LAND USE CHANGES LITERATURE REVIEW

Marina Campano-Méndez, july 2021

CONTENTS

1. FORESTS

According to FRA 2020, forests currently cover 30.8% (4.06 billion ha) of the global land area. More than half of the world's forests are found in only five countries (the Russian Federation, Brazil, Canada, the United States of America and China) and two-thirds (66%) of forests are found in ten countries (FAO and UNEP., 2020).

Forest area decreased from 32.5% to 30.8% (of the global land area), a loss of 178 million ha, between 1990 and 2020. However the rate of loss slowed down, from a 7.84 million ha/year decrease between 1990 and 2010 to a 4.74 million ha/year decrease in the next decade, 2010-2020 (FAO and UNEP., 2020). Forest loss is primarily caused by agricultural expansion, while forest area increase may occur through natural expansion of forests (e.g. on abandoned agricultural land) or through reforestation[1] or afforestation[2].

- Between 2010 and 2020 Africa had the **highest net loss**, 3.94 million ha/year, followed by South America with 2.60 million ha/year of loss. However, in Africa the rate of net loss has increased since 1990, while in South America it has substantially decreased, since 2010 it has more than halved compared to the previous decade.
- Asia had the **highest net gain** in forest area in the period 2010–2020, followed by Oceania and Europe. Both Europe and Asia reported a net forest gain in both decades 1990-2010 and 2010-2020, although both of them show a substantial reduction in the gain rate since 2010. Forest cover has significantly increased in China, Costa Rica, the Republic of Korea and Viet Nam as a result of government policies.

Even though there has been same progress: the rate of deforestation has decrease from 16 million ha/year in the 1990s to 10 million ha/year during 2015-2020 and the examples of restored degraded land are numerous the goals are not being accomplished. Since 2000 only 18% of the 2020 goal (restore 150 million ha of degraded landscapes and forest lands by 2020) has been accomplished (FAO and UNEP., 2020). The world is not in track to accomplish the United Nations Strategic Plan for Forests (UN, 2017 as cited in FAO and UNEP., 2020) to increase forest area by 3 percent worldwide by 2030 (relative to 2015).

<u>FAO consider five major climatic domains</u>: boreal (27% of global forest area), polar, temperate (16%), subtropical (11%) and tropical (45%). FAO further divides these domains in ecological zones. 20 of them contain forest cover and, among them, 10 showed a net increase and other 10 a net decrease of forest area between 1992 and 2015 (FAO and UNEP., 2020).

---

[1] Reforestation defined as the re-establishment of forest through planting and/or deliberate seeding on land classified as forest (FAO, 2012a as cited in (FAO, 2016)).

[2] Afforestation defined as the establishment of forest through planting and/or deliberate seeding on land that, until then, was not classified as forest (FAO, 2012a as cited in (FAO, 2016))

- The largest negative change in tree cover was seen in the tropical rainforest, which covers much of Central Africa, the Amazon Basin, Indonesia and Papua New Guinea, while the largest positive change was found in the boreal tundra woodland, which is found in Canada and the Russian Federation (FAO and UNEP., 2020).

FAO categorize forest into naturally regenerating forests, which are further disaggregated into primary forests and other naturally regenerating forests and account for 93% of the world's forest area, the remaining 7% are planted forests, further disaggregated into forest plantations and other planted forests (FAO and UNEP., 2020).

- Primary forests[3]: 34% of the world's forests are primary forests, nevertheless large extents of such forests now occur only in tropical and boreal regions (FRA 2020, as cited in FAO and UNEP., 2020). 61% of them are found in only three countries: Brazil, Canada and the Russian Federation. They continue to decline globally. Since 1990, primary forest area worldwide has decreased by 81 million ha, nevertheless the rate of loss more than halved over the last decade. Drivers of deforestation in primary forests include unsustainable industrial timber extraction, agricultural expansion and fires, however they are context specific. (Section 1.2.)
- Planted forests: Its area has increased by 123 million ha since 1990 and now covers 294 million hectares, but the rate of increase has slowed since 2010. 45% of the planted forests (3% of all forests) are plantation forests[4] and the remaining 55% are "other planted forests"[5]. In South America 99% of planted forest area are forest plantations (2% of the total forest area). Conversely in Europe plantation forests are just 6% of planted forests' area (0.4% of its forest area) (Section 1.4.2.).

1.1. Historical dynamics (Forest-Agriculture Land) (FAO, 2016)

1.1.1. Before the 21st century

Some estimates suggest that global forest area has decreased by around 1.8 billion ha in the past 5 000 years. Until the late 19th century, the highest rates of deforestation were in the world's temperate regions.

- In **western and central Europe**, an estimated 80% of the land was covered with forests 1.500 years ago and about half of them were cleared in the subsequent 800 years (Williams, 2003 as cited in FAO, 2016). Population declines due to severe diseases 650 years ago led to arable land abandonment, where forest re-grew. Renewed population pressure brought back the previous high deforestation rates but it also woke up concern about forest sustainability.
- In **China** more than 60% of the land was covered by trees (population 1.4 million people). By 1840 population reached 413 million people and forest cover decreased by

---

[3] Primary forests defined as naturally regenerated forests of native tree species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed (FRA 2020 as cited in FAO and UNEP., 2020).

[4] Plantation forests defined as intensively managed forests, mainly composed of one or two tree species, native or exotic, of equal age, planted with regular spacing and mainly established for productive purposes.

[5] "Other planted forests" defined as forests that can resemble natural forest at stand maturity and include forests established for ecosystem restoration and protection of soil and water.

17%. It is likely that the forest area in southern Asia has declined by more than half in the last 500 years.

- In **North America** the large forest conversions began with the arrival of Europeans in the late 15th century. The rate of forest conversion rose as the human population grew; nevertheless, while settlers pushed to the west in the 19th century forest regrew on abandoned agricultural land in the east. In **Central and South America**, forest covered about 75% of the land area before the arrival of Europeans; deforestation in the 18th and 19th centuries reduced it to about 70% by the early 20th century.
- In **Africa** fluctuations in population density drove forest cover changes.

Between 1990 and 2000 the major deforestation continued to be agricultural expansion that was facilitated by mechanization. Other drivers were urban expansion, infrastructure development and mining. During this period deforestation slowed or even reversed in the temperate and boreal domains.

- In **western Europe**, deforestation rates declined as a result of: (i) improvements in the agricultural lands' productivity; (ii) remaining forest not being suitable for farming; (iii) industrialization urbanization; (iv) increase in timber imports from other parts of the world; (v) replacement of wood by coal as the main source of fuel. By the end of the 20th the forest area in most of Europe was stable or increasing, with forests covering around 33% of the total land area.
- **North America's** forest area has been stable since the early 20th century, after two centuries of deforestation.
- Although forest cover in **China** had fallen to a historical low of less than 10% of the land area by 1949, it had recovered to nearly 20% of the land area by the end of the 20th century as a result of major reforestation and afforestation.
- Deforestation generally increased in the tropical domain. **Latin America's** forest area declined to around 50% percent of the land area by the end of the 20th century.
- Nigeria lost more than 90% of its primary forest. However, in general, deforestation in **sub-Saharan Africa** was lower than elsewhere in the tropics.

The difference between land cover in 1900 and 2000 can be found in Annex 1 (Figure A1).

1.1.2. 21st century

Asia has the highest proportion of agricultural land (52%) and the lowest proportion of forest (19%). Europe, including the Russian Federation, has the lowest proportion of agricultural land (21%) and the second-highest proportion of forest (46%). Globally, agriculture accounts for 37.7% of the land area, and forest and "other" for just under one-third each (30.7% and 31.6%, respectively). More about the land distribution by land use (in 2000) can be seen in Figure A6a (Annex 6).

The tropical domain had the highest **decrease in forest area** (7 million ha/year) and it was the only domain to show an increase (6 million ha/year) in agricultural area. The changes in forest area in the boreal and subtropical domains are minor. The forest most vulnerable to agricultural conversion tend to be on flat, easily accessible land with high-fertility soils, such as coastal and island forests with good seas transport links to markets.

- FAO reported 33 countries that experimented loss of forest and gain of agricultural area, all locate in Africa, South and Central America, and South and Southeast Asia. 17, 6 of them small developing islands, countries shows a decreased in both areas. 15 showed increase of both areas, the increase of forest area was 8% (31% increase in planted forest area). 29 reported that the agricultural land decreased and the forest land increased, 6% increase of forest area (25% increase of planted forests).

Although unsustainable wood removal, including illegal harvesting, is sometimes regarded as a cause of deforestation, it is more often associated with forest degradation because wood removal does not necessarily lead to changes in land use.

In both boreal and temperate domain, the area of **forest increased** and the area of agricultural land declined, due to the natural expansion of forest on abandoned agricultural land, in territories that were part of the former Soviet Union (Belarus, Kazakhstan and the Russian Federation). Agriculture land conversion to forest may occur when agricultural land is abandoned due to rural population declines, land becomes so degraded that it becomes unproductive or more productive agricultural land becomes available elsewhere. 1990–2015, 93 countries recorded net forest losses (242 million ha), but 88 countries had net gains in forest area (113 million ha) (FAO, 2015a as cited in FAO, 2016). Afforestation policies are particularly evident in high-income countries such as the United States of America or those in Western Europe.

- In Asia 24 countries experienced a net increase in forest area in the period 1990–2015 (73.1 million ha), mainly due to large-scale afforestation programmes in Chin a.
- In Europe, 35 countries recorded a net increase in forest area (21.5 million hectares).
- 13 in Africa, / in Oceania, 6 countries in North and Central America, and 2 countries in South America.

1.2. Primary forests

While 234 countries reported forest cover data just 187 in 1990 and 202 in 2015 reported primary forest area data. The primary forest area of these 202 countries in 2015 was 1.277 million ha, 32% of the forest area reported by the 234 countries. The Russian Federation, Canada, Brazil, the Democratic Republic of the Congo, United States, Peru and Indonesia together accounted for the 75% of it.

Globally primary forest area experienced a net decrease of 31 million ha (2.5%) over the period 1990-2015. Tropical countries showed an overall decline of 62 million ha (10%). Subtropical countries reported a similar proportional reduction of 5 million ha.
These declines were roughly in line with the rates of overall forest area loss for these domains (Keenan et al., 2015 as cited in Morales-Hidalgo et al., 2015).
The reported increases in temperate (6 million ha) and boreal (30 million ha) countries are accounted for almost entirely by Russia (boreal) and the United States (temperate), being the increasing rates of these countries 0.4%/year and 0.3% year, respectively. A few countries reported large percentage increases in primary forest, the largest being Bulgaria with 7%/year growth, however most of this increment is related to a change in the methods to assess primary forests and change in definitions.

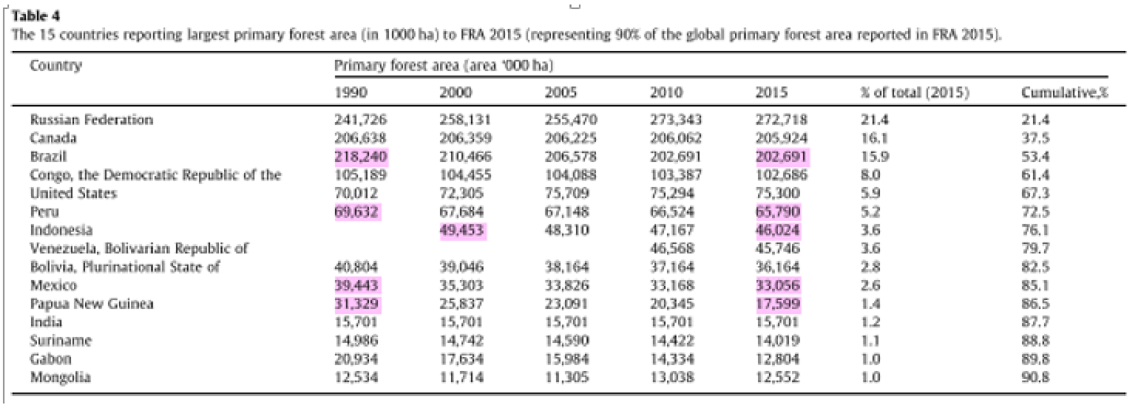


Table 4
The 15 countries reporting largest primary forest area (in 1000 ha) to FRA 2015 (representing 90% of the global primary forest area reported in FRA 2015).

Country	Primary forest area (area '000 ha)						
	1990	2000	2005	2010	2015	% of total (2015)	Cumulative,%
Russian Federation	241,726	258,131	255,470	273,343	272,718	21.4	21.4
Canada	206,638	206,359	206,225	206,062	205,924	16.1	37.5
Brazil	218,240	210,466	206,578	202,691	202,691	15.9	53.4
Congo, the Democratic Republic of the	105,189	104,455	104,088	103,387	102,686	8.0	61.4
United States	70,012	72,305	75,709	75,294	75,300	5.9	67.3
Peru	69,632	67,684	67,148	66,524	65,790	5.2	72.5
Indonesia		49,453	48,310	47,167	46,024	3.6	76.1
Venezuela, Bolivarian Republic of				46,568	45,746	3.6	79.7
Bolivia, Plurinational State of	40,804	39,046	38,164	37,164	36,164	2.8	82.5
Mexico	39,443	35,303	33,826	33,168	33,056	2.6	85.1
Papua New Guinea	31,329	25,837	23,091	20,345	17,599	1.4	86.5
India	15,701	15,701	15,701	15,701	15,701	1.2	87.7
Suriname	14,986	14,742	14,590	14,422	14,019	1.1	88.8
Gabon	20,934	17,634	15,984	14,334	12,804	1.0	89.8
Mongolia	12,534	11,714	11,305	13,038	12,552	1.0	90.8

Figure 1. Primary forest area evolution (Morales-Hidalgo et al., 2015).

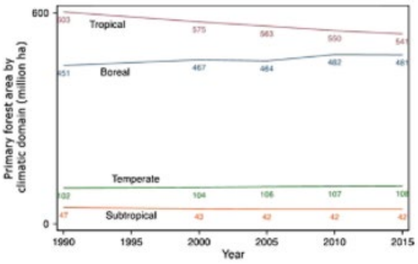


Fig. 5. Trends in primary forest area by climatic domain (Countries that did not report in all years are excluded from the domain totals in this figure). The consistently reporting countries included in the domain totals accounted for about 88–89% of the global forest area in each year.

Figure 2. Primary forest trends by climatic domain (Morales-Hidalgo et al., 2015).

