositional similarity is back transformed[3]. Based on these predictions, regression coefficients of both models are multiplied with the land use raster data for each land use intensity class. The BII is then the product of the resulting abundance and compositional similarity raster datasets[3] (Eq. 3).

$$BII = \left(\frac{Abundance_{LandUse_{Class}} * LU_{Class}}{Abundance_{Reference}} * \frac{Compositional\ Similarity_{LandUse_{Contrast}} * LU_{Class}}{Compositional\ Similarity_{Reference}}\right)$$

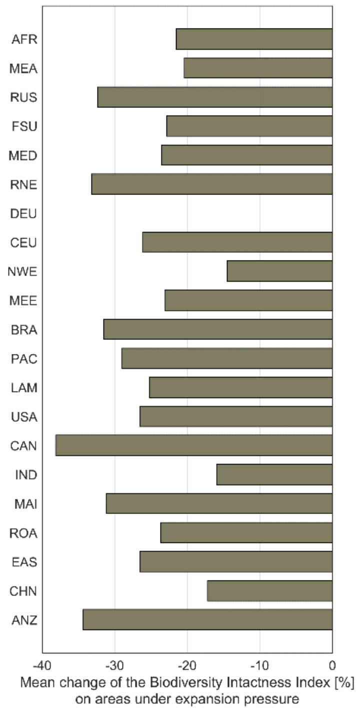
2.3 Additional results of the biodiversity intactness assessment



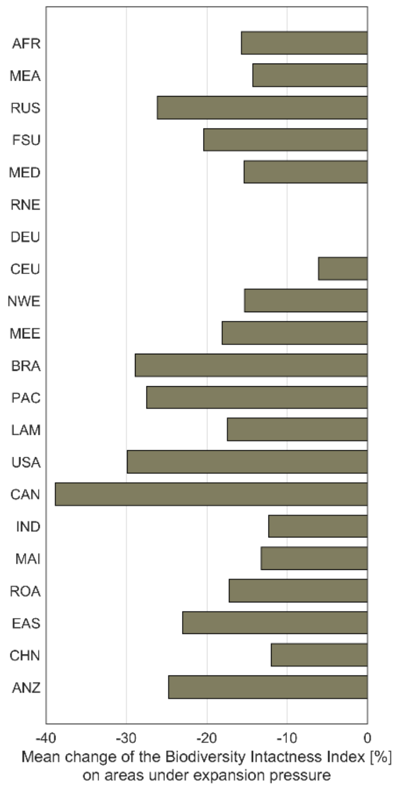
Supplementary Figure 19: Reference Biodiversity Intactness Index [%] globally and for each world region under the reference scenario based on current land-use/ -cover and using intensity. The Boxplots show the distribution of Biodiversity Intactness values for each pixel in the corresponding region.



Supplementary Figure 20: Reference Biodiversity Intactness Index [%] for each economic region under the reference scenario based on current land-use/ -cover and using intensity. The Boxplots show the distribution of Biodiversity Intactness values for each pixel in the corresponding region. The region mapping and abbreviations are displayed and explained in the Extended Data Figure 3.



Supplementary Figure 21: Regional impact of the transformation of the areas under expansion pressure into cropland on the biodiversity intactness in the 3.6% EXP scenario. The bars display the relative changes in the BII across the potential expansion areas for each economic region [%]. No cropland expansion is located in the region DEU and thus no change in the BII displayed.

