Supplementary Information (SI)

Assessing human and environmental pressures of global land-use change 2000-2010

Felix Creutzig[1,2], Christopher Bren d'Amour[1,2], Ulf Weddige[1], Sabine Fuss[1], Tim Beringer[1], Anne Gläser[1], Matthias Kalkuhl[1,3], Jan Steckel[1,2,4], Alexander Radebach[1,2], Ottmar Edenhofer[1,2,4]*

[1]Mercator Research Institute on Global Commons and Climate Change, Torgauer Straße 12-15, 10829 Berlin

[2]Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin

[3]Universität Potsdam, Am Neuen Palais 10, 14469 Potsdam

[4]Potsdam Institute for Climate Impact Research, P.O.Box 601203, 14412 Potsdam, Germany

[*]to whom correspondence should be addressed: creutzig@mcc-berlin.net

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This document entails the following:

Figures S1-3

Figure S1 – Principal Component Analysis (PCA)

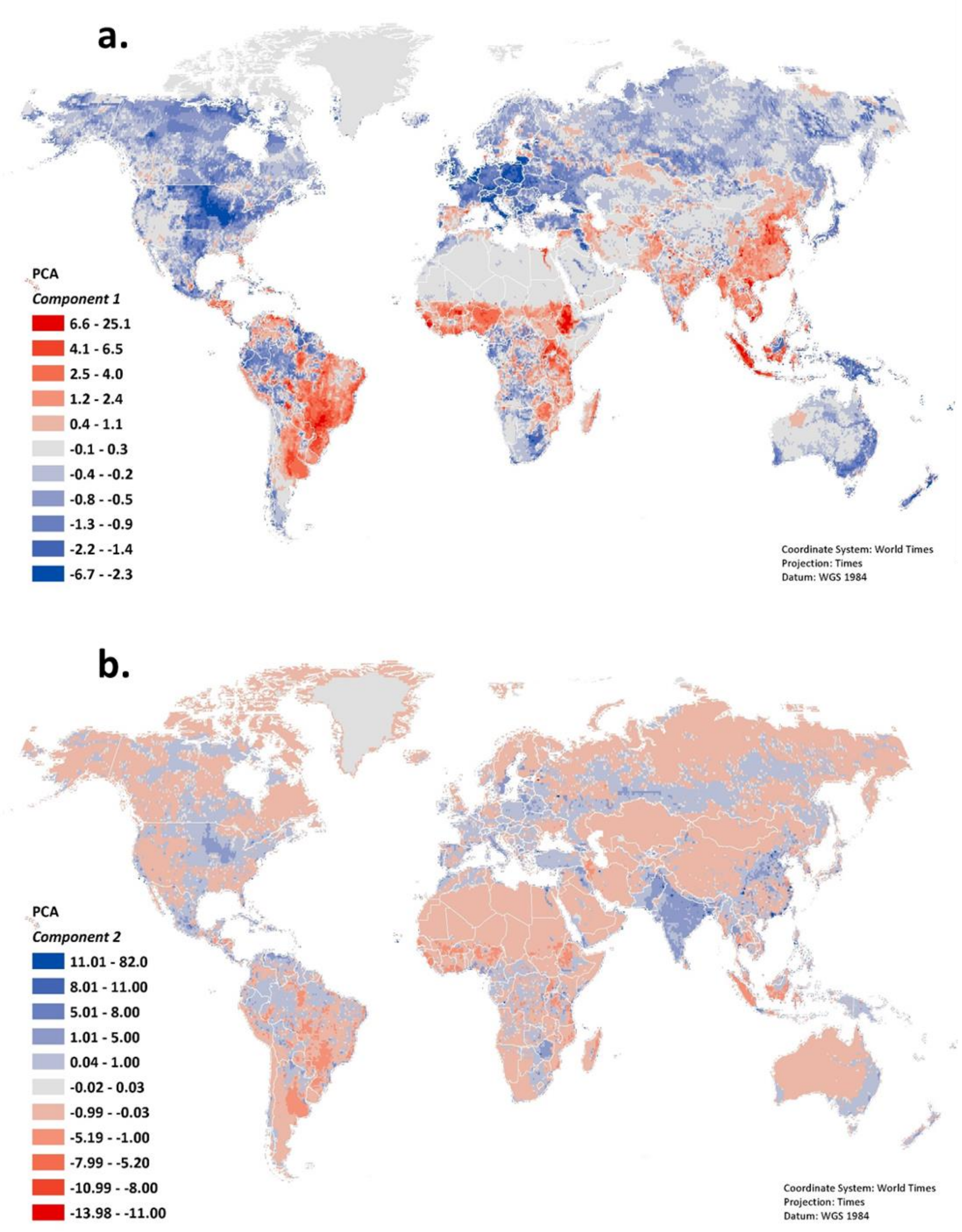

Figure S1 – Principal Component Analysis (PCA). This figure contains maps of the Z-scores of the PCA for **a)** component 1 **b)** component 2. Z-scores are calculated as the product of the eigenvectors from the PCA with the standardized data of intensity changes. They show the reduction of the underlying data to the lower-dimensional space (here: two dimensions as we consider only the first two components) while maintaining highest explanatory power.

Figure S2 – Shift diagrams

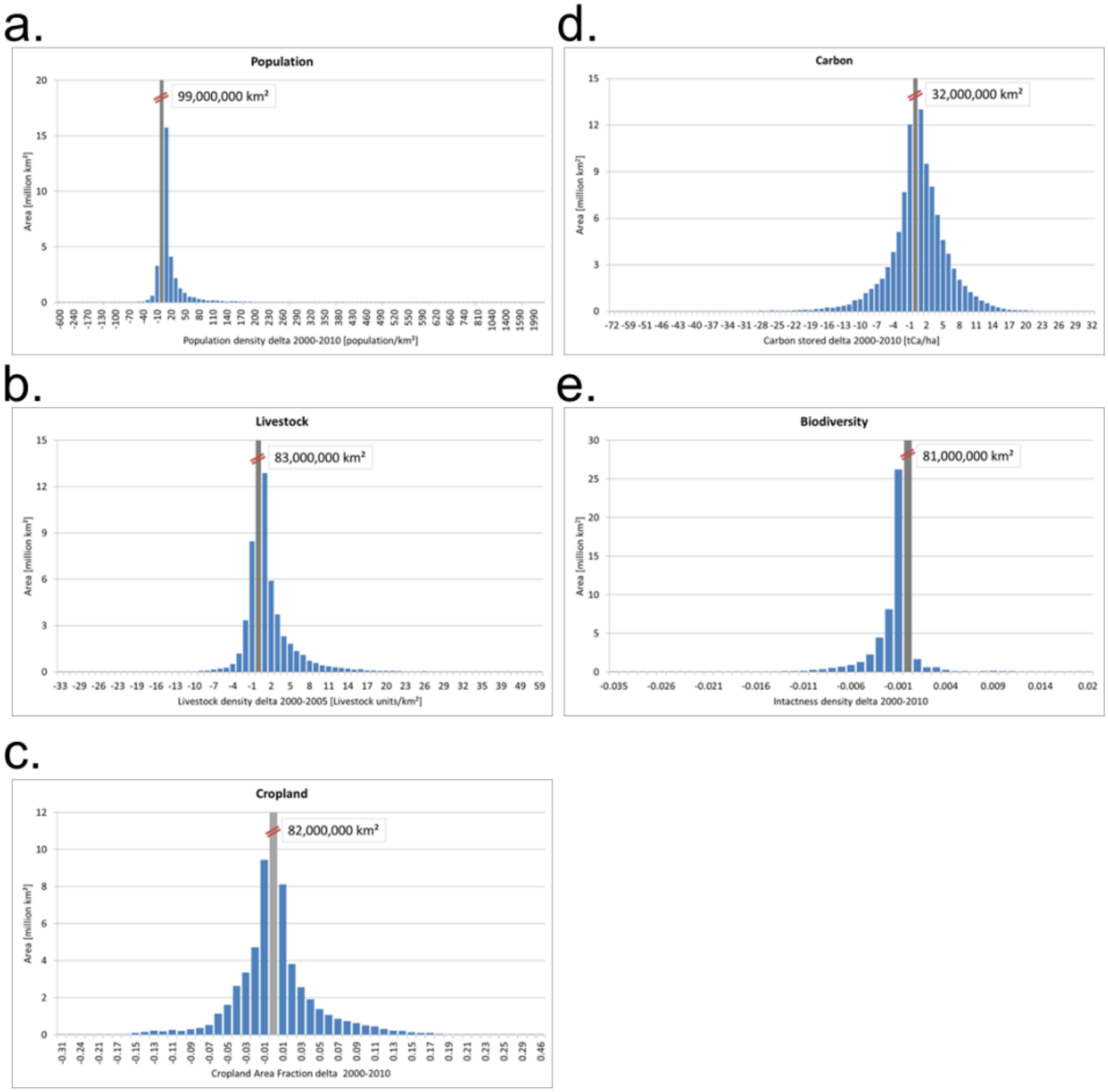

Figure S2 – Shift diagrams. The shift diagrams depict the frequency distribution in terms of area of the intensity changes between 2000 and 2010 from negative (on the left) to positive (on the right) for a) population density; b) livestock density; c) cropland area fraction; d) carbon stock; e) Intactness. The grey bar represents the area without notable changes.

