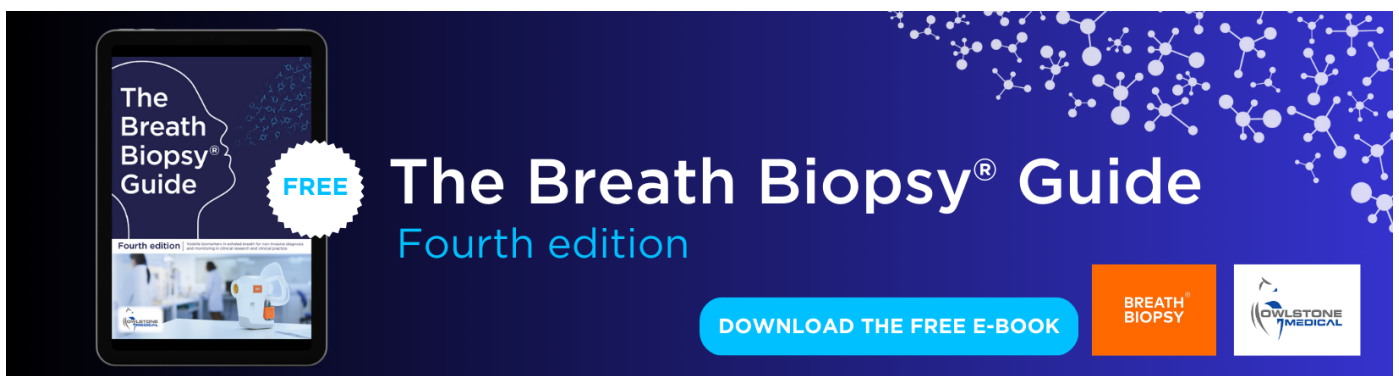**LETTER • OPEN ACCESS**

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LETTER

Emission savings through the COP26 declaration of deforestation could come at the expense of non-forest land conversion

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Abstract

The majority of signatories to The United Nations Climate Change Conference in 2021 (COP26) made a declaration to end deforestation by 2030. Here, we quantify future changes in land use and associated CO_2 emissions to examine the impact of ending deforestation by 2030 on global land dynamics and emissions using an open-source land-use model. We show that if the COP26 declaration to end deforestation is fully implemented globally, about 167 Mha of deforestation could be avoided until 2050, compared to a baseline scenario which does not have extended forest protection. However, avoided deforestation and associated emissions come at the cost of strongly increased conversion of unprotected non-forested land to agricultural land, while land-use intensification in most regions is similar compared to a baseline scenario. Global initiatives are needed to facilitate a common dialogue on addressing the possible carbon emissions and non-forest leakage effects due to the expedited loss of non-forested land under a policy aimed at halting deforestation by 2030.

1. Introduction

The world has lost one-third of its forest, an area approximately the size of the USA, China and India combined (ca. 2000 Mha) compared to 10 000 years ago [1–3]. In the past three decades (1990 to 2020), the net global forest area loss was 178 Mha (420 Mha deforestation and 242 Mha forest expansion) [4]. Global forest loss was, and still is, driven mainly by the continued expansion of land for agricultural use [5, 6] with about 80% of the global deforestation being a result of agricultural production [7, 8].

Large-scale deforestation has the potential to alter the local climate and can contribute to global warming [9]. Global emissions from deforestation due to agricultural expansion amounted to 3 Gt CO_2 in 2019 [10]. Reducing deforestation (and forest degradation) reduces CO_2 emissions, with an estimated technical mitigation potential of 0.4–5.8 GtCO$_2$ yr^{-1} [11–15]. With such global (and

local) consequences, it is imperative that natural forests are protected from deforestation.

The United Nations Climate Change Conference in 2021 (COP26) in Glasgow, Scotland, marked a renewed international focus on reducing emissions from the world's forests, with 145 nations representing 91% of global forest cover committing to work collectively to halt deforestation by 2030 [16].

Protecting forest areas and reducing deforestation plays an important role in climate change mitigation [17]. The strict implementation of protected areas in forests has been successful in limiting agricultural expansion into forests both on regional [18] and global scale [19]. Yet, there is a risk that forest protection efforts may stop deforestation in newly protected areas while displacing forest loss to unprotected areas [20–23].

Investments in agricultural intensification while protecting tropical forests is also shown to be a successful measure to tackle deforestation from cropland

and pastures expanding into forests if enforceable policy mechanisms are in place [24]. Partial or non-exhaustive land-use restrictions (e.g. logging bans) have had mixed success in combating deforestation for agriculture, in part because of the difficulties in enforcing selective bans on clearing activities across large areas [24].

Protecting existing carbon stores on land is a priority for efficient natural climate solutions [25]. As a recurring element of the nationally determined contributions (NDCs) submitted after the Paris Agreement, the land system has the potential to generate up to 25% of the planned emission reductions by 2030 with forests playing an important role in achieving this goal [26] by 2030. Pathways that prevent the loss of native ecosystems are also estimated to provide more than half of the pan-tropical cost-effective climate mitigation potential by 2050 [27].

Quantifying the implications that the COP26 declaration on stopping deforestation by 2030 have on land use is crucial because it bears the risk to generate additional pressure on agricultural systems to intensify and the risk to displace land-use change to other ecosystems [23, 28]. To the best of our knowledge the effects of the COP26 declaration to end deforestation on global and regional land-use dynamics and emissions, as well as future emission pathways, have not yet been studied comprehensively.

Currently, there is no single global land-use modeling study, which specifically accounts for the aspiration of stopping deforestation by 2030 while simultaneously accounting for the competition of land between agriculture and forestry. It also remains unclear if and to what extent such a mandate could affect competition for land in the future. In this study, we estimate for the first time the potential CO_2 emissions and land-use consequences of the declaration made at COP26 to end deforestation by 2030 using the recursive-dynamic partial equilibrium land-use model of agricultural production and its impact on the environment (MAgPIE) [29]. MAgPIE accounts for competition for land between agriculture and forestry at global and regional level [30]. We also quantify the relative CO_2 emission savings from such a policy compared to a baseline scenario (see section 2).

We analyze two scenarios: 1) a baseline deforestation scenario following the middle of the road shared socioeconomic pathway (SSP2) over the course of this century, and, 2) a COP26 scenario where the declaration to end deforestation by 2030 is realized globally assuming full enforcement of such a policy in every country across the globe. Global policy to halt agriculture-driven deforestation is ramped up before 2030 and fully achieved by 2030 in the COP26 scenario.

In the scenarios discussed here, deforestation is considered as the removal of trees followed by conversion of the erstwhile forest area to another land-use (e.g. agriculture). Such reclassification of forest land to alternative land-use(s) means that the opportunity to have regrowing trees after tree removal is lost. Deforestation in MAgPIE under both the scenarios is driven by demand for agricultural land needed to meet food, feed and livestock demand, determined via the socio-economic drivers (figure 1) in an SSP2 world. We assume that the COP26 declaration is implemented by 2030 uniformly across the globe to be in line with the COP26 declaration of stopping deforestation by 2030.

The COP26 scenario presented here is designed to prevent any conversion of forest land (primary forest, secondary forest and forest plantations) to agricultural use (cropland and pasture) (table 3). Primary forests are untouched forests without any sign of human intervention [31]. Primary forest area cannot increase in MAgPIE in both scenarios, since any human intervention in primary forest area results in reclassification of such area. Primary forests cannot be converted to agricultural land in the COP26 scenario. Roundwood removal from forests is allowed in both the baseline and the COP26 scenarios.
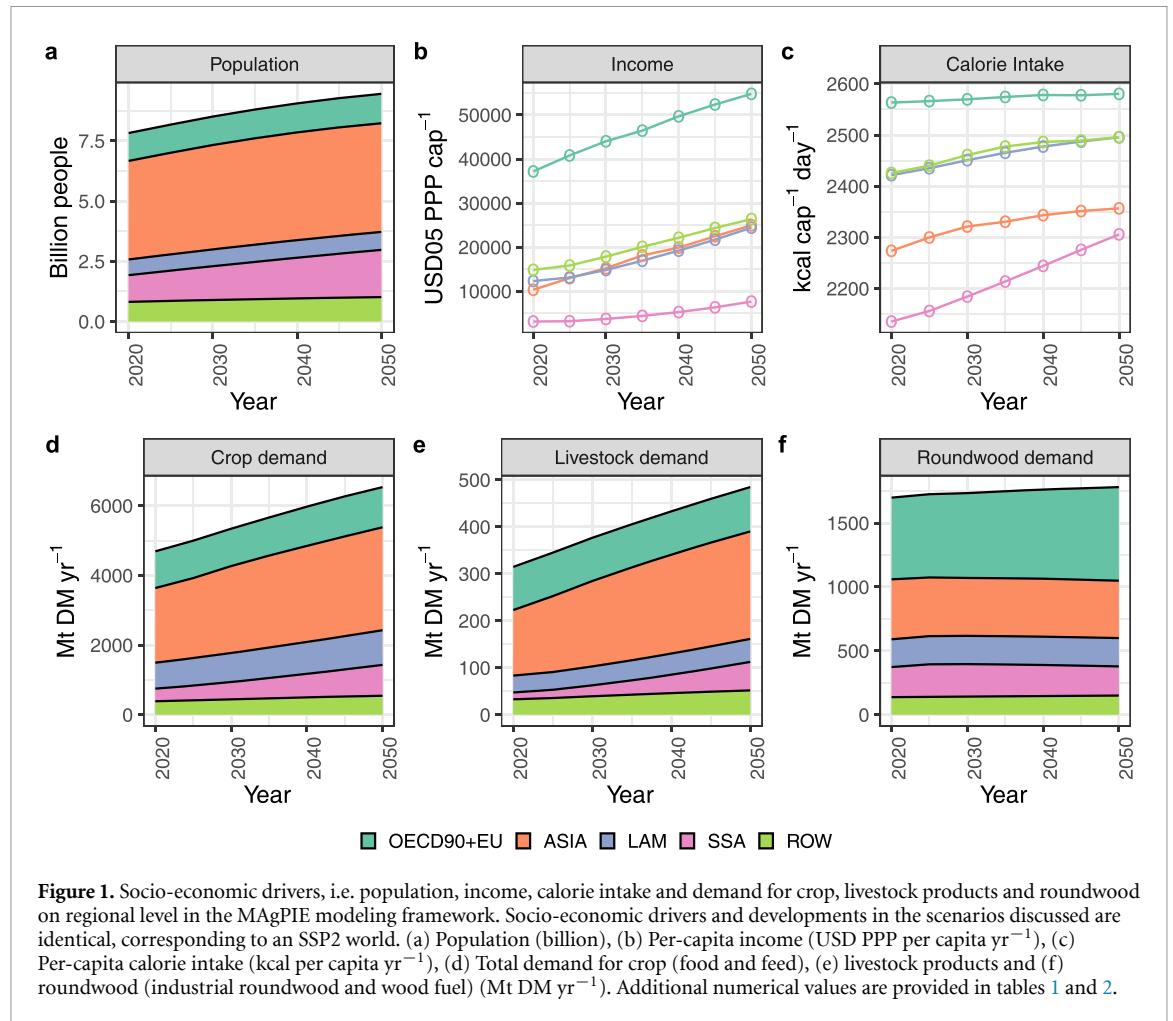
2. Methods

2.1. Land-use model

MAgPIE is a global multi-regional land system modeling framework [29, 30, 32–35] that optimizes food, feed, bioenergy, and timber production throughout the 21st century. It is a partial-equilibrium model that operates recursive-dynamically with limited foresight using a cost-minimization approach. MAgPIE projects future land-use patterns for crop and timber production, and captures the corresponding CO_2 emissions. A graphical representation of the MAgPIE modeling framework is shown in figure A1.

The open-source MAgPIE modeling framework has been used to estimate global land system impacts with competition between agriculture and forestry [30] and quantifying synergies and trade-offs in the global water-land-food-climate nexus [38]. The MAgPIE modeling framework has also contributed towards assessing global land based mitigation pathways [39], analyzing pathways to sustainable land-use and food systems [40], examining land-based implications of early climate actions [41] and assessing land-based measures to mitigate climate change [42]. The contribution of the MAgPIE modeling framework in filling research gaps pertaining to optimal land use and competition for land, while contributing to policy relevant discussions, makes it a useful tool in analyzing the land-use implications from the COP26 declaration of stopping deforestation by 2030.

This paper also incorporates the inclusion of forestry in MAgPIE which has been missing from previous MAgPIE studies [32, 43]. Namely, the MAgPIE model version presented here accounts for age-class

Figure 1. Socio-economic drivers, i.e. population, income, calorie intake and demand for crop, livestock products and roundwood on regional level in the MAgPIE modeling framework. Socio-economic drivers and developments in the scenarios discussed are identical, corresponding to an SSP2 world. (a) Population (billion), (b) Per-capita income (USD PPP per capita yr^{-1}), (c) Per-capita calorie intake (kcal per capita yr^{-1}), (d) Total demand for crop (food and feed), (e) livestock products and (f) roundwood (industrial roundwood and wood fuel) (Mt DM yr^{-1}). Additional numerical values are provided in tables 1 and 2.

distribution in both natural forests and forest plantations, calculation of optimum rotation lengths for forest plantations, competition between agriculture and forestry as well as associated land-use change emissions. An important component of elaborate land-use decision-making in MAgPIE is based on a land-matrix which has been updated to explicitly represent agriculture driven deforestation, which has also been missing from previous MAgPIE studies which included an explicit forestry sector in the modeling framework [22, 30]. Further summary of the MAgPIE modeling lineage is provided in table 4.

2.2. Model drivers
Demand for agricultural and forest commodities (food, feed, roundwood etc) is calculated based on population and income projections for the 21st century [44]. Food demand is derived based on food demand regressions [45] and feed demand is contingent on livestock demand [46]. Roundwood demand is based on changes in population, income and income elasticity of wooden products [30]. Age-class distribution in natural forests is based on the global forest age dataset [47] and age-class distribution in forest plantations is based on forest resources assessment (FRA) data on plantation forests in MAgPIE

[22]. Calculation of rotation lengths in forest plantations is based on maximization of cumulative annual increment [30]. Competition between agriculture and forestry as well as associated land-use change emissions are also based on the implementation of a dynamic forestry sector in MAgPIE [30]. Main model drivers are presented in figure 1 with regional definition provided in table A3.

2.3. Land cover
Land cover data for initializing the land cover in MAgPIE is based on the land-use harmonization (LUH) model [48]. Natural vegetation in MAgPIE is composed of primary forest (i.e. pristine forests with no signs of human intervention), secondary forests (i.e. forests with some indication of human intervention and management), and 'non-forest land' (a land class in MAgPIE consisting of degraded forests or uncultivated land with a lower vegetation carbon density than normal forests). Forests in MAgPIE consists of primary forests, secondary forests, forest plantations and forest plantations used for afforestation purposes (i.e. due to NPIs). The initial distribution of natural vegetation in MAgPIE based on LUH [48] is adjusted and harmonized to match FRA Report data [49] with reallocation of natural

Table 1. Socio-economic drivers, i.e. population, income, calorie intake and demand for crop, livestock products and roundwood on regional and global level in MAgPIE modeling framework between 2020 and 2050. Population (in million), per-capita income (USD PPP per capita yr⁻¹), per-capita calorie intake (kcal per capita yr⁻¹), total demand for crop (food and feed), livestock products and roundwood (industrial roundwood and wood fuel) (Mt DM yr⁻¹). Changes between 2050-2020 values are shown in percentage terms. Regional definitions are provided in table A3. Additional crop demand numbers are shown in table 2.

	Population (million people)			GDP (Income) (US$05 PPP/cap/yr)			Calorie intake (kcal/capita/day)			Crop demand (Mt DM/yr)			Livestock demand (Mt DM/yr)			Roundwood demand (Mt DM/yr)		
	2020	2050	% change 2050-2020	2020	2050	% change 2050-2020	2020	2050	% change 2050-2020	2020	2050	% change 2050-2020	2020	2050	% change 2050-2020	2020	2050	% change 2050-2020
ASIA	4090	4511	10%	10 332	24 963	142%	2274	2357	4%	2143	2954	38%	140	229	64%	469	449	−4%
LAM	652	745	14%	12 315	24 420	98%	2422	2496	3%	744	995	34%	36	49	36%	217	222	2%
OECD90+EU	1158	1221	5%	37 174	54 779	47%	2563	2580	1%	1054	1153	9%	92	94	3%	639	732	15%
ROW	816	1014	24%	14 853	26 369	78%	2426	2496	3%	388	545	41%	33	52	57%	138	150	9%
SSA	1109	1959	77%	3132	7657	144%	2136	2306	8%	362	886	145%	15	61	318%	235	228	−3%
World	7824	9449	21%	14 023	25 137	79%	2328	2400	3%	4690	6534	39%	315	485	54%	1699	1781	5%

Table 2. Regional and global crop demand by major crop categories in MAgPIE in 2020 and 2050. Cereals include Maize, Rice, Temperate cereals and Tropical cereals. Oil crops include cotton seed, groundnut, oil-palm, soybean, sunflower and other oil crops (including rapeseed). Other crops which include fruits, vegetables, nuts, potatoes, pulses and tropical roots. Sugar crops include sugar-beet and sugarcane. All values in Mt DM yr^{-1} except for changes between 2050-2020 values which are shown in percentage terms. Regional definitions are provided in table A3.