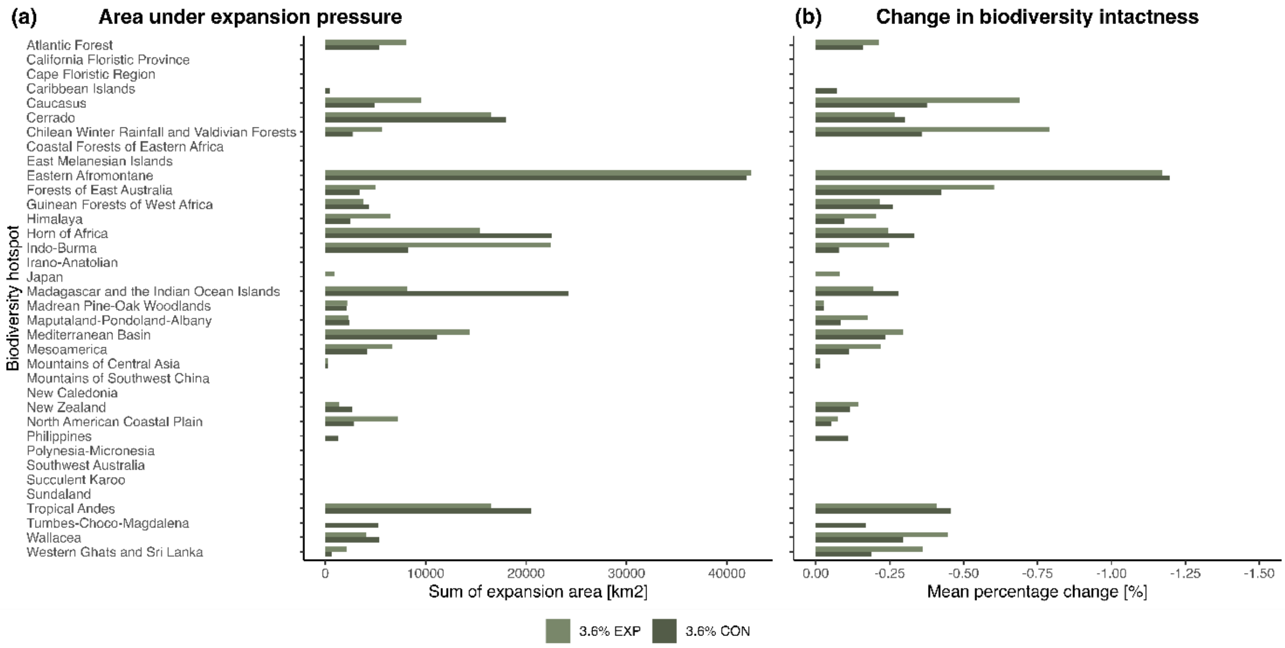


Supplementary Figure 22: Regional impact of the transformation of the areas under expansion pressure into cropland on the biodiversity intactness in the 3.6% CON scenario. The bars display the relative changes in the

BII across the potential expansion areas for each economic region [%]. No cropland expansion is located in the regions RNE and DEU and thus no change in the BII displayed.

2.4 Biodiversity intactness across biodiversity hotspots

We assessed the area under expansion pressure within the 3.6% EXP and CON scenario that is located in biodiversity hotspots that have already lost 70% of primary vegetation, while hosting at least 1,500 vascular plant species[2] and how biodiversity intactness changes across the biodiversity hotspot when the identified areas are converted into cropland.



Supplementary Figure 23: Expansion pressure and changes in the biodiversity intactness in different Biodiversity Hotspots[2] for a global increase in current cropland by 3.6% under the EXP scenario and CON scenario. (a) displays the area that is under expansion pressure in each Biodiversity hotspot (b) shows the resulting changes in the Biodiversity Intactness Index across the biodiversity hotspot if these areas under pressure were converted into cropland.

6.2.3 Supplementary Note 3: Sensitivity towards assumptions on agricultural intensification

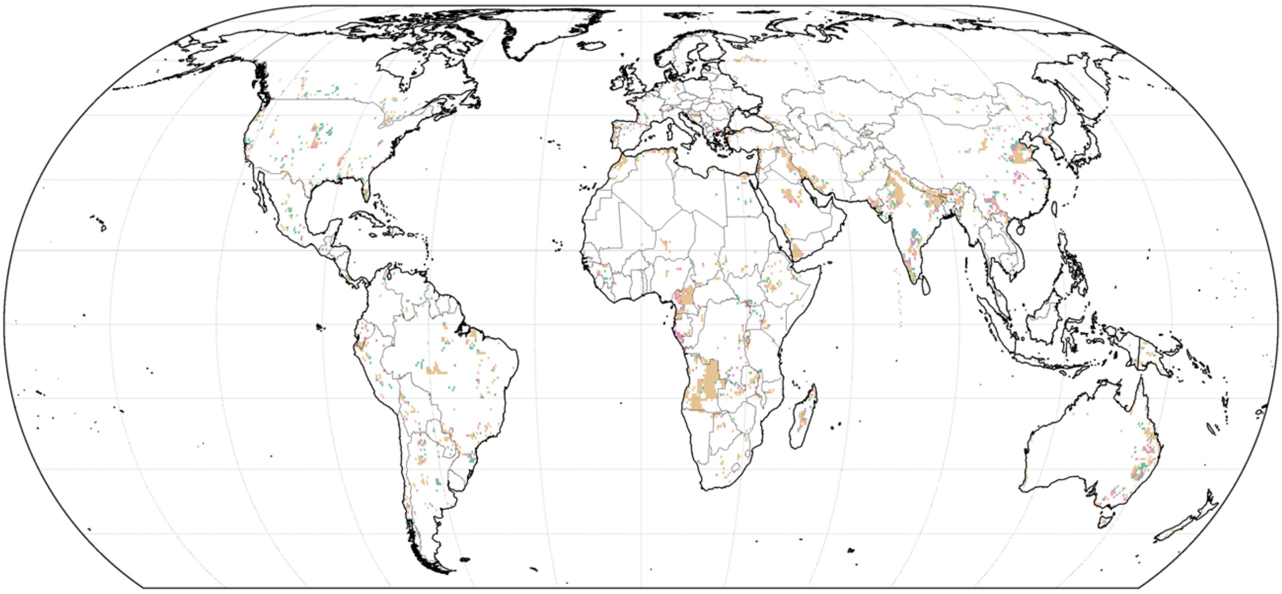
As described in Methods 2, we assume the potential expansion areas to be managed in the same intensity like the current cropland within the AES to focus solely on the dynamics of cropland expansion. Accordingly, the yield gap, which can be defined as the difference between the current yield and the yields that could potentially be achieved with agricultural intensification with optimized management under the given environmental conditions in each AES, are not closed. Even though agricultural intensification was and is projected to be a main source of growth in agricultural production[23], it can cause several environmental problems, such as groundwater pollution and depletion[24,25], increasing greenhouse gas emissions[26-29] or a negative impact on biodiversity[30,31]. However, its environmental effects also strongly depend on the implementation and the applied management practices[28,32-37], as there are also manifold concepts of sustainable intensification[38], contributing to close yield gaps without or with reduced negative environmental impacts, such as conservation agriculture[39] or smart farming technologies[40].