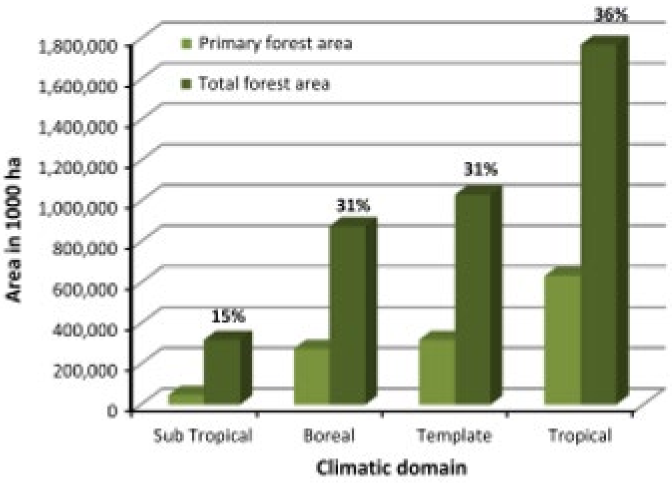


Fig. 6. Total and primary forest area and percentage of primary forest by climatic domain reported for all countries in year 2015 to FRA.

Figure 3. Primary forest and total forest area by climatic domain (Morales-Hidalgo et al., 2015).

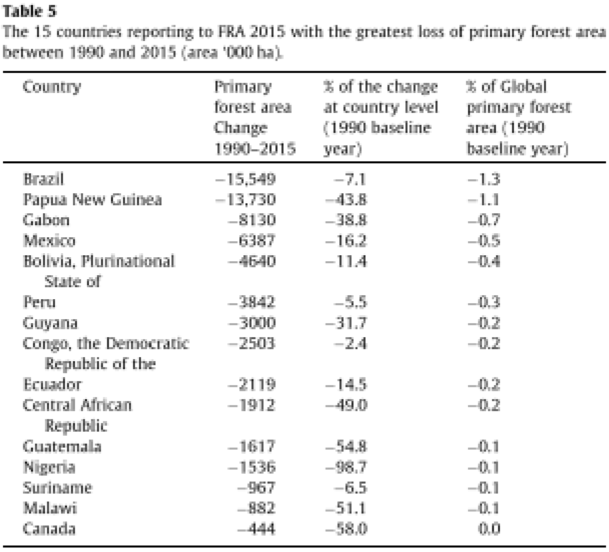


Table 5
The 15 countries reporting to FRA 2015 with the greatest loss of primary forest area between 1990 and 2015 (area '000 ha).

Country	Primary forest area Change 1990–2015	% of the change at country level (1990 baseline year)	% of Global primary forest area (1990 baseline year)
Brazil	−15,549	−7.1	−1.3
Papua New Guinea	−13,730	−43.8	−1.1
Gabon	−8130	−38.8	−0.7
Mexico	−6387	−16.2	−0.5
Bolivia, Plurinational State of	−4640	−11.4	−0.4
Peru	−3842	−5.5	−0.3
Guyana	−3000	−31.7	−0.2
Congo, the Democratic Republic of the	−2503	−2.4	−0.2
Ecuador	−2119	−14.5	−0.2
Central African Republic	−1912	−49.0	−0.2
Guatemala	−1617	−54.8	−0.1
Nigeria	−1536	−98.7	−0.1
Suriname	−967	−6.5	−0.1
Malawi	−882	−51.1	−0.1
Canada	−444	−58.0	0.0

Figure 4. Greatest primary forest losses (Morales-Hidalgo et al., 2015).

Regarding Hosonuma et al.'s classification it was found that intact forest (primary) area follows a similar forest cover curve to forest that when assessing general forest, but the change in intact forest cover from the late- to post-transition phase remains quite small, what suggests that a large proportion of forests in post-transition countries remains degraded (Hosonuma et al., 2012).

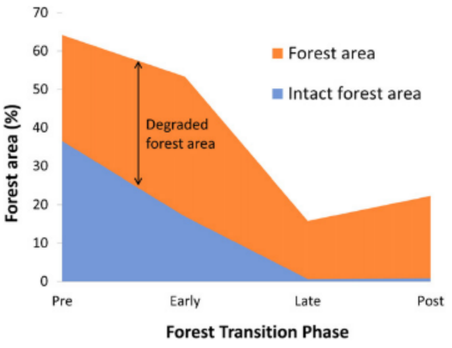


Figure 4. Average forest cover (FAO 2010) and intact forest area in 2005 for each FT phase.

Figure 5. Primary forest curves (Hosonuma et al., 2012).

1.3. Forest losses

1.3.1. Hosonuma et al., 2012

Summary in Figure 6

Hosonuma did a study about the drivers of deforestation[6] and forest degradation[7] In the study the countries were divided in the following categories: (i) pre-transition countries , high forest cover and low deforestation rates; (ii) early-transition countries, high forest cover that is been

---

[6] Deforestation here understood as complete removal of trees and the conversion from forest into other land uses such as agriculture (forest vegetation is not expected to regrow in the area) (Hosonuma et al., 2012).

[7] Forest degradation here stands for thinning of the canopy and loss of carbon in remaining forests, where damage is not associated with a change in land use (the forest is expected to regrow in the area) (Hosonuma et al., 2012).

lost at an increasingly rapid rate; (iii) late-transition countries, small fraction of remaining forests and slowing rate of the deforestation; (iv) post-transition phase, small forest cover and the forest area change rate becomes positive and forest cover increases through reforestation (Hosonuma et al., 2012). Of the 100 non-Annex I countries reviewed (see Figure A2 for classification), 13 were found to be pre-transition phase, 39 early transition, 33 late transition and 15 post-transition. Many pre-transition countries in Africa and America were found to be located around the equator, surrounded by early- and late-transition countries mostly located in sub-tropical regions (Hosonuma et al., 2012). Forest curves on Figure A2b.

The possible deforestation drivers considered were: (i) commercial agriculture, clearing for cropland, pasture and tree plantations for both domestic and international market (medium/large scale); (ii) subsistence agriculture, permanent subsistence and shifting cultivation (local smallholders); (iii) mining (surface mining); (iv) infrastructure such as roads, railroads, dams, pipelines; (v) urban expansion.

Regarding deforestation, commercial agriculture was found to be the most important driver in Latin America (68%), while in Africa and Asia it contributed to around 35% of deforestation. Local and subsistence agriculture was quite equally distributed among the continents (27–40%), which makes sense since subsistence agriculture remains widespread in the tropics and sub-tropics. Overall, agriculture caused around 80% of deforestation worldwide for the 1980s and 1990s. Mining plays a larger role in Africa and Asia than in Latin America. Urban expansion is most significant in Asia.
It was found that the contribution of commercial agriculture rises until the late-transition phase, after which it decreases again. The relative importance of subsistence agriculture remains fairly stable throughout the different phases. The importance of urban expansion and infrastructure is largest in the post-transition phase. Nevertheless, the total area deforested is largest in the early-transition phase and then it is driven by agriculture expansion. Mining seems to play an important role in the pre-transition phase, but this is likely due to the fact that some resource-rich countries are classified in that phase (Figure 6) (Hosonuma et al., 2012).

Regarding degradation, timber extraction and logging account for more than 70% of the total in Latin America and Asia. Fuelwood collection and charcoal production is the main degradation driver in Africa and is of small to moderate importance in Asia and Latin America. Uncontrolled fires are most prominent in Latin America.
The effect of timber and logging activities is pronounced in all phases but decreases in the late-transition phase. In the late-transition phase, fuelwood and charcoal and fires are much more prominent. In the post-transition phase, fuelwood collection and charcoal production decline as the economic development make other energy sources available. (Figure 6).

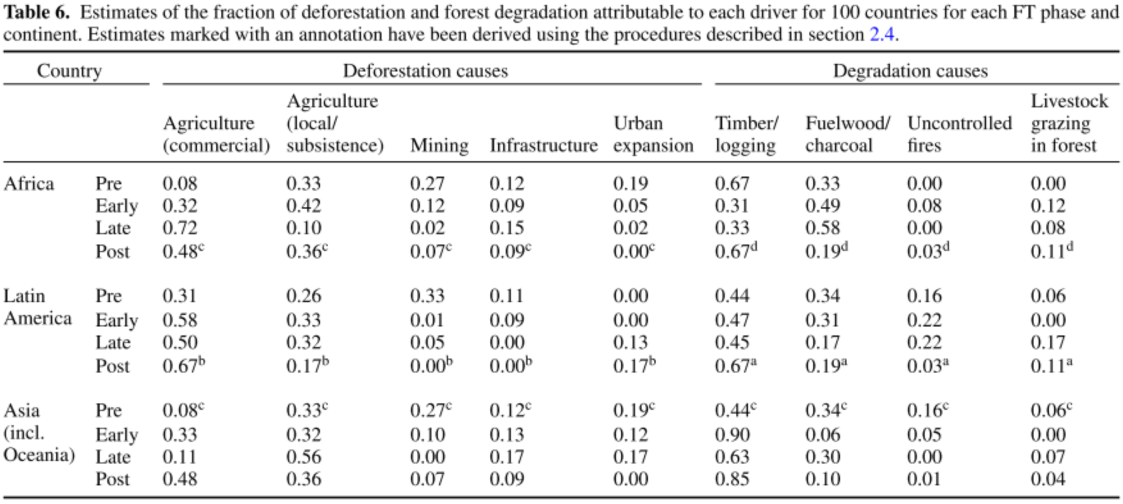
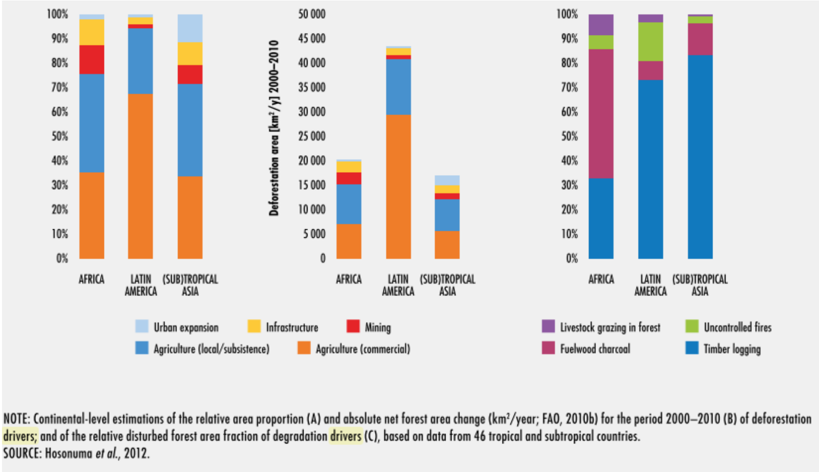


Table 6. Estimates of the fraction of deforestation and forest degradation attributable to each driver for 100 countries for each FT phase and continent. Estimates marked with an annotation have been derived using the procedures described in section 2.4.

Country		Deforestation causes					Degradation causes			
		Agriculture (commercial)	Agriculture (local/ subsistence)	Mining	Infrastructure	Urban expansion	Timber/ logging	Fuelwood/ charcoal	Uncontrolled fires	Livestock grazing in forest
Africa	Pre	0.08	0.33	0.27	0.12	0.19	0.67	0.33	0.00	0.00
	Early	0.32	0.42	0.12	0.09	0.05	0.31	0.49	0.08	0.12
	Late	0.72	0.10	0.02	0.15	0.02	0.33	0.58	0.00	0.08
	Post	0.48[c]	0.36[c]	0.07[c]	0.09[c]	0.00[c]	0.67[d]	0.19[d]	0.03[d]	0.11[d]
Latin America	Pre	0.31	0.26	0.33	0.11	0.00	0.44	0.34	0.16	0.06
	Early	0.58	0.33	0.01	0.09	0.00	0.47	0.31	0.22	0.00
	Late	0.50	0.32	0.05	0.00	0.13	0.45	0.17	0.22	0.17
	Post	0.67[b]	0.17[b]	0.00[b]	0.00[b]	0.17[b]	0.67[a]	0.19[a]	0.03[a]	0.11[a]
Asia (incl. Oceania)	Pre	0.08[c]	0.33[c]	0.27[c]	0.12[c]	0.19[c]	0.44[c]	0.34[c]	0.16[c]	0.06[c]
	Early	0.33	0.32	0.10	0.13	0.12	0.90	0.06	0.05	0.00
	Late	0.11	0.56	0.00	0.17	0.17	0.63	0.30	0.00	0.07
	Post	0.48	0.36	0.07	0.09	0.00	0.85	0.10	0.01	0.04

Figure 6. Deforestation and degradation drivers (%) (Hosonuma et al., 2012)



NOTE: Continental-level estimations of the relative area proportion (A) and absolute net forest area change (km²/year; FAO, 2010b) for the period 2000–2010 (B) of deforestation drivers; and of the relative disturbed forest area fraction of degradation drivers (C), based on data from 46 tropical and subtropical countries.
SOURCE: Hosonuma *et al.*, 2012.

Figure 7. Deforestation and degradation drivers (graphs) (Hosonuma et al., 2012).

1.3.2. De Sy et al., 2015 as cited in FAO, 2016

A study about deforestation drivers in seven South American countries (De Sy et al., 2015 as cited in FAO, 2016) highlighted that 71% of deforestation in those South American countries in 1990–2005 was driven by increased demand for pasture, 14% was driven by increased demand for commercial cropland, and less than 2% was the result of infrastructure and urban expansion.

1.3.3. Gibbs et al., 2009

Summary in Figure 8
Gibbs et al. carried out a study of the deforestation drivers in the tropics between 1980 and 2000. They found that 55% of the new agricultural land that appeared over the period came from intact forest (what we call primary forests), 28% of it came from disturbed forests that previously had been affected by shifting cultivation, logging, fuel wood collection, or other forms of gradual degradation (what we call managed forests), the remaining 8% was provided by shrubland conversion.

Even though in this study agricultural land stands for both pastures and croplands it was found that outside Latin America, the pasture area has remained relatively constant. Therefore, outside Latin America most agricultural expansion is for croplands (FAOSTAT 2009 as cited in Gibbs et al., 2009).

In Latin America the greatest expansion of agricultural land was for pastures, which increased by about ~35 million ha in South America and by ~7 million ha in Central America while croplands increased by ~5 million ha in South America which is more than double the increase in Central America (FAOSTAT 2009 as cited in Gibbs et al., 2009).

- In South America the new area coming from intact rainforests in was 13% higher in the 1990s than the 1980s. Shrublands and disturbed forests provided 25%, each, of the new agricultural areas in the 1980s but only 13% and 20%, respectively, in the 1990s.
- In Central America, the role of intact forests of decreased from 73% in the 1980s to 67% in the 1990s and that of disturbed forests became more important.. Shrubland conversion declined from7% to 4%.