Regions	Period	Cereals					Oil crops							Other crops					Sugar crops		
		Total	Maize	Rice	Temperate cereals	Tropical cereals	Total	Cotton seed	Groundnuts	Oil-plam	Other oil crops incl rapeseed	Soybean	Sunflower	Total	Fruits, Vegetables and Nuts	Potatoes	Pulses	Tropical roots	Total	Sugarbeet	Sugarcane
OECD90+EU	2020	770.7	409.5	22.1	327.9	11.3	140.0	7.5	3.4	0.0	44.1	73.8	11.3	85.2	49.5	20.3	10.0	5.4	57.6	39.9	17.8
	2050	815.3	413.7	24.1	363.1	14.4	152.6	8.6	3.7	0.0	23.2	104.3	12.7	91.6	58.1	19.4	9.7	4.4	93.2	58.0	35.2
	2050-2020	6%	1%	9%	11%	27%	9%	15%	9%		-47%	41%	12%	8%	17%	-4%	-3%	-17%	62%	46%	98%
ASIA	2020	1220.7	351.6	550.5	292.3	26.3	321.5	27.0	31.9	97.3	54.5	107.8	3.1	339.8	173.5	34.5	33.7	98.1	260.5	3.7	256.8
	2050	1642.9	545.1	580.6	470.0	47.3	461.5	35.7	41.1	150.4	58.3	172.1	4.0	423.5	202.6	37.8	46.4	136.7	426.3	4.9	421.4
	2050-2020	35%	55%	5%	61%	80%	44%	32%	29%	55%	7%	60%	29%	25%	17%	10%	38%	39%	64%	32%	64%
LAM	2020	217.6	127.3	27.7	46.3	16.3	119.0	3.5	1.1	5.9	9.3	93.1	6.2	54.1	17.6	4.7	7.6	24.2	353.8	0.4	353.4
	2050	337.1	223.0	31.1	58.2	24.8	159.7	3.2	1.2	5.3	11.4	133.1	5.6	63.4	23.2	5.1	7.5	27.6	435.0	0.5	434.5
	2050-2020	55%	75%	12%	26%	52%	34%	-9%	17%	-10%	22%	43%	-10%	17%	31%	10%	0%	14%	23%	32%	23%
SSA	2020	176.7	62.5	38.6	31.9	43.6	19.5	1.6	5.8	5.4	2.7	3.1	0.8	137.3	15.1	4.4	15.6	102.2	28.2	0.0	28.2
	2050	405.5	164.9	62.9	76.9	100.7	47.0	1.5	10.5	13.6	6.5	14.7	0.3	331.8	53.9	8.3	28.3	241.3	101.9	0.0	101.9
	2050-2020	130%	164%	63%	141%	131%	141%	-12%	79%	151%	140%	373%	-62%	142%	258%	89%	81%	136%	261%	860%	261%
ROW	2020	270.9	49.7	19.5	193.8	8.0	33.2	3.1	1.6	0.0	2.2	8.8	17.5	58.8	31.0	19.2	6.3	2.3	25.2	14.4	10.8
	2050	375.5	81.9	26.7	255.6	11.3	45.6	3.0	2.3	0.0	2.8	15.0	22.5	76.2	47.0	19.3	7.8	2.1	48.2	24.6	23.6
	2050-2020	39%	65%	37%	32%	42%	37%	-2%	42%		28%	70%	28%	30%	52%	1%	23%	-11%	91%	71%	119%
World	2020	2656.6	1000.5	658.3	892.2	105.5	633.4	42.7	43.8	108.5	112.9	286.5	38.9	675.1	286.7	83.1	73.1	232.3	725.4	58.3	667.0
	2050	3576.2	1428.5	725.5	1223.8	198.5	866.4	52.0	58.8	169.3	102.3	439.1	45.0	986.5	384.7	90.1	99.6	412.1	1104.7	88.0	1016.6
	2050-2020	35%	43%	10%	37%	88%	37%	22%	34%	56%	-9%	53%	16%	46%	34%	8%	36%	77%	52%	51%	52%

Table 3. Summary of scenarios under consideration in an SSP2 world over the course of this century. a) the baseline scenario. b) the COP26 scenario. Gray cells represent within land-class transition (e.g. cropland staying cropland). Empty cells represent additional land transitions which are allowed (e.g. conversion from cropland to pasture land and vice versa are allowed in both scenarios). Cells with x marked in red show the land transitions which are not allowed (e.g. primary forests cannot be converted to non-forest land in both scenarios). Some land transitions are allowed in the baseline scenario but not in the COP26 scenario (e.g. conversion of primary and secondary forests to cropland and pasture land is allowed in baseline scenario but prohibited in COP26 scenario). Both, baseline and COP26 scenarios account for existing National Policies Implemented (NPIs) and offer land protection according to the World Database on Protected Areas (WDPA). Food, feed and roundwood demand is the same in both scenarios.

a. Baseline scenario

		Transition to					
		Cropland	Pasture	Primary forest	Secondary forest	Forest plantations	Non-forest land
Transition from	Cropland			x			
	Pasture			x			
	Primary forest						x
	Secondary forest			x			x
	Forest plantations			x			
	Non-forest land			x			

b. COP26 scenario

		Transition to					
		Cropland	Pasture	Primary forest	Secondary forest	Forest plantations	Non-forest land
Transition from	Cropland			x			
	Pasture			x			
	Primary forest	x	x			x	x
	Secondary forest	x	x	x			x
	Forest plantations	x	x	x			x
	Non-forest land			x			

vegetation area to match country level data. Natural forests in MAgPIE consist of primary and secondary forests, and are defined as natural forests in MAgPIE because these forests are not planted according to the FRA definition of planted forests [4, 49].

2.4. Deforestation

The United Nations Framework Convention on Climate Change (UNFCCC) defines deforestation as the direct human-induced conversion of forest to non-forested land [50]. FAO defines deforestation as conversion of forest to other land use (whether human induced or not) [31]. The FAO definition of deforestation explicitly excludes places or cases where trees have been harvested or logged and where the forest is expected to regenerate naturally or with the use of silvicultural methods [31].

In MAgPIE, we use the UNFCCC definition of deforestation. Primary forests and secondary forests, after harvesting or logging, are reclassified as secondary forests, as long as they are not converted into agricultural land. Primary forests can be converted to agricultural land only in the baseline scenario. Conversion of primary forests to secondary forests in MAgPIE is allowed in both the baseline and the COP26 scenario. This is followed by the expectation of natural regrowth afterwards when primary forests are re-classified as secondary forests due to human intervention or management.

We also interpret the COP26 declaration as stopping gross deforestation [51]. If new plantations are established on natural forests, without classifying this process as deforestation, this would only stop net deforestation where primary forests could simply be replaced with forest plantations [51, 52]. Relaxing this constraint, i.e. ending net deforestation instead of gross deforestation has shown to have worse outcomes for annual CO_2 fluxes, resulting in higher gross emissions and lower gross removals, resulting in overall higher net emissions [51]. Therefore, conversion of primary or secondary forests to forest plantations is considered as deforestation in MAgPIE. This interpretation additionally allows us to account for biodiversity implications of replacing natural forests with plantations [53].

2.5. Land use emissions

CO_2 fluxes in land use, land-use change and forestry (LULUCF) includes CO_2 fluxes from biomass removal for industrial roundwood or wood fuel production, deforestation due to conversion of forests for alternative land use, regrowth of forests following wood harvest or abandonment, and afforestation. Some of these activities release CO_2 into the atmosphere (e.g. conversion of forests for agricultural use, burning wood fuel), whereas others lead to CO_2 removals from the atmosphere (e.g. regrowth, afforestation).

Table 4. Non-exhaustive summary of MAgPIE developments, with focus on the implementation of forestry sector within the MAgPIE modeling framework.

	MAgPIE Version	Description	Reference
Mishra *et al* 2021	4.3.5	First implementation of a dynamic forestry module in MAgPIE which simulates competition for land between agriculture and forestry on same spatial scale. Also introduced forest growth dynamics in the MAgPIE modeling framework which included age-class calculations, rotation constraints, dynamic carbon removal calculations and demand for roundwood driven by socioeconomic changes.	[30]
Mishra *et al* 2022	4.3.5	Additional demand for engineered wood production for timber cities of the future. Increase demand for roundwood add further pressure on the limited land resources increasing competition between agriculture and forestry.	[22]
Humpenöder *et al* 2022	4.4.0	If sustainable land development stays exclusive to rich nations, global land-use change emissions will stay high. Closing the inequality gap is crucial for land-based climate efforts to meet the Paris Agreement goals.	[36]
von Jeetze *et al* 2023	4.3.5	Conserving semi-natural habitat within farmed landscapes by spatially relocating cropland outside conservation priority areas, without additional carbon losses from land-use change, primary land conversion or reductions in agricultural productivity.	[37]
This study	4.6.9	Stopping agriculture driven deforestation by 2030 to simulate COP26 declaration on ending deforestation by 2030. MAgPIE is expanded by an updated land-transition matrix which explicitly blocks the conversion of forest land for agricultural uses. The updated land-transition matrix also blocks indirect pathways of converting forest land to non-forest land which are converted to agricultural land. See table 3 for allowed transitions within land-uses in the MAgPIE version used in this study.	

In MAgPIE, for LULUCF emissions, we account for gross land-use change emissions (land-use change emissions not including regrowth), regrowth in forests and non-forested land[5], long-term carbon storage in harvested wood products (HWPs), slow release of CO_2 back into the atmosphere from existing HWP pool due to decay. We account for long-term carbon storage in HWPs according to the tier I methodology of the Intergovernmental Panel on Climate Change (IPCC) [54].

2.6. Land protection
MAgPIE simulates two types of land protection: a) land protection based on the World Database on Protected Areas (WDPA) [55], and b) land protection based on national policies implemented (NPI) in accordance with the Paris Agreement [56]. Land protection based on WDPA and halting agriculture-driven deforestation is ramped up before 2030 and fully achieved by 2030. NPI policies are also ramped up until 2030 and are assumed constant afterwards. Protected areas in MAgPIE are summarized in table A4 and shown in figure A12.

The WDPA-based level of land protection is based on International Union for Conservation of Nature

(IUCN) categories Ia (strict nature reserves), Ib (wilderness areas), III (natural monument or feature), IV (habitat or species management areas), V (protected landscapes), VI (protected areas with sustainable use of natural resources) and 'not assigned' but legally designated areas [57]. The areas earmarked under these protection categories are distributed equally across all sub-land-types in MAgPIE (primary forest, secondary forest, and other non-forested land).

WDPA is one of the largest collection of data about terrestrial and marine protected areas worldwide, including over 260 000 protected areas, which makes it the most comprehensive database available globally [58]. WDPA database is also built using a bottom-up approach with data aggregated from the ground level, provided by international organizations, governments, and non-governmental organizations. This makes WDPA a key resource when used in MAgPIE for establishing a layer of protected areas to make cost-optimal land-use decisions.

3. Results

3.1. Land-use change and land transition
Projected land-use changes between 2030-2050 differ considerably in the baseline and the COP26 scenario. In the baseline scenario, cropland expands at the cost of pasture land, primary forest, secondary

[5] Non-forested land in MAgPIE covers non-forest vegetation, deserts, and shrublands.

Table 5. Global land use in 2020, 2030 and 2050. Projections shown for cropland, pasture, forest (primary forest, secondary forest and forest plantations), non-forested land and urban areas in MAgPIE. Protected areas in MAgPIE are summarized separately in table A4.

	2020	2030		2050				2050-2030	
	Baseline and COP26 (Mha)	Baseline (Mha)	COP26 (Mha)	Baseline (Mha)	COP26 (Mha)	COP26-Baseline (Mha)	COP26-Baseline (%)	Baseline (Mha)	COP26 (Mha)
Cropland	1578	1626	1595	1725	1686	−39	−2	99	91
Pasture	3238	3226	3218	3204	3169	−35	−1	−22	−49
Primary forest	1295	1270	1285	1233	1281	48	4	−37	−4
Secondary forest	2346	2332	2363	2250	2369	119	5	−82	6
Forest plantations	152	181	181	224	222	−2	−1	43	41
Afforestation (NPIs)	177	180	180	180	180	0	0	0	0
Non-forest land	3880	3839	3831	3816	3717	−99	−3	−23	−114
Urban	61	73	73	95	95	0	0	22	22

forest and non-forest land between 2030 and 2050 at the global level (figure 2(a)). The increase in cropland (99 Mha) by 2050, compared to 2030 is driven by demand for crops (for food and feed) (table 5, figure 1(d)). Between 2030–2050, the loss of primary forest (37 Mha), secondary forest (82 Mha) and non-forest land (23 Mha) is largely driven by continued deforestation in sub-Saharan Africa and Asia (figure 2(b)) in the baseline scenario. In 2050, the global avoided deforestation is estimated to be 167 Mha (119 Mha in secondary forests and 48 Mha in primary forests) in the COP26 scenario compared to the baseline scenario, largely due to the expansion of cropland area on non-forested land in the COP26 scenario (table 5, figure A9).

Even if forest protection or conservation schemes are implemented and enforced globally, they may result in another sort of carbon leakage by encouraging farmland expansion into non-forested areas that are not subject to forest conservation schemes (non-forest leakage). The cropland expansion happening on pasture land and non-forested land in the COP26 scenario instead of forest land (primary forest, secondary forest and forest plantations) in the baseline scenario comes from the explicit prohibition of agriculture-driven deforestation in the COP26 scenario (figure 3), making unprotected non-forested land one of the remaining cost-effective resources for agricultural expansion [23, 59].

Annual primary and secondary forest conversion to cropland between 2030 and 2050 in the baseline scenario is projected to be 0.6 Mha yr^{-1} and 3.8 Mha yr^{-1} (figure 3). The full implementation of COP26 declaration is projected to lead to an increased conversion of non-forested land into cropland (4.2 Mha yr^{-1}) as well as pasture land (1.2 Mha yr^{-1}) during the same period (2030–2050).

Most of this dynamic is driven by conversion of non-forested land for cropland in sub-Saharan Africa and Asia (figure A20) in the COP26 scenario. The COP26 scenario also points towards higher total global growing stocks in primary and secondary forests compared to the baseline scenario because of

its higher forest area i.e. 167 Mha of avoided deforestation in the COP26 scenario compared to the baseline scenario between 2030-2050 (figure A10).

Concurrently, annual conversion of non-forested land into pasture land increases in the COP26 scenario (1.3 Mha yr^{-1}) compared to the baseline scenario (0.1 Mha yr^{-1}) between 2030-2050 globally. Similar to the conversion of non-forested land for cropland, this dynamic is also driven by conversion of non-forested land to pasture land in sub-Saharan Africa and Asia (figure A20) in the COP26 scenario.

3.2. Cropland intensification and agricultural commodity prices

In MAgPIE, food, feed and roundwood demand are simultaneously accounted for while accommodating competition between cropland and forestry. Yield-increasing technological change in MAgPIE is realized by intensifying agricultural land use and is measured using a τ factor [60]. MAgPIE estimates a marginal global agricultural yield increase of 15% in the baseline scenario and 17% in the COP26 scenario by 2050 compared to 2030 (figure 4(a) and table 6). Highest projected increase in τ factor is seen in sub-Saharan Africa, with estimated agricultural yield increase needed by 35% in the baseline scenario and 41% in the COP26 scenario by 2050 compared to 2030 (figure 4(a) and table 6).