Figure S3 – Intensity change maps

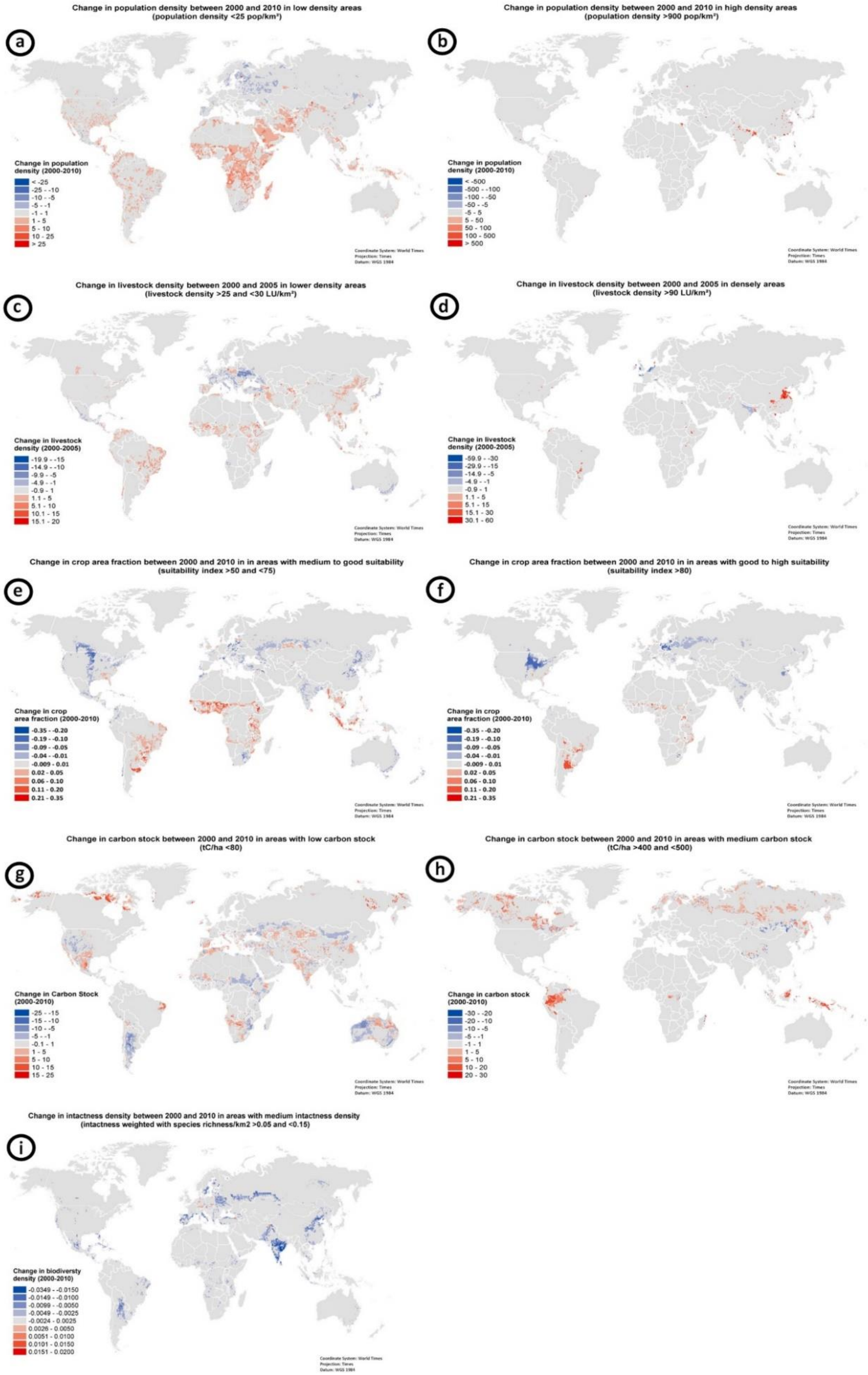

Figure S3 – Intensity change maps. The following maps show the spatial distribution of the areas in intensity bins of interest (red boxes) as identified in Figure 2 of the manuscript. The headings of the individual panels indicate the most likely explanation for the observed dynamics. These are non-exhaustive and mostly illustrative. **a) Rural densification and pristine land take:** Change in population density between 2000 and 2010 in low density areas (population density <25 pop/km2); **b) Urbanization:** Change in population density between 2000 and 2010 in high density areas (population density >900 pop/km2); **c) Intensification in peripheral areas:** Change in livestock density between 2000 and 2010 in lower density areas (livestock density >25 and <30 LU/km2); **d) Intense husbandry:** Change in livestock density between 2000 and 2010 in higher density areas (livestock density >90 LU/km2); **e) Expansion in South America, Sub-Saharan Africa and South East Asia:** Change in cropland area fraction between 2000 and 2010 in areas with medium to good suitability (suitability index >50 and <75); **f) Cropland abandonment in OECD countries:** Change in cropland area fraction between 2000 and 2010 in areas with medium to high suitability (suitability >80); **g) Increase in ice-free areas:** Change in carbon stock between 2000 and 2010 in areas with low carbon stock (tC/ha <80); **h) Increase in boreal areas:** Change in carbon stock between 2000 and 2010 in areas with medium carbon stock (tC/ha >400 and <500); **i) Human pressures:** Change in intactness density between 2000 and 2010 in areas with medium intactness density (intactness weighted with species richness/km2 >0.05 and <0.15).

Tables S1-7

Table S1 – Datasets

This table provides an overview over the datasets used in this study. Data selection is based on quality and availability for the year 2000 and 2010. Modelled data is only used if alternatives were unavailable.

Land-use dimension	Name of dataset	Resolution	Comments	Units	Points in time	Source/Link
Population	SEDAC's Gridded Population of the World (GPW), v3 (Center for International Earth Science Information Network - CIESIN - Columbia University and Centro Internacional de Agricultura Tropical - CIAT, 2005)	50x50km (5x5km possible)	The grid for 2010 was produced in collaboration with the United Nations Food and Agriculture Program (FAO) as Population Count and Density Grid.	Total population, Population density (pop/km^2)	2000 and 2010 (projected)	(Gridded Population of the World, Version 3 (GPWv3): Population Count Grid. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4639MPP. Accessed, Jan 2016)
Livestock	Gridded Livestock of the World (GLW) (Robinson et al., 2014; Wint et al., 2007)	5x5 arc-minute	Aggregate Livestock units, compromising multiple livestock types	Livestock units, livestock density (LU/km^2)	2000 and 2005	http://www.fao.org/ag/againfo/resources/en/glw/GLW_dens.html
Cropland	History Database of the Global Environment (HYDE 3.2) (Klein Goldewijk et al., 2016) Global Agro-Ecological Zones (GAEZ) (IIASA, 2012)	0.5x0.5 degree	HYDE data is based on FAO's categories 'Arable land and permanent crops', complemented by sub-national statistics for important producing regions (cf. Table S1 in Klein Goldewijk et al., 2016) GAEZ suitability for cereals only, high input level	Crop area fraction, i.e. percentage of a grid cell Suitability Index [from 0-1]	2000 and 2010 2000 (for suitability)	ftp://ftp.pbl.nl/hyde/hyde3.2/ http://themasites.pbl.nl/tridion/en/themasites/hyde/ http://gaez.fao.org/Main.html#
Carbon Storage	Lund-Potsdam-Jena managed Land model (LPJ) (Bondeau et al., 2007) Deforestation	0.5x0.5 degree 30mx30m (GFW)	Modelled data.	tC stored (total, and per ha)	2000 and 2010	https://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml

Land-use dimension	**Name of dataset**	**Resolution**	**Comments**	**Units**	**Points in time**	**Source/Link**
	Forest canopy from Global Forest Watch (GFW)				2001-2010 (GFW)	
Biodiversity	Predicts database (Hudson et al., 2014) Newbold et al. (Newbold et al., 2015) (SI) LUHa u2t1 Land Use Harmonization (Hurtt et al., 2011)		See method section for further explanation on data processing.	Species Richness Intactness Land Uses	n/a n/a 2000 and 2010	http://www.predicts.org.uk/ http://www.biodiversityinfo.org/spcdownload/r5h8a1/ http://www.nature.com/nature/journal/v520/n7545/full/nature14324.html http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=about
Land embodied in trade	Kastner et al, 2014 (Kastner et al., 2014)	Country level	Used to capture teleconnected dimension	Net share of croplands used for exports	2000 and 2009	http://iopscience.iop.org/1748-9326/9/3/034015/media
Land footprint	Weinzettel et al, 2013 (Weinzettel et al., 2013)	Country level	Used for Fig. 5	global hectares (gha) per capita	2004	http://www.sciencedirect.com/science/article/pii/S0959378012001501

Table S2 - First two components (eigenvectors) of the Principle Component Analysis

The eigenvector with the highest eigenvector is the principle component which gives a one-dimensional reduction of the data that explains the highest share of the variation. Adding further eigenvectors allows to account for more variability (but increases also dimensionality). The eigenvectors are used to calculate the z-scores.

Variable	Component 1	Component 2	Unexplained
Population	0.2441	0.8602	0.1821
Carbon	-0.5388	0.2566	0.5111
Crop area	0.5185	-0.2997	0.5187
Livestock	0.5229	-0.0411	0.5992
Biodiversity	-0.3285	-0.3203	0.7411

Table S3 - Cropland associated to trade (net exports) as a share of the cropland under domestic production [in %]

(a) relative to total regional cropland in 2000. (b) relative to total regional cropland in 2009. Numbers are calculated using detailed country data from the Supplementary Appendix in (Kastner et al., 2014) which contains land embedded in crop trade flows. As data for 2009 is the most recent available, we use 2009 data instead of 2010. Entries are ordered according to the largest changes between 2009 and 2000 (last column). Positive (negative) numbers for the year 2000 and 2009 indicate that a country is a net land exporter (importer), with the net export share of land on total cropland represented by the respective entries. The last column shows the change of the land net export share.