In Africa the cropland area increased by~50% in East Africa and by~25% in West Africa while it decreased in Central Africa (FAOSTAT 2009 as cited in Gibbs et al., 2009). 60% of new agricultural land was derived from intact forests, 35% from disturbed forests and the remaining 5% from shrublands, which were a significant source just in East Africa (less densely forest areas).

- In Central Africa, 75% came from forests in the 1980s, but the percentage decreased by ~10% during the 1990s.
- East Africa increased clearing of intact forests by ~20%, and conversion of disturbed forests decreased by the same amount.
- In West Africa: 20% less agricultural land came from intact forests, and 20% more came from disturbed forests in the 1990s than in the 1980s.

In Asia

- Southeast Asia relied on intact forests for nearly 60% of new agricultural land and on disturbed forests for more than 30%.
- Southern Asia depended on disturbed forests for ~60% of new land and on intact forests for 35%.
- Mainland Asia and the Philippines are the only regions where shrublands were primary sources.

Plantations: Southeast Asia is the only region where tree plantations occupy a large portion of total agricultural land, it increased from 11 million ha to 17.4 million ha between 1980 and 2000 (FAOSTAT 2009 as cited in Gibbs et al., 2009). During the 1980s, roughly half of new plantations came from forests; most of the remaining area came from conversion of agricultural land. By the end of the 1990s, conversion of agricultural land accounted for nearly 70% of new plantations. It is remarkable that Tropical Resources and Environment monitoring by Satellites project (TREES) (Achard F, et al., 2002 as cited in Gibbs et al., 2009) identified intact and disturbed forests as the sources for ~90% of new plantations between 1990 and 1997.

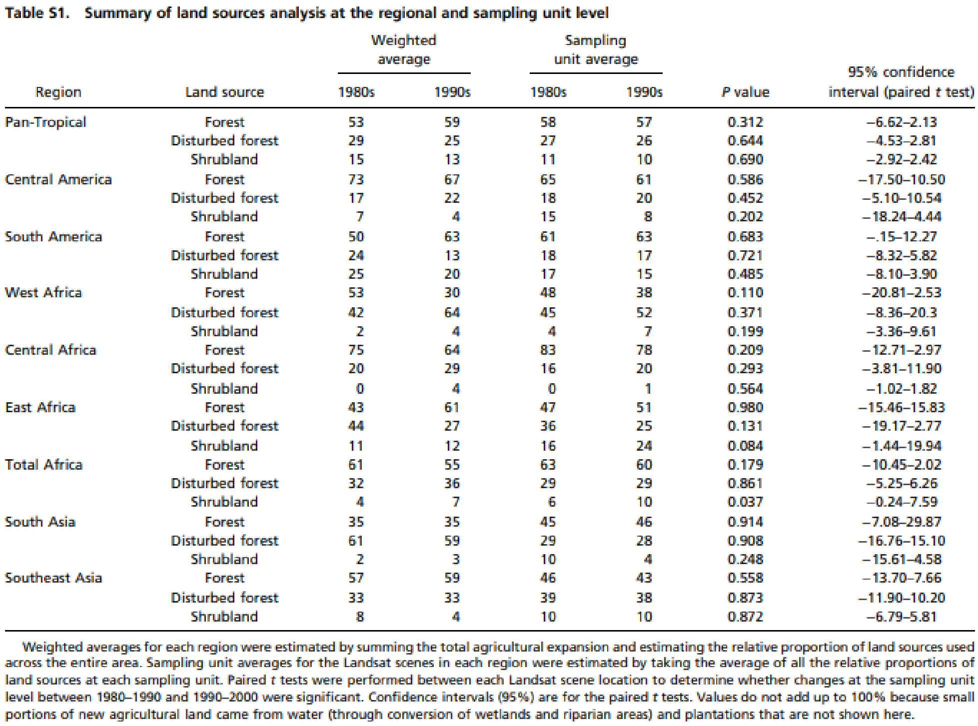


Table S1. Summary of land sources analysis at the regional and sampling unit level

Region	Land source	Weighted average		Sampling unit average		*P* value	95% confidence interval (paired *t* test)
		1980s	1990s	1980s	1990s		
Pan-Tropical	Forest	53	59	58	57	0.312	−6.62–2.13
	Disturbed forest	29	25	27	26	0.644	−4.53–2.81
	Shrubland	15	13	11	10	0.690	−2.92–2.42
Central America	Forest	73	67	65	61	0.586	−17.50–10.50
	Disturbed forest	17	22	18	20	0.452	−5.10–10.54
	Shrubland	7	4	15	8	0.202	−18.24–4.44
South America	Forest	50	63	61	63	0.683	−.15–12.27
	Disturbed forest	24	13	18	17	0.721	−8.32–5.82
	Shrubland	25	20	17	15	0.485	−8.10–3.90
West Africa	Forest	53	30	48	38	0.110	−20.81–2.53
	Disturbed forest	42	64	45	52	0.371	−8.36–20.3
	Shrubland	2	4	4	7	0.199	−3.36–9.61
Central Africa	Forest	75	64	83	78	0.209	−12.71–2.97
	Disturbed forest	20	29	16	20	0.293	−3.81–11.90
	Shrubland	0	4	0	1	0.564	−1.02–1.82
East Africa	Forest	43	61	47	51	0.980	−15.46–15.83
	Disturbed forest	44	27	36	25	0.131	−19.17–2.77
	Shrubland	11	12	16	24	0.084	−1.44–19.94
Total Africa	Forest	61	55	63	60	0.179	−10.45–2.02
	Disturbed forest	32	36	29	29	0.861	−5.25–6.26
	Shrubland	4	7	6	10	0.037	−0.24–7.59
South Asia	Forest	35	35	45	46	0.914	−7.08–29.87
	Disturbed forest	61	59	29	28	0.908	−16.76–15.10
	Shrubland	2	3	10	4	0.248	−15.61–4.58
Southeast Asia	Forest	57	59	46	43	0.558	−13.70–7.66
	Disturbed forest	33	33	39	38	0.873	−11.90–10.20
	Shrubland	8	4	10	10	0.872	−6.79–5.81

Weighted averages for each region were estimated by summing the total agricultural expansion and estimating the relative proportion of land sources used across the entire area. Sampling unit averages for the Landsat scenes in each region were estimated by taking the average of all the relative proportions of land sources at each sampling unit. Paired *t* tests were performed between each Landsat scene location to determine whether changes at the sampling unit level between 1980–1990 and 1990–2000 were significant. Confidence intervals (95%) are for the paired *t* tests. Values do not add up to 100% because small portions of new agricultural land came from water (through conversion of wetlands and riparian areas) and plantations that are not shown here.

Figure 8. Sources of agricultural land (Gibbs et al., 2009).

1.3.4. Graesser et al., 2015

Summary in Figure 9

Latin America had the most rapid agricultural expansion during the twenty-first century. From 2001 to 2013, 17% of new cropland and 57% of new pasture land replaced forests.. Cropland expansion from 2001 to 2013 was less (44.27 Mha) than pastureland (96.9 Mha), but 44% of the total cropland in 2013 was new cropland total while just a 27% was new pastures. From 2001 to 2007, there was a 1.385 ha/year increase of croplands and 48 ha/year of pasturelands, while between 2007 and 2013 the increase of cropland was 9 ha/year and the pastureland one of 22 ha/year.

The majority of significant agricultural changes from 2001 to 2013 occurred in a few Latin American and there were five major keys found: (1) significant cropland expansion was limited to Argentina, Brazil, Paraguay and Uruguay; (2) there was a post-2007 regional slowdown; (3) agriculture-led deforestation rates were high outside of the Amazon; (4) cropland, in addition to pastureland, drove deforestation in eastern Paraguay, central Mato Grosso, and the Argentine Chaco; (5) new cropland came from non-forested land, particularly in the Argentine Pampas region and in the Brazilian Cerrado.

During the 21st century pastureland often expanded into intact forests, whereas cropland expanded into pastureland.

- In **Argentina** 40% of new croplands came from pasturelands while the 4% came from forested areas. 30% of its pastures were new, 12% came from forest and 6% from croplands.
- In **Bolivia** 69% of new pastures (17.52 Mha) cameḍ from forests. Cropland expansion was limited.

- In **Brazil** between 2001 and 2013 appeared 17.35 Mha of new croplands and 40.54 Mha of new pastures. Mato Grosso suffered a cropland expansion coupled with a pastureland contraction.
- In **Colombia** new agriculture was almost completely due to pastureland expansion (4.3 Mha), which led to deforestation.
- In northern **Guatemala** pastureland expanded into forest while in western Nicaragua new cropland expansion came from pastures.
- In eastern **Paraguay** cropland expansion rates were high, while the western Paraguay pastureland expansion rates were among the highest of Latin America, the vast majority coming from forested area (62%).
- In **Uruguay** the changes were due to continued cropland expansion and pastureland the 1990s and early 2000s. Since Uruguay was mainly dominated by pastureland, 79% of new croplands came from pastures.

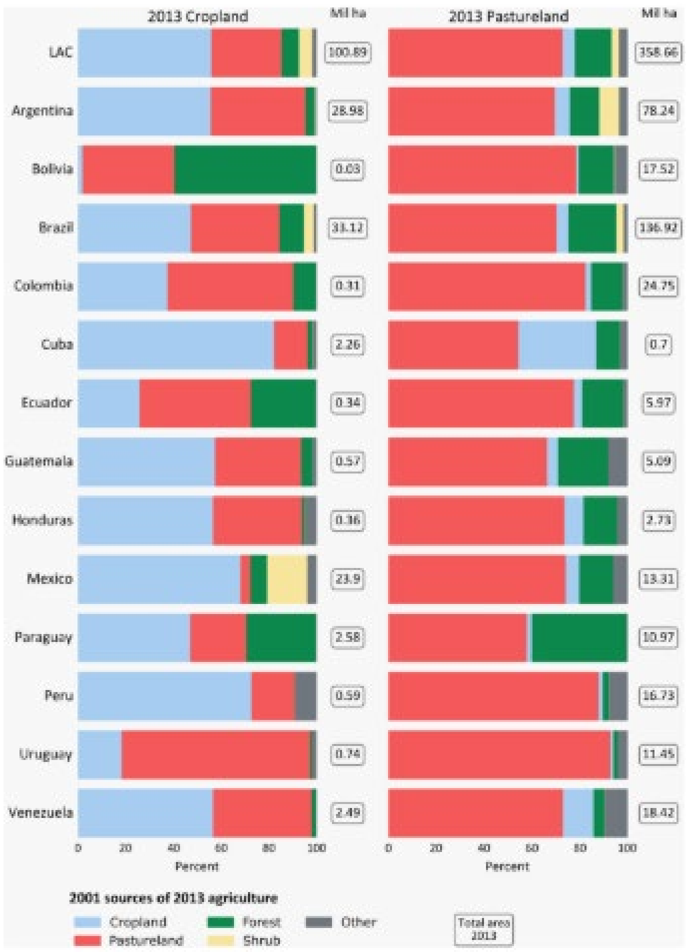


Figure 3. Proportion of 2013 cropland and pastureland from different sources in 2001, calculated from hexagon zones with statistically significant change rates. (See table S1 for class details.)

Figure 9. Cropland and pastures land sources (Graesser et al., 2015)

Pendrill et al. (Pendrill et al., 2019) summarized that forests and other native vegetation (such as wood-lands and shrublands) are the main sources of new agricultural land (pastures and croplands) in the tropics (Gibbs et al., n.d.), that the expansion of forest plantations tend to come at the expense of natural forests (Heilmayr, 2014; Nahuelhual et al., 2012; Gaveau et al., 2016; Gerber, 2011),but also that (at least in the tropical Americas) pastures are a significant source of new cropland (Gibbs et al., 2009; Graesser et al., 2015).

A study linked to the subject is done in Figure 19 (Section 2 van Vliet, 2019) and in Section 1.5. (Pendrill et al., 2019).

Natural land losses by country Figure A6a.
Land use changes caused by agricultural expansion Figure A6b.

1.4. Forest gains

1.4.1. Land suitable for expansion

1.4.1.a. (Bastin et al., 2019)

Bastin et al. (Bastin et al., 2019) presented a study in which it was estimated that, according to FAO's definition of forest[8], there are 8.7 billion ha of land that could support forest establishment on them. Nevertheless it is estimated that 1.4 billion ha of that area is found in croplands (>99%) and urban areas (<1%). From the total area with potential to support forest 1.7 to 1.8 billion ha exist in previously degraded areas, dominated by sparse vegetation, grasslands and degrades bare soils, of which 0.9 billion ha are found outside cropland and urban region. Thus, there could be a "canopy cover"[9] increase of 0.9 billion ha without natural areas nor croplands damaged (Bastin et al., 2019). More than 50% of the tree restoration potential area can be found in only six countries (in million ha: Russia, +151; United States, +103; Canada, +78.4; Australia, +58; Brazil, +49.7; and China, +40.2). This study does not focus on whether the land is private or public, therefore the amount of land really available for restoration could vary.

The study also remarks that he global forest restoration target of 1 billion ha proposed by the IPCC is undoubtedly achievable under the current climate. Nevertheless, it also points out that regions where tree growth is possible could be altered in the future due to climate change.

- Tree cover is likely to increase in cold regions with low tree cover such as northern boreal regions (e.g. Siberia) or open forests (e.g. tropical drylands). Potential increases of canopy area: in boreal (~130 Mha), desertic (~30 Mha), montane (~30 Mha), and temperate (~30 Mha) regions.
- There is also forecasted a consistent decline of tropical rainforests with high tree cover. Potential loss of forest habitat in tropical regions (~450 Mha).
- Since the area expanding boreal region (30 to 40%) is lower than that in declining tropical regions (90 to 100%), the study suggests a global loss of 223 Mha of canopy cover by 2050 under future climate scenarios.

---

[8] Forest defined as land of at least 0.5 ha covered by at least 10% tree cover and without agricultural activity or human settlements.

[9] "Canopy cover" defined as the area of the land that is covered by tree crown vertically projected to the ground (for example, 50% of tree cover over 1 ha corresponds to 0.5 ha of canopy cover).