Increased competition for land is a direct result of scarcity of land, which is exacerbated by the end of agriculture-driven deforestation in the COP26 scenario. The agricultural commodity price index is higher in regions where investments needed in yield-increasing technological change (figure 4(a)) are high (i.e. sub-Saharan Africa) (figure 4(b)). However, the percentage change between 2030–2050 in the agricultural commodity price index estimated globally (−1.0%) is rather small (figure 4(b)) when compared to 2030. This indicates that agricultural commodity prices remain relatively stable even under the COP26 scenario, and there appears to be only a minimal trade-off between forest protection and agricultural commodity prices. This is however not the case
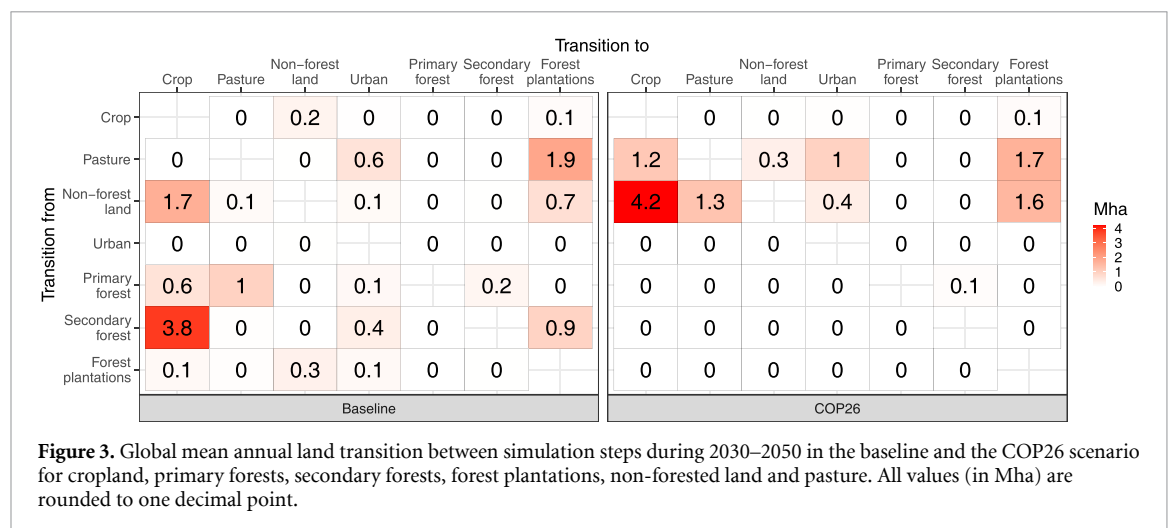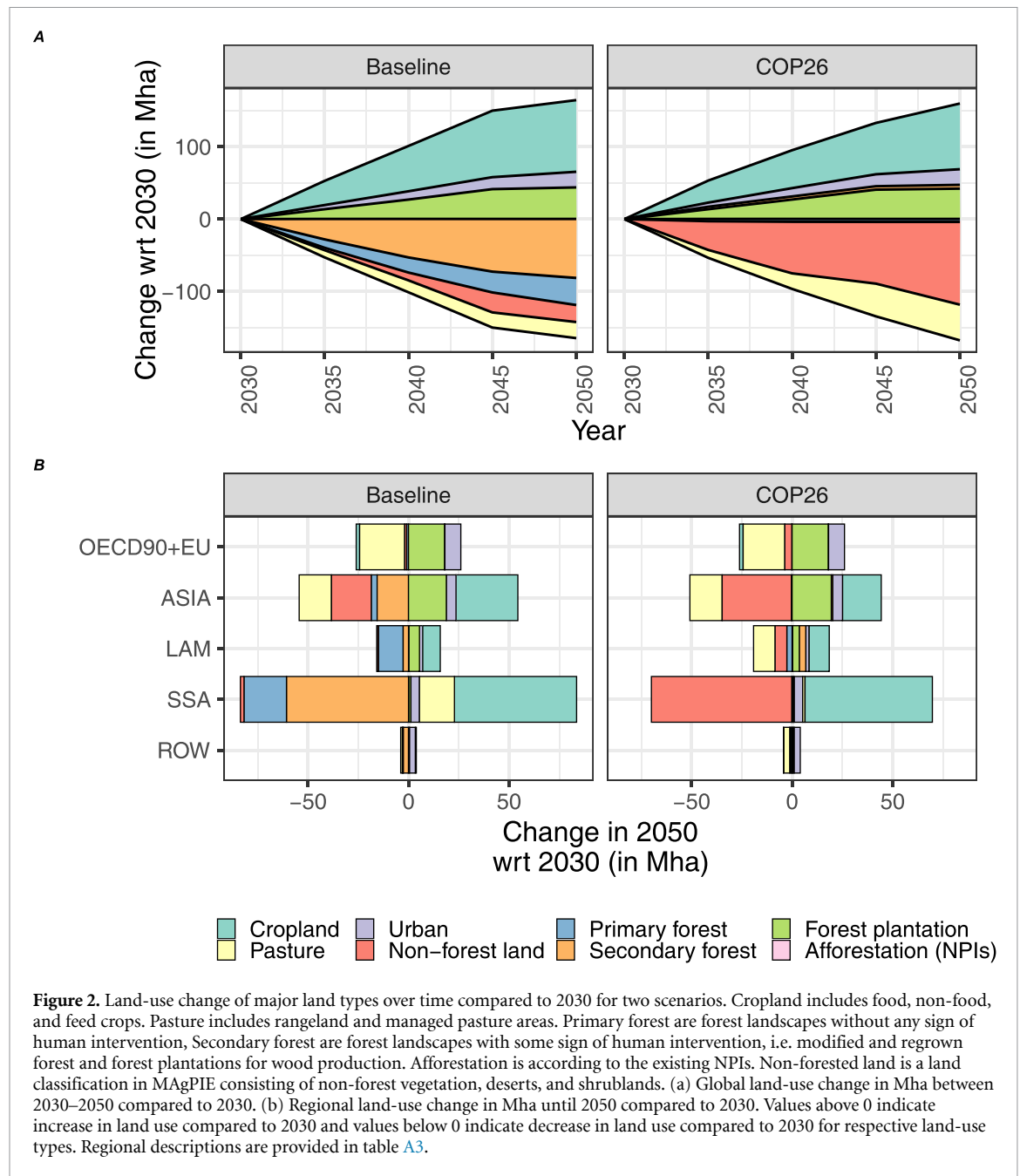
Figure 2. Land-use change of major land types over time compared to 2030 for two scenarios. Cropland includes food, non-food, and feed crops. Pasture includes rangeland and managed pasture areas. Primary forest are forest landscapes without any sign of human intervention, Secondary forest are forest landscapes with some sign of human intervention, i.e. modified and regrown forest and forest plantations for wood production. Afforestation is according to the existing NPIs. Non-forested land is a land classification in MAgPIE consisting of non-forest vegetation, deserts, and shrublands. (a) Global land-use change in Mha between 2030–2050 compared to 2030. (b) Regional land-use change in Mha until 2050 compared to 2030. Values above 0 indicate increase in land use compared to 2030 and values below 0 indicate decrease in land use compared to 2030 for respective land-use types. Regional descriptions are provided in table A3.

Figure 3. Global mean annual land transition between simulation steps during 2030–2050 in the baseline and the COP26 scenario for cropland, primary forests, secondary forests, forest plantations, non-forested land and pasture. All values (in Mha) are rounded to one decimal point.

Table 6. Global and regional estimated land use intensity indicator (τ) between 2030-2050.

	2030	2050		Change compared to 2030 (%)	
	Baseline	Baseline	COP26	Baseline	COP26
OECD90+EU	1.8	1.9	1.9	5.2	5.7
ASIA	1.6	1.8	1.9	18.3	19.7
LAM	1.4	1.5	1.5	9.3	12.5
ROW	1.0	1.2	1.2	23.7	27.1
SSA	0.9	1.2	1.3	35.0	40.5
World	1.3	1.5	1.6	14.7	17.4

in sub-Saharan Africa (in both the baseline and the COP26 scenario) where the agricultural commodity price index is expected to be relatively higher than the 2030 levels.

3.3. CO$_2$ emissions from land-use change

Global annual CO$_2$ emissions from land-use change are strongly driven by changes in forest cover (figures 2, 3, 5 and table 5). In the baseline scenario, global net CO$_2$ emissions from land-use change decrease from 1442 Mt CO$_2$ yr^{-1} in 2030 to -681 Mt CO$_2$ yr^{-1} in 2050 (figure 5(A)). The global decrease in net CO$_2$ emissions is largely driven by decreasing CO$_2$ emissions in the OECD countries and EU, as well as Latin America (table A6). In the COP26 scenario, net annual CO$_2$ emissions from land-use change amounts to -1649 Mt CO$_2$ yr^{-1} in 2050 (figure 5(B)), also driven by decreasing CO$_2$ emissions majorly in the OECD countries (table A6). Compared to the baseline scenario, the majority of annual emission reductions are realized in Sub-Saharan Africa, followed by Asia and the OECD countries (table A6).

In the baseline scenario, global annual emission from deforestation i.e. primary and secondary forest conversion to non-forest areas is estimated to increase from 6451 Mt CO$_2$ yr^{-1} in 2030 to 7192 Mt CO$_2$ yr^{-1} in 2050 (figure 5(C)). In the COP26 scenario, global annual emission from deforestation is estimated to increase from 4836 Mt CO$_2$ yr^{-1} in 2030 to 5567 Mt CO$_2$ yr^{-1} in 2050 (figure 5(C)).

Reduction in global annual emissions from deforestation in the COP26 scenario are realized in Latin-America (LAM), Asia and Sub-Saharan Africa (SSA), regions which are affected the most by cropland driven deforestation [5] (figure 5(C)). Alternatively, increase in global annual emissions from increased conversion of non-forested land in the COP26 scenario are realized in Asia and Sub-Saharan Africa (SSA), regions where cropland expansion would likely occur on non-forested land (figures 2(B) and 5(D)).

4. Discussion

4.1. This study

We used the MAgPIE land-use modeling framework with a detailed representation of food, feed and roundwood production taking competition for land into account to scrutinize the effects and consequences of the declaration made at COP26 to stop deforestation by 2030. Given limited land resources, stopping agriculture-driven deforestation limits the expansion potential of agricultural land and implies trade-offs in terms of agricultural land use [23].

We find that a global realization of the COP26 declaration on deforestation could avoid about 167 Mha of deforestation globally by 2050 compared to a baseline scenario. However, avoided deforestation and associated emission reductions come at the cost of strongly increasing conversion of unprotected non-forested land to agricultural land, while land-use intensification in most regions is similar compared to the baseline scenario (figures 3 and 4(a)).

We also show that prohibiting agriculture-driven deforestation leads to excessive conversion of unprotected non-forested land to both cropland and pasture land (figure 3). Additionally, pasture land is also converted to cropland under the COP26 scenario. Non-forested land and pastures are often considered to be available for large-scale reforestation/restoration projects [61]. In the COP26 scenario, we estimate that a considerable amount of non-forested land will need to be converted for agricultural use globally (5.5 Mha yr^{-1} for cropland and pasture, figure 3).

If non-forested land is converted to agriculture in an extensive way, e.g. through agroforestry, the COP26 scenario might offer a synergistic opportunity by means of co-existence between agricultural production and restoration/reforestation [62]. If the conversion of non-forested land to agricultural land is characterized by a focus on intensive agriculture, this could reduce the land area available for restoration/reforestation. This could indirectly lead to a conflict with climate change mitigation through reducing deforestation or through restoring non-forested/degraded lands.

4.2. Comparison to current literature

Our estimated overall range of emission savings via stopping deforestation i.e. 19 Gt CO$_2$ or 0.95 GtCO$_2$ yr^{-1} on average between 2030–2050 (table A5), is within the range estimated in IPCC Special Report on Climate Change and Land between 2020–2050 (0.41–5.8 GtCO$_2$e yr^{-1}) [63]. The annual emissions
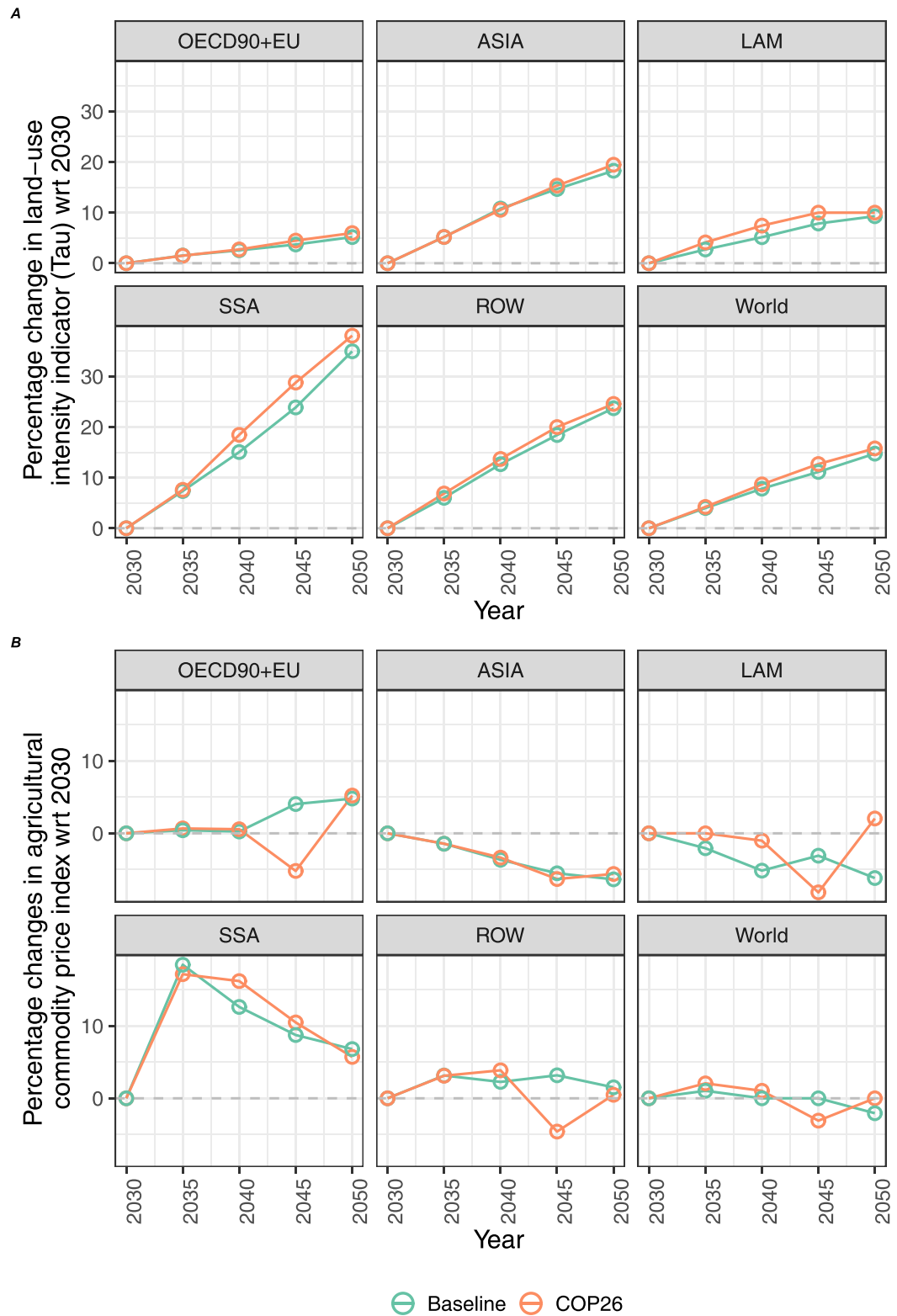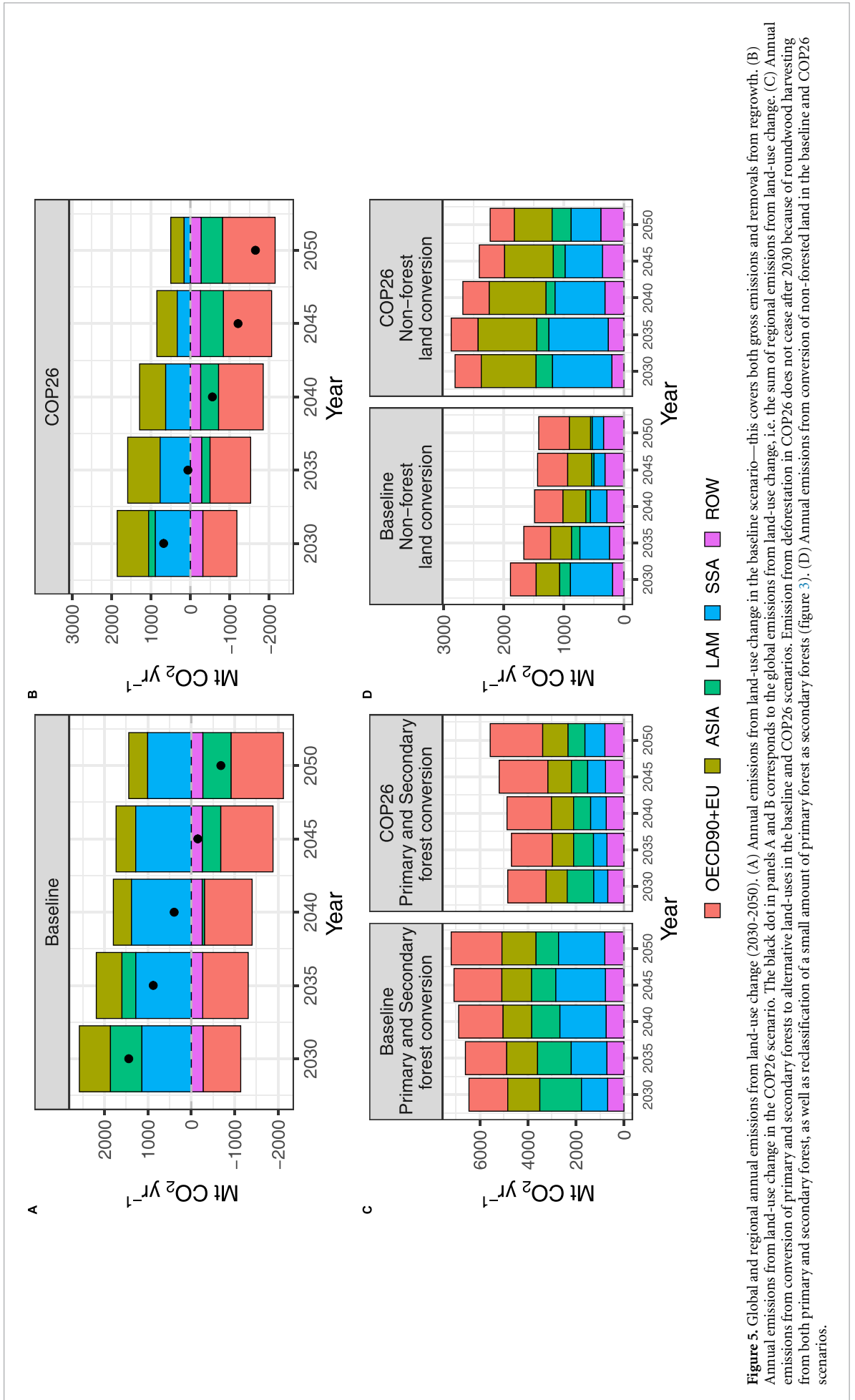
Figure 4. Global and regional estimated land use intensity indicator (τ) and changes in agricultural commodity price index between 2030–2050. (a) τ in MAgPIE as a surrogate measure for land-use intensity. Changes in (τ) are directly proportional to relative changes in agricultural land-use intensity [60]. In MAgPIE, τ doubles if crop yield doubles (e.g. because of improved management, technological development etc) [60]. τ values are scaled to have the index value of 2030 to be 1. τ values in the boxes are shown for 2050. (b) Percentage change in agricultural commodity price index, which includes both plant-based food products and livestock products. Numbers displayed are for the difference in 2050 compared to 2030.

