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SUPPLEMENTARY INFORMATION

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Direct and indirect loss of natural area from urban expansion

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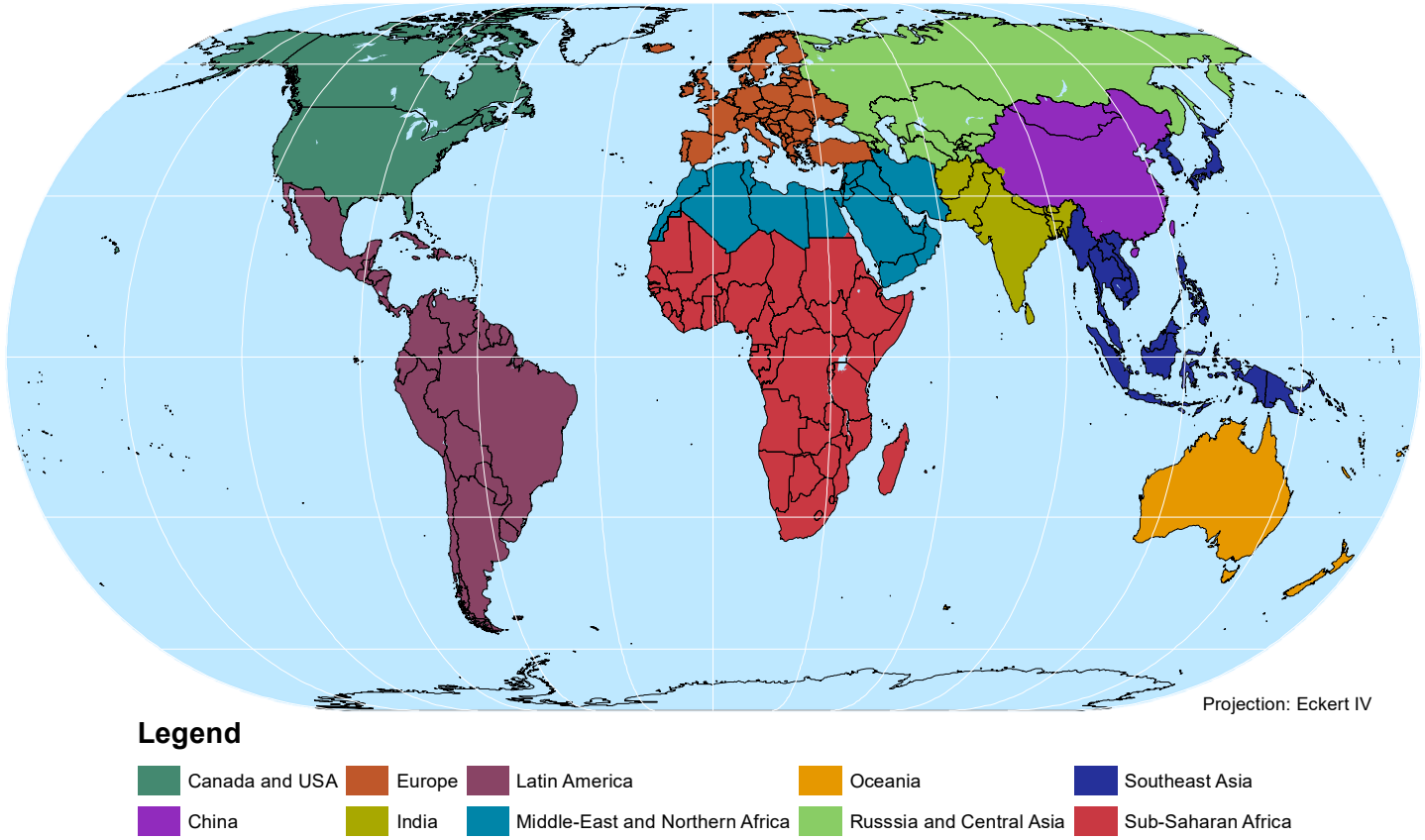
Supplementary material for Direct and indirect loss of natural areas from urban expansion