Due to the simulation of potential yields achievable under optimized management conditions, our approach allows for individual assumptions on agricultural intensification and accordingly on the degree to which yield gaps are closed. We can thus assess how sensitive the spatial location of the most profitable land for expansion is towards changes in the assumption on future agricultural intensification and yield gap closing. This is done by identifying the most profitable expansion areas under the EXP scenario in steps of 10 from 0% yield gap closing to 100% yield gap closing. By enabling yield gap closing instead of a fixed proportion of the biophysical yield potential, regional differences in current yields and yield gaps can be taken into account that reflect, inter alia, the socio-economic framework within each sub-region. This approach was also evaluated by stakeholders within a co-design process for scenario-development[41].

By analyzing how often an area is identified as being among the globally most profitable ones for expansion, we classify the expansion areas as areas with a low sensitivity, if they are classified as profitable in at least 8 out of the 11 runs with various yield gap closing assumptions. Areas have a medium sensitivity towards agricultural intensification, if they are identified 4 to 7 times as most profitable expansion areas, and are highly sensitive, if they are only identified as profitable in 1 to 3 yield gap closing runs (Supplementary Fig. 24).

Analyzing the areas under expansion pressure for a cropland increase of up to 30% until 2030, we find that globally, around 83% of the areas show a low sensitivity towards changes in the assumptions on agricultural intensification, while 10% are highly sensitive and identified as most profitable areas only in one to three yield gap closing runs. The lowest sensitivity can be observed in the Middle East and Northern Africa, Sub-Saharan Africa, Russia and Middle Eastern Europe, but also North and North Western Europe and Central and South America. In these regions, more than 80% of the identified most profitable expansion areas are identified as such independently of the assumed yield gap closing scenario. Accordingly, those areas are most likely to be under a high expansion pressure in the future, regardless of potential future developments in agricultural intensification.

Regions with the highest sensitivity towards yield gap closing assumptions, on the other hand, are regions with an already strongly intensified and industrialized agriculture and accordingly small yield gaps, such as Central Europe and Germany in particular, Canada and the USA. As yields rise with agricultural intensification also in other regions with currently larger yield gaps, those areas in industrialized regions become less profitable for cropland expansion compared to land in regions with large yield gaps and are thus not any more among the globally most profitable expansion areas.



Supplementary Figure 24: Sensitivity of the identified most profitable expansion areas towards changing assumptions on the intensity of crop cultivation on the expanded land. Areas with a low sensitivity (yellow) are identified in at least eight out of eleven model runs under different scenarios of yield gap closure as the globally most profitable ones under a global cropland expansion of up to +30% without conservation policies. Areas with a medium sensitivity (pink) are in around half of the yield gap scenario runs (four to seven times) among the globally most profitable areas. Areas with a high sensitivity (green) towards different assumptions on the agricultural intensity of crop cultivation are only identified in one to three out of eleven runs as globally among the most profitable expansion areas.

6.2.4 Supplementary Note References

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