Figure 5. Global and regional annual emissions from land-use change (2030–2050). (A) Annual emissions from land-use change in the baseline scenario—this covers both gross emissions and removals from regrowth. (B) Annual emissions from land-use change in the COP26 scenario. The black dot in panels A and B corresponds to the global emissions from land-use change, i.e. the sum of regional emissions from land-use change. (C) Annual emissions from conversion of primary and secondary forests to alternative land-uses in the baseline and COP26 scenarios. Emission from deforestation in COP26 does not cease after 2030 because of roundwood harvesting from both primary and secondary forest, as well as reclassification of a small amount of primary forest as secondary forests (figure 3). (D) Annual emissions from conversion of non-forested land in the baseline and COP26 scenarios.

from land-use change in the baseline scenario are also comparable to other IAMs [64] but lower than the estimates of land use models which do not account for competition for land at the same spatial scale as MAgPIE [65].

4.3. Caveats

Our research has certain limitations due to the assumptions that are made in MAgPIE and the simulation design. Results discussed here are contingent on the socioeconomic assumptions from the SSP2 ('middle-of-the-road') scenario. As a corollary, our results are as uncertain as future socioeconomic developments. As established by other global land-use models [66], uncertainty in future socioeconomic developments brings a range of uncertainty about the future development of the forest sector and associated land-use change. Future studies in this regard could explore the role of the COP26 declaration on deforestation under the full range of SSPs to assess a broader range of uncertainty of the results.

The signatory countries of the COP26 declaration on deforestation must differentiate between all three types of forests [51], i.e. primary forests, regenerated and restored forests (secondary forest in MAgPIE), and forest plantations when trying to meet their commitments. Ideally, avoiding deforestation in the best case would mean complete protection of primary forests i.e. stopping gross deforestation [51]. Such differentiation already exists in the modeling framework used here [22, 30] but stopping gross deforestation is not fully accounted for as primary forests can be re-classified as secondary forests followed by human intervention or management (for example due to wood harvest, also see section 2). It is important to consider the full protection of primary forests globally because it would likely exacerbate competition for land with possible negative consequences for biodiversity beyond the assessment presented here. These negative effects could also result from increased wood harvest from secondary forests and additional land demand for establishing forest plantations to meet increasing roundwood demand but also from increased conversion of non-forested land for agricultural uses.

The non-forest leakage effects in the COP26 scenario presented here, i.e, conversion of non-forested areas for cropland use supports the findings of the potential land-use impacts of forest conservation schemes [23] and also points towards forest protection to realize the COP26 declaration on deforestation resulting in increased emissions from conversion of non-forested land (figure 5(c)). We assume that the potential policy discussed here, i.e. the declaration made to end global deforestation by 2030, can be uniformly implemented globally. This is hardly the case due to regional differences in governance, ownership and legal frameworks.

Latest research [67] also suggests that international supply chains can play a crucial role in decreasing deforestation, helped by interventions in deforestation risk areas that concentrate on bolstering sustainable rural development and land governance. The modeling framework we used here does not account for grass-root level interventions and governance which might help in reducing deforestation. For example, this study does not account for regulations on deforestation free products like the one implemented by European Union which entered into force on the 29th of June 2023 [68]. For this reason, the results and indicators discussed in this study should be understood as projections or expectations, which are valid under current modeling assumptions.

The roundwood demand (figure 1) is the same between the baseline and the COP26 scenario. Under the assumptions made in MAgPIE in this study, (figure 1), the roundwood demand is also fulfilled in the COP26 scenario, saving as much carbon in HWPs as in the baseline scenario (figure A11). Yet, our study does not provide any insights into potential trade-offs of stopping deforestation and providing additional biomass as part of a developing bio-economy that increases biomass demands.

In the scenarios presented here, we also do not account for the increasing demand for bioenergy, i.e. bioenergy from non-wood fuel in MAgPIE. While harnessing bioenergy from specifically grown energy crops could provide a cost-effective addition to our future energy blend [69], we cannot ignore the linkage of increased bioenergy demand to deforestation and biodiversity along with potential effects on food and water security [69, 70]. Recent research has also suggested that the overall carbon impact of bioenergy production for replacing fossil fuels tends to be either negative or uncertain, and at shows no relevancy to time-sensitive climate targets [71].

5. Conclusion

To prevent negative spill-over effects from the conversion of non-forest land to agriculture in the COP26 scenario endemic species in such areas may require additional protection [72]. To achieve this, specific protection schemes would have to be put in place [23]. Initiatives like the Global Grassland and Savannah Dialogue Platform [73] can be critical in facilitating a common dialogue on addressing loss of biodiversity and CO_2 emissions due to the expected loss of non-forested land in the COP26 scenario.

By preserving and improving the carbon sink and lowering greenhouse gas emissions associated with deforestation, forest-based climate mitigation could be possible [26, 27]. Reduced deforestation and forest degradation as a mitigation option appears in 26% of the NDCs from 191 parties to the Paris Agreement

[74] with many developing countries looking at it as a priority with high mitigation potential.

Yet, the NDCs submitted to the NDC registry [75] do not foresee the potential displacement effects of forest conservation to other land uses, especially for agriculture. Our study highlights the importance of integrated land-use perspectives in reducing deforestation as a mitigation policy and its eventual contribution to climate change mitigation and competition for land. Our study could also be used by signatories to the Paris Agreement for updated formulations of NDCs by addressing the potential carbon and biodiversity loss due to the loss of non-forested areas under a COP26-like global forest protection policy.

Future research with a more detailed representation of the regional implementation of the declaration made at the COP26 would also be needed to better estimate the long-term land-use repercussions and trade-offs from stopping deforestation by 2030. There is presently a considerable amount of emphasis on avoiding deforestation [75], including recent commitments to achieve this goal at the COP26, with further legislative initiatives in some of the leading global economies like the European Union (EU) [8, 68, 76, 77], the United Kingdom (UK) [78], China [79], and the United States of America (USA) [80]. It is crucial to fuel the current global policy-driven momentum for stopping deforestation, and such policy initiatives could benefit from a holistic perspective on land use.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https:// zenodo.org/records/8329558.

The data and results that support the findings of this study are openly available at the following URL/DOI: https://zenodo.org/record/8329542. Code for the MAgPIE model used in this manuscript is available under the GNU Affero General Public Licence as published by the Free Software Foundation, version 3 of the Licence or later (AGPLv3) via GitHub and Zenodo. The model documentation for MAgPIE 4.6.9 can be found at https:// rse.pik-potsdam.de/doc/magpie/4.6.9/. Data used for processing the results and for reproducing the plots used throughout this paper are also hosted on Zenodo.

Acknowledgments

Author contributions statement

A M, F H, H L C and A P proposed and led this study. AM and FH wrote the original model extension for forestry, natural vegetation, forest age class and timber modules in MAgPIE. A M implemented the forest protection scenarios based on the proposal by F H. F H, C P O R, F D B, A P, and H L C guided the model development and manuscript text development. AM prepared the model input data. F H and F D B provided technical support for the development. F H, C P O R and F D B provided theoretical support for the development. A M made the model runs and processed the model outputs and produced the figures. A M and F H wrote the additional model documentation. A M and F H prepared the extended model for release. All authors contributed to the writing and editing processes.

Conflict of interest
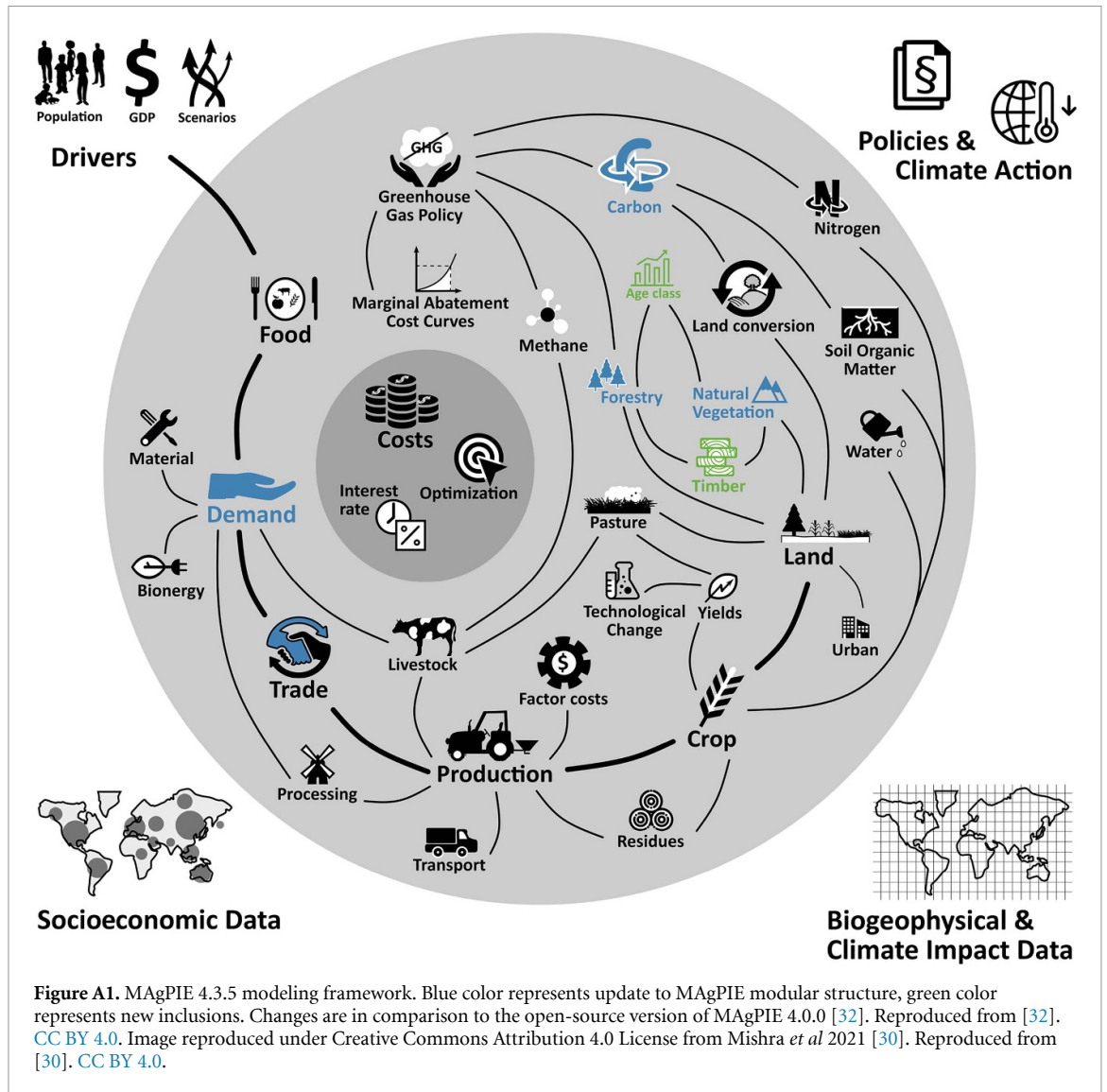
The authors declare no competing interests.

Appendix

A.1. Additional information

A.1.1. Model setup

In this study, we employed the MAgPIE 4 open-source land-use modeling framework, specifically version 4.6.9 with a modified land-transition matrix (details in table 3). MAgPIE integrates economic and biophysical methods to simulate global land-use scenarios and their environmental impacts in a spatially explicit manner (figures A1 and A2). Previously, the MAgPIE framework has been instrumental in modeling mitigation strategies for various shared socio-economic pathways (SSPs) and has made considerable contributions to multiple IPCC reports like IPCC Special Report on land [81] and IPCC special report on Global Warming of 1.5°C [82].

MAgPIE's operational scale is at aggregated spatial units (simulation clusters). These clusters are aggregated from finer spatial data on 0.5° resolution [32, 83]. Geographically explicit data on biophysical conditions are provided by the global gridded crop, vegetation and hydrology model, i.e. Lund-Potsdam-Jena managed land model (LPJmL)

Figure A1. MAgPIE 4.3.5 modeling framework. Blue color represents update to MAgPIE modular structure, green color represents new inclusions. Changes are in comparison to the open-source version of MAgPIE 4.0.0 [32]. Reproduced from [32]. CC BY 4.0. Image reproduced under Creative Commons Attribution 4.0 License from Mishra *et al* 2021 [30]. Reproduced from [30]. CC BY 4.0.

[84, 85] on a 0.5 degree resolution. Biophysical constraints provided by LPJmL to MAgPIE include carbon densities, agricultural productivity, i.e. crop yields and water availability for irrigation. These biophysical indicators act as additional constraints within MAgPIE. The MAgPIE model version used here (4.6.9) implements the COP26 declaration on deforestation using explicit implementation of land-transitions which prohibit conversion of forest land to other land use types [86].

As a measure of technological advancements enhancing yield, MAgPIE computes and utilizes an agricultural land-use intensity factor known as (τ) endogenously. (τ) represents the extent of crop yield improvement resulting from human interventions or management. The model encompasses various crop types (detailed in table 2), in both rainfed and irrigated systems. International trade patterns in MAgPIE are informed by historical data, self sufficiency ratios [87] and comparative advantages. Food demand

projections stem from socioeconomic shifts such as changes in GDP and population dynamics. For this study, we aggregate the 12 standard model regions of MAgPIE into 5 broader regions (as shown in table A3).

A.1.2. Forest area, age-class allocation and roundwood production

The area allocated to primary forests is assumed to exist in the oldest age class. The area allocated to secondary forests in MAgPIE follows the age classes distribution based on the global forest age dataset [47]. Initial forest plantation area in MAgPIE is distributed so that a higher weight is provided to younger age classes, reflecting the notion that plantation area establishment has increased over the last decades. After the initialization of forest areas, the changes in forest cover are modeled endogenously in MAgPIE. Changes in forest cover are directly or indirectly driven by roundwood demand, timber

harvest costs, expected yields, carbon prices, demand for agricultural land, land-use change costs and land-use change constraints.

Demand for roundwood can be fulfilled by realizing production from either forest plantations or available natural forests. Timber plantations are harvested at maturity defined by optimal rotation lengths.