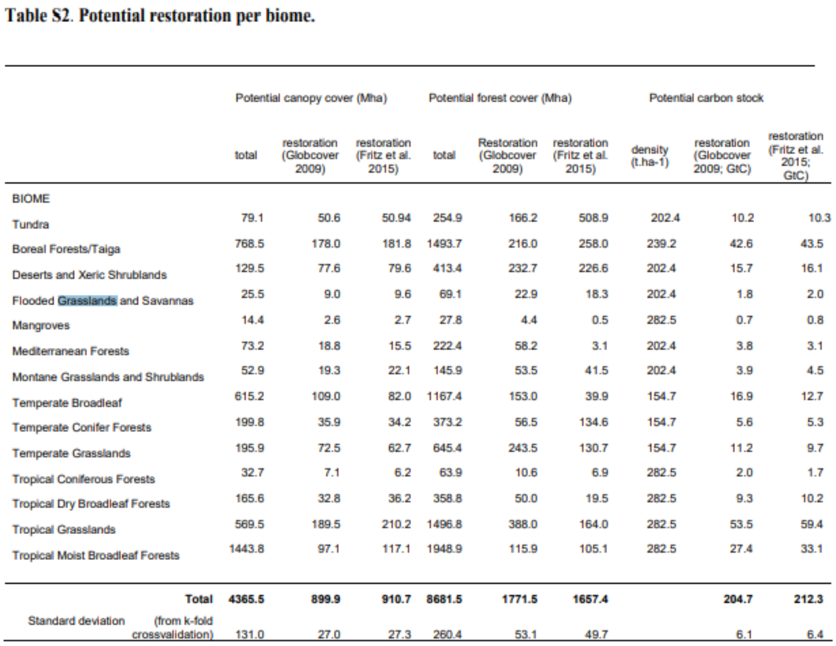


Table S2. Potential restoration per biome.

	Potential canopy cover (Mha)			Potential forest cover (Mha)			Potential carbon stock		
	total	restoration (Globcover 2009)	restoration (Fritz et al. 2015)	total	Restoration (Globcover 2009)	restoration (Fritz et al. 2015)	density (t.ha-1)	restoration (Globcover 2009; GtC)	restoration (Fritz et al. 2015; GtC)
BIOME									
Tundra	79.1	50.6	50.94	254.9	166.2	508.9	202.4	10.2	10.3
Boreal Forests/Taiga	768.5	178.0	181.8	1493.7	216.0	258.0	239.2	42.6	43.5
Deserts and Xeric Shrublands	129.5	77.6	79.6	413.4	232.7	226.6	202.4	15.7	16.1
Flooded Grasslands and Savannas	25.5	9.0	9.6	69.1	22.9	18.3	202.4	1.8	2.0
Mangroves	14.4	2.6	2.7	27.8	4.4	0.5	282.5	0.7	0.8
Mediterranean Forests	73.2	18.8	15.5	222.4	58.2	3.1	202.4	3.8	3.1
Montane Grasslands and Shrublands	52.9	19.3	22.1	145.9	53.5	41.5	202.4	3.9	4.5
Temperate Broadleaf	615.2	109.0	82.0	1167.4	153.0	39.9	154.7	16.9	12.7
Temperate Conifer Forests	199.8	35.9	34.2	373.2	56.5	134.6	154.7	5.6	5.3
Temperate Grasslands	195.9	72.5	62.7	645.4	243.5	130.7	154.7	11.2	9.7
Tropical Coniferous Forests	32.7	7.1	6.2	63.9	10.6	6.9	282.5	2.0	1.7
Tropical Dry Broadleaf Forests	165.6	32.8	36.2	358.8	50.0	19.5	282.5	9.3	10.2
Tropical Grasslands	569.5	189.5	210.2	1496.8	388.0	164.0	282.5	53.5	59.4
Tropical Moist Broadleaf Forests	1443.8	97.1	117.1	1948.9	115.9	105.1	282.5	27.4	33.1
Total	**4365.5**	**899.9**	**910.7**	**8681.5**	**1771.5**	**1657.4**		**204.7**	**212.3**
Standard deviation (from k-fold crossvalidation)	131.0	27.0	27.3	260.4	53.1	49.7		6.1	6.4

Figure 10. Potential suitable land for restoration (Bastin et al., 2019).

1.4.1.b. Zomer et al., 2008

Summary in Figure 11

Zomer et al. (Zomer et al., 2008) studied the land suitable for afforestation or reforestation projects which may be one of the following: (i) new, large-scale, industrial plantations; (ii) agroforestry; (iii) small-scale plantations rehabilitation of degraded areas through tree planting; (iv) reforestation of marginal areas with native species; (v) establishment of biomass plantation for energy production. The study did not consider the following areas as possible for the establishment of restoration projects: (i) drier arid/semi-arid areas (Aridity Index[10]<0.65); (ii) high elevation areas (above 3500m); (iii) water bodies; (iv) urban areas; (v) tundra; (vi) irrigated cropland (since being high productive systems); (vii) forested areas; (viii) ineligible areas due to legal reasons.

The world is divided in six regions: Central Asia, East Asia, Sub-Saharan Africa, South America, South Asia, and Southeast Asia. 46% (330 Mha) of the global suitable land is found in South America and 27% in Sub-Saharan Africa (200 Mha). The three Asian regions together accounted for just 200 Mha of suitable land.

In five out of the six regions cropland was half or more of the suitable land (364 Mha). The exception is being Sub-Saharan Africa, where the majority of available land was savannah.

- In both **South Asia and Southeast** Asia 76% of suitable land was agricultural land, with much smaller shares coming from shrubland and savannah, which is because of high population densities and extensive areas of agriculture of these regions.
- More than 52% (172 Mha) of the land in **South America** identified as suitable is classified as cropland. An additional 29 Mha is mixed shrubland/grassland, and is likely to be under some form of livestock production activity.

---

[10] Aridity Index = MAP/MAE. MAP stands for mean annual precipitation and MAE for mean annual evapotranspiration (Zomer et al., 2008).

- **Sub-Saharan Africa** has a large amount of savannah (132 Mha) classified as suitable (68%).

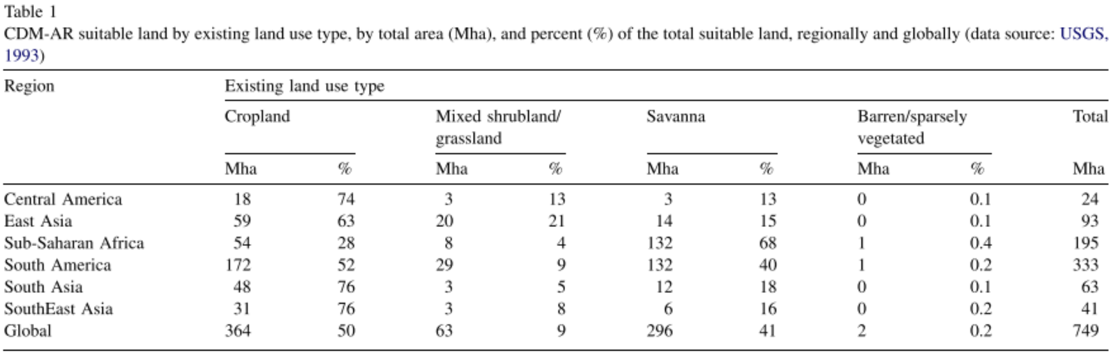


Table 1
CDM-AR suitable land by existing land use type, by total area (Mha), and percent (%) of the total suitable land, regionally and globally (data source: USGS, 1993)

Region	Existing land use type								
	Cropland		Mixed shrubland/ grassland		Savanna		Barren/sparsely vegetated		Total
	Mha	%	Mha	%	Mha	%	Mha	%	Mha
Central America	18	74	3	13	3	13	0	0.1	24
East Asia	59	63	20	21	14	15	0	0.1	93
Sub-Saharan Africa	54	28	8	4	132	68	1	0.4	195
South America	172	52	29	9	132	40	1	0.2	333
South Asia	48	76	3	5	12	18	0	0.1	63
SouthEast Asia	31	76	3	8	6	16	0	0.2	41
Global	364	50	63	9	296	41	2	0.2	749

Figure 11. Afforestation/Plantations land sources (Zomer et al., 2008).

The identified suitable lands fall into low to moderate productivity categories, 25% of them are affected by some degree of degradation. Moderately degraded lands have greatly reduced productivity, they require major improvements often the ability of local farmers. Severely degraded lands are those considered essentially beyond remediation without major engineering work (Oldeman et al., 1991 as cited in Zomer et al., 2008).

- In East Asia 45% of the suitable lands may have some degree of degradation.
- In Africa and South America as well, much of the land in degraded categories is savannah and grasslands, reflecting the role of livestock and grazing in land degradation processes.

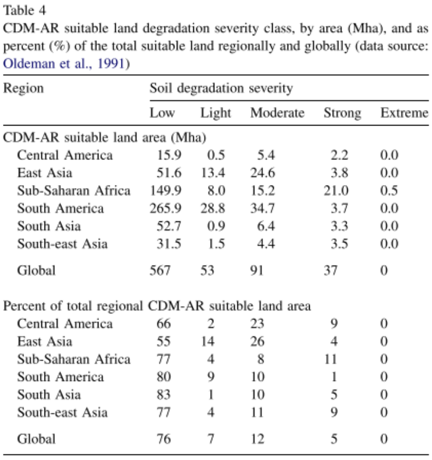


Table 4
CDM-AR suitable land degradation severity class, by area (Mha), and as percent (%) of the total suitable land regionally and globally (data source: Oldeman et al., 1991)

Region	Soil degradation severity				
	Low	Light	Moderate	Strong	Extreme
CDM-AR suitable land area (Mha)					
Central America	15.9	0.5	5.4	2.2	0.0
East Asia	51.6	13.4	24.6	3.8	0.0
Sub-Saharan Africa	149.9	8.0	15.2	21.0	0.5
South America	265.9	28.8	34.7	3.7	0.0
South Asia	52.7	0.9	6.4	3.3	0.0
South-east Asia	31.5	1.5	4.4	3.5	0.0
Global	567	53	91	37	0
Percent of total regional CDM-AR suitable land area					
Central America	66	2	23	9	0
East Asia	55	14	26	4	0
Sub-Saharan Africa	77	4	8	11	0
South America	80	9	10	1	0
South Asia	83	1	10	5	0
South-east Asia	77	4	11	9	0
Global	76	7	12	5	0

Figure 12. % of suitable land that is degraded (Oldeman et al., 1991 as cited in Zomer et al., 2008)

1.4.2. Plantations

This subject was also mentioned in Section 1.3.3. (Gibbs et al., 2019).

The previous study (Zommer et al., 2008, Section 1.4.1.b) also reviewed the potential suitable land for industrial plantations. Nevertheless, it excluded forest area as potential area for further forest expansions and, according to FAO (FAO, 2001 as cited in Gerber, 2011), tree plantations accounts for about 7% of the global tropical forest losses. Ghazoul (Ghazoul, 2013) found that conversion of natural forest to tree plantations has occurred, although currently such practice is depreciated and less common.

Nevertheless, it has also been stated that much of the deceleration in the rate of net forest loss is due to the rapid expansion of planted forests (FAO, 2010 as cited in Heilmayr, 2014). Plantation forests compete for land with natural forests, but they can also ease demand for forest products from natural forests (Heilmayr, 2014). Heilmayr demonstrated that forest expansion (plantation) has been accompanied by a contraction of natural forests dedicated to timber extraction (what we call managed forests), but an expansion of unharvested natural forests (what we call primary forests). Plantations reduce the extent of natural forests through two mechanisms: (1) by directly displacing forest through land competition; (2) reducing the value of timber from natural forests, which eliminated eliminate an incentive for harvesting. Second effect may reduce the extent of managed forests, but it also reduces harvest pressure on natural forests.

Profitable plantations risk undermining the value of natural forest which may accelerate their conversion of these to plantations in the future (Ghazoul, 2013). However, plantations should be to locate plantations on already cut-over, abandoned, or degraded land, in order to help deflect pressure away from natural forest (Ghazoul, 2013).

1.4.2.a. Chile (Nahuelhual et al., 2012)

Summary in Figure 13
Between 1995 and 2009 Chile showed one of the highest annual rates of afforestation (49.020 ha) and reforestation (53.610 ha) in South America (FAO, 2010 as cited in Nahuelhual et al., 2012). The area of plantations went from 29.213 ha in 1975 (5.5% of the landscape) to 95.049 ha in 1990 (17.9%) and 224.716 ha in 2007 (42.4%).

Five land categories where considered: (i) agricultural land, APL, accounting for croplands and pastures; (ii) shrubland, SH, land where trees cover less than 10% and shrubs cover between 10% and 75% of the area; (iii) arboreous shrubland, ASH, land where tree species cover between 10% and 25% and shrub species, between 75% and 90%; (iv) native forest, NF, land where tree crowns cover over 25% and in most cases over 50%; (v) plantations, PL. And the possible drivers reviewed were: (i) biophysical factors (e.g. yield potential of land and costs of farming compared to planting); (ii) accessibility factors; (iii) farm related factors (e.g. farm structure, property).

During the period **1975–1990**, 41.5% of the plantation net gains came from native forests and 32% from arboreous shrublands. In the period **1990–2007** the main contributor was shrubland (41.1%), followed by arboreous shrubland (28.4%) and native forests (22.8%). During both periods agricultural land accounted just a small part, 5.9% and 7.3%, respectively.

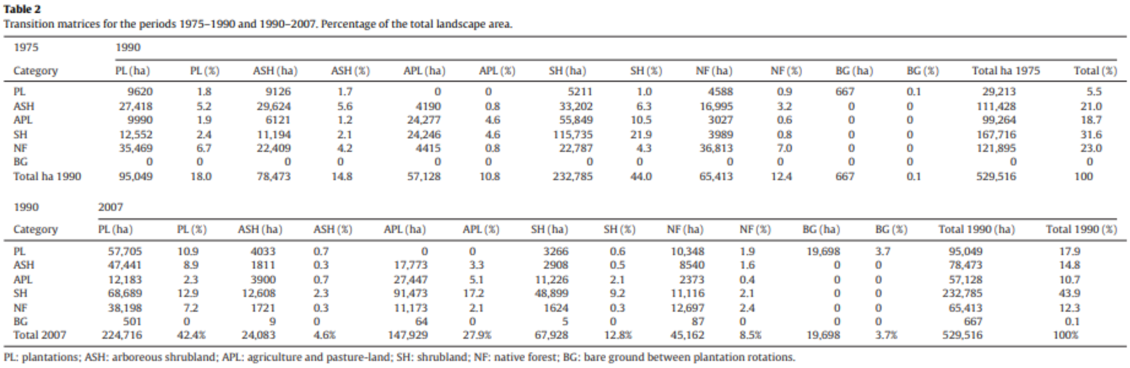


Table 2
Transition matrices for the periods 1975–1990 and 1990–2007. Percentage of the total landscape area.