Supplementary figures



Supplementary Figure 1: *Analysis regions as used in this study, with country boundaries added for spatial reference.*

Supplementary tables

Supplementary Table 1: *Land cover change as a result of built-up area expansion between 1992 and 2015. Percentages indicate the percentage relative to all built-up area expansion within each region. Values are rounded to the nearest percent, hence row-totals might not exactly add to 100%. MENA indicates Middle East and Northern Africa.*

Region	Cropland		Forest		Shrubland		Grassland		Other	
	[Mha]	[%]	[Mha]	[%]	[Mha]	[%]	[Mha]	[%]	[Mha]	[%]
Canada and USA	2.3	39%	1.2	19%	1.3	21%	1.2	19%	0.1	1%
China	6.7	76%	0.2	3%	0.5	6%	1.2	14%	0.1	2%
Europe	6.3	75%	0.7	8%	0.4	4%	0.5	6%	0.5	6%
India	2.0	84%	0.1	3%	0.2	7%	0.1	5%	0.0	1%
Latin America	1.4	45%	0.3	11%	1.1	35%	0.2	8%	0.1	2%
MENA	0.7	40%	0.0	1%	0.2	10%	0.0	1%	0.8	48%
Oceania	0.1	16%	0.1	22%	0.2	49%	0.1	11%	0.0	3%
Russia	1.5	67%	0.2	8%	0.3	12%	0.2	9%	0.1	4%
Southeast Asia	2.5	85%	0.2	6%	0.2	5%	0.0	1%	0.1	3%
Sub-Saharan Africa	0.7	38%	0.3	16%	0.6	33%	0.2	10%	0.1	3%
World total	24.3	64%	3.3	9%	4.9	13%	3.7	10%	1.9	5%

Supplementary Table 2: *Land cover change as a result of cropland expansion between 1992 and 2015. Percentages indicate the percentage relative to all built-up area expansion within each region. Values are rounded, hence row-totals might not exactly add to 100%.*

Region	Built-up		Forest		Shrubland		Grassland		Other	
	[Mha]	[%]	[Mha]	[%]	[Mha]	[%]	[Mha]	[%]	[Mha]	[%]
Canada and USA	0	0%	2.4	39%	1.5	25%	2.2	36%	0.0	0%
China	0	0%	5.7	44%	2.1	16%	3.3	25%	2.0	16%
Europe	0	0%	6.0	80%	0.9	12%	0.4	6%	0.2	2%
India	0	0%	1.8	48%	0.9	24%	0.7	18%	0.4	11%
Latin America	0	0%	30.6	81%	6.9	18%	0.2	1%	0.2	0%
MENA	0	0%	0.3	5%	4.6	75%	0.0	1%	1.2	20%
Oceania	0	0%	0.7	20%	2.8	77%	0.1	2%	0.0	1%
Russia	0	0%	3.4	20%	8.7	52%	4.2	25%	0.6	4%
Southeast Asia	0	0%	12.7	86%	1.9	13%	0.1	1%	0.1	1%
Sub-Saharan Africa	0	0%	15.9	49%	12.3	38%	3.9	12%	0.2	1%
World total	0	0%	79.5	56%	42.5	30%	15.1	11%	5.0	3%

Supplementary Table 3: *Direct and indirect land cover change due to urban expansion, based on actual yields for wheat, maize, and rice, and assuming that cropland is only displaced within the same world region.*