Region	2000	2009 (a)	2009 (b)	Change (2000 vs 2009 (a))
Latin and Central America	14.0	37.8	31.2	23.8
Eastern Europe & Central Asia	2.3	17.9	16.7	15.7
Oceania	68.1	71.0	62.6	2.9
South-Eastern Asia	4.1	3.6	3.0	-0.5
Sub-Saharan Africa	3.6	2.9	2.4	-0.7
Southern Asia	-0.3	-3.4	-3.2	-3.0
North America	33.9	30.9	31.8	-3.1
Eastern Asia	-21.4	-31.7	-30.0	-10.3
Europe	-39.5	-50.3	-53.0	-10.8
Middle East and North Africa	-36.8	-53.9	-52.0	-17.1

Table S4 - Regional overview over gain and loss per land use dimension in hotspots (top 10%) between 2000 and 2010 (2000 and 2005 for livestock)

Units used are 1) Population (Pop): population/km2 (density) and million people (total); 2) Livestock (Livest): livestock units/km2 (density and million livestock units (total); 3) Cropland (Crop): cropland area fraction (% of cropland in a grid cell, density) and '000 km2 (total); 4) Carbon: tC/ha (density) and megatons Carbon (total); 5) Biodiversity: Intactness/km2 (weighted with species richness, density) and Intactness weighted with species richness (total).

Top 10%	Dimension	Share of area with gain	Average density 2000	Average density 2010	Density 2010 – density 2000	Change in intensity (%)	Average density change for areas with gain	Share of global area with gain	Average density change for areas with loss	Share of global area with loss
Eastern Asia	Pop	59%	505.7	556.8	51.1	10%	117	14%	-19	30%
	Livest	98%	52.1	59.5	7.3	14%	32	26%	0	1%
	Crop		0.6	0.5	-0.1	-11%	0	0%	-34	4%
	Carbon	23%	276.3	272.8	-3.5	-1%	5.6	1%	6.4	3%
	Bio		0.109	0.103	0.0	-5%	0	0%	-7	4%
Eastern Europe & Central Asia	Pop	37%	256.1	245.8	-10.2	-4%	7	1%	-9	14%
	Livest	35%	22.5	20.9	-1.6	-7%	2	2%	-4	13%
	Crop	7%	0.5	0.4	-0.1	-18%	2	0%	-31	4%
	Carbon	67%	291.9	296.6	4.7	2%	9.6	2%	7.3	1%
	Bio	3%	0.117	0.111	0.0	-5%	0	4%	-7	5%
Europe (excl. Eastern Europe)	Pop	60%	463.2	470.3	7.1	2%	6	1%	-4	5%
	Livest	6%	72.2	65.9	-6.3	-9%	0	0%	-4	14%
	Crop	1%	0.5	0.4	-0.1	-17%	0	0%	-25	3%
	Carbon	96%	153.0	160.4	7.4	5%	8.0	1%	5.3	0%
	Bio	10%	0.104	0.097	0.0	-7%	0	6%	-5	3%
Latin and Central America	Pop	100%	294.8	342.5	47.7	16%	54	6%	0	0%
	Livest	94%	40.8	47.5	6.7	16%	28	23%	-1	4%
	Crop	96%	0.4	0.5	0.1	24%	146	16%	-4	0%
	Carbon	54%	265.3	264.8	-0.5	-0.2%	9.8	12%	13.4	15%
	Bio		0.171	0.165	0.0	-3%	0	1%	-28	19%
Middle East and Northern Africa	Pop	99%	216.9	264.0	47.1	22%	56	7%	0	1%
	Livest	96%	37.1	42.1	5.0	13%	4	3%	0	0%
	Crop	46%	0.4	0.4	0.0	-4%	15	2%	-19	2%
	Carbon	29%	133.8	132.2	-1.5	-1.2%	5.2	0.1%	5.6	0.2%
	Bio	11%	0.083	0.079	0.0	-5%	0	3%	-1	1%
North America	Pop	100%	414.5	459.5	45.0	11%	18	2%	0	0%
	Livest	99%	56.3	60.8	4.5	8%	1	1%	0	0%
	Crop	1%	0.7	0.6	-0.1	-14%	1	0%	-158	20%
	Carbon	93%	242.5	250.4	7.9	3.3%	9.1	5.2%	8.8	0.4%
	Bio		0.105	0.099	0.0	-6%	0	0%	-1	1%
Oceania	Pop	100%	251.0	283.3	32.3	13%	2	0%	0	0%
	Livest	28%	63.0	62.9	-0.1	0%	0	0%	0	1%
	Crop	0%	0.5	0.4	-0.1	-16%	0	0%	-19	2%
	Carbon	80%	306.1	315.6	9.5	3.1%	13.1	3.6%	8.2	0.6%
	Bio		0.118	0.113	0.0	-4%	0	0%	-1	0%
	Pop	99%	322.8	370.9	48.2	15%	61	7%	-1	1%
	Livest	97%	27.7	33.4	5.7	21%	5	4%	0	1%

Top 10%	**Dimension**	**Share of area with gain**	**Average density 2000**	**Average density 2010**	**Density 2010 – density 2000**	**Change in intensity (%)**	**Average density change for areas with gain**	**Share of global area with gain**	**Average density change for areas with loss**	**Share of global area with loss**
South-Eastern Asia	Crop	100%	0.3	0.4	0.1	27%	111	12%	0	0%
	Carbon	64%	312.4	317.6	5.1	1.6%	11.0	4.6%	11.4	3.2%
	Bio		0.181	0.175	0.0	-3%	0	0%	-6	4%
Southern Asia	Pop	100%	357.4	420.6	63.2	18%	243	29%	0	0%
	Livest	73%	71.8	74.0	2.3	3%	3	3%	-1	4%
	Crop	99%	0.4	0.5	0.1	17%	13	1%	0	0%
	Carbon	49%	192.6	192.2	-0.4	-0.2%	7.9	0.3%	10.4	0.4%
	Bio	2%	0.104	0.096	0.0	-8%	0	4%	-18	12%
Sub-Saharan Africa	Pop	99%	131.5	170.4	39.0	30%	128	15%	-1	2%
	Livest	99%	33.7	40.7	7.0	21%	13	11%	0	0%
	Crop	93%	0.4	0.4	0.1	23%	232	26%	-14	2%
	Carbon	32%	188.4	184.0	-4.4	-2.3%	7.1	3.0%	10.1	9.7%
	Bio	4%	0.168	0.162	0.0	-4%	0	6%	-13	8%

Table S5 - Regional overview over gain and loss per land use dimension (top 80%) between 2000 and 2010 (2000 and 2005 for livestock)

Units used are 1) Population (Pop): population/km2 (density) and million people (total); 2) Livestock (Livest): livestock units/km2 (density and million livestock units (total); 3) Cropland (Crop): cropland area fraction (% of cropland in a grid cell, density) and ‘000 km2 (total); 4) Carbon: tC/ha (density) and megatons Carbon (total); 5) Biodiversity: Intactness/km2 (weighted with species richness, density) and Intactness weighted with species richness (total).

Top 80%	Dimension	Share of area with gain	Average density 2000	Average density 2010	Density 2010 – Density 2000	Change in intensity (%)	Average density change for areas with gain	Share of global area with gain	Average density change for areas with loss	Share of global area with loss
Eastern Asia	Pop	63%	154.2	164.4	10.3	7%	126	15%	-29	44%
	Livest	82%	22.5	25.4	2.9	13%	36	30%	-2	7%
	Crop	2%	0.2	0.2	0.0	-10%	1	0%	-152	19%
	Carbon	34%	169.9	168.6	-1.3	-1%	2.7	4%	3.5	10%
	Bio	3%	0.095	0.094	0.0	-2%	0	1%	-13	9%
Eastern Europe & Central Asia	Pop	17%	22.1	21.3	-0.8	-4%	11	1%	-21	32%
	Livest	27%	4.3	4.0	-0.3	-7%	4	4%	-9	29%
	Crop	20%	0.3	0.3	0.0	-5%	22	2%	-128	16%
	Carbon	73%	423.2	424.9	1.7	0%	3.0	19%	2.2	5.4%
	Bio	5%	0.112	0.111	0.0	-1%	1	16%	-20	13%
Europe (excl. Eastern Europe)	Pop	34%	104.3	104.8	0.5	0%	10	1%	-8	13%
	Livest	24%	24.8	23.4	-1.3	-5%	1	1%	-6	21%
	Crop	43%	0.2	0.2	0.0	-3%	12	1%	-40	5%
	Carbon	91%	202.1	205.6	3.5	2%	4.1	7%	2.0	0.3%
	Bio	48%	0.094	0.092	0.0	-2%	1	17%	-6	4%
Latin and Central America	Pop	85%	35.9	40.8	5.0	14%	77	9%	-2	3%
	Livest	80%	15.4	17.1	1.7	11%	36	30%	-3	10%
	Crop	74%	0.1	0.1	0.0	13%	258	29%	-38	5%
	Carbon	47%	193.3	192.3	-1.0	-1%	5.5	23%	7.2	35%
	Bio	4%	0.164	0.162	0.0	-1%	1	11%	-42	28%
Middle East and Northern Africa	Pop	98%	39.9	47.9	8.0	20%	76	9%	-1	2%
	Livest	88%	9.4	10.1	0.7	7%	7	6%	-1	3%
	Crop	39%	0.2	0.2	0.0	-2%	39	4%	-53	7%
	Carbon	38%	43.8	43.5	-0.3	-1%	1.6	1%	1.6	2%
	Bio	3%	0.054	0.053	0.0	-2%	0	4%	-6	4%
North America	Pop	88%	38.9	42.3	3.4	9%	28	3%	0	1%
	Livest	54%	6.8	6.9	0.1	2%	3	2%	-1	4%
	Crop	17%	0.3	0.2	0.0	-10%	15	2%	-248	31%
	Carbon	74%	334.4	337.0	2.6	1%	4.0	19%	2.1	4%
	Bio	9%	0.105	0.105	0.0	0%	0	2%	-5	3%
Oceania	Pop	92%	17.7	19.9	2.2	12%	4	0%	0	0%
	Livest	28%	7.7	7.4	-0.3	-4%	0	0%	-2	6%
	Crop	16%	0.2	0.2	0.0	-11%	2	0%	-56	7%
	Carbon	44%	90.8	92.0	1.2	1%	4.9	6%	2.1	3%
	Bio	46%	0.074	0.074	0.0	-1%	0	7%	-4	2%
	Pop	94%	134.9	153.7	18.8	14%	72	9%	-1	1%
	Livest	90%	10.3	11.7	1.4	14%	9	7%	0	2%