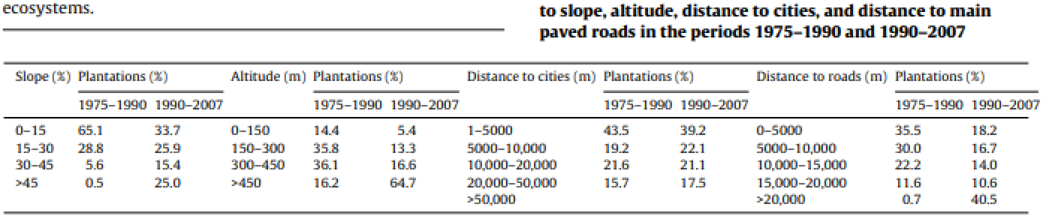
1975	1990													
Category	PL (ha)	PL (%)	ASH (ha)	ASH (%)	APL (ha)	APL (%)	SH (ha)	SH (%)	NF (ha)	NF (%)	BG (ha)	BG (%)	Total ha 1975	Total (%)
PL	9620	1.8	9126	1.7	0	0	5211	1.0	4588	0.9	667	0.1	29,213	5.5
ASH	27,418	5.2	29,624	5.6	4190	0.8	33,202	6.3	16,995	3.2	0	0	111,428	21.0
APL	9990	1.9	6121	1.2	24,277	4.6	55,849	10.5	3027	0.6	0	0	99,264	18.7
SH	12,552	2.4	11,194	2.1	24,246	4.6	115,735	21.9	3989	0.8	0	0	167,716	31.6
NF	35,469	6.7	22,409	4.2	4415	0.8	22,787	4.3	36,813	7.0	0	0	121,895	23.0
BG	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total ha 1990	95,049	18.0	78,473	14.8	57,128	10.8	232,785	44.0	65,413	12.4	667	0.1	529,516	100

1990	2007													
Category	PL (ha)	PL (%)	ASH (ha)	ASH (%)	APL (ha)	APL (%)	SH (ha)	SH (%)	NF (ha)	NF (%)	BG (ha)	BG (%)	Total 1990 (ha)	Total 1990 (%)
PL	57,705	10.9	4033	0.7	0	0	3266	0.6	10,348	1.9	19,698	3.7	95,049	17.9
ASH	47,441	8.9	1811	0.3	17,773	3.3	2908	0.5	8540	1.6	0	0	78,473	14.8
APL	12,183	2.3	3900	0.7	27,447	5.1	11,226	2.1	2373	0.4	0	0	57,128	10.7
SH	68,689	12.9	12,608	2.3	91,473	17.2	48,899	9.2	11,116	2.1	0	0	232,785	43.9
NF	38,198	7.2	1721	0.3	11,173	2.1	1624	0.3	12,697	2.4	0	0	65,413	12.3
BG	501	0	9	0	64	0	5	0	87	0	0	0	667	0.1
Total 2007	224,716	42.4%	24,083	4.6%	147,929	27.9%	67,928	12.8%	45,162	8.5%	19,698	3.7%	529,516	100%

PL: plantations; ASH: arboreous shrubland; APL: agriculture and pasture-land; SH: shrubland; NF: native forest; BG: bare ground between plantation rotations.

Figure 13. Transition matrix for Chile 1975-1990 and 1990-2007 (Nahuelhual et al., 2012).

It is reported that between **1975-1990** plantations were more likely to expand on located at higher slopes (65.1% of the new plantations were established on slopes between 0% and 15%). In the period **1990-2015** plantations continued to expand at higher elevation, but they also began to establish on soils suitable for cropland and pasture (Figure 14).
Between **1975-1990** 43.5% of plantations were established near cities, while between **1990-2007** this was no longer a significant predictor (40.5% of new plantations were established more than 20 km farther from a road) (Figure 14).
This reveals than between 1975-1990 plantations expanded based on drivers such as steep slopes, proximity to main cities or large farms, while between 1990 and 2007 they expanded in all directions. However, in both periods the major expansion took place on natural areas, native forests, arboreous shrublands and shrublands. A literature review made by the author demonstrate than this phenomenon has also take place in countries like Indonesia, Australia, Spain and New Zealand. Finally he stated that the areas more vulnerable for further expansion are those located in marginal soils for agriculture.



human activities and the critical status of different species and ecosystems.

Appendix A. Distribution of new plantations (%) in relation to slope, altitude, distance to cities, and distance to main paved roads in the periods 1975–1990 and 1990–2007

Slope (%)	Plantations (%)		Altitude (m)	Plantations (%)		Distance to cities (m)	Plantations (%)		Distance to roads (m)	Plantations (%)	
	1975–1990	1990–2007		1975–1990	1990–2007		1975–1990	1990–2007		1975–1990	1990–2007
0–15	65.1	33.7	0–150	14.4	5.4	1–5000	43.5	39.2	0–5000	35.5	18.2
15–30	28.8	25.9	150–300	35.8	13.3	5000–10,000	19.2	22.1	5000–10,000	30.0	16.7
30–45	5.6	15.4	300–450	36.1	16.6	10,000–20,000	21.6	21.1	10,000–15,000	22.2	14.0
>45	0.5	25.0	>450	16.2	64.7	20,000–50,000	15.7	17.5	15,000–20,000	11.6	10.6
						>50,000			>20,000	0.7	40.5

Figure 14. Factors that affects plantation establishment, Chile (Nahuelhual et al., 2012).

1.4.2.b. Borneo (Gaveau et al., 2016)

It was studied to what extent plantations are located in areas where they replace natural forests or in areas already lacking such forests in Borneo. It is estimated that at least 56% (1.7 Mha) of Indonesia's new large-scale industrial plantations (oil-palm and pulpwood) replaced forests between 1990-2015. It is considered whether forest was rapidly converted to plantations, it was deforested and in less than five years a plantation was established (plantation is responsible of the clearance), or, if the period is higher to 5 years, it is considered that the area was deforested for other purposes (e.g, logging) and years later it was used to establish a plantation.

Approximately 7.0 Mha (76%) of the total area of industrial plantations in 2015 (9.2 Mha), were old-growth forest in 1973. Plantations expanded by 9.1 Mha (7.8 Mha oil-palm; 1.3 Mha pulpwood) between 1973 and 2015. They reached 9.2 Mha in 2015, 12% of Borneo's land area. More than half of the (4.8 Mha) were planted between 2005 and 2015 in Indonesian Borneo. In contrast, plantation expansion in Malaysian Borneo has been relatively constant over time. Industrial plantations covered only 2.625 ha in Brunei Darussalam in 2015.

- **Rapid conversions** represent 24-26% of all post-1973 deforestation in Borneo. For Indonesian Borneo it is 15-16% and for Malaysian Borneo 57-60%. From 2005 to 2015 2.2 Mha were rapidly converted across Borneo. In Indonesian Borneo rapid conversion increased from 7% in 1973–2000 to 51% in 2010–2015. In Malaysian Borneo, this share has always surpassed 52%, peaking at 68% in 2005–2010.
- Conversely, 3.7 Mha (41%) of plantations developed between 1973 and 2015 (9.1 Mha) were established on land that had lacked forest for more than five years. In Indonesian Borneo the figure was of 1.8 Mha (55%) of oil-palm plantations added since 2005 (3.3 Mha). In Malaysian Borneo it was of less than 26%.

The study suggests that the plantation industry was the principle driver of deforestation loss of forest in Malaysian Borneo (57–60% rapid conversion), while in Indonesian Borneo (15–16%) plantations were developed on lands cleared before 1973 and on degraded lands.

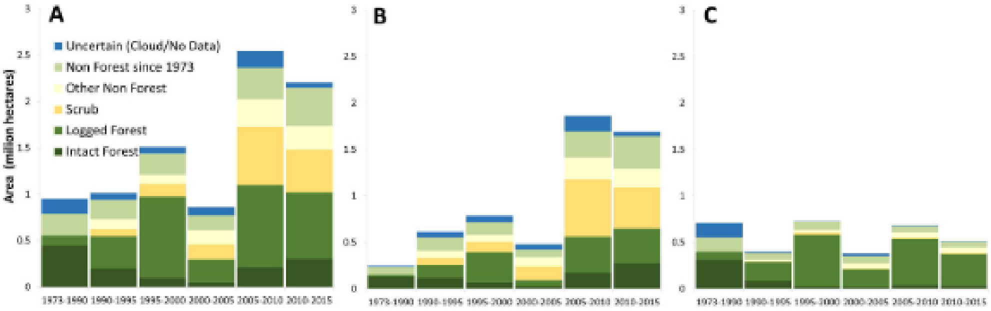


Figure 3. The expanding area (9.1 Mha) of industrial plantations (oil-palm and pulpwood) in six time periods from 1973 to 2015 with vegetation cover of the land just before observed conversion to plantations in Borneo (**A**), Indonesian Borneo (**B**), and Malaysian Borneo (**C**). Intact Forest: pristine old-growth forests. Logged Forest: old-growth forests that have lost their original structure and canopy cover through industrial-scale selective timber harvest at some point since 1973, indicated principally by the construction of logging roads. Scrub: old-growth forests impacted by drought and fire; these burn/drought scars tend to recover slowly. They are vulnerable to further burning and conversion to short vegetation follows; hence they appear as "deforested" in satellite assessments (see also methods). Non Forest since 1973: areas that have been cleared before 1973. Other Non-Forest: areas that have been cleared after 1973, but not converted to scrubs. We recognize that Non Forest since 1973 and Other Non-Forest may include secondary forests: young-growth, forest fallow or agro-forest.

Figure 15. Land sources of new plantations, Borneo (Gaveau et al., 2016).

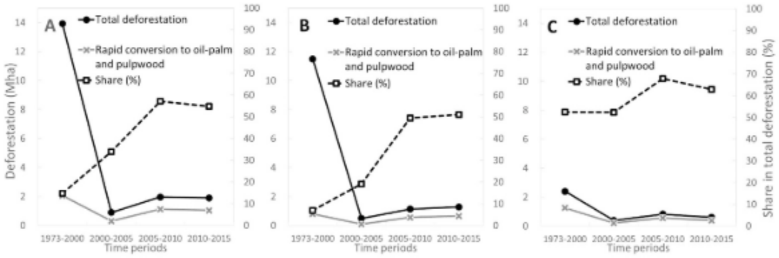


Figure 4. Role of industrial plantations (oil-palm and pulpwood) in deforestation by period for Borneo (**A**), Indonesian Borneo (**B**) and Malaysian Borneo (**C**). On the primary axis (left Y axis), the grey solid line indicates the area of forest rapidly converted to industrial plantations (i.e. within five years of clearance), while the black solid line indicates the total area of deforestation by time period on Borneo (see also Fig. 1A). On the secondary axis (right Y axis), the dashed line represents the share of rapid conversion in total deforestation, expressed in percentage terms.

Figure 16. % of deforestation for plantations, Borneo (Gaveau et al., 2016)

1.5. Deforestation displaced (Pendrill et al., 2019)

Pendrill et al. carried a study about deforestation trends. It takes into consideration 156 primarily tropical and subtropical countries, excluding those with less than 5% of forest cover and the classification mentioned by Hosonuma et al. was used (Section 1.3.1. Hosonuma et al., 2012). The study focuses on agricultural expansion, thus it does not consider as deforestation drives mining, expansion of urban settlements nor infrastructure, since its contribution to deforestation is in most instances small, being their major impact being indirect (Pendrill et al., 2019).

In total, between 2005 and 2013, the studied attributed an average of 5.5 Mha/year of forest loss in the tropics and sub-tropics (62% of the total) was caused by expansion of the agricultural and forestry land. The remaining 3.4 Mha/year (38%) loss is likely due to a mix of causes, primarily logging and natural causes (e.g. forest fires) (Kastner T. et al., 2014 as cited in Pendrill et al., 2019). The deforestation attributed to expanding cropland, pastures and tree plantations is heavily dominated by a handful of countries: Brazil and Indonesia together accounted for almost half (44%), followed by Argentina (7%) and Paraguay (4%). All remaining countries account for less than 3% each. In Latin America, cattle meat accounted for more than 60% of the deforestation, whereas in Asia-Pacific palm oil and forestry products caused around a third of the total deforestation. In Africa, cattle meat causes just over 25%, while the remainder was due to a diverse mix of other cereals, roots and tubers, pulses and other oil- seeds.

While deforestation was mainly driven by domestic demand, in total 26% of the embodied deforestation was exported. The share of exported deforestation was greater for crops (40%), while just 11% of cattle meat was exported.

- For the **early-transition** countries, 33% of the deforestation was exported, but most of those exports (0.5 out of 0.6 Mha/year) were originated from just two countries: Indonesia exported 48% of the total exported deforestation and Paraguay, with 65%. In the rest of early-transition countries deforestation was mainly for domestic uses.
- In **late- and post-transition** countries, around 25% of the deforestation was exported. However there the percentage vary hugely among countries (between 0% and 78% for late-transition countries, and between 0% and 90% for post-transition countries).
- For the **pre-transition** countries, only Papua New Guinea (with 24%–50% range between years), exported more than 35% of its embodied deforestation.

The vast majority (79%) of the exported deforestation is consumed in post-transition countries. Late-transition countries consumed another 8%. The largest export flows went from early- and late-transition countries to post-transition countries, plus the exported deforestation from pre-transition was primarily consumed in post-transition countries in Europe. 10 countries account for half of the imports, 8 of them being post-transition mainly located in Europe and Asia-Pacific. China, India, Russia and the US together accounted for about a third of the total imports.

Since post-transition countries consume most of the exported deforestation the forest's gains in these countries have been partly offset by deforestation elsewhere, in fact, in some countries the imported deforestation exceed the reforested area.

- For all post-transition countries, 30% of the net reforestation gains were offset by imports.
- For the 20 late-transition countries where the forest cover decreased in the period 2005-2014, 10 increased their imports (24% offset of reduced deforestation) and 10 decreased them (11% offset). Among those in the first group a few of countries imported more deforested area than its reduction of deforested area.

The trend in post-transition countries suggests that, in many cases, reforestation projects have in part been enabled by not only importing land demanding products from abroad, but also by displacing some of the deforestation, and its impacts, to other countries.