Region	Urban expansion [Mha]	Direct loss [Mha]					Displaced crop production [Mton]	Displaced cropland [Mha]	Indirect loss [Mha]				Leverage factor [-]
		Forest	Shrub	Grass	Other	Crop			Forest	Shrub	Grass	Other	
Canada and USA	6.1	1.2	1.4	1.2	0.1	2.3	10.39	3.2	1.2	0.8	1.2	0.0	1.37
China	8.8	0.2	0.5	1.2	0.1	6.7	54.18	10.7	4.7	1.7	2.7	1.7	1.61
Europe	8.4	0.7	0.9	0.5	0.5	6.3	27.30	13.1	8.0	3.5	1.3	0.4	2.08
India	2.4	0.1	0.2	0.1	0.0	2.0	7.11	2.9	1.4	0.7	0.5	0.3	1.43
Latin America	3.1	0.3	0.5	0.2	0.1	1.4	3.26	1.6	1.3	0.3	0.0	0.0	1.13
MENA	1.6	0.0	0.0	0.0	0.8	0.7	1.02	0.7	0.0	0.5	0.0	0.1	1.10
Oceania	0.5	0.1	0.1	0.1	0.0	0.1	0.11	0.1	0.0	0.1	0.0	0.0	0.90
Russia and CA	2.2	0.2	0.3	0.2	0.1	1.5	2.44	2.5	0.5	1.3	0.6	0.1	1.64
Southeast Asia	3.0	0.2	0.2	0.0	0.1	2.5	15.22	7.0	6.0	0.9	0.0	0.0	2.77
Sub-Saharan Africa	1.9	0.3	0.5	0.2	0.1	0.7	1.06	1.0	0.5	0.4	0.1	0.0	1.29
World total	38.0	3.3	4.6	3.7	1.9	24.3	122.10	32.5	17.8	7.0	5.3	2.3	1.34

Supplementary Table 4: *Direct and indirect land cover change due to urban expansion, based on actual yields for wheat, maize, and rice, and assuming that cropland is displacement across all world regions.*

Region	Urban expansion [Mha]	Direct loss [Mha]					Displaced crop production [Mton]	Displaced cropland [Mha]	Indirect loss [Mha]				Leverage factor [-]
		Forest	Shrub	Grass	Other	Crop			Forest	Shrub	Grass	Other	
Canada and USA	6.1	1.2	1.4	1.2	0.1	2.3	10.4	4.9	2.8	1.5	0.5	0.2	2.8
China	8.8	0.2	0.5	1.2	0.1	6.7	54.2	25.7	14.4	7.7	2.7	0.9	14.4
Europe	8.4	0.7	0.9	0.5	0.5	6.3	27.3	13.0	7.2	3.9	1.4	0.5	7.2
India	2.4	0.1	0.2	0.1	0.0	2.0	7.1	3.4	1.9	1.0	0.4	0.1	1.9
Latin America	3.1	0.3	0.5	0.2	0.1	1.4	3.3	1.5	0.9	0.5	0.2	0.1	0.9
MENA	1.6	0.0	0.0	0.0	0.8	0.7	1.0	0.5	0.3	0.1	0.1	0.0	0.3
Oceania	0.5	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Russia and CA	2.2	0.2	0.3	0.2	0.1	1.5	2.4	1.2	0.6	0.3	0.1	0.0	0.6
Southeast Asia	3.0	0.2	0.2	0.0	0.1	2.5	15.2	7.2	4.0	2.2	0.8	0.3	4.0
Sub-Saharan Africa	1.9	0.3	0.5	0.2	0.1	0.7	1.1	0.5	0.3	0.2	0.1	0.0	0.3
World total	38.0	3.3	4.6	3.7	1.9	24.3	122.1	58.0	32.4	17.4	6.2	2.0	32.4

Supplementary Table 5: *Direct and indirect land cover change due to urban expansion, based on potential yields for wheat, maize, and rice, and assuming that cropland is only displaced within the same world region.*