Calculation of optimal rotation lengths in forest plantations is based on maximization of cumulative annual increment [30]. After every harvesting cycle, forest age classes are shifted forward. Forest plantations are protected from harvest during the specified rotation period. Natural vegetation in MAgPIE is not bounded by such rotational constraints.
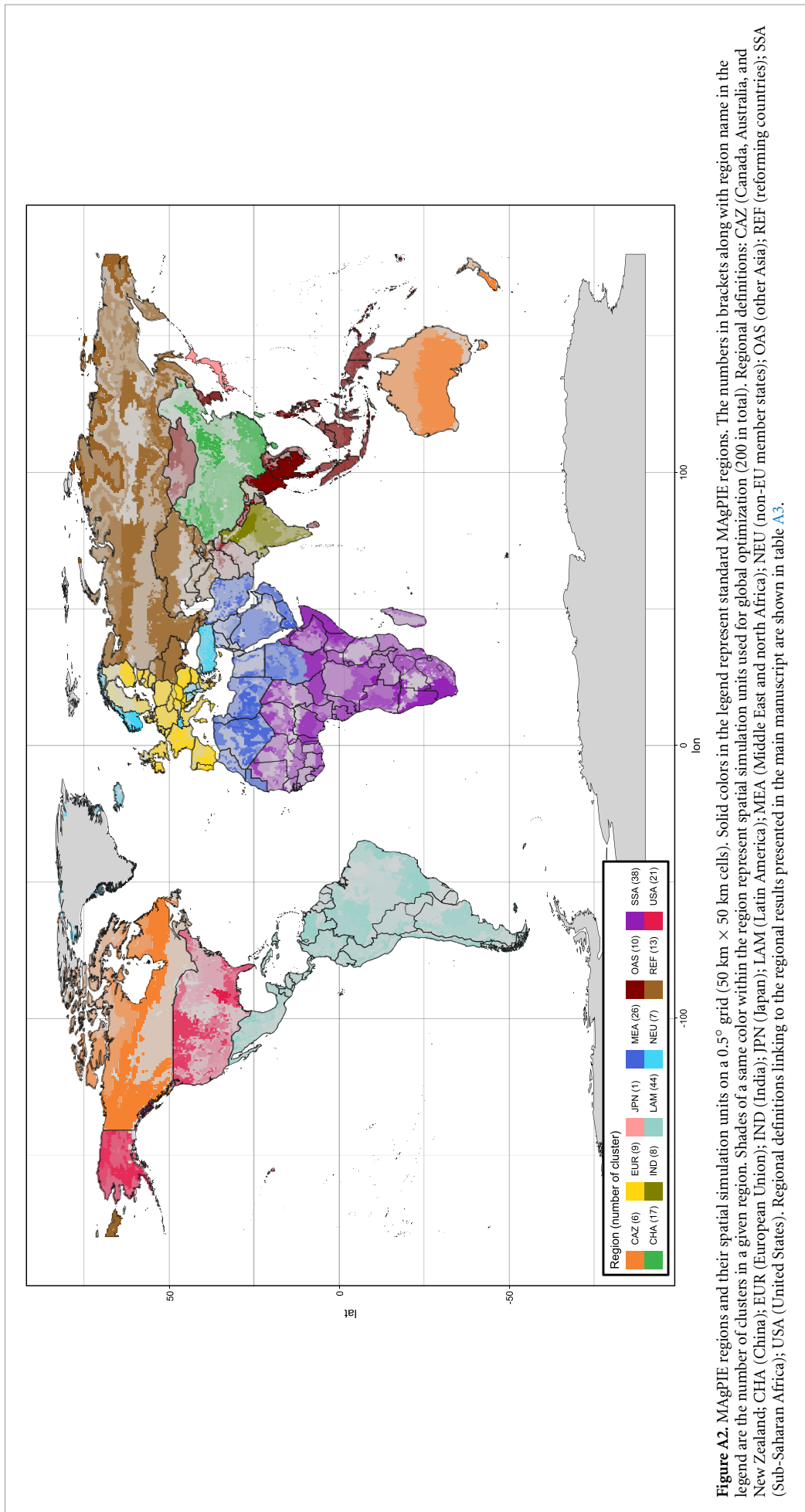
Figure A2. MAgPIE regions and their spatial simulation units on a 0.5° grid (50 km × 50 km cells). Solid colors in the legend represent standard MAgPIE regions. The numbers in brackets along with region name in the legend are the number of clusters in a given region. Shades of a same color within the region represent spatial simulation units used for global optimization (200 in total). Regional definitions: CAZ (Canada, Australia, and New Zealand; CHA (China); EUR (European Union); IND (India); JPN (Japan); LAM (Latin America); MEA (Middle East and north Africa); NEU (non-EU member states); OAS (other Asia); REF (reforming countries); SSA (Sub-Saharan Africa); USA (United States). Regional definitions linking to the regional results presented in the main manuscript are shown in table A3.

A.1.3. Validation of relevant indicators in MAgPIE
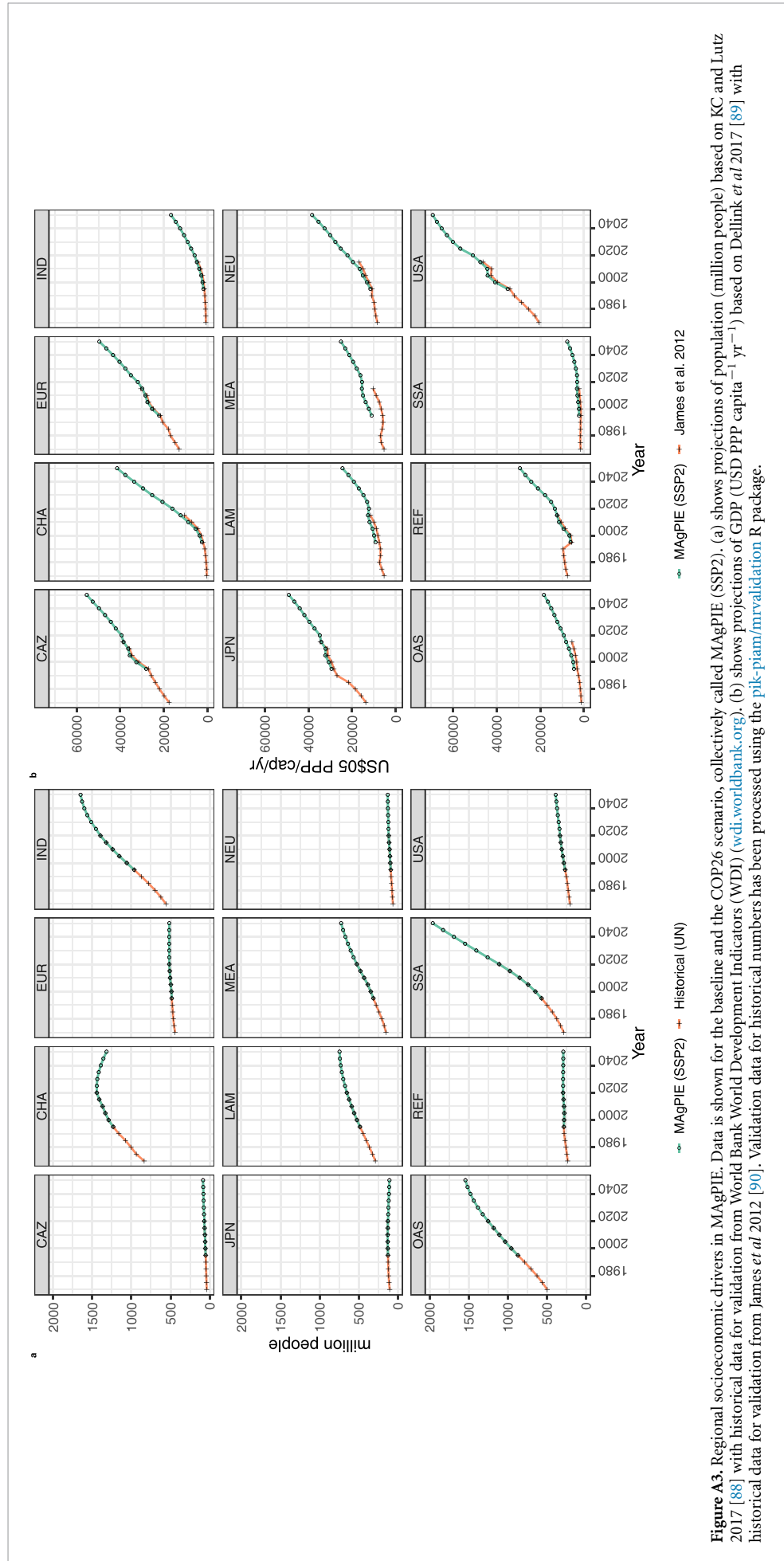
Figure A3. Regional socioeconomic drivers in MAgPIE. Data is shown for the baseline and the COP26 scenario, collectively called MAgPIE (SSP2). (a) shows projections of population (million people) based on KC and Lutz 2017 [88] with historical data for validation from World Bank World Development Indicators (WDI) (wdi.worldbank.org). (b) shows projections of GDP (USD PPP capita $^{-1}$ yr^{-1}) based on Dellink *et al* 2017 [89] with historical data for validation from James *et al* 2012 [90]. Validation data for historical numbers has been processed using the pik-piam/mrvalidation R package.
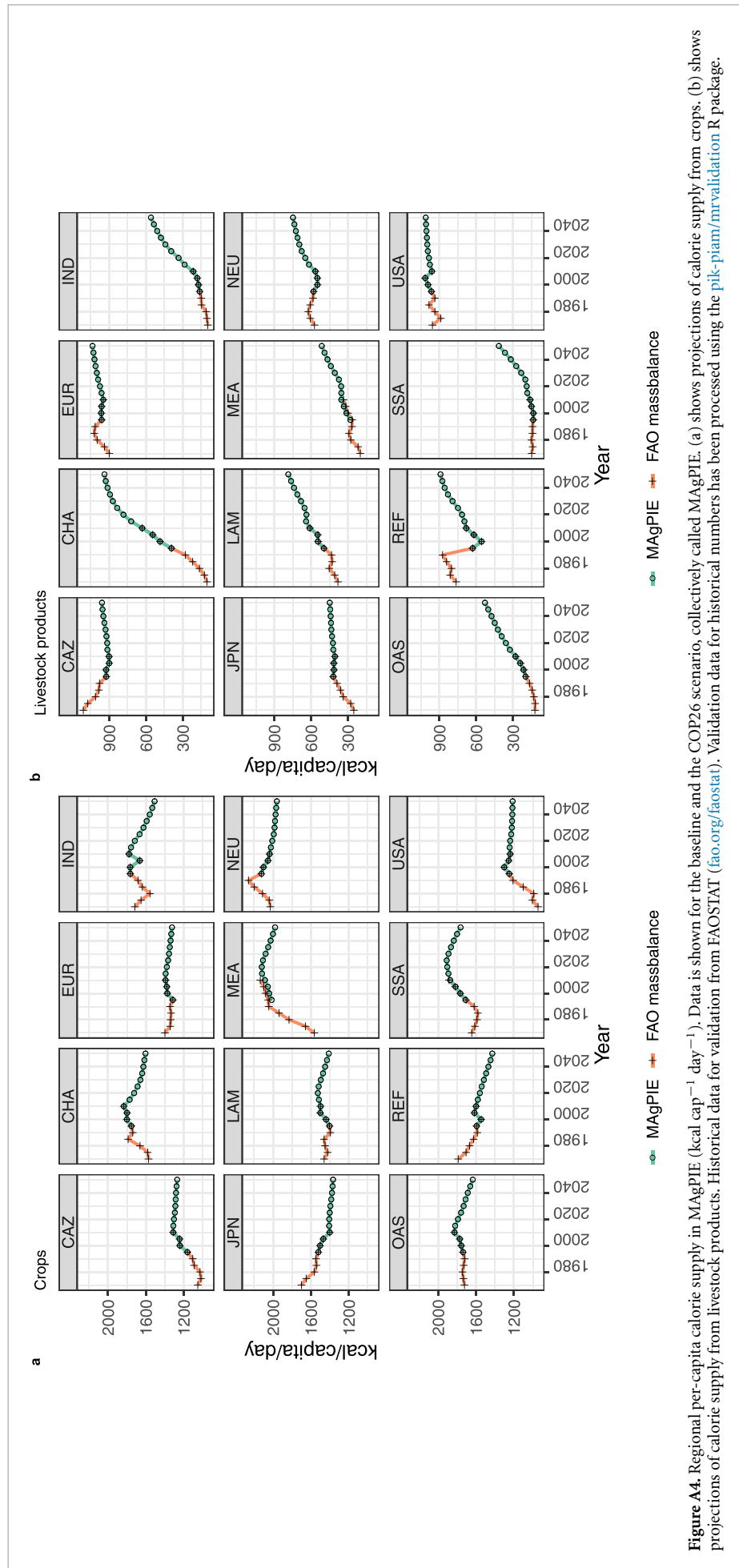
Figure A4. Regional per-capita calorie supply in MAgPIE (kcal cap^{-1} day^{-1}). Data is shown for the baseline and the COP26 scenario, collectively called MAgPIE. (a) shows projections of calorie supply from crops. (b) shows projections of calorie supply from livestock products. Historical data for validation from FAOSTAT (fao.org/faostat). Validation data for historical numbers has been processed using the pik-piam/mrvalidation R package.
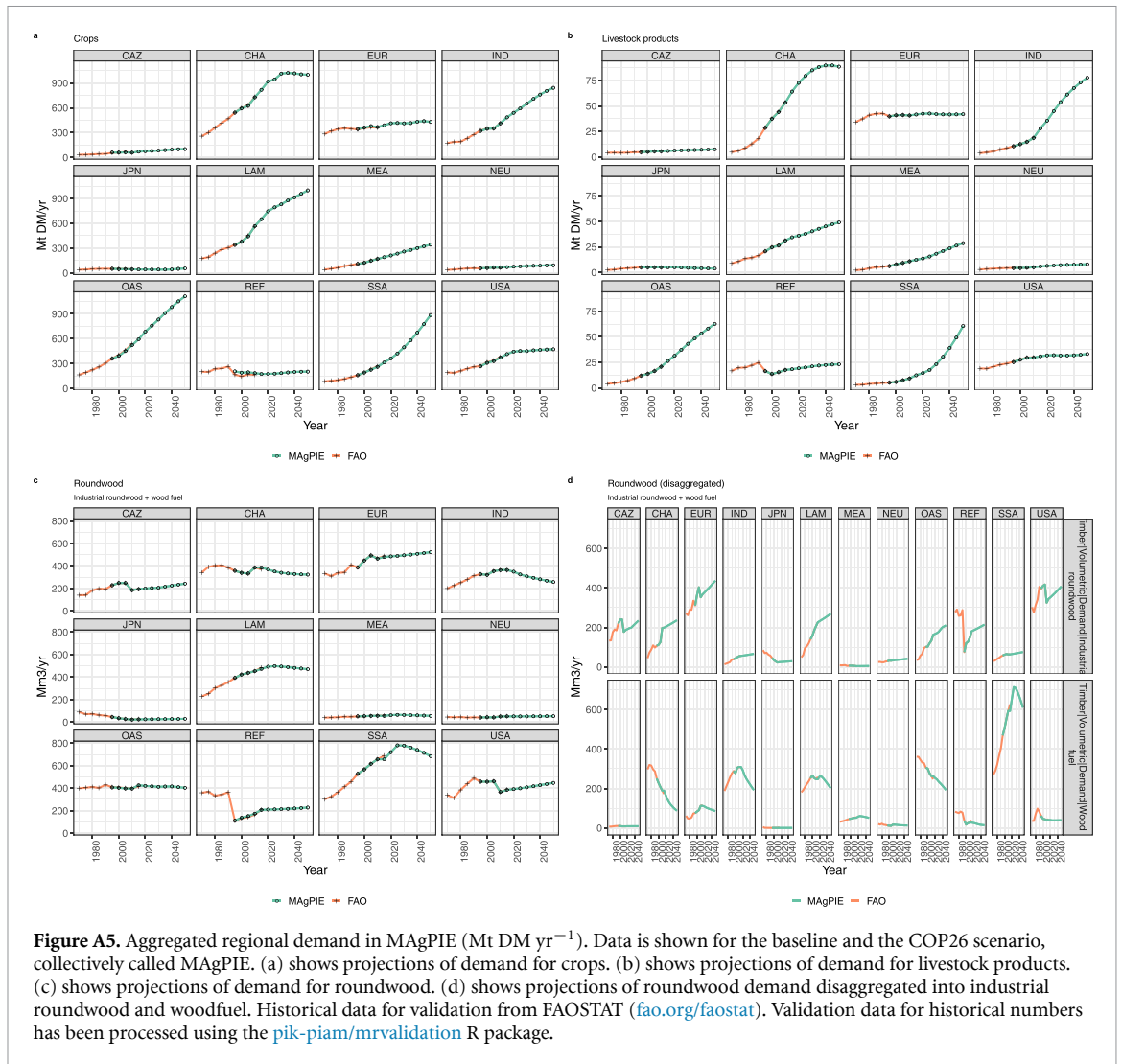
Figure A5. Aggregated regional demand in MAgPIE (Mt DM yr^{-1}). Data is shown for the baseline and the COP26 scenario, collectively called MAgPIE. (a) shows projections of demand for crops. (b) shows projections of demand for livestock products. (c) shows projections of demand for roundwood. (d) shows projections of roundwood demand disaggregated into industrial roundwood and woodfuel. Historical data for validation from FAOSTAT (fao.org/faostat). Validation data for historical numbers has been processed using the pik-piam/mrvalidation R package.
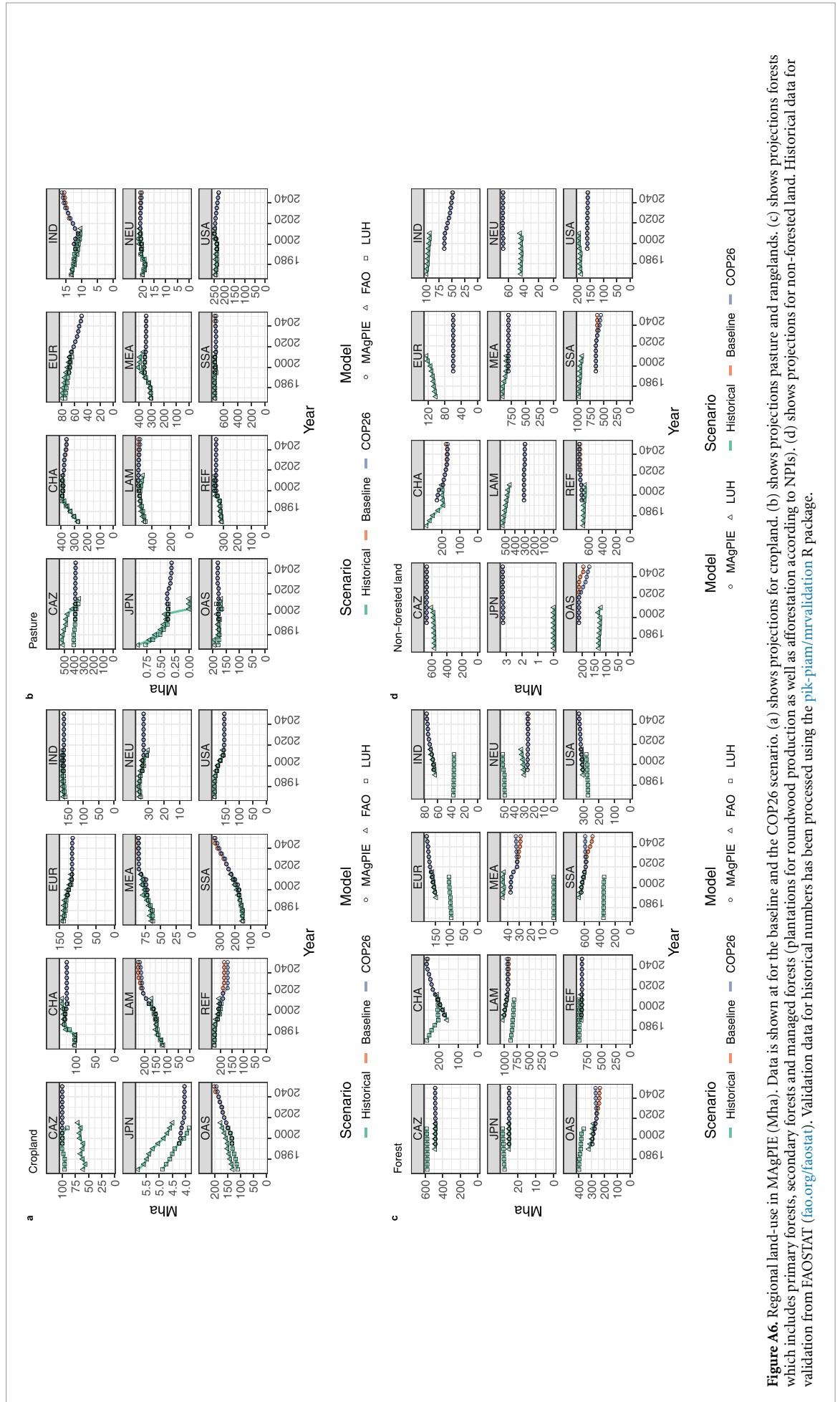
Figure A6. Regional land-use in MAgPIE (Mha). Data is shown at for the baseline and the COP26 scenario. (a) shows projections for cropland. (b) shows projections pasture and rangelands. (c) shows projections forests which includes primary forests, secondary forests and managed forests (plantations for roundwood production as well as afforestation according to NPIs). (d) shows projections for non-forested land. Historical data for validation from FAOSTAT (fao.org/faostat). Validation data for historical numbers has been processed using the pik-piam/mrvalidation R package.
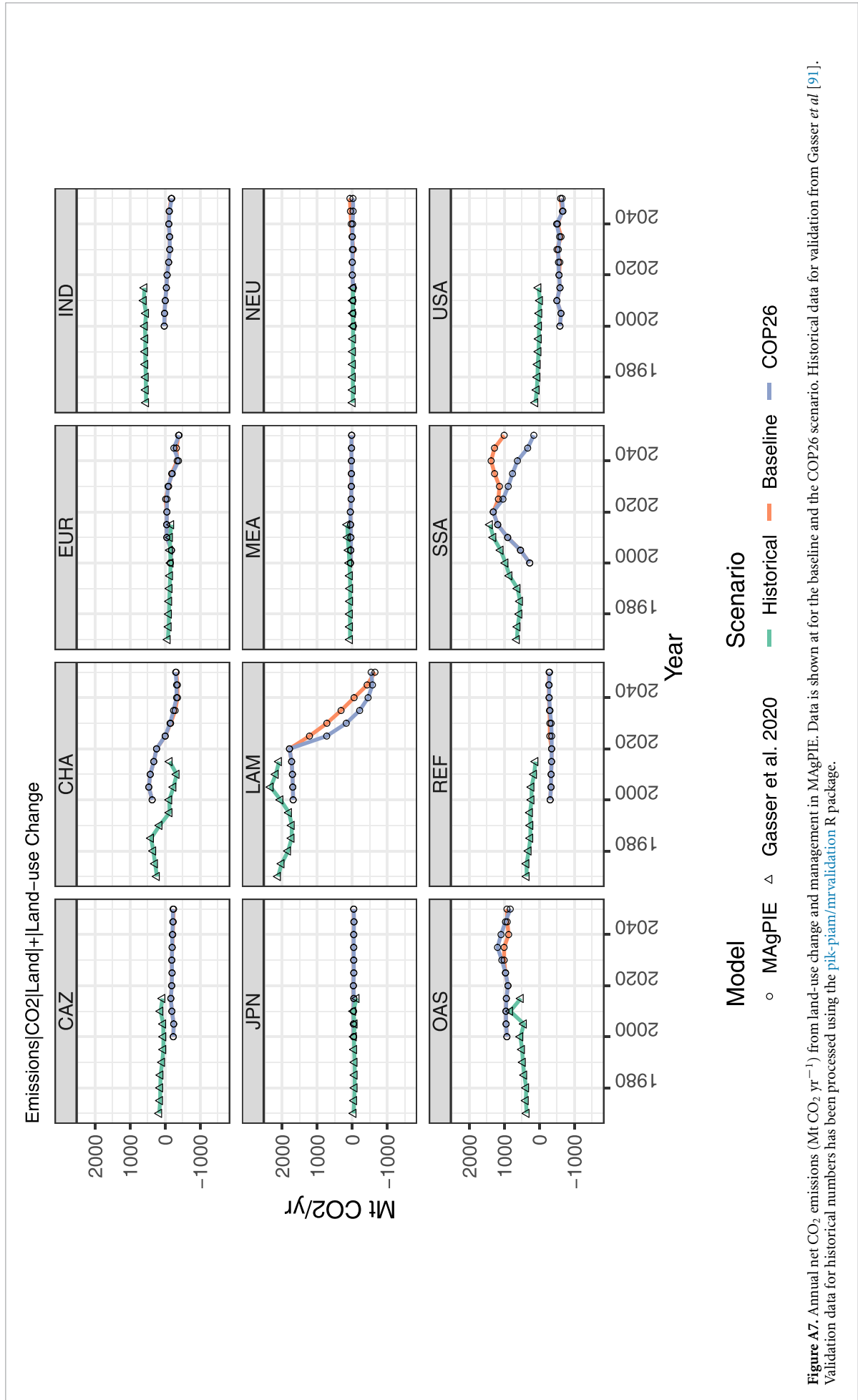
Figure A7. Annual net CO$_2$ emissions (Mt CO$_2$ yr^{-1}) from land-use change and management in MAgPIE. Data is shown at for the baseline and the COP26 scenario. Historical data for validation from Gasser *et al* [91]. Validation data for historical numbers has been processed using the pik-piam/mrvalidation R package.