Top 80%	Dimension	Share of area with gain	Average density 2000	Average density 2010	Density 2010 – Density 2000	Change in intensity (%)	Average density change for areas with gain	Share of global area with gain	Average density change for areas with loss	Share of global area with loss
South-Eastern Asia	Crop	93%	0.2	0.3	0.0	18%	168	19%	-4	0%
	Carbon	48%	277.8	277.8	0.0	0%	8.2	7%	10.6	12%
	Bio	2%	0.149	0.147	0.0	-2%	0	1%	-10	7%
Southern Asia	Pop	100%	221.0	259.7	38.8	18%	254	30%	0	0%
	Livest	51%	37.1	37.2	0.1	0%	5	5%	-4	15%
	Crop	30%	0.4	0.4	0.0	0%	33	4%	-37	5%
	Carbon	53%	71.0	71.0	-0.1	0%	2.1	2%	2.6	3%
	Bio	31%	0.092	0.089	0.0	-3%	1	28%	-20	13%
Sub-Saharan Africa	Pop	94%	34.9	44.5	9.5	27%	173	21%	-3	4%
	Livest	71%	10.0	11.1	1.1	11%	20	16%	-1	4%
	Crop	82%	0.1	0.2	0.0	18%	354	39%	-31	4%
	Carbon	43%	132.0	130.7	-1.3	-1%	3.4	11%	4.9	22%
	Bio	1%	0.121	0.119	0.0	-1%	0	9%	-25	17%

Table S6 – Supporting data for Figure 4 of the manuscript

Numbers on the share of croplands used for exports are calculated using detailed country data from the Supplementary Appendix in (Kastner et al., 2014) which contains land embedded in crop trade flows. As data for 2009 is the most recent available, we use 2009 data instead of 2010. Entries are ordered according to table S3. Positive (negative) numbers for the year 2000 and 2009 indicate that a country is a net land exporter (importer), with the net export share of land on total cropland represented by the respective entries. Population density growth is computed from GPW data (Center for International Earth Science Information Network - CIESIN - Columbia University and Centro Internacional de Agricultura Tropical - CIAT, 2005). The land-use footprint is based on data from (Weinzettel et al., 2013). South-Eastern Asia and Eastern Asia a further supplemented with disaggregated country level data on Indonesia, China, and Japan.

Region	Share of croplands used for exports (net)	Share of croplands used for exports (net)	Population density growth	land use footprint
	2000	2009	in %	(global hectares per capita)
Latin and Central America	14	38	14	1.7
Eastern Europe & Central Asia	2	18	-4	1.4
Oceania	68	71	12	3.4
South-Eastern Asia	4	4	14	0.8
Indonesia	5	16	12	0.8
Sub-Saharan Africa	4	3	27	1.2
Southern Asia	0	-3	18	0.5
North America	34	31	9	3.6
Eastern Asia	-21	-32	7	0.9
China	-6	-19	7	0.8
Japan	-554	-486	1	2.0
Europe	-40	-50	0	2.7
Middle East and North Africa	-37	-54	20	1.1

Table S7 – Overview over references used to validate findings from table 2 of the manuscript

The list is non-exhaustive and only lists the references relevant in the context of table 2 of the main manuscript. Additional references can be found in the Supplementary Information Text, which provides a more detailed overview over the different world regions.

World region	Key references from table 2
Multiple regions	Kastner, T., Rivas, M. J. I., Koch, W. & Nonhebel, S. Global changes in diets and the consequences for land requirements for food. Proc. Natl. Acad. Sci. 109, 6868–6872 (2012). Chaudhary, A. & Kastner, T. Land use biodiversity impacts embodied in international food trade. Glob. Environ. Change 38, 195–204 (2016). West, P. C. et al. Leverage points for improving global food security and the environment. Science 345, 325–328 (2014). Weinzettel, J., Hertwich, E. G., Peters, G. P., Steen-Olsen, K. & Galli, A. Affluence drives the global displacement of land use. Glob. Environ. Change 23, 433–438 (2013). Bren d'Amour, C. et al. Future urban land expansion and implications for global croplands. Proc. Natl. Acad. Sci. (2016). doi:10.1073/pnas.1606036114 Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A Large and Persistent Carbon Sink in the World's Forests. Science 333, 988–993. https://doi.org/10.1126/science.1201609
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Supplementary Information Text

Region-specific analysis

The following includes a description of observed land-use dynamics in the 10 world regions analysed. If not indicated otherwise, data reported refer to Table S5.

Sub-Saharan Africa

Description of key dynamics

Sub-Saharan Africa experiences large changes across all land-use dimensions and can be considered a hotspot region. Generally, **population** density shows increasing trends, in particular in coastal areas in West Africa, and in East-Africa, in particular in the Lake Victoria region and Ethiopia. **Livestock** density increased in East Africa (Ethiopia, Uganda, Kenya and Rwanda) as well as in the semi-arid regions of West Africa. **Cropland** grew strongly in the Guinean Savannah regions of West Africa, East Africa as well as Southeast Africa and decreased particularly in Southern Africa. 38% of the world's cropland extensification took place in Sub-Saharan Africa. **Carbon** density shows mixed and dispersed dynamics with decreases in the Guinean Savannah and increases in tropical forest areas. 28% of the global net reduction in terrestrial carbon happened in Sub-Saharan Africa. **Biodiversity** decreases in most areas, with some exceptions.

Main Drivers

Population dynamics are characterized by high fertility rates as well as migration from sparsely populated rural areas to urban areas (Buhaug and Urdal, 2013). Urbanization in Sub-Saharan Africa is driven by population growth in resource constrained rural areas rather than economic growth in cities that attract labour for higher wages (Holden and Otsuka, 2014). Natural resource endowments and good conditions for agricultural production are the main cause for the strong population growth in the Lake Victoria region (UNEP, 2006). Debates about high fertility rates in West Africa emphasize social, cultural and religious norms, as well as beliefs about fertility behaviour (Adeyemo, 2018; Ezea, 2018).

Like many developing and emerging regions, Sub-Saharan Africa experiences strong demand increases for livestock products (Thornton, 2010), implying increased **livestock** production. In some countries, such as Ethiopia, targeted policies to foster the livestock sector have been a priority strategy to improve rural livelihoods and reduce poverty (Shapiro et al., 2017). Beyond its role for income generation and food production, livestock is considered as asset and insurance in many traditional societies, also reflecting wealth and social status (Thornton, 2010). Pastoralism is in general widespread among arid and semi-arid regions (Homewood et al., 2012). However, land reforms which grant private property rights to individuals induce a structural change in the livestock sector from nomadic pastoralism to more intense agricultural and livestock systems (Andela and van der Werf, 2014).

Regarding the **agricultural land dynamics** in South Africa, the horticulture sector increased strongly at the expense of conventional staple food production and large commercial farms replaced small-scale and subsistence farming (Liebenberg and Pardey, 2010). These processes likely explain the reduction of croplands, which is also reflected in national statistics on cropland dynamics (FAOSTAT, 2015). Outside of South Africa, cropland expanded strongly in the Guinean Savannah region that is considered a potential breadbasket of Africa (Morris et al., 2009). Roughly two thirds of the Savannah region could be used for agricultural production, a steep increase from the 10% that are currently used (Morris et al., 2009). The increase in cropland expansion in this area therefore mirrors not only the biophysical feasibility but also the economic attractiveness of using the Savanna lands for agricultural production – as well as the potential challenges related to conservation. This attractiveness is, in turn, also influenced by international demand, changing political and institutional environments (e.g. facilitating foreign land investments (Deininger and Byerlee, 2011; Kuusela and Amacher, 2015)) and improved access (via infrastructure) to remote areas (Chamberlin et al., 2014). Recent cross-country and household survey evidence suggests that rural population growth is also a driver of higher cropping intensities (so-called ‘Boserupian intensification’) (Jayne et al., 2014).

Above-ground **carbon** changes are very heterogeneous. Large carbon releases occur in the Savannah regions which simultaneously experience cropland expansion. Simulated conversion from Savannah wet lands to maize or soybean crop land indicate major carbon releases (T. Searchinger et al., 2015). Fires have been a common tool to convert bushland into cropland as well as grazing land practiced by small-holder farmers (Andela and van der Werf, 2014). Changes in fire incidence are, however, also associated to precipitation dynamics, in particular the ENSO phenomenon (Andela and van der Werf, 2014). Globally, 40% of fire-related CO_2 emissions are linked to Savannah burning and land-use emissions are in Sub-Saharan Africa higher than emissions from burning fossil fuels (Ciais et al., 2011). Contrary to Savannah regions, tropical forest areas show increases in carbon stocks (despite large heterogeneity). The main factors for increased carbon in Sub-Saharan Africa forest areas are carbon fertilization and increased precipitation trends (Ciais et al., 2011). Agricultural expansion explains more than 70% of deforestation in Africa, with commercial farming and subsistence farming contributing roughly equally (Hosonuma et al., 2012).