Region	Urban expansion [Mha]	Direct loss [Mha]					Displaced crop production [Mton]	Displaced cropland [Mha]	Indirect loss [Mha]				Leverage factor [-]
		Forest	Shrub	Grass	Other	Crop			Forest	Shrub	Grass	Other	
Canada and USA	6.1	1.2	1.4	1.2	0.1	2.3	13.5	3.1	1.2	0.8	1.1	0.0	1.30
China	8.8	0.2	0.5	1.2	0.1	6.7	75.3	10.4	4.5	1.6	2.6	1.6	1.56
Europe	8.4	0.7	0.9	0.5	0.5	6.3	43.7	10.3	6.3	2.7	1.0	0.3	1.63
India	2.4	0.1	0.2	0.1	0.0	2.0	11.0	2.3	1.1	0.6	0.4	0.2	1.11
Latin America	3.1	0.3	0.5	0.2	0.1	1.4	6.2	1.4	1.1	0.3	0.0	0.0	1.02
MENA	1.6	0.0	0.0	0.0	0.8	0.7	2.2	0.7	0.0	0.5	0.0	0.1	1.08
Oceania	0.5	0.1	0.1	0.1	0.0	0.1	0.2	0.1	0.0	0.1	0.0	0.0	0.98
Russia and CA	2.2	0.2	0.3	0.2	0.1	1.5	5.3	2.0	0.4	1.0	0.5	0.1	1.31
Southeast Asia	3.0	0.2	0.2	0.0	0.1	2.5	18.3	5.1	4.4	0.7	0.0	0.0	2.00
Sub-Saharan Africa	1.9	0.3	0.5	0.2	0.1	0.7	3.3	0.8	0.4	0.3	0.1	0.0	1.12
World total	38.0	3.3	4.6	3.7	1.9	24.3	179.0	28.0	14.9	6.1	4.9	2.2	1.15

Supplementary Table 6: *Direct and indirect land cover change due to urban expansion, based on potential yields for wheat, maize, and rice, and assuming that cropland is displacement across all world regions.*

Region	Urban expansion [Mha]	Direct loss [Mha]					Displaced crop production [Mton]	Displaced cropland [Mha]	Indirect loss [Mha]				Leverage factor [-]
		Forest	Shrub	Grass	Other	Crop			Forest	Shrub	Grass	Other	
Canada and USA	6.1	1.2	1.4	1.2	0.1	2.3	13.5	3.1	1.8	0.9	0.3	0.1	1.34
China	8.8	0.2	0.5	1.2	0.1	6.7	75.3	17.5	9.8	5.3	1.9	0.6	2.63
Europe	8.4	0.7	0.9	0.5	0.5	6.3	43.7	10.2	5.7	3.1	1.1	0.4	1.61
India	2.4	0.1	0.2	0.1	0.0	2.0	11.0	2.6	1.4	0.8	0.3	0.1	1.26
Latin America	3.1	0.3	0.5	0.2	0.1	1.4	6.2	1.4	0.8	0.4	0.2	0.1	1.03
MENA	1.6	0.0	0.0	0.0	0.8	0.7	2.2	0.5	0.3	0.2	0.1	0.0	0.78
Oceania	0.5	0.1	0.1	0.1	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.73
Russia and CA	2.2	0.2	0.3	0.2	0.1	1.5	5.3	1.2	0.7	0.4	0.1	0.0	0.81
Southeast Asia	3.0	0.2	0.2	0.0	0.1	2.5	18.3	4.3	2.4	1.3	0.5	0.1	1.68
Sub-Saharan Africa	1.9	0.3	0.5	0.2	0.1	0.7	3.3	0.8	0.4	0.2	0.1	0.0	1.05
World total	38.0	3.3	4.6	3.7	1.9	24.3	179.0	41.7	23.3	12.5	4.4	1.5	1.72

Supplementary Table 7: *Direct and indirect land cover change due to urban expansion, based on actual caloric productivity of 16 different crop types, and assuming that cropland is only displaced within the same world region.*