Figure A8. Land-use intensity factor (τ) MAgPIE. τ is a unitless indicator in MAgPIE where a doubling of τ corresponds to a doubling of crop yields (under fixed environmental conditions). Data is shown for the baseline and the COP26 scenario. Historical data for validation from Dietrich *et al* [60]. Validation data for historical numbers has been processed using the pik-piam/mrvalidation R package.
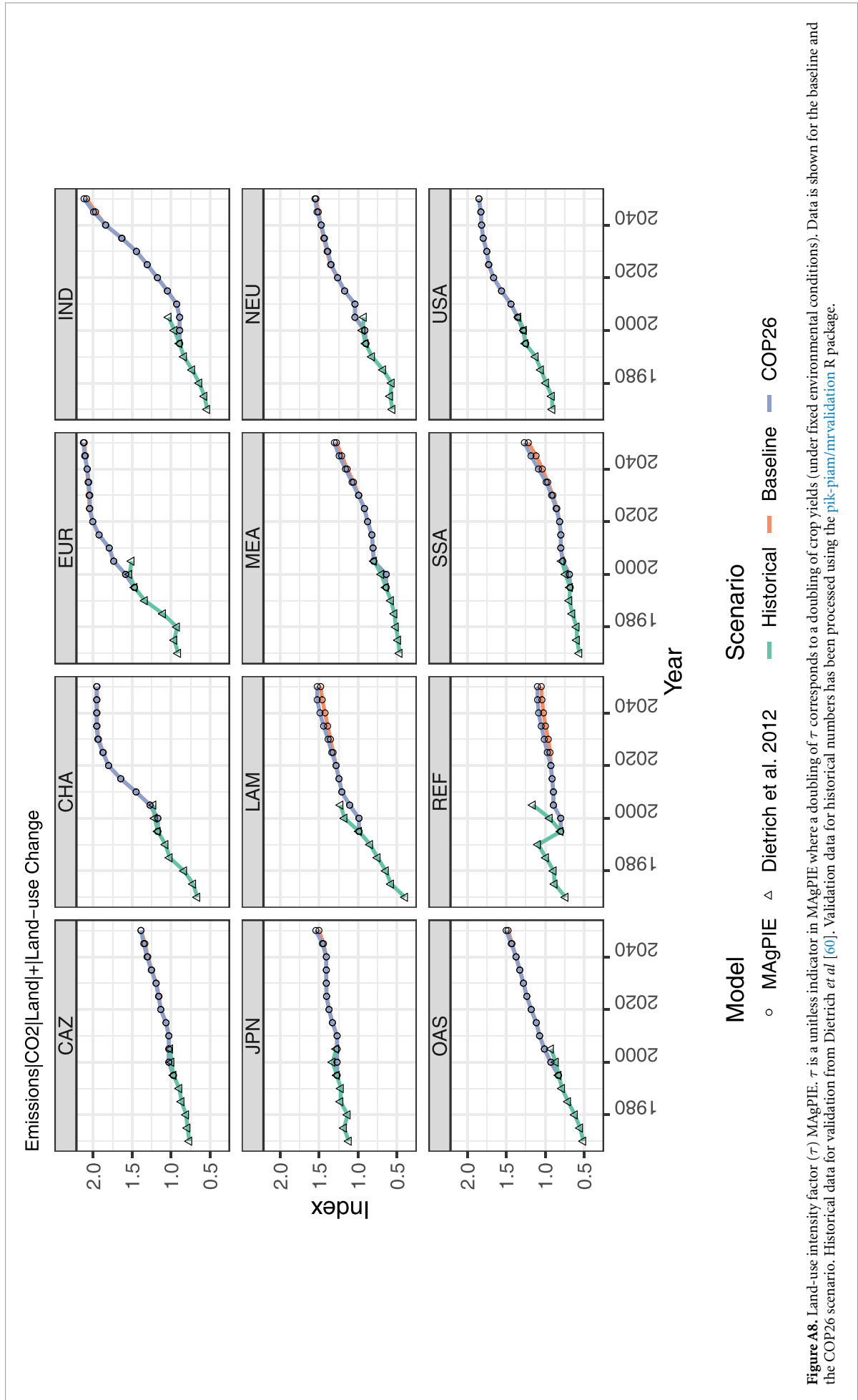
A.2. Tables

Table A1. General settings used for the baseline and the COP26 scenarios. Additional description of model settings are described in https://rse.pik-potsdam.de/doc/magpie/4.6.9/. Specific model settings are part of the repository from Code and data availability section.

Model driver	Setting
GDP	SSP2 projection
Population	SSP2 projection
Food	Exogenous/Inelastic
Waste	Regression-based estimation of food waste
Diet	Regression-based estimation of diet
Trade balance reduction	10 percent trade liberalization for secondary and livestock products in 2030 2050 2100 and 20 percent for crops
Additional land conservation target based on conservation priority areas	None except WDPA defined restrictions
Irrigation for bioenergy crops	Rainfed
Pasture suitability areas	SSP2+RCP4.5
Restriction of afforestation in certain latitudes	Not allowed in Boreal regions (above 50 $^\circ$N)
Changes in Urban areas	SSP2 projection
Afforestation policy	National Policies Implemented (NPIs)
Planning horizon for afforestation	50 years
Avoided deforestation policy	National Policies Implemented (NPIs)
Avoided Other Land Conversion policy	National Policies Implemented (NPIs)
Year by which damages to natural forests from shifting agriculture has faded out	2050
Scenario for non agricultural water demand from WATERGAP model	SSP2 projection
Irrigation efficiency	Regional static values from gdp regression
1st generation bioenergy demand scenarios based on Lotze Campen *et al* (2014)	Constant at 2020 numbers
Residue demand for 2nd generation bioenergy scenarios	SSP2 projection
Distribution of age classes in forest plantations	Higher weight to plantations established after 1990
Harvest from forest plantations	Endogenously decided based on existing roundwood demand. Harvest from plantations including age-class shifting. All plantations are harvested at rotation age. Plantation establishment is endogenous.
Distribution of age-classes during secondary forest initialization	Based on Poulter *et al* 2018 using MODIS satellite data
Harvest from natural forests	Endogenously decided based on existing roundwood demand. Harvest from natural forests includes age-class shifting.
Roundwood demand	FAOSTAT number extrapolated based on socioeconomic changes and Lauri *et al* 2019
Land transition matrix	table 1 in main manuscript

Table A2. Full forms of abbreviations used in the manuscript along with explanatory notes where needed. Regional abbreviations are shown in table A3.

Abbreviation	Full form	Notes
COP	Conference of the Parties to the United Nations Climate Change Conferences	
COP26	The 2021 United Nations Climate Change Conference	Held in Glasgow, Scotland, United Kingdom, from 31 October to 13 November 2021.
EU	European Union	
FRA	Forest Resources Assessment Report	Food and Agriculture Organization of the United Nations (FAO) report released in 5 year cycles to provide essential information for understanding the extent of forest resources, their condition, management and uses globally.
HPC	High Performance Cluster	
HU	Humboldt University of Berlin	
HWPs	Harvested Wood Products	
IPCC	Intergovernmental Panel on Climate Change	
IUCN	International Union for Conservation of Nature	
LUH	Land-Use Harmonization	University of Maryland hosted project to prepare a harmonized set of land-use scenarios that smoothly connects the historical reconstructions of land-use with the future projections in the format required for Earth System Models.
LULUCF	Land use, land-use change and forestry	
MAgPIE	Model of Agricultural Production and its Impact on the Environment	
NDCs	Nationally Determined Contribution	Previously known as intended nationally determined contribution (INDC)
NPIs	National Policies Implemented	
PIK	Potsdam Institute for Climate Impact Research	
SSP2	Middle of the road Shared Socioeconomic Pathway	SSP2 is the second amongst the five Shared Socioeconomic Pathways (SSPs)
UK	United Kingdom	
UNFCCC	The United Nations Framework Convention on Climate Change	
USA	United States of America	
WDPA	World Database on Protected Areas	

Table A3. Regional mapping and ISO3 codes of countries.

Region name	Region code	Standard MAgPIE Region name	Standard MAgPIE region code	ISO3 country codes
OECD countries as of 1990 and European Union (incl. UK)	OECD90+EU	Canada, Australia, New Zealand	CAZ	AUS; CAN; HMD; NZL; SPM
Asia	ASIA	China	CHA	CHN; HKG; MAC; TWN
OECD countries as of 1990 and European Union (incl. UK)	OECD90+EU	Europe	EUR	ALA; AUT; BEL; BGR; CYP; CZE; DEU; DNK; ESP; EST; FIN; FRA; FRO; GBR; GGY; GIB; GRC; HRV; HUN; IMN; IRL; ITA; JEY; LTU; LUX; LVA; MLT; NLD; POL; PRT; ROU; SVK; SVN; SWE
Asia	ASIA	India	IND	IND
OECD countries as of 1990 and European Union (incl. UK)	OECD90+EU	Japan	JPN	JPN
Latin America	LAM	Latin America	LAM	ABW; AIA; ARG; ATA; ATG; BES; BHS; BLM; BLZ; BMU; BOL; BRA; BRB; BVT; CHL; COL; CRI; CUB; CUW; CYM; DMA; DOM; ECU; FLK; GLP; GRD; GTM; GUF; GUY; HND; HTI; JAM; KNA; LCA; MAF; MEX; MSR; MTQ; NIC; PAN; PER; PRI; PRY; SGS; SLV; SUR; SXM; TCA; TTO; URY; VCT; VEN; VGB; VIR
Rest of the world	ROW	Middle East Asia	MEA	ARE; BHR; DZA; EGY; ESH; IRN; IRQ; ISR; JOR; KWT; LBN; LBY; MAR; OMN; PSE; QAT; SAU; SDN; SYR; TUN; YEM
OECD countries as of 1990 and European Union (incl. UK)	OECD90+EU	Non European Countries	NEU	ALB; AND; BIH; CHE; GRL; ISL; LIE; MCO; MKD; MNE; NOR; SJM; SMR; SRB; TUR; VAT
Asia	ASIA	Other Asian Countries	OAS	AFG; ASM; ATF; BGD; BRN; BTN; CCK; COK; CXR; FJI; FSM; GUM; IDN; IOT; KHM; KIR; KOR; LAO; LKA; MDV; MHL; MMR; MNG; MNP; MYS; NCL; NFK; NIU; NPL; NRU; PAK; PCN; PHL; PLW; PNG; PRK; PYF; SGP; SLB; THA; TKL; TLS; TON; TUV; UMI; VNM; VUT; WLF; WSM
Rest of the world	ROW	Reforming Economies	REF	ARM; AZE; BLR; GEO; KAZ; KGZ; MDA; RUS; TJK; TKM; UKR; UZB
Sub-Saharan Africa	SSA	Sub-Saharan Africa	SSA	AGO; AZE; BDI; BEN; BFA; BWA; CAF; CIV; CMR; COD; COG; COM; CPV; DJI; ERI; ETH; GAB; GHA; GIN; GMB; GNB; GNQ; KEN; LBR; LSO; MDG; MLI; MOZ; MRT; MUS; MWI; MYT; NAM; NER; NGA; REU; RWA; SEN; SHN; SLE; SOM; SSD; STP; SWZ; SYC; TCD; TGO; TZA; UGA; ZAF; ZMB; ZWE
OECD countries as of 1990 and European Union (incl. UK)	OECD90+EU	United States of America	USA	USA

Table A4. Global and regional protected areas for MAgPIE from 2030 onwards (in Mha). Forest area is the sum of protected primary forests and protected secondary forests.