Drivers of **biodiversity** changes are correlated to increases in cropland which is in line with the main explanation for biodiversity loss in Sub-Saharan Africa, deforestation and habitat loss (Brooks et al., 2002). Various factors have contributed to biodiversity losses in the Ethiopian Rift Valley, ranging from population growth, expansion of smallholder agriculture but also commercial farming as well as poor institutions (e.g. property rights on land) (Dessie and Christiansson, 2008; Dessie and Kleman, 2007). Zimbabwe faces high biodiversity loss compared to other South-African countries (Scholes and Biggs, 2005), with tobacco farming as most important cash crop to be considered the key driver of deforestation and habitat loss (Moyo, 2015; The Financial Gazette, 2013). Biodiversity loss in Tanzania and Kenya is located around the Eastern Arc Mountains and Coastal Forests, a biodiversity hot spot (Myers et al., 2000). Because habitats are scattered, increased activities by smallholders in surrounding areas related to agricultural expansion, timber extraction and fuel-wood extraction have degraded forests and contributed to biodiversity loss (Burgess et al., 2007, 2002). As the Savannah regions are rich in species, cropland expansion may reduce biodiversity substantially (T. Searchinger et al., 2015). The few and very small hotspots of increasing biodiversity are difficult to explain and we could not find studies providing explanations for these dynamics. One possible reason for increased biodiversity is the establishment and improved enforcement of protected areas and national parks in East African countries that may attract further wildlife as a ‘save haven’.

South-East Asia

Description of key dynamics

South-East Asia has experienced major changes in all land-use dimensions and can be considered as a hotspot region in terms of land-use change and competition. Severe losses in **biodiversity** occurred in Sumatra, the Malaysian peninsula, parts of Borneo, North Western Thailand, Cambodia and Vietnam (98% of all land with notable biodiversity changes displays loss). At the same time, those regions (with the exception of the Malaysian Peninsula) have also experienced a large extension of **croplands** (altogether in 93% of all areas with notable changes). In population centres, particular Java and the Mekong Delta region, **livestock density** has increased, while it has remained relatively constant in the rest of the region (altogether 90% of land areas with notable changes). **Population** has increased largely around urban centres, including Kuala Lumpur (Malaysia), the densely populated island of Java (Indonesia), Bangkok (Thailand), Saigon (Vietnam), Phnom Penh (Cambodia) and Manila (The Philippines), and in the Southern and Eastern parts of Sumatra (Indonesia), altogether in 94% of land areas. For **carbon intensity** a rather mixed picture evolves. While it increases in Borneo, Java and Papua New Guinea (both parts), it decreases in Sumatra and the Malaysian Peninsula.

Main drivers

The scientific literature has highlighted the prominent role of deforestation in South East Asia. The most important driver for deforestation in South East Asia is commercial **agriculture** (Hosonuma et al., 2012), particularly driven by increasing production of cash crops (palm-oil), logging and transformation of natural forests to forest plantations (Davis et al., 2015; Gaveau et al., 2013; Stibig et al., 2014). The former is satisfying an international market, with >30% of palm oil produced for the world market now stemming from South East Asia , while the latter is also driven by an increasing pulp-and paper industry in the region (Wilcove et al., 2013). Davis et al. (2015 for the case of Cambodia) find that increasing land acquisitions are a major driver of deforestation.

Transformation of primary forest has severe implications for **biodiversity** (J. B. C. Harris et al., 2014; Huijnen et al., 2016; Miettinen et al., 2011; Phalan et al., 2013), with different impacts of new plantations on various species. Palm oil plantations are in particular damaging for biodiversity, while logging (in particular selected logging as practiced, inter alia, in Myanmar) has less consequences for most species in the region (Ahrends et al., 2015; Wilcove et al., 2013).

Draining and burning of peatlands has been the largest source of **carbon** in the region, corresponding to nearly twice the carbon that has been released by forest conversion to shifting cultivation and cropland, respectively (Houghton, 2012). Carbon-intensive peat swamps in particular have experienced a higher rate of deforestation than lowland or forests or montane forests. Highest rates (-5.2% yr^{-1}) are reported in Sumatra, followed by Borneo (Wilcove et al., 2013). Deforestation of peat-land forest is found to increase the likelihood of forest fires, again holding implications for human health (Turetsky et al., 2014).

Between 2000 and 2010 **population growth** in South East Asia has been mainly driven by growth of urban agglomerations. While the urban population climbed by > 31%, urban land area increased by 22% in the East-South-East-Asian region. Population growth has been in particular strong (with cities growing at an average rate between 3 and 7.8%) in Malaysia, Vietnam, Cambodia and Laos, while urban land has grown particular strong (higher than 2% per year) in the Philippines, Cambodia and Laos (Schneider et al., 2015).

Increasing urbanization and income is generally related to **dietary shifts** towards more demand for meat, a pattern that can also be observed in South East Asia (Thornton, 2010). Lipoeto et al. (2013) find that traditional food still plays a major role within the region, with a rapid transition towards Western-style food predominantly in urban areas.

Eastern Europe and Central Asia (Russia)

Description of key dynamics

Moving from 2000 to 2010, the Russian Federation has been characterized by a stagnating – if not declining - **population** with increases only in the major cities (83% of land has reduction in population density). This is also the general trend observed for **livestock density** (73% of land area has reduced livestock density). There is also a significant decline in **cropland** (80% of all land area has less cropland), specifically in the Central, Volga and South Federal Districts (between the Black and Caspian Sea) and in Southern Siberia and Southern Ural (bordering Kazakhstan and part of Mongolia).

However, this decline has not translated into a recovery of nature in Southern Siberia and Southern Ural, as both **carbon stocks** and species intactness have been developing negatively in these regions. On the other hand, large parts of Northern and Central Russia have experienced improvements in carbon density during the observation period. Altogether 69% of land displays an increase in terrestrial carbon. **Biodiversity** has seen a decline in the Far-Eastern Russia (around the Yakutsk region).

Main drivers

The lack of **population** growth and slow urbanization during the observation period can be attributed to, inter alia, low fertility in urban areas (about 1 compared to 1.55 in rural areas in 2000) and the fact that by 2009 life expectancy at birth for males was still more than a decade less than in Europe, the US, Japan or Korea. In addition, urbanization rates were already above 70% in 2000 (Becker et al., 2012). Russia often serves as the prime example of a region where birth rates have fallen behind death rates (Bongaarts, 2009).

The large overall increase in **carbon density** between 2000 and 2010 is consistent with the findings by Pan et al. (2011)for forest carbon in European Russia, which the authors attribute to several factors: increased areas of forests after agricultural abandonment (31.3 million ha), reduced harvesting, and changes of forest age structure to more productive stages, particularly for deciduous forest. In European Russia the carbon gain amounts to more than 44 tons of CO_2 per hectare during our observation period, which makes it outstanding as a sink in the boreal region and comparable to sinks in the temperate biome. However, Pan et al. (2011) find a stable sink over the same time period for Asian Russia, which is not matched by our data, which show an increase. This could be due to the increased carbon stock in dead wood and on-ground litter (Dolman et al., 2012) that could have at least balanced reductions in carbon stocks from disturbances that can be connected to climate change, e.g. large wildfires in Siberia and Far-Eastern Russia (Kukavskaya et al., 2012; Shvidenko et al., 2011; van der Werf et al., 2010), which are not captured in the model providing our carbon data. The damage from these disturbances could, however be limited, by an improvement in institutions and policies, not only for prevention and increased response times, but also for better management on the hitherto unused increment (Petrov and Lobovikov, 2012). What the model does capture, however, is the beneficial increase of CO_2 fertilization on biomass in the region, not included in other publications that report NPP (Dolman et al., 2012).

Finally, carbon density losses in the South East bordering China are also increasingly driven by consumption of wood products abroad (see e.g. (Liang et al., 2016) on timber demand) and might, to a large extent, be associated with illegal deforestation for timber exports to China, for which there is anecdotal evidence. Our observation period is characterized by the large Russian roundwood footprints of China, the United States, Japan, Finland, and Germany, where China is not only the most important Russian timber importer, but also the largest foreign final consumer driving Russian timber harvest (Liang et al., 2016). This indicates the strong role that institutions and policies can play in this context. Consumption-side measures in importing countries could lead to substantial improvements, e.g. by "taking shared responsibility and improving the production efficiency of key sectors in consuming nations" (Liang et al., 2016).

The apparent contradiction between the cropland abandonment in Southern Siberia and Southern Ural and decrease in carbon density might be explained by the lag in the sequestration response (Schierhorn et al., 2013). A similarly slow recovery might be the case for **biodiversity**. Again, one has to keep in mind that the map shows an absolute change from 2000 to 2010 and that those areas showing a negative change actually do not imply that intactness has crossed a critical level (e.g. the extinction of a species). In fact, the boreal area and tundra have been least affected by land use pressures in 2005 and are still within planetary boundaries, whereas many tropical, subtropical and temperate biomes have already declined beyond planetary boundary limits (Newbold et al., 2016).

Oceania

Description of key dynamics

Oceania experiences little (population, biodiversity, livestock) to moderate (cropland, carbon) changes. Generally, **population** hotspots are located where major cities are and indicate continued urbanization rates. **Livestock** density is reduced in 72% of all areas. **Cropland** reduces in the South West and South East of Australia as well as in New Zealand. Altogether 84% of all areas experience cropland loss, with overall 11% less cropland. **Carbon** density shows mixed and dispersed dynamics with increases in the North West of Australia and reductions in the costal South East Australia. In comparison to other world regions, **biodiversity** is less affected with only 54% of all areas with notable changes displaying biodiversity loss, which remains also relatively small.

Main Drivers

Cropland in Australia is subject to strong salinization which affects roughly 50% of the farmland in Western Australia and even 85% of the farmland related to grain production (ABS [Australian Bureau of Statistics], 2003). Hence, productive land shows diminishing trends due to continuing land degradation which is partly irreversible (MSEIC, 2010). Additionally, changed precipitation patterns and continued drought conditions between 1995 and 2007 had strong impacts on crop production in the entire Oceania region (Gallant et al., 2012; MSEIC, 2010). Hence, local environmental changes can be considered as main driver for cropland reduction, which may be partly also related to anthropogenic climate change (Gallant et al., 2012).

Population hotspots are clearly located where major cities are and indicate continued urbanization rates.

Livestock density shows no major changes.