Region	Urban expansion [Mha]	Direct loss [Mha]					Displaced crop production [Tcal]	Displaced cropland [Mha]	Indirect loss [Mha]				Leverage factor [-]
		Forest	Shrub	Grass	Other	Crop			Forest	Shrub	Grass	Other	
Canada and USA	6.1	1.2	1.4	1.2	0.1	2.3	27.5	3.0	1.1	0.8	1.1	0.0	1.27
China	8.8	0.2	0.5	1.2	0.1	6.7	154.7	11.6	5.1	1.8	2.9	1.8	1.74
Europe	8.4	0.7	0.9	0.5	0.5	6.3	84.6	10.5	6.6	2.7	1.0	0.3	1.67
India	2.4	0.1	0.2	0.1	0.0	2.0	20.2	3.1	1.5	0.7	0.5	0.3	1.51
Latin America	3.1	0.3	0.5	0.2	0.1	1.4	13.4	1.6	1.3	0.3	0.0	0.0	1.19
MENA	1.6	0.0	0.0	0.0	0.8	0.7	2.6	0.6	0.0	0.5	0.0	0.1	0.93
Oceania	0.5	0.1	0.1	0.1	0.0	0.1	0.4	0.1	0.0	0.1	0.0	0.0	0.88
Russia and CA	2.2	0.2	0.3	0.2	0.1	1.5	7.3	2.6	0.5	1.4	0.7	0.1	1.74
Southeast Asia	3.0	0.2	0.2	0.0	0.1	2.5	65.9	2.9	2.5	0.4	0.0	0.0	1.13
Sub-Saharan Africa	1.9	0.3	0.5	0.2	0.1	0.7	7.7	1.4	0.7	0.5	0.2	0.0	1.92
World total	38.0	3.3	4.6	3.7	1.9	24.3	384.1	29.8	15.0	6.8	5.6	2.5	1.23

Supplementary Table 8: *Direct and indirect land cover change due to urban expansion, based on actual caloric productivity of 16 different crop types, and assuming that cropland is displacement across all world regions.*

Region	Urban expansion [Mha]	Direct loss [Mha]					Displaced crop production [Tcal]	Displaced cropland [Mha]	Indirect loss [Mha]				Leverage factor [-]
		Forest	Shrub	Grass	Other	Crop			Forest	Shrub	Grass	Other	
Canada and USA	6.1	1.2	1.4	1.2	0.1	2.3	27.5	3.1	1.7	0.9	0.3	0.1	1.33
China	8.8	0.2	0.5	1.2	0.1	6.7	154.7	17.6	9.8	5.3	1.9	0.6	2.64
Europe	8.4	0.7	0.9	0.5	0.5	6.3	84.6	9.6	5.4	2.9	1.0	0.3	1.53
India	2.4	0.1	0.2	0.1	0.0	2.0	20.2	2.3	1.3	0.7	0.2	0.1	1.12
Latin America	3.1	0.3	0.5	0.2	0.1	1.4	13.4	1.5	0.9	0.5	0.2	0.1	1.10
MENA	1.6	0.0	0.0	0.0	0.8	0.7	2.6	0.3	0.2	0.1	0.0	0.0	0.45
Oceania	0.5	0.1	0.1	0.1	0.0	0.1	0.4	0.0	0.0	0.0	0.0	0.0	0.56
Russia and CA	2.2	0.2	0.3	0.2	0.1	1.5	7.3	0.8	0.5	0.2	0.1	0.0	0.55
Southeast Asia	3.0	0.2	0.2	0.0	0.1	2.5	65.9	7.5	4.2	2.2	0.8	0.3	2.95
Sub-Saharan Africa	1.9	0.3	0.5	0.2	0.1	0.7	7.7	0.9	0.5	0.3	0.1	0.0	1.18
World total	38.0	3.3	4.6	3.7	1.9	24.3	384.1	43.7	24.4	13.1	4.6	1.5	1.80

Supplementary Table 9: *Direct and indirect land cover change due to urban expansion, based on potential caloric productivity of 16 different crop types, and assuming that cropland is only displaced within the same world region.*