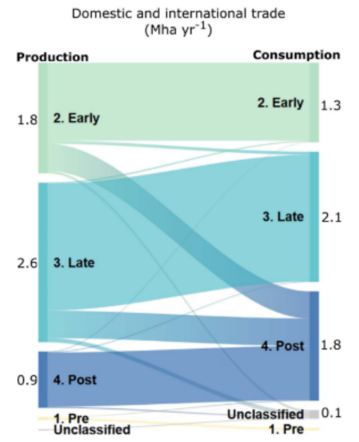


Figure 5. Trade flows of deforestation embodied in domestic consumption and international trade aggregated by forest transition stage. The left-hand side shows the area of deforestation embodied in production, while the right hand side shows the deforestation embodied in consumption. While most deforestation was embodied in production of agricultural and forestry commodities in early- and late-transition countries, most (79%) of deforestation embodied in export was consumed in post-transition countries. Unclassified countries consumed 9% of deforestation attributed to export.

Figure 17. Forest trade (Pendrill et al., 2019)

1.6. Forest and other aspects

1.6.1. Forest intactness

In a study of forest intactness and fragmentation carried in (FAO and UNEP., 2020) it was found that the most intacted forest area is located tropical rainforest and boreal coniferous forest, the ecological zones with the biggest forest area. These ecosystems are characterized by difficulties of access and low population density.

- The **least fragmented forest** are in the tropical rainforests (Amazon and Congo basins) and in the boreal coniferous forests (Canada and the Russian Federation). In te boreal-zone fragmentation is mainly linked to natural disturbances, such as wild-fires (Walker et al., 2019 as cited in FAO and UNEP., 2020). Mountain systems in boreal, temperate and tropical climates, biomes with limited accessibility and low population density, are also less fragmented than average.
- The **most fragmented areas** are found in tropical shrubland, subtropical steppe, subtropical dry forest and temperate oceanic forest (areas where less than a 33% of their area is forest) and boreal tundra woodland, tropical dry forest and tropical moist forest (where more than 40% of their area is forest). In the boreal tundra woodlands defradation is primarily a consequence of natural disturbances (climate, wildfire), while in tropical dry and moist forests the main cause is land-use dynamics.

1.6.2. Effect of fires (FAO and UNEP., 2020)

A global analysis of forest area affected by fire between 2003 and 2012 identified approximately 67 million ha/year being burned (van Lierop et al., 2015 as cited in FAO and UNEP., 2020). In 2015, around 98 million ha of forest were affected by fires. These fires occurred mainly in the tropics, where they affected to 4% of the forest area. Over 66% of the burned area was in South America and Africa. The effect of fires can also be seen in Figure 6 (Section 1.3.1 Hosonuma et al., 2012).
About 90% of fires are readily contained and account for 10% or less of the total area burned. The remaining 10% accounts for the 90% of the burned area. In the future, climate change is expected to bring longer fire seasons and more-severe fires over much of the globe, including some areas where fire has not previously been a common problem (FAO and UNEP., 2020).

1.6.3. Forest and Protected Areas

Creation of protected areas has historically been the forest governance instrument to enhance biodiversity conservation. However, it has been seen that natural reserves alone are not sufficient to conserve biodiversity since they are usually too small and they still are vulnerable to exogenous factors such as climate change (Fung et al., 2017 as cited in FAO and UNEP., 2020).

Globally, 18% of the world's forest area, more than 700 million ha, is reported to fall within legally established protected areas. The largest share of forest in protected areas is found in South America (31%) and the lowest in Europe (5%) (FAO and UNEP., 2020). Oceania reported a large increase in forest protection during the past 10 years, going from almost zero protection in 1990 to 15% in 2015. North America, Caribbean, East and Southern Africa, showed a more modest growth in forest protection. Other areas with small protected area are West and Central Asia (5.6%) and North America (8.6%) (Morales-Hidalgo et al., 2015). More about land and land types under protected areas can be seen in Figure A6b.

According to FRA 2020, since 1990 the area of forest within protected area s has increased by at least 191 million ha, but the rate has slowed during the past decade.

- In tropical rainforest, subtropical dry forest and temperate oceanic forest more than 30% of the tree cover is now in legally protected areas. Interestingly, despite having the highest rates of forest cover loss, the tropical rainforest experienced the highest levels of growth in tree cover in protected areas. In 2015, temperate oceanic forest (Europe, Chile and parts of Oceania) had the greatest percentage of forest in protected areas.
- In subtropical humid forest, temperate steppe and boreal coniferous forest less than 10% of the tree cover is in protected areas. Areas having such a low proportion of forest in protected areas are mostly at higher latitudes.

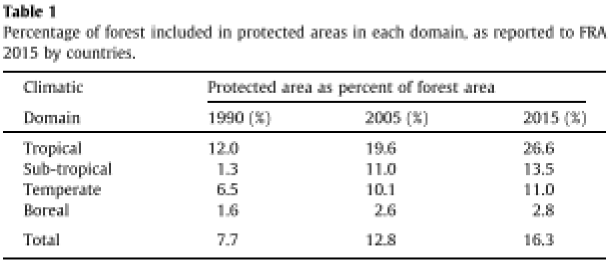


Table 1

Percentage of forest included in protected areas in each domain, as reported to FRA 2015 by countries.

Climatic	Protected area as percent of forest area		
Domain	1990 (%)	2005 (%)	2015 (%)
Tropical	12.0	19.6	26.6
Sub-tropical	1.3	11.0	13.5
Temperate	6.5	10.1	11.0
Boreal	1.6	2.6	2.8
Total	7.7	12.8	16.3

Figure 18. Forest under protected areas (Morales-Hidalgo et al., 2015).

Morales-Hidalgo et al. found in their analysis that increases in protected areas within countries are associated with increases in forest area but the effect is not large. Many protected forest areas are specifically situated in areas that are unsuitable for other use by humans (Millennium Ecosystem Assessment, 2005 as cited in Morales-Hidalgo et al., 2015). Some studies reviewed by Morales-Hidalgo et al. similarly reported that protected areas may not be successful at preventing deforestation (Andam et al., 2008; Nagendra, 2008; DeFries et al., 2005 as cited in Morales-Hidalgo et al., 2015).

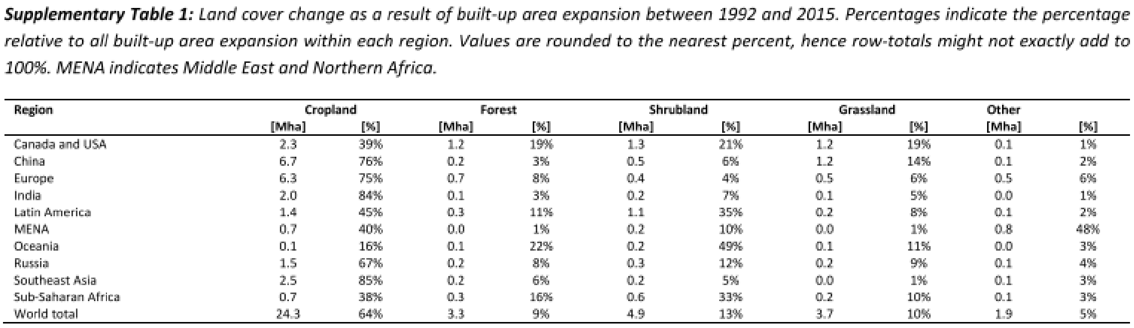
2. URBAN LAND

Contrary to cropland expansion, identified as the main driver of natural loss, urban development is only associated with a small fraction of all forest losses (Curtis, P. G. et al., 2018; Geist, H. J. &

Lambien, E. E., 2002 as cited in van Vliet, 2019). Nevertheless, as urban expansion often takes place in cropland areas and cropland expansion takes place on natural area, cropland displacement relates urban expansion and natural area losses elsewhere. In the study natural area refers to forest, shrubland and grassland, due to impossibility natural grasslands and pastures are not differenced. Van Vliet studied the direct changes refered to natural area converted to urban land and the indirect changes refered to natural area converted into cropland to compensate the expansion of urban land into cropland between 1992 and 2015 (van Vliet, 2019).

The study is based on data from the European Space Agency's Climate Change Initiative (ESA CCI). 38.0 Mha of **new urban** land appeared globally between 1992 and 2015, a 115% increase. About 64% of it took place on former cropland, while 9% came (directly) from forests, 13% from shrublands and 10% from grassland. The remaining 5% came from other land (mainly bare land) (Figure 19).

- Regionally: More than 75% of the urban expansion in Southeast Asia, India, China and Europe took place on former cropland, whereas in Oceania, Sub-Saharan Africa and Middle East and Northern Africa (MENA) was 40% or less.



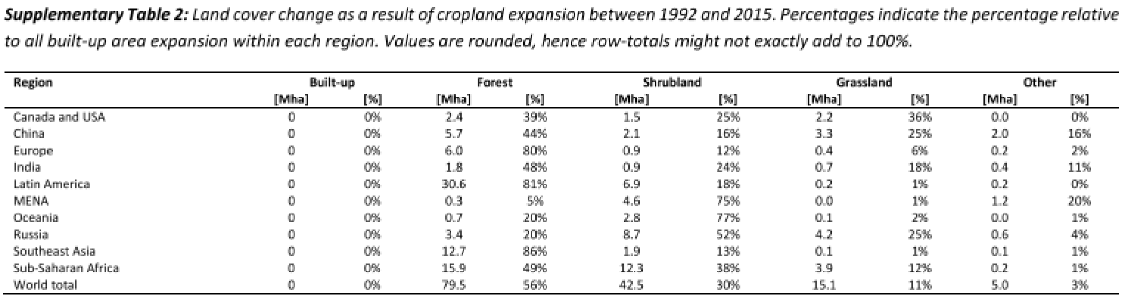
Supplementary Table 1: *Land cover change as a result of built-up area expansion between 1992 and 2015. Percentages indicate the percentage relative to all built-up area expansion within each region. Values are rounded to the nearest percent, hence row-totals might not exactly add to 100%. MENA indicates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

Figure 19. New urban land direct sources (van Vliet, 2019)

New cropland mostly led to a conversion of forest (56%) and shrubland (30%), another 11% came from grassland and 3% from other land (Figure 20).

- Regionally: Cropland expansion in Southeast Asia and Latin America mainly led to forest loss, but in Oceania and MENA mainly led to shrubland loss. In some regions, notably China, Russia, Central Asia and Sub-Saharan Africa, there was a considerable amount of grassland that converted into cropland.



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%

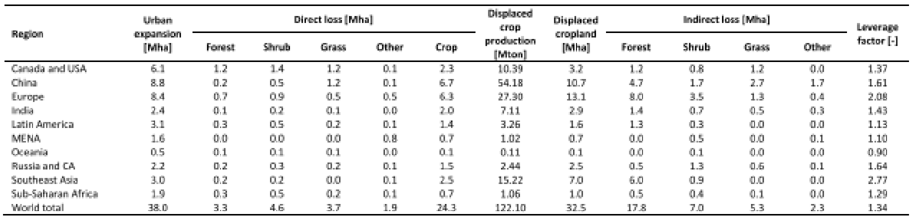
Figure 20. New cropland direct sources (van Vliet, 2019)

The amount of cropland needed to compensate the losses caused by urban expansion depend on where the new croplands were developed due to the difference on land productivity between regions. To study this difference the author uses the "leverage factor" defined as the ratio between the productivity of cropland converted into urban land and the productivity of new cropland. If it is greater than 1 indicates that the cropland converted into urban land had a higher productivity than the displaced cropland, therefore, the area of new cropland required to compensate the loss was greater than the amount of cropland replaced. Conversely, of it is smaller than 1 it indicates that the cropland converted into urban land had a lower productivity than the new and displaced cropland, which means that less area is needed. Two scenarios are studied: (1) cropland is displaced within the same world region; (2) cropland is displaced across all regions.

- Under the within the same region assumption the leverage factor was 1.34, which means that an area of new cropland 34% bigger than the area of replaced croplands was required to compensate the loss (Figure 21).
- Under the across regions assumption the leverage factor was 2.39. On regional level, the leverage factor of 2.06 of Europe, for example, means that that average productivity of cropland converted into urban land in Europe is 106% higher than the average productivity of all new croplands, globally (Figure 21).

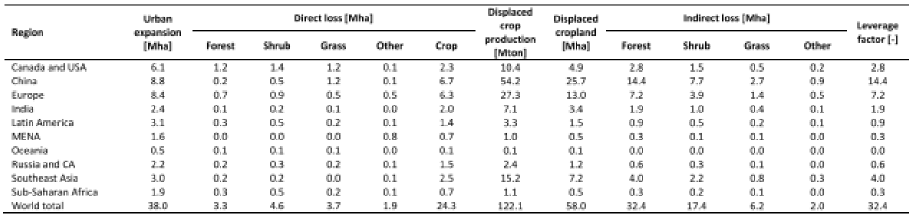
Globally, cropland displacement across all world regions led to a higher leverage factor and thus to a greater indirect loss of forest and shrubland than within world regions. The difference was caused by a large amount of urban expansion in regions with relatively high cropland productivity, such as China, Canada and the United States, in combination with a large amount of cropland expansion in regions with relatively low average productivity, such as Sub-Saharan Africa and Latin America.

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.*



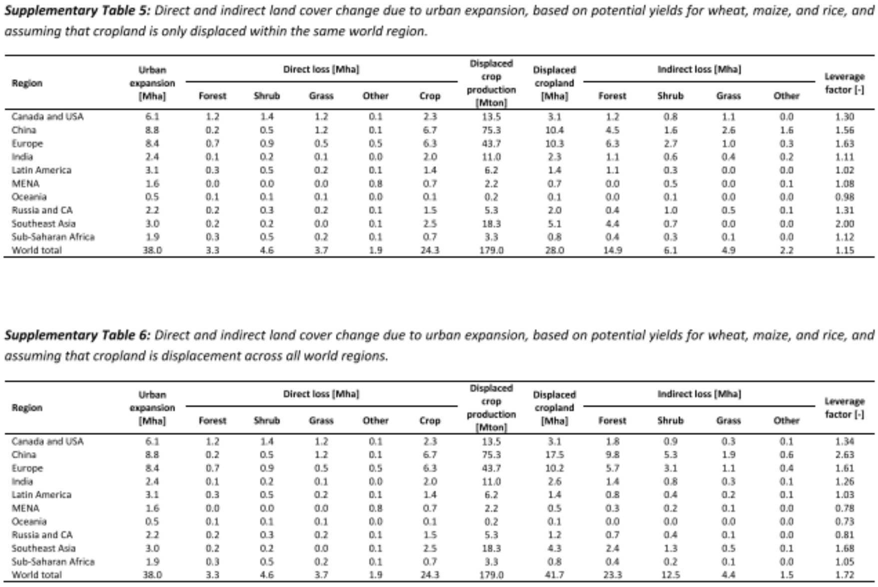
Region	Urban expansion [Mha]	Direct loss [Mha]					Displaced crop production [Mton]	Displaced cropland [Mha]	Indirect loss [Mha]				Leverage factor [-]
		Forest	Shrub	Grass	Other	Crop			Forest	Shrub	Grass	Other	
Canada and USA	6.1	1.2	1.4	1.2	0.1	2.3	10.4	4.9	2.8	1.5	0.5	0.2	2.8
China	8.8	0.2	0.5	1.2	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

Figure 21. Direct and indirect land cover changes due to urban expansion, within and across regions, actual yields (van Vliet, 2019).