Carbon: mixed dynamics. Changes in biomass (and thus, carbon) are highly driven by heterogeneous rainfall trends with northern Australia getting wetter and southeast Australia dryer (Liu et al., 2015). Apart from the impact on natural vegetation, growth of forest plantations may also contribute to changes in carbon stocks. Carbon sequestration in forest plantations responds to rainfall variability (Paul et al., 2008). Forest plantations almost doubled in Australia (1.54% of total forest area in 2010) while total forest area declined by 4.4% and total carbon in forests above ground remained constant. In New Zealand, forest area remained constant but carbon above ground increased by 4% (FAO, 2015). Forest plantations in Australia are located in coastal areas in Southwest and Southeast and correspond partly to increases in carbon in our hotspot map (ASFB, 2013). The inclusion of forestry into carbon markets led to additional increases in forest plantations ('carbon forestry') of about 65,000 ha in Australia (equal to 3.4% of the area of total forest plantations) (Mitchell et al., 2012). New Zealand introduced an emissions trading scheme in 2009 and included the forestry sector, leading to a doubling in forest plantations in 2011 compared to the previous year (Rhodes and Stephens, 2014).

Biodiversity: Major reasons for decrease in biodiversity related to agricultural issues: Land clearing for agriculture, changes in water availability due to agricultural land uses; application of fertilizers; introduction of new species (mammals but also weeds) to the sensitive ecosystem that evolved largely isolated from other continental systems (Steffen et al., 2009)

North America

Description of key dynamics

The **population** of the United States grew from 283 Million to 310 Million between 2000 and 2010 (FAO, 2016b). Urbanization trends continued as reflected by rising population densities in urban areas along the coasts and some interior metropolitan areas. Spatial patterns of urbanization are also the main driver of **biodiversity** loss in the United States during our study period. **Livestock densities** remained constant during this period while total **cropland** area declined especially in the northeast and increased in the southeast – overall cropland was lost in 83% of areas. Persistent carbon sinks in the World's forests (Pan et al., 2011) explain the spatial pattern of growing in **carbon stocks** concentrated in the large forest areas of the eastern United States (72% of all areas gain terrestrial carbon in North America).

Main Drivers

The United States went through three distinct phases of land-use change. Large-scale deforestation for agricultural lands and cultivation of prairie soils accompanied the expansion of European settlements across the continent with a peak in total cropland area around 1940 (Houghton et al., 1999; Waisanen and Bliss, 2002). Farm abandonment in the second half of the 20th century resulted in several decades of cropland area decline, reforestation, and the rapid expansion of developed lands (Lark et al., 2015; Sleeter et al., 2013). Increasing forest area and recovering forests contribute to the widespread increase in carbon density that also driven by enhanced plant growth due to CO_2 fertilization and nitrogen deposition. Average carbon gains in forests of the United States amount to 38 tons of CO_2 per hectare in recent years (Pan et al., 2011). At the same time, drought stress, pest infestations and fire events affected forests in the western United States over the past few decades and reduced their capacity to sequester carbon or even resulted in carbon losses from vegetation and soils.

In our analysis of croplands, we rely on HYDE data, which in turn use inputs from FAOSTAT and in the case of the US from the USDA. Biofuels are covered. Both FAO and USDA show decreases in croplands for the period from 2000-2010 (table S8).

Table S8 – cropland in the United States of America

in million hectares	2000	2010	Net change 2000-2010	Comment
USDA	140	136	-4	Cropland harvested+crop failiure+cultivated summer fallow
FAOSTAT	178	159	-19	Arable land an permanent crops

This main dynamic camouflages crop-specific dynamics that are relevant to discuss.

High commodity prices driven by the rising demand for biofuel feedstocks since the late 2000s provided new incentives to expand crop production (Lark et al., 2015; Wright and Wimberly, 2013). Consequently, wide-spread conversion of grasslands, shrublands, and wetlands to agricultural uses reappeared across the United States with hotspots of change located in the Corn Belt and the Lake States. In addition, federally subsidized crop insurance mitigated the risk of farming even in less productive areas characterized by high erosion risk, shallow soils, and drought vulnerability (Feng et al., 2013).

Corn was the most common crop cultivated on new agricultural land followed by soy and wheat. Corn was also responsible for the majority of recent land use change through its displacement of other crops (Lark et al., 2015; Mladenoff et al., 2016). Between 2006 and 2008 the area harvested for corn and soybean in the United States increased by 3.2 Mha, even as overall cropland decreased (Wallander et al., 2011), and another 5 Mha between 2008 and 2012 mostly at the expense of grasslands (Faber et al., 2012; Lark et al., 2015). This new wave of expanding corn and soy production occurred most rapidly on land less suitable for agriculture characterized by high erosion risk, shallow soils, and drought vulnerability (Lark et al., 2015). The concentration of grassland conversion in the Corn Belt around wetlands threatens wildlife habitats and may also increase flood risk (Wright and Wimberly, 2013). In some regions of the Western Corn Belt rates of grassland conversion were comparable to deforestation rates in Brazil, Malaysia, and Indonesia (Wright and Wimberly, 2013) and the ongoing loss of grassland is expected to create adverse effects on native biodiversity (Meehan et al., 2010).

Increased market demand for biofuels feedstocks also triggered crop switching, especially from wheat to corn and soybean, which forces wheat production to expand onto other land. Cascading land replacements occurred in some areas where land cover change from agricultural land to developed land was offset by a conversion of open lands to agricultural lands. In other areas open lands were converted to developed lands to offset the conversion of developed lands to agricultural lands (Mladenoff et al., 2016).

Overall, recent patterns of land use change lead to further simplification and homogenization of mixed-use landscapes to large-scale cultivation of annual crops displaces the former crop to other locations (Meehan and Gratton, 2015; Wright, 2015).

These most recent land use dynamics are not visible in our analysis due to two factors. First, switching from one crop to another does not change cropland area. Second, total cropland continued to decrease in the United States in recent years (USDA, 2016) and this trend may outweigh and hence hide grassland expansion under the coarse resolution of the land use data we analysed here.

Middle East and North Africa

Description of key dynamics

Population density growth has been concentrated along the coastlines of the Mediterranean, and the river valleys and deltas. The **livestock** density remained more or less stable in most of the region but increased along the Nile River, in Syria and to some extent in North-Western Iran as well as in Yemen. Slight increases were observed in Turkey. Overall livestock density increased by 7%. Along the Mediterranean coastline, the **cropland** area fraction has largely increased. Morocco's cropland area fraction has decreased. The biggest changes, however, took place in Iraq and Iran. The cropland area fraction decreases substantially in Iraq's east, in the fertile region along the Euphrates and Tigris valleys, while it increased in Iran's west and north. Croplands decreased in the semiarid mountainous regions of Turkey and its Mediterranean coastline. The region's **carbon** intensity has been largely constant with the exception of Turkey, Algeria, Morocco and Tunisia, with different, heterogeneous dynamics displayed. Despite considerable human activity in the Middle East and Northern Africa (MENA) region, **biodiversity** was not impacted significantly, the only exception being the stretch of land in Algeria's Northern Sahara as well as Turkeys coastlines with the Black Sea and the Mediterranean.

Main drivers

The MENA region is characterized by arid to semi-arid climate and is one of the world's most water-scarce regions. Human and economic activities are concentrated around the few water sources, mostly rivers, deltas, oases, but also coastal zones, and the competition between land uses is particularly fierce. Wherever there is access to fresh water, there is a high competition due to the accumulation of anthropogenic activities, best exemplified by the river Nile and the Nile delta in Egypt, where urban area expansion is forecast to convert valuable croplands (Bren d'Amour et al., 2016). The MENA region is also expected to be among the most adversely affected by Climate Change: heat extremes are likely to increase across the entire region (Lelieveld et al., 2016), while precipitation is forecast to decrease in the Middle East part (Evans, 2009), potentially leading to increasing levels of desertification. Sea-level rise and the sinking of deltas will further increase the risk for the flood-prone urban coastal zones (Bohannon, 2010). Attempts to resettle are underway, but have yet to prove to be efficient (Bohannon, 2010). Biodiversity remains largely unchanged with the exception of Turkey, where important wetlands, grasslands, even rivers are disappearing due to human activities (Şekercioğlu et al., 2011).

Regardless of any biophysical constraints, the **population** grew by 19% to a total of more than 200 million in Northern Africa compared to 2000 levels, and by 25% in Middle East, totalling 230 million in 2010 (UN

DESA, 2015). The population has quadrupled in the second half of the last century. Fertility rates have slowed but the population is still expected to reach almost 700 million by 2050 (Roudi-Fahimi and Kent, 2007). More than 50% of the population lived in urban areas in Northern Africa in 2010, and more than 68% in the Middle East. Both urbanization rates are expected to increase further. Population increases mostly take place in and around major cities as well as larger villages in the more rural areas. The MENA region still contains a significant number of pastoralists and the pastoral farming system can be found across almost a quarter of the land area (Dixon et al., 2001). Seasonal migration, also across borders, plays an important role for the often small herds of goats and sheep, depending on the availability of grass and water.

We observe co-occurrences of significant population and **livestock** increases across the region, and of population and **croplands** in Northern Africa. In the Middle East, population growth mostly takes place at the expense of croplands, and we can expect similar dynamics for Northern Africa, as urban areas continue to increase (Bren d'Amour et al., 2016). In the second half of the century, climate change impacts are likely to have reduced the little lands viable for rain-fed agriculture by over 170.000 km^2 across the region (Evans, 2009). Croplands can be very productive, especially in Northern Africa, but rely largely on complex irrigation systems (Fetzel et al., 2016). While the magnitude of the competition in areas with competing land uses in the MENA region can be very strong, it is also contained to a relatively small fraction of the total area. Large expanses are still not impacted by human activity, mostly because they are uninhabitable. Nevertheless, continuous population growth increases demand for livestock and cereals products, also leading to an expansion in pastures and croplands (Headey, 2016; Zdruli, 2014).