Region	Urban expansion [Mha]	Direct loss [Mha]					Displaced crop production [Tcal]	Displaced cropland [Mha]	Indirect loss [Mha]				Leverage factor [-]
		Forest	Shrub	Grass	Other	Crop			Forest	Shrub	Grass	Other	
Canada and USA	6.1	1.2	1.4	1.2	0.1	2.3	27.5	2.9	1.1	0.7	1.0	0.0	1.22
China	8.8	0.2	0.5	1.2	0.1	6.7	154.7	11.2	4.9	1.8	2.8	1.7	1.67
Europe	8.4	0.7	0.9	0.5	0.5	6.3	84.6	9.1	5.7	2.3	0.9	0.3	1.45
India	2.4	0.1	0.2	0.1	0.0	2.0	20.2	2.4	1.1	0.6	0.4	0.3	1.18
Latin America	3.1	0.3	0.5	0.2	0.1	1.4	13.4	1.6	1.3	0.3	0.0	0.0	1.16
MENA	1.6	0.0	0.0	0.0	0.8	0.7	2.6	0.5	0.0	0.4	0.0	0.1	0.72
Oceania	0.5	0.1	0.1	0.1	0.0	0.1	0.4	0.1	0.0	0.1	0.0	0.0	0.87
Russia and CA	2.2	0.2	0.3	0.2	0.1	1.5	7.3	2.1	0.4	1.1	0.5	0.1	1.40
Southeast Asia	3.0	0.2	0.2	0.0	0.1	2.5	65.9	2.6	2.2	0.3	0.0	0.0	1.02
Sub-Saharan Africa	1.9	0.3	0.5	0.2	0.1	0.7	7.7	1.4	0.7	0.6	0.2	0.0	1.96
World total	38.0	3.3	4.6	3.7	1.9	24.3	384.1	27.1	13.6	6.0	5.1	2.3	1.11

Supplementary Table 10: *Direct and indirect land cover change due to urban expansion, based on potential caloric productivity of 16 different crop types, and assuming that cropland is displacement across all world regions.*

Region	Urban expansion [Mha]	Direct loss [Mha]					Displaced crop production [Tcal]	Displaced cropland [Mha]	Indirect loss [Mha]				Leverage factor [-]
		Forest	Shrub	Grass	Other	Crop			Forest	Shrub	Grass	Other	
Canada and USA	6.1	1.2	1.4	1.2	0.1	2.3	27.5	2.3	1.3	0.7	0.2	0.1	0.98
China	8.8	0.2	0.5	1.2	0.1	6.7	154.7	14.1	7.9	4.2	1.5	0.5	2.12
Europe	8.4	0.7	0.9	0.5	0.5	6.3	84.6	8.6	4.8	2.6	0.9	0.3	1.36
India	2.4	0.1	0.2	0.1	0.0	2.0	20.2	2.0	1.1	0.6	0.2	0.1	0.98
Latin America	3.1	0.3	0.5	0.2	0.1	1.4	13.4	1.4	0.8	0.4	0.2	0.1	1.04
MENA	1.6	0.0	0.0	0.0	0.8	0.7	2.6	0.4	0.2	0.1	0.0	0.0	0.55
Oceania	0.5	0.1	0.1	0.1	0.0	0.1	0.4	0.0	0.0	0.0	0.0	0.0	0.57
Russia and CA	2.2	0.2	0.3	0.2	0.1	1.5	7.3	1.0	0.6	0.3	0.1	0.0	0.69
Southeast Asia	3.0	0.2	0.2	0.0	0.1	2.5	65.9	5.0	2.8	1.5	0.5	0.2	1.97
Sub-Saharan Africa	1.9	0.3	0.5	0.2	0.1	0.7	7.7	1.4	0.8	0.4	0.1	0.0	1.90
World total	38.0	3.3	4.6	3.7	1.9	24.3	384.1	36.3	20.3	10.9	3.9	1.3	1.49

Supplementary Table 11: *Reclassification of ESA-CCI land cover classes for the purpose of this study.*