	ASIA	LAM	OECD90+EU	ROW	SSA	World
Cropland	5	10	23	12	27	76
Non-forest land	35	72	196	120	144	567
Pasture	17	11	45	14	26	113
Forests	60	329	178	121	155	843
of which, Primary forest	*29*	*260*	*52*	*25*	*44*	*410*
of which, Secondary forest	*31*	*69*	*126*	*96*	*112*	*433*
Total	118	422	441	266	352	1599

Table A5. Global and regional cumulative emissions from land-use change. Values are for the year 2050 in comparison to 2030. COP26-Baseline column shows the difference between the COP26 and the baseline scenario in 2050. All values in Gt CO_2.

	Baseline	COP26	Baseline-COP26
ASIA	10	−23	−33
LAM	−4	12	16
OECD90+EU	−23	−9	14
ROW	−5	−5	0
SSA	25	9	−15
World	3	−16	−19

Table A6. Global and regional annual emissions from land-use change. All values in Mt CO_2 yr^{-1}.

	2030		2050		2050-2030		
	Baseline	COP26	Baseline	COP26	Baseline	COP26	COP26-Baseline in 2050
ASIA	717	797	436	339	−282	−457	−97
LAM	725	171	−649	−541	−1373	−712	108
OECD90+EU	−867	−863	−1209	−1336	−342	−473	−127
ROW	−272	−315	−265	−271	7	45	−5
SSA	1138	888	1006	159	−133	−729	−847
World	1442	677	−681	−1649	−2123	−2327	−968

A.3. Additional figures

Figure A9. Forest area change in 2050 compared to 2030 for two scenarios. Forest includes primary forest (forest landscapes without any sign of human intervention), secondary forest (forest landscapes with some sign of human intervention, i.e. modified and regrown forest) and forest plantations (for wood production). Values above 0 indicate increase in land-use in 2050 compared to 2030 and values below 0 indicate decrease in land-use in 2050 compared to 2030 for respective land-use types. Regional descriptions are provided in table A3.

Figure A10. Global and regional change in total growing stock by 2050 compared to 2030 in primary and secondary forest (Billion m_3).

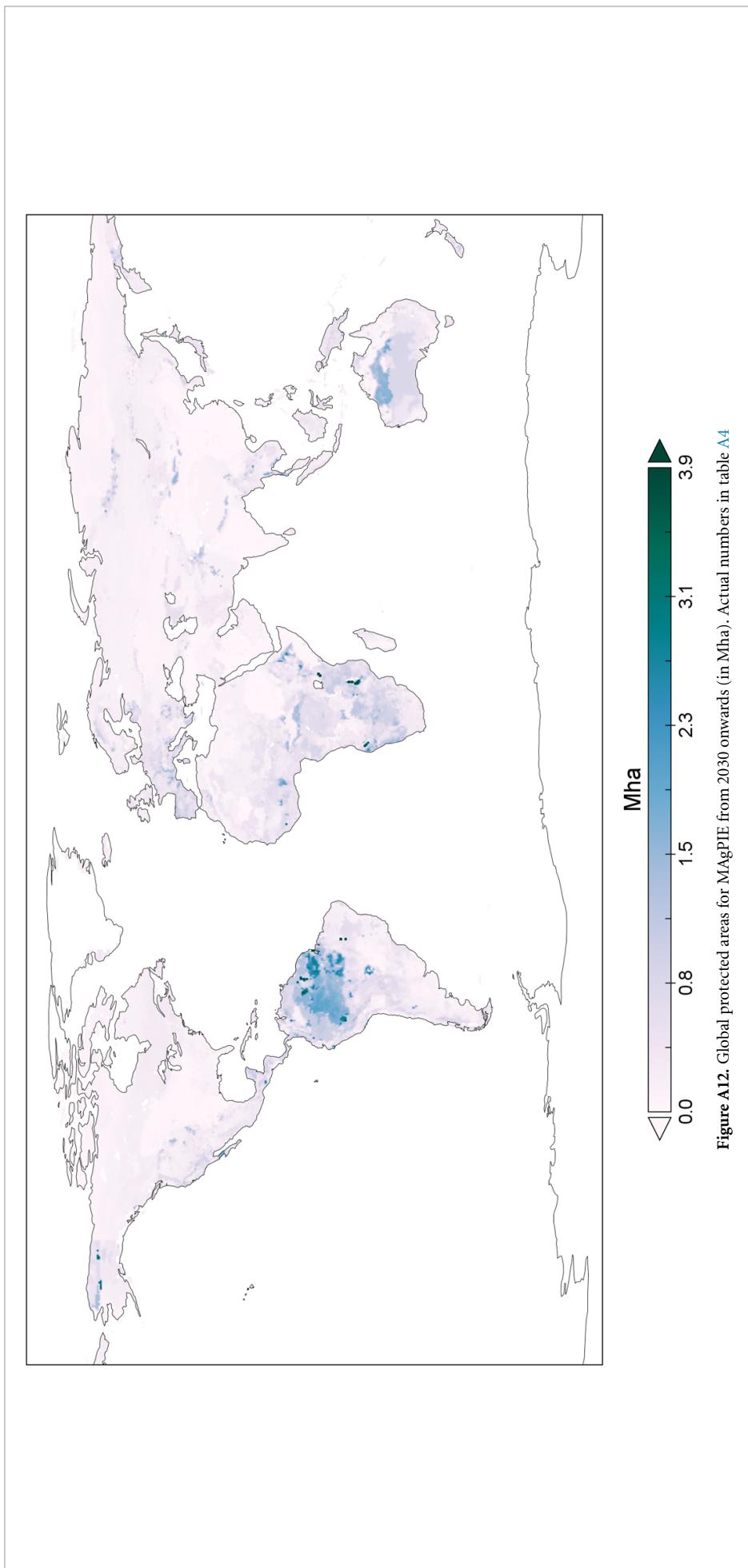**Figure A11.** Global cumulative land-use change emissions disaggregated into regions and components.

Figure A12. Global protected areas for MAgPIE from 2030 onwards (in Mha). Actual numbers in table A4

Figure A13. Difference in cellular (0.5° resolution) land use share between the baseline and the COP26 scenario in 2050 for cropland. Cells with red shade indicate that the cropland share in a particular 50 × 50 km cell in 2050 is lower in the COP26 scenario compared to the baseline scenario, i.e. loss of cropland in COP26 scenario compared to the baseline. Cells with green shade indicate that the cropland share in a particular 50 × 50 km cell in 2050 is higher in the COP26 scenario compared to the baseline scenario, i.e. increase in cropland use in COP26 scenario compared to the baseline.

Figure A14. Difference in cellular (0.5° resolution) pasture land use share between the baseline and the COP26 scenario in 2050 for pasture land. Cells with red shade indicate that the pasture land share in a particular 50 × 50 km cell in 2050 is lower in the COP26 scenario compared to the baseline, i.e. loss of pasture land in COP26 scenario compared to the baseline. Cells with green shade indicate that the pasture land share in a particular 50 × 50 km cell in 2050 is higher in the COP26 scenario compared to the baseline scenario, i.e. increase in pasture land use in COP26 scenario compared to the baseline.
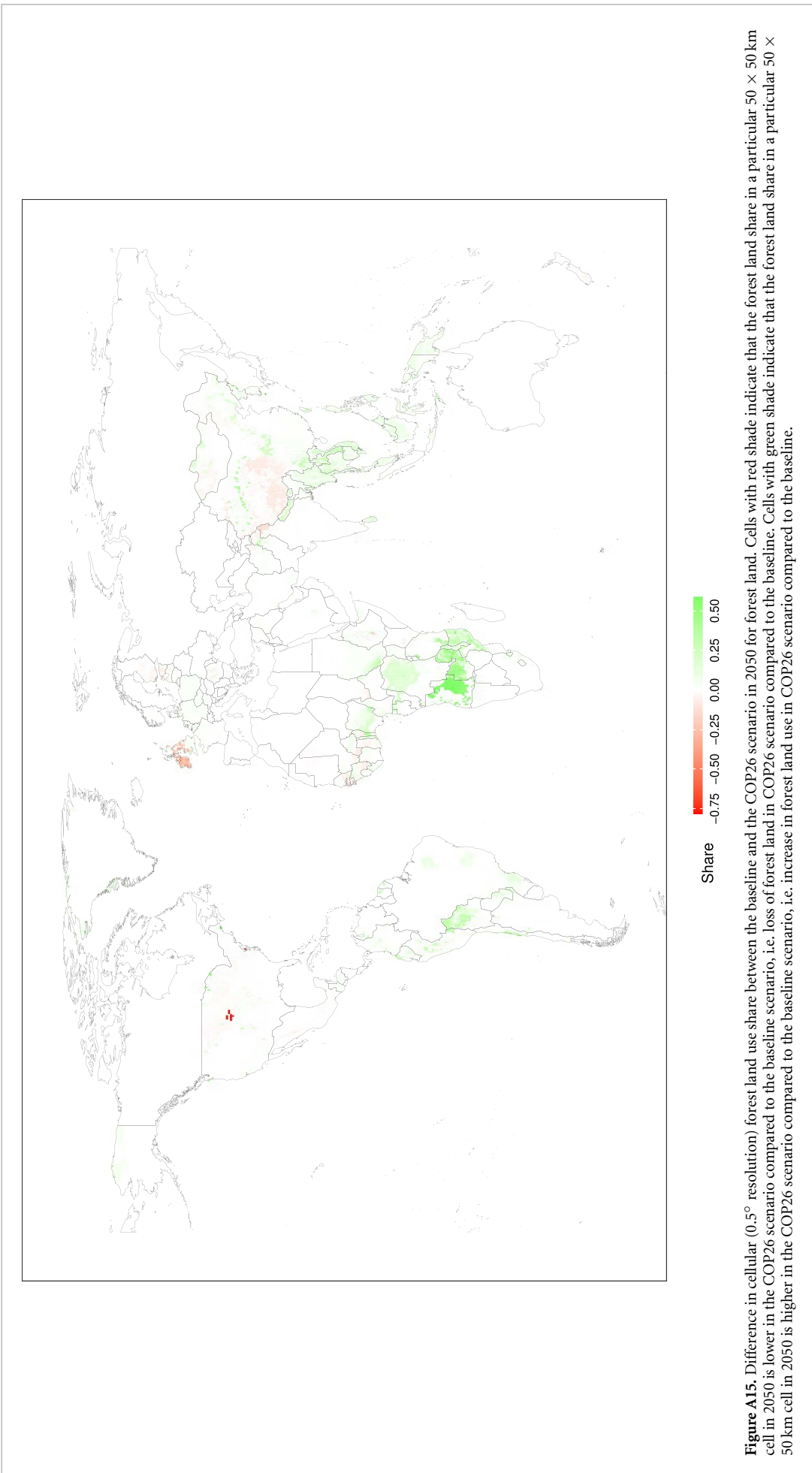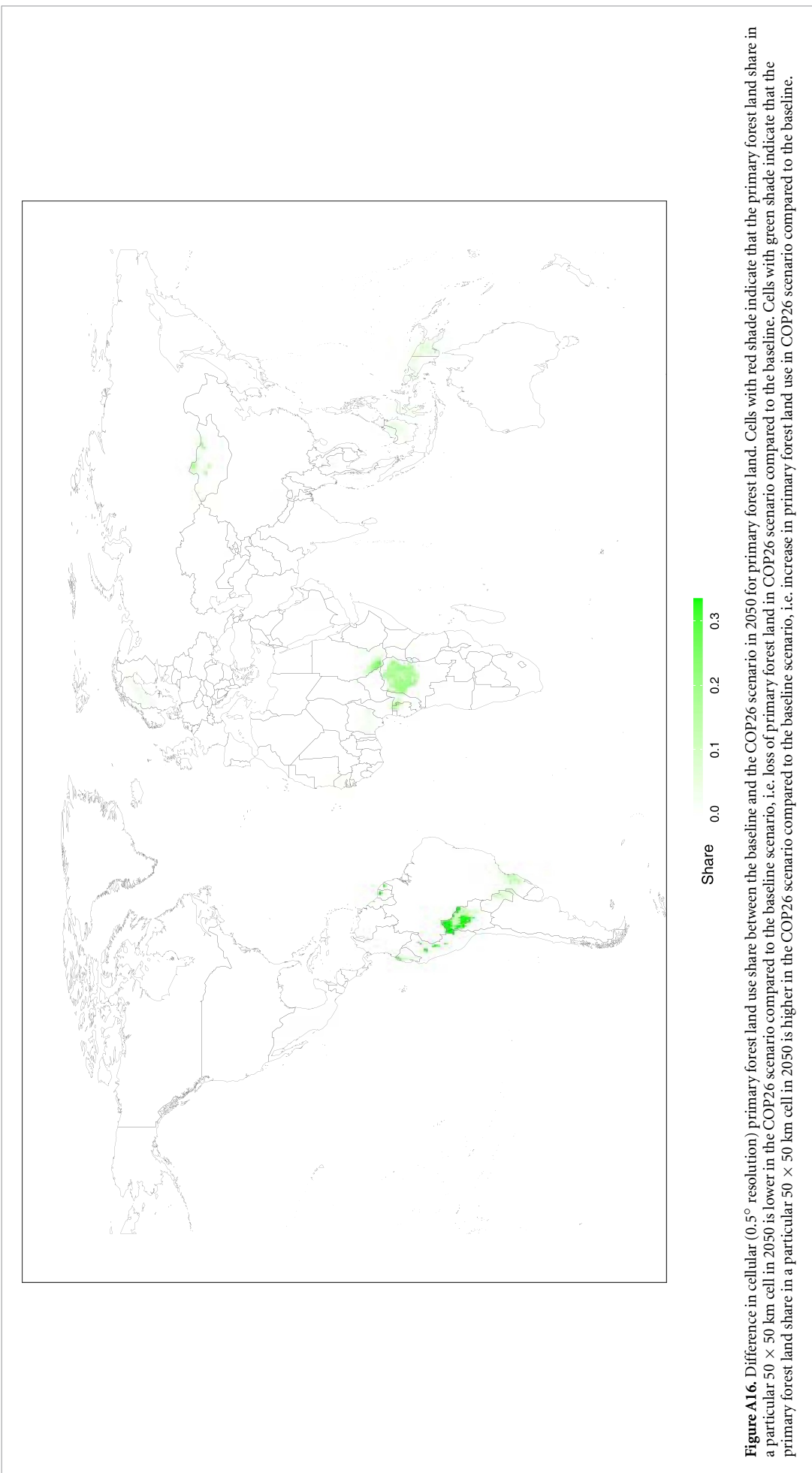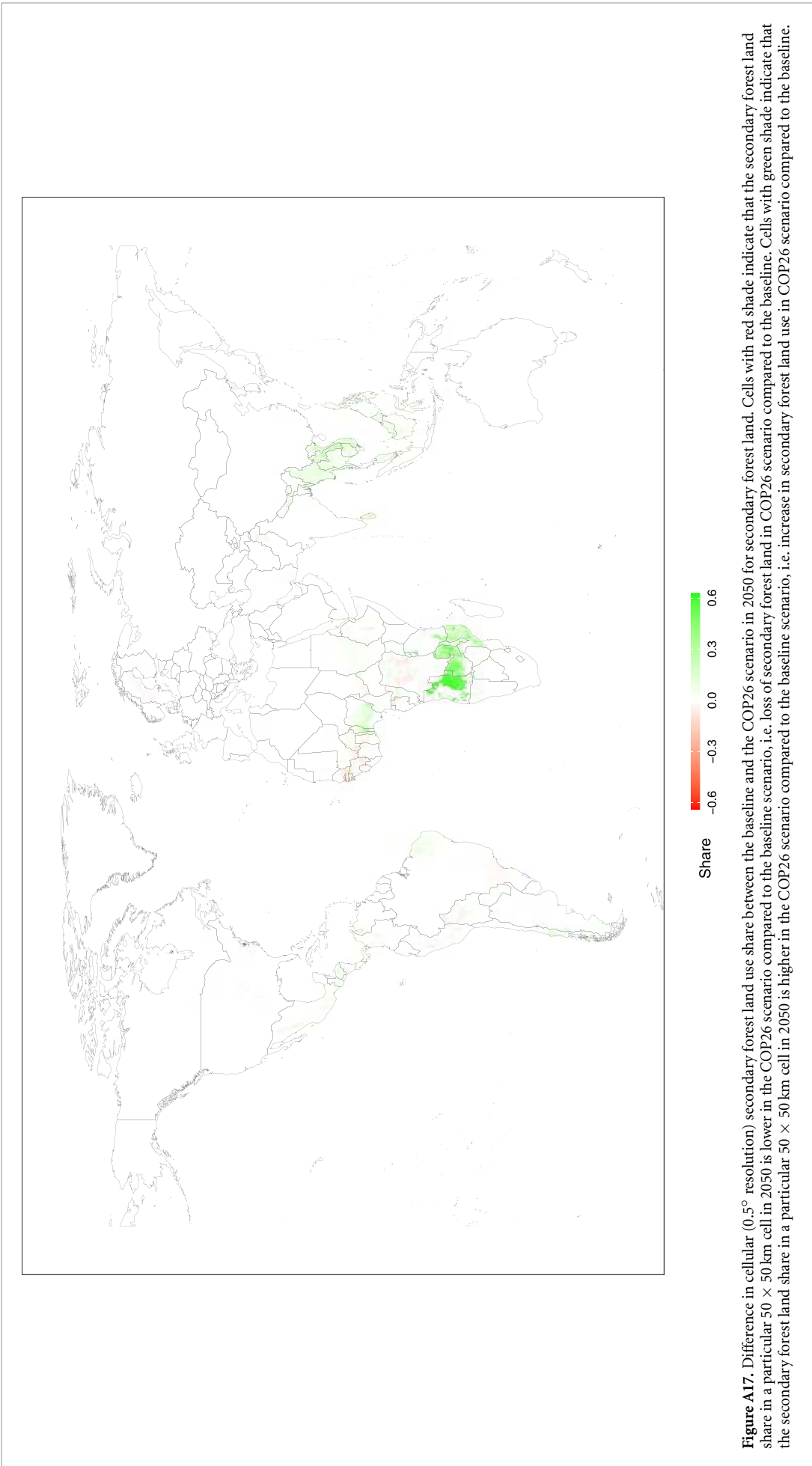
Figure A15. Difference in cellular (0.5° resolution) forest land use share between the baseline and the COP26 scenario in 2050 for forest land. Cells with red shade indicate that the forest land share in a particular 50 × 50 km cell in 2050 is lower in the COP26 scenario compared to the baseline scenario, i.e. loss of forest land in COP26 scenario compared to the baseline. Cells with green shade indicate that the forest land share in a particular 50 × 50 km cell in 2050 is higher in the COP26 scenario compared to the baseline scenario, i.e. increase in forest land use in COP26 scenario compared to the baseline.
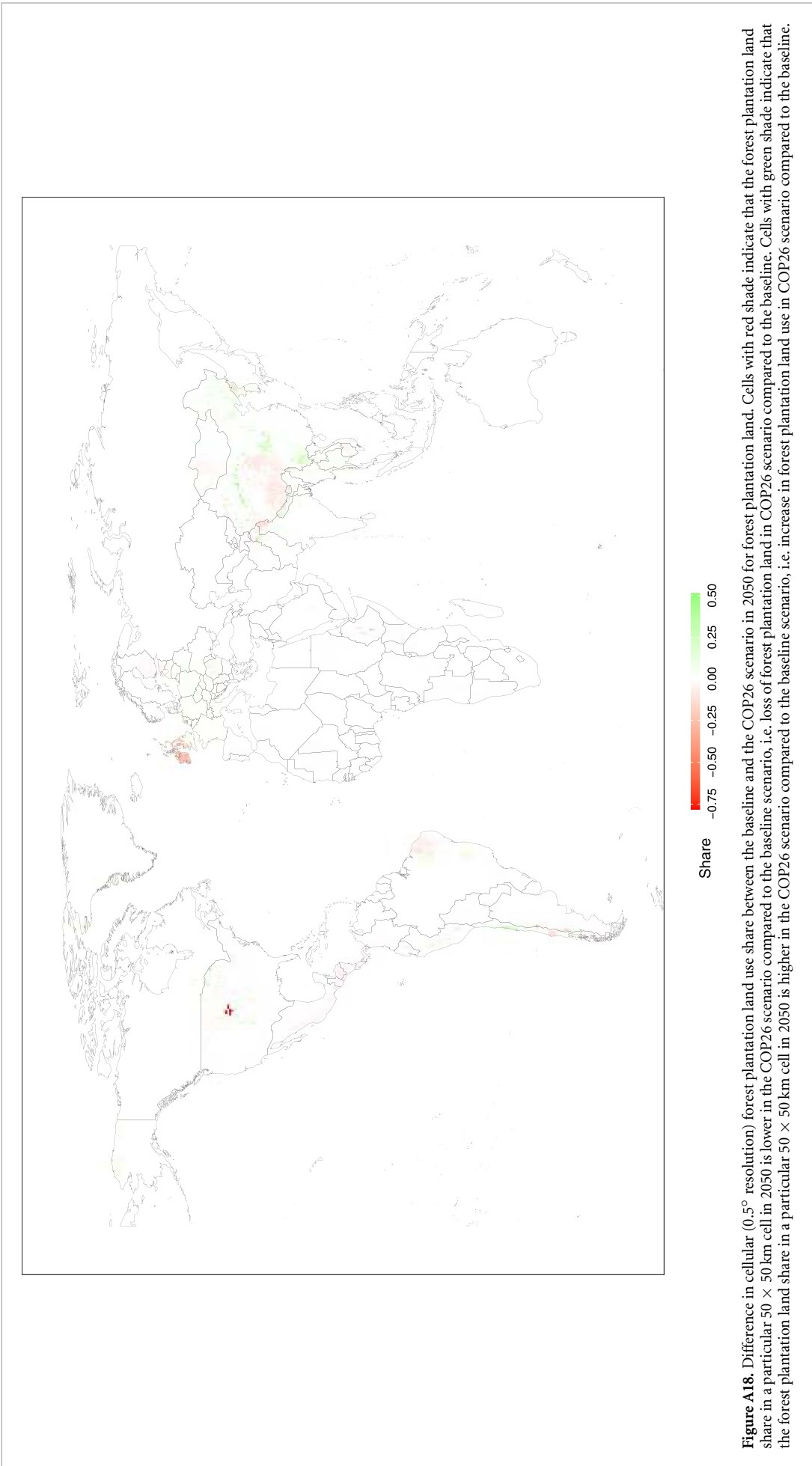
Figure A16. Difference in cellular (0.5° resolution) primary forest land use share between the baseline and the COP26 scenario in 2050 for primary forest land. Cells with red shade indicate that the primary forest land share in a particular 50 × 50 km cell in 2050 is lower in the COP26 scenario compared to the baseline scenario, i.e. loss of primary forest land in COP26 scenario compared to the baseline. Cells with green shade indicate that the primary forest land share in a particular 50 × 50 km cell in 2050 is higher in the COP26 scenario compared to the baseline scenario, i.e. increase in primary forest land use in COP26 scenario compared to the baseline.