The above-ground **carbon** stored in the MENA region decreases, however we could not find studies providing explanations for these dynamics. In Northern Africa, this dynamic is likely driven by population growth, whereas in the Middle East, it is likely explained by cropland expansion. **Biodiversity** will also be affected by the increase in anthropogenic land uses, mostly by population and livestock intensification (in the Middle East). For Northern Africa, we see an increase in biodiversity which is mostly driven by Egypt which showed an almost country wide transition from plantation to secondary vegetation. This development would substantially impact the intactness factor but is likely an artefact. As we were not able to substantiate these dynamics, these findings should be taken with care.

The rising demand for agricultural and livestock goods pushes some farmers to overexploit the rangeland resources, risking transforming productive land to marginal rangeland, as documented for example in Morocco (Croitoru and Sarraf, 2010). In addition, some mountainous areas are threatened by overgrazing, which increases soil erosion and eventually degradation. The construction of dams (in Turkey), the draining of wetlands (in Turkey, Iran, Iraq) and unsustainable irrigation are widespread threats to biodiversity and carbon stored in the region (Croitoru and Sarraf, 2010; Galli et al., 2017; Odhiambo, 2016; Şekercioğlu et al., 2011).

Latin- and Central America (and the Caribbean)

Description of key dynamics

Population growth in Latin America and the Caribbean between 2000 and 2010 has been less pronounced than in Sub-Saharan Africa and large parts of Asia (population growth in 85% of all areas). It has been mostly concentrated in Central America (Guatemala, Honduras, El Salvador, Nicaragua and parts of Costa

Rica and Panama) and along the coastal lines of Southern America (mainly the coastal areas in the North West Venezuela, Colombia, Ecuador, Peru and large parts of Eastern Brazil), and some hotspots where urban areas had already expanded before (e.g. Buenos Aires in Argentina or São Paulo in Brazil, which is also apparent in the dynamic described in the main text, cf. Fig. 1A).

Areas dedicated to growing **crops** have increased in Brazil, parts of Chile, Uruguay, Honduras, El Salvador, Nicaragua, Northern Colombia and Venezuela. Interestingly, much of Central America, Northern Colombia, Ecuador and central Chile feature the opposite picture, i.e., a decrease in cropland intensity. **Livestock** intensity generally increased in the same period (80% of all area). We also observe an expansion of livestock density for Brazil, Uruguay, Argentina, Paraguay, Bolivia and Peru. Even though the Caribbean islands are less prominent in terms of absolute numbers, there seems to be a shift from cropland to larger areas dedicated to livestock on some islands.

This pressure from human demands (infrastructure, livestock, and cropland) has come at the cost of **biodiversity** losses across the whole of Latin America and the Caribbean, as is apparent from the Latin American panel in Fig. 3 (indicating a co-occurrence of increases in the three human demands with decreases in biodiversity). In 96% of all areas biodiversity is lost, representing 28% of the global biodiversity loss. The density of **carbon**, on the other hand, has been evolving in a much more dispersed way, with gains in Mexico, Panama, Costa Rica, but also Colombia, Peru, Guyana, Suriname, French Guiana and Brazil. Much of the carbon increases in Brazil coincide with the Amazon Basin, where we also partially observe lower than expected biodiversity losses compared to other parts. This is also reflected in the more mixed pattern for carbon in Fig. 3. Nonetheless 29% of the global net loss in terrestrial carbon is attributed to Latin America.

The latter regions (Mexico and El Salvador, parts of Costa Rica and Panama, parts of the Amazon Basin, Ecuador and Colombia, Northern Guyana, Suriname and French Guiana, small parts of Peru, Bolivia and Argentina and large parts of Chile) are characterized by an improvement in nature (cf. Principal Component Analysis in main text, Fig. 1F), while most of middle and Southern Brazil, Uruguay, coastal Peru, Venezuela, mid-Central America and Caribbean are dominated by the influence of human pressures.

Main Drivers

The observed **population dynamics** can mainly be explained by reference to three drivers: Latin America has – in contrast to Sub-Saharan Africa – seen a decline in fertility rates (Cohen, 2006). Partially counteracting this trend is the fact that Latin America has been a front runner in catching up with Northern mortality rates. Indeed, the projections for our period of investigation (made in 1990) indicated that in 2015, Latin America would have a rate of around 29 deaths of children under 1 for every 1,000 born alive, whereas new estimates show that this rate has dropped to 19 deaths on a regional average in 2015 (Observatorio Demográfico de América Latina y el Caribe, 2014). Regional variations are large and range from 5.4 in Cuba to 41.3 in Haiti. With a high level of **urbanization** in Southern America, which has matched Northern levels already at the beginning of our observation period, it is no surprise that the rate of (further) urbanization is relatively low compared to other regions (Cohen, 2006) and growth is no longer predominantly driven by rural-urban migration for economic motives, but also by natural population growth in the cities and migration between cities (Cerrutti and Bertoncello, 2003). These larger urban populations in turn can be associated with increased demand for food and especially meat (Thornton, 2010) and more inefficient agricultural practices (Grau and Aide, 2008), explaining part of the observed increases in

cropland and livestock density. In Central America, rural-urban migration still plays a bigger role in urbanization, but the effects are more heterogeneous here. For example, Mexico and El Salvador see lower **losses of biodiversity** (Mendoza-González et al., 2012) and partially gains in **carbon density**, which some authors have explained by the positive correlation between remittances and forest recovery (e.g. Hecht and Saatchi, 2007). In Southern America the roots of deforestation are no longer only associated with the traditional development pattern shifting agriculture and cattle ranching; instead, the combination of the availability of fertile land and low production costs has led to deforestation through **export-oriented industrial agriculture** (De Sy et al., 2015, 2015, Grau and Aide, 2008, 2008; Kastner et al., 2014; Yu et al., 2013). Both in terms of **biodiversity** (species intactness) and **carbon** density, the hotspots of the past can still be singled out for the period 2000-2010 (the Amazon Basin in Ecuador, Columbia and Venezuela, Southern Guyana/Rio Negro, Acre, the Peruvian Amazon and Mato Grosso, cf. (Grau and Aide, 2008). Still, the change from 2000 to 2010 appears to be less pronounced in parts of Brazil, which can be attributed to a substantial decrease in deforestation rates during the time (Gibbs et al., 2015; Nepstad et al., 2014).

In addition, it has been observed that the combination of agricultural modernization and rural-urban migration has led to abandonment of marginal cropland and pastures, enabling ecosystem recovery (Aide et al., 2013; Grau and Aide, 2008). Grau and Aide (2008) provide an overview of the literature on the recovery of degraded forests in Puerto Rico and the Dominican Republic in the Caribbean, in Mexico, El Salvador, Honduras, Costa Rica and Panama in Central America and in parts of South America.

This points to an important role for institutions and policy, where the Latin American experience has been two-sided: on the one hand, our observation period has seen a decrease in deforestation rates due to enhanced monitoring and enforcement in Brazil (Nepstad et al., 2009). On the other hand, most of the current deforestation in Latin America is related to meat production, either by planting pastures for livestock or by planting soybean to supply feed for animals (Aide et al., 2013), which confronts decision-makers with new institutional challenges and points towards the need for transboundary governance concepts. In general, forest transitions in the regions show asymmetric patterns of change depending on the individual development level of the countries (as approximate by socio-economic variables). Variables associated with development, such as Human Development Index or GDP per capita, have been associated with forest gains (Redo et al., 2012), whereas variables such as infant mortality were associated with deforestation.

Southern Asia

Description of key dynamics

The highest **population growth** can be observed on the Indian subcontinent (India, Pakistan, Bangladesh, and Nepal), with the highest changes along the Southern Himalayan range (100% of areas with notable changes display population growth). Suitable **cropland** is slightly decreasing across South Asia (in 70% of the area), and it most frequently co-occurs with increases in population. However, in hotspot areas (i.e. where absolute cropland intensity changes belong to the highest 10% globally), we observe a clear co-occurrence of both cropland and population growth.

Livestock intensities generally increase in the region, but display heterogeneous dynamics. Livestock has a mostly balanced interaction with other land-uses, co-occurring both with positive and negative changes, and approximately increasing in as many areas as it is decreasing. Hotspots of livestock increase co-occur with population. The land **carbon stock** is both increasing (60% of all area with notable changes) and decreasing (40%), with both dynamics co-occurring with increases in population densities. **Biodiversity** is reduced across the subcontinent (69% of all areas), mostly where there is also relevant population growth but not along the Himalaya ranges.

Main drivers

India's land use challenge is dominated by a rapidly growing **population** and ensuing land use change. Population is expected to grow from 1.3 billion in 2016 to 1.7 billion in 2050; India is expected to overtake China as the world's most populous country in 2022 (U.S. Census Bureau, 2016). The total urban population is expected to nearly double from 420 million in 2015 to about 814 million in 2050 (United Nations, 2014). This urbanization translates into large urban land expansion, which is mostly driven by population growth, and less by economic growth (Seto et al., 2011). While the total urban land expansion is uncertain, it is estimated that in 2030 more than 100.000 km^2 will be urbanized with likelihood higher than 75% (in 2000 30.000 km^2 were urbanized) (Seto et al., 2012). There is lower probability of urbanization but for much larger area along the Himalayan range, reflecting the rapid population growth of mostly rural populations. Growing population will increase demand for food; it is expected that likely rice yield increases of about 1%/year would be sufficient to maintain per capita consumption rates (Ray et al., 2013).