ID	ESA-CCI land cover class	Cropland	Forest	Urban land	Shrubland	Grassland	Other
0	No data	0	0	0	0	0	1
10	Cropland, rainfed	1	0	0	0	0	0
11	Herbaceous cover	1	0	0	0	0	0
12	Tree or shrub cover	1	0	0	0	0	0
20	Cropland, irrigated or post-flooding	1	0	0	0	0	0
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	0.6	0.1	0	0.3	0	0
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	0.4	0.1	0	0.5	0	0
50	Tree cover, broadleaved, evergreen, closed to open (>15%)	0	1	0	0	0	0
60	Tree cover, broadleaved, deciduous, closed to open (>15%)	0	1	0	0	0	0
61	Tree cover, broadleaved, deciduous, closed (>40%)	0	1	0	0	0	0
62	Tree cover, broadleaved, deciduous, open (15-40%)	0	1	0	0	0	0
70	Tree cover, needleleaved, evergreen, closed to open (>15%)	0	1	0	0	0	0
71	Tree cover, needleleaved, evergreen, closed (>40%)	0	1	0	0	0	0
72	Tree cover, needleleaved, evergreen, open (15-40%)	0	1	0	0	0	0
80	Tree cover, needleleaved, deciduous, closed to open (>15%)	0	1	0	0	0	0
81	Tree cover, needleleaved, deciduous, closed (>40%)	0	1	0	0	0	0
82	Tree cover, needleleaved, deciduous, open (15-40%)	0	1	0	0	0	0
90	Tree cover, mixed leaf type (broadleaved and needleleaved)	0	1	0	0	0	0
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	0	0.4	0	0.6	0	0
110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	0	0.2	0	0.8	0	0
120	Shrubland	0	0	0	1	0	0
121	Shrubland evergreen	0	0	0	1	0	0
122	Shrubland deciduous	0	0	0	1	0	0
130	Grassland	0	0	0	0	1	0
140	Lichens and mosses	0	0	0	1	0	0
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	0	0	0	1	0	0
151	Sparse tree (<15%)	0	0	0	1	0	0
152	Sparse shrub (<15%)	0	0	0	1	0	0
153	Sparse herbaceous cover (<15%)	0	0	0	1	0	0
160	Tree cover, flooded, fresh or brakish water	0	1	0	0	0	0
170	Tree cover, flooded, saline water	0	1	0	0	0	0
180	Shrub or herbaceous cover, flooded, fresh/saline/brakish water	0	0	0	1	0	0
190	Urban areas	0	0	1	0	0	0
200	Bare areas	0	0	0	0	0	1
201	Consolidated bare areas	0	0	0	0	0	1
202	Unconsolidated bare areas	0	0	0	0	0	1
210	Water bodies	0	0	0	0	0	1
220	Permanent snow and ice	0	0	0	0	0	1

Supplementary Table 12: *Data sources and properties used for the different variables in this study.*

Variable	Spatial resolution	Time period covered	Source	Data processing
Land cover	~300 meter	1992-2015, yearly intervals	ESA-CCI [1]	Original land cover types are reclassified into six classes.
Actual cereal yields [ton]	5 arcminutes	Around 2000 (1997-2003)	Mueller et al (2008) [2]	Actual yields are calculated as the potential yield reduced by the yield gap.
Potential cereal yields [ton]	5 arcminutes	Around 2000 (1997 – 2003)	Mueller et al (2008)	
Actual yields of 16 crops [ton]	5 arcminutes	Around 2000 (1997 – 2003)	Mueller et al (2008) [2]	Actual yields are calculated as the potential yield reduced by the yield gap. Yields are converted to caloric values using nutritive values.
Potential yields of 16 crops [ton]	5 arcminutes	Around 2000 (1997 – 2003)	Mueller et al (2008) [2]	Yields are converted to caloric values using nutritive values.
Cropland area	5 arcminutes	Around 2000 (1997 – 2003)	Ramankutty et al., 2008) [3]	
Harvested area	5 arcminutes	Around 2000 (1997 – 2003)	Monfreda et al (2008) [4]	Harvested area is calculated as the sum of all 175 crops included.
Nutritive values	N.A.	N.A.	FAO [5]	

Supplementary references

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