Figure A17. Difference in cellular (0.5° resolution) secondary forest land use share between the baseline and the COP26 scenario in 2050 for secondary forest land. Cells with red shade indicate that the secondary forest land share in a particular 50 × 50 km cell in 2050 is lower in the COP26 scenario compared to the baseline scenario, i.e. loss of secondary forest land in COP26 scenario compared to the baseline. Cells with green shade indicate that the secondary forest land share in a particular 50 × 50 km cell in 2050 is higher in the COP26 scenario compared to the baseline scenario, i.e. increase in secondary forest land use in COP26 scenario compared to the baseline.
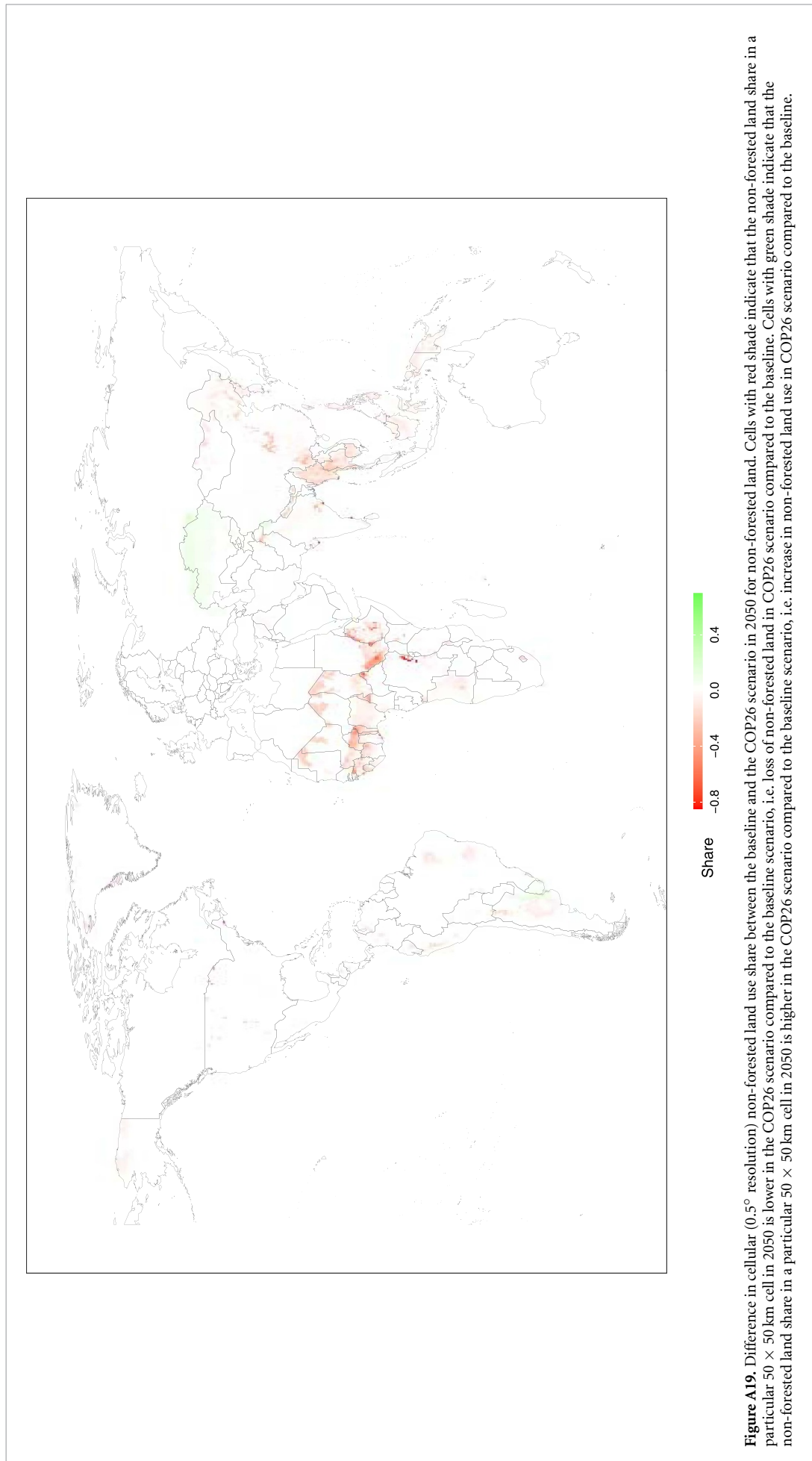
Figure A18. Difference in cellular (0.5° resolution) forest plantation land use share between the baseline and the COP26 scenario in 2050 for forest plantation land. Cells with red shade indicate that the forest plantation land share in a particular 50 × 50 km cell in 2050 is lower in the COP26 scenario compared to the baseline scenario, i.e. loss of forest plantation land in COP26 scenario compared to the baseline. Cells with green shade indicate that the forest plantation land share in a particular 50 × 50 km cell in 2050 is higher in the COP26 scenario compared to the baseline scenario, i.e. increase in forest plantation land use in COP26 scenario compared to the baseline.
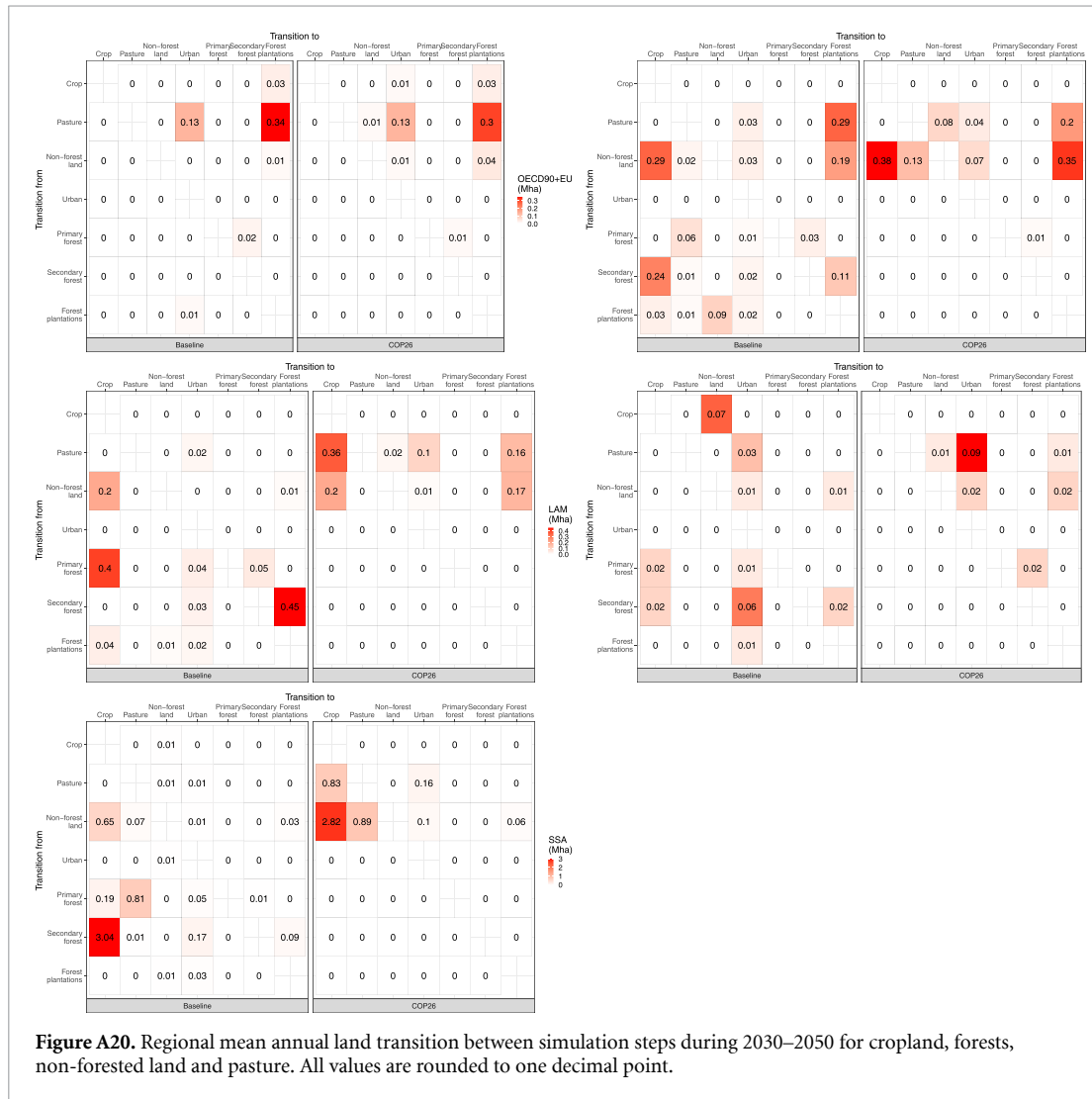
Figure A19. Difference in cellular (0.5° resolution) non-forested land use share between the baseline and the COP26 scenario in 2050 for non-forested land. Cells with red shade indicate that the non-forested land share in a particular 50 × 50 km cell in 2050 is lower in the COP26 scenario, i.e. loss of non-forested land in COP26 scenario compared to the baseline. Cells with green shade indicate that the non-forested land share in a particular 50 × 50 km cell in 2050 is higher in the COP26 scenario compared to the baseline, i.e. increase in non-forested land use in COP26 scenario compared to the baseline.

Figure A20. Regional mean annual land transition between simulation steps during 2030–2050 for cropland, forests, non-forested land and pasture. All values are rounded to one decimal point.

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