The impact of land use management was also studied by comparing the results obtained with actual and potential yields. It was found that with potential[11] yields the leverage factor decreased: to 1.15 under within regions assumption (1.34 with actual yields) and to 1.74 under the across regions assumption (2.39 with actual yields) (Figure 22).

---

[11] Potential yields defined as the attainable yield after water and nutrient deficiencies have been removed. It serves as a way to separate the impact of land management from the inherent biophysical suitability of locations to produce crops.



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

Figure 22. Direct and indirect land cover changes due to urban expansion, within and across regions, actual yields (van Vliet, 2019).

The results show indirect losses of forest and shrubland due to urban expansion are much greater than direct losses. Considering that it also leads to a conversion of grasslands (no difference between natural grassland and pastures) it is expected that urban expansion causes pastureland displacement which would cause more indirect losses as pastures have to be replaced.

Seto et al. carried a study of the amount of land likely to suffer from urban conversion before 2030 (Seto et al., 2012). They found that, globally, more than 5.87 million km2 of land have a positive probability (>0%) of being converted to urban areas by 2030, and 20% of this (1.2 million km2) have high probabilities (>75%) (Figure 23). If all areas with high probability (>75%) undergo urban land conversion, there will be a 185%. Nearly 50% is forecasted to occur in Asia, with China and India absorbing 55%. The highest increase of urban land is expected in Africa, at 590% over the 2000 levels. 48 of the 221 countries in the study will experience negligible amounts of urban expansion.
However, the highest rates of growth in urban area are forecasted to take place in regions that were relatively undisturbed by urban development circa 2000.

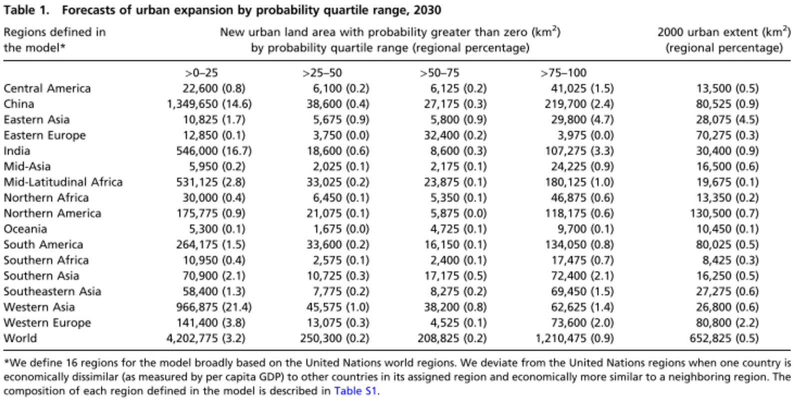


Table 1. Forecasts of urban expansion by probability quartile range, 2030

Regions defined in the model*	New urban land area with probability greater than zero (km^2) by probability quartile range (regional percentage)				2000 urban extent (km^2) (regional percentage)
	>0–25	>25–50	>50–75	>75–100	
Central America	22,600 (0.8)	6,100 (0.2)	6,125 (0.2)	41,025 (1.5)	13,500 (0.5)
China	1,349,650 (14.6)	38,600 (0.4)	27,175 (0.3)	219,700 (2.4)	80,525 (0.9)
Eastern Asia	10,825 (1.7)	5,675 (0.9)	5,800 (0.9)	29,800 (4.7)	28,075 (4.5)
Eastern Europe	12,850 (0.1)	3,750 (0.0)	32,400 (0.2)	3,975 (0.0)	70,275 (0.3)
India	546,000 (16.7)	18,600 (0.6)	8,600 (0.3)	107,275 (3.3)	30,400 (0.9)
Mid-Asia	5,950 (0.2)	2,025 (0.1)	2,175 (0.1)	24,225 (0.9)	16,500 (0.6)
Mid-Latitudinal Africa	531,125 (2.8)	33,025 (0.2)	23,875 (0.1)	180,125 (1.0)	19,675 (0.1)
Northern Africa	30,000 (0.4)	6,450 (0.1)	5,350 (0.1)	46,875 (0.6)	13,350 (0.2)
Northern America	175,775 (0.9)	21,075 (0.1)	5,875 (0.0)	118,175 (0.6)	130,500 (0.7)
Oceania	5,300 (0.1)	1,675 (0.0)	4,725 (0.1)	9,700 (0.1)	10,450 (0.1)
South America	264,175 (1.5)	33,600 (0.2)	16,150 (0.1)	134,050 (0.8)	80,025 (0.5)
Southern Africa	10,950 (0.4)	2,575 (0.1)	2,400 (0.1)	17,475 (0.7)	8,425 (0.3)
Southern Asia	70,900 (2.1)	10,725 (0.3)	17,175 (0.5)	72,400 (2.1)	16,250 (0.5)
Southeastern Asia	58,400 (1.3)	7,775 (0.2)	8,275 (0.2)	69,450 (1.5)	27,275 (0.6)
Western Asia	966,875 (21.4)	45,575 (1.0)	38,200 (0.8)	62,625 (1.4)	26,800 (0.6)
Western Europe	141,400 (3.8)	13,075 (0.3)	4,525 (0.1)	73,600 (2.0)	80,800 (2.2)
World	4,202,775 (3.2)	250,300 (0.2)	208,825 (0.2)	1,210,475 (0.9)	652,825 (0.5)

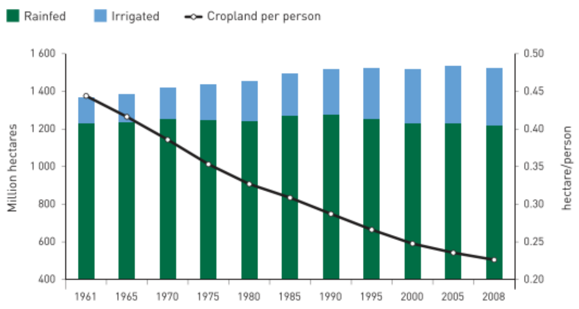
*We define 16 regions for the model broadly based on the United Nations world regions. We deviate from the United Nations regions when one country is economically dissimilar (as measured by per capita GDP) to other countries in its assigned region and economically more similar to a neighboring region. The composition of each region defined in the model is described in Table S1.

Figure 23. Probability of urban expansion by region (Seto et al., 2012).

Land conversions caused by urban expansion by country Figure A6c.

3. AGRICULTURE LAND

The world's net cultivated area has grown by 12% over the last 50 years, mostly at the expense of forest, wetland and grassland. At the same time, the global irrigated area has doubled and, in fact, all this increase in cultivated area is attributable to an increase in irrigated cropping. On the other hand, rainfed systems have shown a very slight decline. The scope for further expansion of cultivated land is limited. Only parts of South America and sub-Saharan Africa still offer scope for some expansion (United Nations, 2016).



Source: FAO (2010b)

Figure 24. Rainfed and Irrigated cropland evolution (FAO, 2010b as cited in United Nations, 2016)

3.1. Rainfed croplands

Rainfed agriculture is the predominant agricultural production system worldwide, it accounts for 80% (1.300 Mha) of the world cultivated area (1.600 Mha) and it produces 60% of the global crop output. It is also the system in which small-holders predominate (highland and dry and humid tropics).

- The most productive systems are concentrated in temperate zones of Europe, followed by those in North America and rainfed systems in the subtropics and humid tropics.
- Conversely, rainfed cropping in highland areas and the dry tropics tends to be relatively low yielding, often associated with subsistence farming systems. Their poverty makes the risks of degradation higher.

In Sub-Saharan Africa 97% of rainfed croplands and its cultivated cereals area has doubled since 1960. In Latin America and the Caribbean, rainfed cultivation has expanded by 25% in the last 40 years (FAO, 2010b as cited in United Nations, 2016).

The extent of rainfed area has not grown in recent years, but this masks the abandonment of some land too degraded and its replacement with new land from forests and grasslands. Rainfed production is highly dependent on rainfall, temperature and soil conditions.

3.2. Irrigated croplands

In recent decades irrigation has expanded what contributed greatly to the improvements in global agricultural productivity. In developing countries about 20% of the arable land is irrigated but it accounts for 47% of the crop production (60% of cereal's production). In the least developed countries just 17% of the harvested cereals area is irrigated but it produces 38% of the cereal. Irrigation systems typically have yields at least twice those of nearby rainfed crops.

However, most irrigated farming systems are performing well below their potential, and there is considerable scope for improvement.

About 70% of the world's area equipped for irrigation is in Asia, where it accounts for 39% of the cultivated area. South and East Asia account for over 50% of the world's area equipped for irrigation, with India and China alone accounting for 40% (62 Mha each). Most of this irrigation is large-scale, primarily for paddy rice production. Irrigation is also very important in Western Asia, 37% of the cultivated area. In Northern Africa it accounts for 23% of the cultivated area in sub-Saharan Africa, it is just the 3%.

Most irrigation expansion has taken place by conversion from rainfed agriculture. Part of irrigation, however, takes place on arid and hyper-arid (desert) land that is not suitable for rainfed agriculture. 40 Mha out of the 209 Mha of irrigated croplands in developing countries are located on arid and hyper-arid land, which could increase to 43 Mha in 2050. 19 out of 28 Mha in the Near East and Northern Africa and 15 out of 85 Mha in South Asia. Eastern Europe and the Russian Federation have seen large areas equipped for irrigation abandoned in the last two decades.

There are already very severe water shortages, in particular in Western, Central and South Asia, regions that use 50% or more of their water resources for irrigation and in Northern Africa, where withdrawals for irrigation exceed renewable resources due to groundwater overdraft and recycling.

The rate of expansion of land under irrigation is slowing substantially, FAO has projected that by 2050 the area equipped for irrigation will reach 318 Mha compared to tge 301 Mha in 2006 (6% increase at a 0.12%/year rate) (Figure 25). Most of the expansion of irrigated land will be made by converting land from rainfed croplands.

- **Sub-Saharan Africa and Latin America** are the two regions that have exploited the least of their potential area for irrigation. In sub-Saharan Africa there is technically ample scope for expansion.
- Conversely, **Northern Africa, West Asia, Central Asia**, and large parts of South Asia and East Asia have reached or are reaching their potential. FAO estimates that, among these regions, 8 countries have expanded beyond its potential, while 20 countries (including China) expanded to above 75% of their potential.
- Although the overall arable area in **China** is expected to decrease further, the irrigated area is projected to continue to expand through conversion of rainfed land.

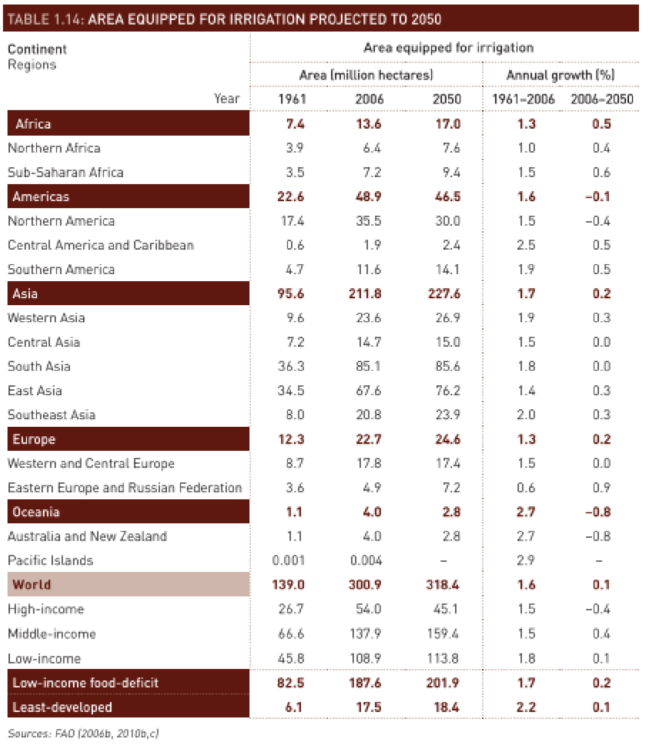


TABLE 1.14: AREA EQUIPPED FOR IRRIGATION PROJECTED TO 2050

Continent Regions	Area equipped for irrigation				
	Area (million hectares)			Annual growth (%)	
Year	1961	2006	2050	1961–2006	2006–2050
Africa	**7.4**	**13.6**	**17.0**	**1.3**	**0.5**
Northern Africa	3.9	6.4	7.6	1.0	0.4
Sub-Saharan Africa	3.5	7.2	9.4	1.5	0.6
Americas	**22.6**	**48.9**	**46.5**	**1.6**	**–0.1**
Northern America	17.4	35.5	30.0	1.5	–0.4
Central America and Caribbean	0.6	1.9	2.4	2.5	0.5
Southern America	4.7	11.6	14.1	1.9	0.5
Asia	**95.6**	**211.8**	**227.6**	**1.7**	**0.2**
Western Asia	9.6	23.6	26.9	1.9	0.3
Central Asia	7.2	14.7	15.0	1.5	0.0
South Asia	36.3	85.1	85.6	1.8	0.0
East Asia	34.5	67.6	76.2	1.4	0.3
Southeast Asia	8.0	20.8	23.9	2.0	0.3
Europe	**12.3**	**22.7**	**24.6**	**1.3**	**0.2**
Western and Central Europe	8.7	17.8	17.4	1.5	0.0
Eastern Europe and Russian Federation	3.6	4.9	7.2	0.6	0.9
Oceania	**1.1**	**4.0**	**2.8**	**2.7**	**–0.8**
Australia and New Zealand	1.1	4.0	2.8	2.7	–0.8
Pacific Islands	0.001	0.004	–	2.9	–
World	**139.0**	**300.9**	**318.4**	**1.6**	**0.1**
High-income	26.7	54.0	45.1	1.5	–0.4
Middle-income	66.6	137.9	159.4	1.5	0.4
Low-income	45.8	108.9	113.8	1.8	0.1
Low-income food-deficit	**82.5**	**187.6**	**201.9**	**1.7**	**0.2**
Least-developed	**6.1**	**17.5**	**18.4**	**2.2**	**0.1**

Sources: FAO (2006b, 2010b,c)

Figure 25. Irrigated expansion and expected expansion (FAO, 2006b as cited in United Nations, 2016).