FAO data demonstrate the total area harvested for key **crops** like rice and sugarcane decreased by 4.1% and 1.1% respectively. A case study of Delhi highlights that urban and infrastructure land take predominantly correlates with agricultures land loss, and to lesser degree with dense forest loss (Jain et al., 2016). This area loss was compensated by yield increases per ha of 15% for rice, but yields for sugarcane kept constant (FAOSTAT, 2015). Differing land property rights originating from colonial times lead to very different outcomes in agricultural productivity and well-being in the long run (Banerjee and Iyer, 2005). Crucially, the data used in our analysis (cropland suitability) display the reduced area, but not the increasing yields.

Deforestation due to human pressures has been the leading cause for **biodiversity** but deforestation has significantly decelerated due to effective conversation programs (Reddy et al., 2015). In some areas of the Doda region in the Western Himalaya, anthropogenic pressures on forest systems compromise plant biodiversity (Rashid et al., 2013). Urbanization emerges as a key treat to biodiversity; however, the shift from traditional fuels (wood) to modern fuels accompanying urbanization let to reduced pressure on peri-urban forests and mangroves (Nagendra et al., 2013). The transition from subsistence farming to cash-crop systems leads to loss in agro-biodiversity (Pande et al., 2016). However, conservation with a high level of community involvement is proving to be an effective way to conserve forests, especially if motivation for conversation is coupled with social and economic benefits (Allendorf et al., 2013).

Europe

Description of key dynamics

Biodiversity decline dominates, most prominently in Spain, Italy and Belarus. Biodiversity has increased in Poland and Germany. Strong declines in **agricultural area** can be observed in Poland, Lithuania, Italy and Portugal. Declines in croplands tend to coincide with increasing carbon and decreasing population and livestock. Agricultural area increased in Denmark, the Netherlands and Latvia. With regard to **livestock**, a decrease in intensity dominates in Europe, most strongly in the UK, the Netherlands, Belgium and Ukraine, while pockets of substantial intensification exist in Denmark and Poland. Looking at Europe without the Eastern European countries, 76% of the area in which significant changes occur, manifest a decrease in livestock density. 21% of the global livestock decrease occurs in this region (Europe excl. Eastern Europe).

Population trends are mixed with a tendency for decreasing densities in the East and increasing densities towards the West. Overall, increasing densities in major urban agglomerations (Istanbul, London etc.) are visible. **Carbon** increases dominate the region, coinciding with biodiversity loss in Eastern and Southern Europe and biodiversity gains in Northern and Western Europe. 84% of the area in Europe (excl. Eastern Europe) where significant carbon changes occur, show a gain in land carbon stocks (see Region brief Eastern Europe/ Russia for more details concerning that region).

Main drivers

Land-use change in Europe is characterised by increasing specialisation and polarisation. Key trends involve **agricultural intensification** on the most productive lands (e.g. in Denmark) and **farmland abandonment** in marginal, less competitive regions (e.g. in some former Soviet countries). Both developments are driven by the globalization of agricultural markets resulting in increased competition and (agricultural) land use displacement outside Europe (Cosor, 2014; Kuemmerle et al., 2016; van Vliet et al., 2015). Drivers of **farmland abandonment** in particular include societal change in the form of increasing urbanization and demographic change resulting in rural depopulation (Cosor, 2014; van Vliet et al., 2015). Farmland abandonment and a strong decline in capital-intensive farming practices have been particularly significant in the **former socialist countries** where the process of restitution, low competitiveness and rural outmigration were important drivers (Kuemmerle et al., 2016; van Vliet et al., 2015). After the Soviet Union collapsed prices for inputs and outputs were liberalised, former markets disappeared and international competition increased. Moreover, land ownership changed, often leading to tenure insecurity (Baumann et al., 2011). The great heterogeneity in the extent of abandonment within Eastern and Central Europe results from strong differences in agricultural sector reforms ranging from full-scale market liberalisation in Poland and Romania to gradual reforms in Belarus and Ukraine; stark differences in state support; different approaches concerning land reforms (ranging from restitution to continuing state ownership); and EU accession of some countries (Alcantara et al., 2013). On the other hand, in some former socialist countries, e.g. Poland, a lower baseline level of intensification compared to other regions, technological change enabling increasing mechanization and rising labour costs resulted in intensification in the form of increasing livestock densities (Kuemmerle et al., 2016).

In some EU countries such as the Netherlands and Belgium, P and N application standards and manure fees led many holdings to decrease their **livestock concentrations** (European Commission, DG Agriculture, 2004; Kuemmerle et al., 2016). The 2003 reform of the EU's Common Agricultural Policy which decoupled farm subsidies from output contributed to declining agricultural intensification (WWF, 2010). According to a systematic review of case studies concerning Europe by van Vliet et al. (2015), technological and institutional drivers (incl. subsidies and land-use planning) dominate when it comes to agricultural intensification, while economic (incl. globalization and urbanization) and institutional drivers as well as location factors (incl. topography and soil) dominate with respect to agricultural dis-intensification (van Vliet et al., 2015).

Biodiversity loss due to pollution, habitat loss and fragmentation, invasive species and climate change is widespread throughout the region. Both agricultural intensification and abandonment contribute to the observed decline (European Environment Agency, 2015). In Belarus in particular, biodiversity decline associated with farmland abandonment could be observed (visible in our maps). Expansion of tourism and associated infrastructure development is a strong driver of biodiversity loss along the Mediterranean coast (EPSON, 2014). Underlying causes include governance and market failures (European Commission, DG Environment 2009). Notable exceptions are Poland and Germany where conservation programs were implemented and secondary vegetation established itself after agricultural monoculture and former industrial sites were abandoned (Kolecka et al., 2015).

The observed **urbanization** patterns reflect rural-to-urban migration, the attraction of large urban centres and rural depopulation driven by societal and demographic change.

Carbon stock increases have resulted from forest regrowth on abandoned farmland and afforestation (Cosor, 2014; European Environment Agency, 2015; Kuemmerle et al., 2016). This dynamic is largely responsible for the "nature" dominance in the principal component analysis, which prevails in most of the region.

East Asia

Description of key dynamics

East Asia has experienced land use changes between 2000 and 2010 to various extents. Very prominently, **population** has grown in big metropolitan and urban areas, e.g., in Guangzhou, Chengdu, Shanghai or Beijing in China, as well as in Seoul and Pusan in South Korea. At the same time, the hinterland regions of large metropolitan areas have experienced decreases in population density indicating a rural exodus and inner regional migration in particular in China, and in South Korea. Cities in remote areas, e.g. in Xinjiang province in China and in Mongolia have also grown significantly. The overall net effect on average population densities has been positive, as the rural exodus is more than offset by increases in the high density regions around existing urban areas. 15% of global population growth took place in East Asia.

Population growth has gone hand-in-hand with large increases in **livestock.** 30% of all growth in livestock density took place in East Asia. **Cropland** has decreased in the entire region – 98% of all notable changes in cropland are negative. **Carbon** intensity shows a rather mixed picture, with increases in Eastern China, the Tibetan Plateau, as well as Yunnan. Decreases of carbon intensity can mainly be found in Taiwan, Sichuan and the Southern Chinese provinces as well as in the Northern part of the region, including Mongolia, the Northern Chinese provinces (Heilongjiang, Jilin and Inner Mongolia) and North Korea. **Biodiversity** has decreased mainly in the South of China (across the border to South East Asian countries Myanmar, Laos and Vietnam), as well as in a corridor reaching approximately from Chengdu to the greater Beijing area, covering the provinces of Hubei, Henan Shanxi and Hebei. Altogether 97% of all notable changes in biodiversity are negative.

Main drivers

The literature identifies **population dynamics** to be largely driven by urbanization. In fact, East Asia is among the world regions with the strongest urbanization dynamics, both in terms of scale and pace. From 2000 to 2010, urban **population** in China grew by 3.3% per annum on average (World Bank, 2015), whereas the growth rate of the total population averaged 0.5% (UN DESA, 2015). In the same decade, urban areas expanded by 3.1% p.a. Accordingly, urban population densities mostly increased, moderately remained stable, or even decreased (e.g., in Shanghai).

In China, 87% of urban expansion occurred on arable land which had important implications for agricultural production (World Bank, 2015). There is evidence that the rapid urban area expansion poses substantial threats to China's most productive **croplands** (Chen, 2007). By 2030, China is expected to have urbanized more than 5% of its prime croplands which were used to produce 9% of crop production in 2000 (Bren d'Amour et al., 2016). However, observed decreases in cropland are partly also due to efforts to fight soil erosion (Deng et al., 2014).

Livestock densities increased East Asia, mostly driven by surges in demand for pig meat and poultry (Thornton, 2010). Increasingly, confined livestock production systems are established to meet this demand; metropolitan areas like Shanghai, Beijing, and Guangdong increasingly rely on industrial pig production (Bai et al., 2014) This very intensive form of livestock production has allowed for significant simultaneous increases in both population and livestock.

Terrestrial **carbon Strange** is decreasing in 62% of Land in East Asia (Table S5, cf. (Calle et al., 2016). However, decomposing those changes, significant differences can be identified, both related to land use types as well as across regions. Decreases in Northern China and Mongolia are predominantly rooted in deforestation. Increases in cropland have led to high decreases in terrestrial carbon in Sichuan and Heilongjiang (Zhang et al., 2015). Afforestation and an increase of grassland areas have contributed to increases in stored terrestrial carbon, particularly in Tibet. Parts of that can be attributed to China's fight against soil erosion ("green-for-grain" program), aiming to restore degraded agricultural land by grasslands or afforestation (Deng et al., 2014). However, afforestation does not always lead to increased terrestrial carbon storage; in Inner Mongolia, for example, increasing carbon intensity by afforestation has been compensated by losses in grasslands (Zhang et al., 2015).

Biodiversity losses can to a large extent be attributed to land increasingly being consumed by urban areas, particular in China (He et al., 2014). For example, in the Pearl River delta, 26% of natural habitat and 42% of local wetlands have been prey to urbanization. In particular in Yunnan the loss of primary forest and biodiversity is due to logging and cash crop plantations, particularly rubber (Liu et al., 2013).

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