Although irrigated agriculture is expected to produce most of the increased production needed in coming years, rainfed agriculture, will remain an important contributor to the world's food production.

3.3. Suitability for land cultivation (United Nations, 2016)

FAO defines land suitability for agriculture in terms of capacity to reach potentially attainable yields: (i) prime land is capable of producing 80% of potential attainable yields; (ii) good land main produce 40-80%; (iii) marginal/unsuitable land produces less than 40%. Assuming well-adapted production systems are used. Currently cultivated land is mostly of prime (28%) or good quality (53%). The highest proportion of prime land currently cultivated is found in Central America and the Caribbean (42% percent), Western and Central Europe (38%) and North America (37%).

There is a large area of currently uncultivated land that could, theoretically, be brought into production. However, much of this land is effectively not available, it is under other uses. In addition, it is generally of lower food potential than the existing cultivated land. A distribution of suitable land and its productivity by region it is shown in Figure A6c.

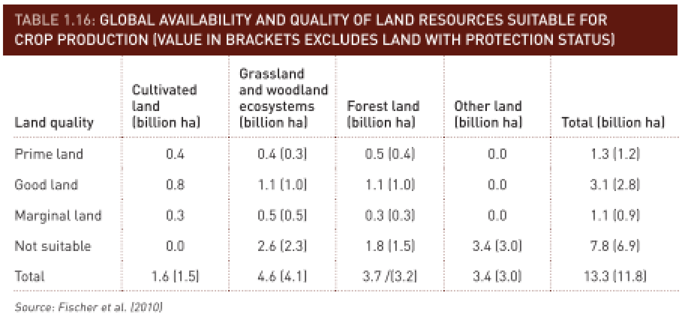


TABLE 1.16: GLOBAL AVAILABILITY AND QUALITY OF LAND RESOURCES SUITABLE FOR CROP PRODUCTION (VALUE IN BRACKETS EXCLUDES LAND WITH PROTECTION STATUS)

Land quality	Cultivated land (billion ha)	Grassland and woodland ecosystems (billion ha)	Forest land (billion ha)	Other land (billion ha)	Total (billion ha)
Prime land	0.4	0.4 (0.3)	0.5 (0.4)	0.0	1.3 (1.2)
Good land	0.8	1.1 (1.0)	1.1 (1.0)	0.0	3.1 (2.8)
Marginal land	0.3	0.5 (0.5)	0.3 (0.3)	0.0	1.1 (0.9)
Not suitable	0.0	2.6 (2.3)	1.8 (1.5)	3.4 (3.0)	7.8 (6.9)
Total	1.6 (1.5)	4.6 (4.1)	3.7 /(3.2)	3.4 (3.0)	13.3 (11.8)

Source: Fischer et al. (2010)

Figure 26. Suitability for agricultural expansion by land use type (Fischer et al., 2010 as cited in United Nations, 2016)

This issue was also mentioned in Section 1.4.1.b. (Zomer et al., 2008).

3.4. Cropland and other land uses (United Nations, 2016)

3.4.1. Effect of urbanization in croplands (irrigated)

Growing cities and industries will have priority for water supply and this is likely to reduce the water available locally for agriculture, which leads to loss of cultivated land, particularly in dry areas. This phenomenon is already under way in the Sana'a Basin in Yemen and in the Oum er Rbia River in Morocco, where water is being transferred to municipal and industrial uses, and the area under irrigation is progressively dwindling (United Nations, 2016).

FAO estimates that 34 Mha (11%) are affected by some level of salinity; Pakistan, China, the United States and India represent more than 60% of the total (21 Mha). An additional 60–80 Mha are affected to some extent by waterlogging and related salinity. This poses a problem since few plants can tolerate much salinity (United Nations, 2016).

More than 60% of world's irrigated cropland are located near urban areas (UNCCD, 2017). Africa and Asia are projected to experience 80% loss due to urban area expansion. These losses take place on prime agricultural lands, much of which is twice as productive as national averages (UNCCD, 2017).

3.4.2. Effects of irrigated cropland on wetlands and water bodies

Many rivers heavily used for irrigation no longer have sufficient levels of flow to keep river systems "open", they no longer discharge to the sea, with causes saline advance upstream. Irrigation withdrawls have also contributed to the shrinkage of vast lakes (water bodies) (United Nations, 2016).

Wetlands have also been drained. In Europe and North America, more than half of wetlands have been drained for agriculture, leading to loss of biodiversity, risk of flooding and downstream eutrophication (FAO, 2008c; Molden, 2007: 249 as cited in United Nations, 2016).

3.4.3. Possible desertification (climate change effects)

3.4.3.a. Irrigated croplands

Among the irrigated systems those **cultivated for other crops not rice**, both irrigated from rivers in dry areas[12] or irrigated from groundwater in interior arid plains[13] are likely to suffer from water scarcity, which leads to desertification. The second ones are also exposed to increase on salinity (groundwater) (United Nations, 2016)..

Rice-based irrigated systems are found mostly in Southeast and Eastern Asia (highly productive) and to a lesser in sub-Saharan Africa (low productive) systems. In Asia land abandonment may occur due to rainfall variability and increase in droughts and there is little opportunity for expansion or intensification. Conversely, for those in Africa the problems come from poor management and the potential for expansion is high (United Nations, 2016)..

Climate change will likely have varying effects on irrigated yields, specially South Asia will suffer large declines (UNCCD, 2017).

3.4.3.b. Rainfed croplands

As for rainfed systems nor the ones located in **densely populated poor highlands**[14] nor those in **temperate[15] zones** are at risk of desertification. In the temperate area, climate change may produce a warming effect in Europe expanding the areas suitable for agriculture. Nevertheless, the potential for expansion in Europe is limited, higher potentials are found in North and South America. As for highlands the risk is of declining productivity due to erosion, higher risk of floods and degradation. There is almost no possibility of expanding (United Nations, 2016)..

On the other hand, rainfed systems located in both **semi-arid tropics[16] and subtropical[17]** showed risk of desertification. In semi-arid tropics the potential of expansion is low-medium. In subtropical area the potential of expansion is reduced since most of the suitable land is already in use (United Nations, 2016)..

3.4.3.c. Grasslands

Rangelands located in fragile soils of Western Africa (Sahel), North Africa and parts of Asia are extremely vulnerable to climate variability (increased temperature and rainfall variability) which affects the productivity of land leading to desertification and land abandonment. Since land in near or beyond the limit of use the possibilities for expansion are very limited (United Nations, 2016).

4. WETLANDS (Wood & van Halsema, 2008)

4.1. General overview

---

[12] Asia, Northern America, Northern China, Central Asia, Northern Africa and the Middle East.

[13] India, China, central USA, Australia, North Africa, Middle East and others.

[14] Himalayas, Andes, Central American highlands, Rift Valley, Ethiopian plateau, Southern Africa.

[15] Highly intensive agriculture in Western Europe and intensive farming in United States, Eastern China, Turkey, New Zealand, parts of India, Southern Africa, Brazil.

[16] Smallholder farming in sub-Saharan African savannahs and agro-pastoral systems in Asia (western India) and Africa.

[17] densely populated and intensively cultivated areas around the Mediterranean basin and in Asia

There is a global trend in wetland degradation and destruction as a result of human interaction, more than 50% of the wetlands in North America, Europe, Australia and New Zealand were lost, converted or degraded during the 20th century (MA, 2005b as cited in Wood & van Halsema, 2008). On inland wetlands, agricultural development has historically been the principle cause of wetland degradation worldwide. By 1985, between 56 and 65% of them were drained for intensive agriculture in Europe and North America (27% in Asia and 6% in South America) (MA, 2005b as cited in Wood & van Halsema, 2008). Other drivers are use of wetlands' water for irrigated agriculture and the destruction of mangroves for shrimp culture. Infrastructure and urban expansion have also led to some losses. Conversely, agriculture in wetlands has made a positive contribution to society.

The effect of agriculture in wetlands can be classified in two groups (we will focus on the first group):

- In-situ interaction, characterized by the complete transformation of wetland to agricultural land to the extent that they no longer retain any natural wetland characteristics or partial transformation. It can also include agricultural exploitation of the wetland, which does not transform the environment.
- External interaction where agriculture activities have some impact (e.g. degradation, salinization) in wetlands.

Even though loss of coastal wetlands is better established, in fact, it is stated than 35% percent of the world's mangrove forests have disappeared within the last two decades, mostly due to aquaculture development (MA, 2005b as cited in Wood & van Halsema, 2008), inland wetlands are more susceptible to direct agricultural interactions than coastal wetlands.

- Swamps, marshes, floodplains and bogs are an important source of water and fertile soil in semi-arid areas what make them an attractive agricultural resource.
- In more temperate areas where the soil moisture in wetlands is perceived to be more of a problem rather than a resource, therefore wetlands are likely to undergo intensive drainage.

Since it is known that wetlands can mitigate flood events and are able to purify contaminated water there have been projects of restoration and construction of new artificial wetlands. There have been some gains especially through the extension of rice cultivation beyond existing wetlands and to a lesser degree through reservoir formation, seepage from dams and irrigation systems, and the rehabilitation of former wetlands. Nevertheless, an increase in wetland degradation and wetland conversion to agricultural land is expected in the next 50 years, with these trends being exacerbated by climate change.

4.2. Drivers of change

A study of 90 cases analysed the wetland-agriculture interactions (Wood & van Halsema, 2008).. It was found that the predominant changes were full or partial transformation of wetlands to agriculture land.

4.2.1. Direct drivers (pressures)

- **Agriculture expansion** (colonization meaning land settlement; transformation of vegetation; clearing of vegetation). It is a driver in 66% of cases in Africa and 75% in Neotropics. In contrast, in Europe and Asia is listed in just 33%. Agricultural expansion is markedly more pronounced in subsistence economies (Figure 27).
- **Agricultural intensification** (intensified crop production and grazing; the study also focuses on intensified fisheries and aquaculture): Asia shows the most pronounced

individual pressures of agricultural intensification (66% of cases intensified crop production). In Africa, 66% of cases intensified crop production and 33% of cases intensified grazing. The small pressure in Europe (50% of cases of intensification are from crops) is offset by its higher values for the agricultural extensification driver. The low values showed by subsistence economies are entirely in line with their high values of agricultural expansion driver (Figure 27).

- **Water use** (surface water extraction and drainage for land settlement): It is more pronounced in North America and Oceania, which is a reflection of their relative water scarcity. Conversely it is less pronounced in the Neotropics region, as it is a water-abundant region. The low value in Europe may be cause of its high value on other pressures. The pressure is slightly higher for inland seasonal and peat wetlands. In the case of peatlands, drainage pressures are reported in 87% of the cases (Figure 27).

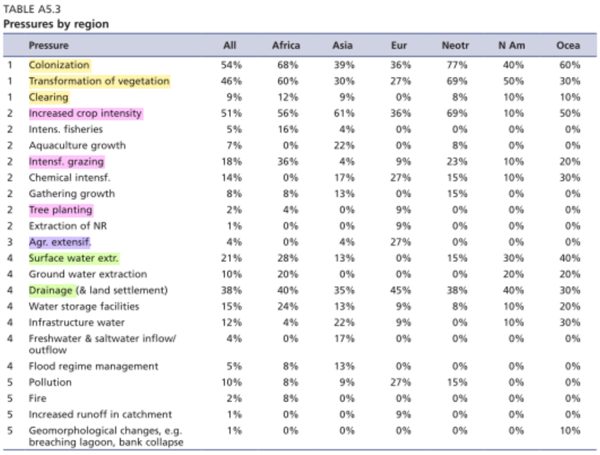


TABLE A5.3

Pressures by region

	Pressure	All	Africa	Asia	Eur	Neotr	N Am	Ocea
1	Colonization	54%	68%	39%	36%	77%	40%	60%
1	Transformation of vegetation	46%	60%	30%	27%	69%	50%	30%
1	Clearing	9%	12%	9%	0%	8%	10%	10%
2	Increased crop intensity	51%	56%	61%	36%	69%	10%	50%
2	Intens. fisheries	5%	16%	4%	0%	0%	0%	0%
2	Aquaculture growth	7%	0%	22%	0%	8%	0%	0%
2	Intensf. grazing	18%	36%	4%	9%	23%	10%	20%
2	Chemical intensf.	14%	0%	17%	27%	15%	10%	30%
2	Gathering growth	8%	8%	13%	0%	15%	0%	0%
2	Tree planting	2%	4%	0%	9%	0%	0%	0%
2	Extraction of NR	1%	0%	0%	9%	0%	0%	0%
3	Agr. extensif.	4%	0%	4%	27%	0%	0%	0%
4	Surface water extr.	21%	28%	13%	0%	15%	30%	40%
4	Ground water extraction	10%	20%	0%	0%	0%	20%	20%
4	Drainage (& land settlement)	38%	40%	35%	45%	38%	40%	30%
4	Water storage facilities	15%	24%	13%	9%	8%	10%	20%
4	Infrastructure water	12%	4%	22%	9%	0%	10%	30%
4	Freshwater & saltwater inflow/ outflow	4%	0%	17%	0%	0%	0%	0%
4	Flood regime management	5%	8%	13%	0%	0%	0%	0%
5	Pollution	10%	8%	9%	27%	15%	0%	0%
5	Fire	2%	8%	0%	0%	0%	0%	0%
5	Increased runoff in catchment	1%	0%	0%	9%	0%	0%	0%
5	Geomorphological changes, e.g. breaching lagoon, bank collapse	1%	0%	0%	0%	0%	0%	10%

Figure 27. Direct drivers of wetland decrease (Wood & van Halsema, 2008).

4.2.2. Indirect drivers

- **Population growth** is still listed as the most important driver (75% of the cases) in Asia and Africa. In the Neotropics is a driver in 50% of the cases (Figure 28).
- **Global and local markets:** Local markets are listed as driving forces in slightly more than 50% of all African cases, which is similar to what happens in Asia, Europe, Oceania and the Neotropics. As for global markets, the importance in Africa seems to be lower than in the other regions. North America region, appears to be centred on global market-oriented agriculture (Figure 28).
- **Government policies**: In Europe it is a driver in 73% of the cases while just in 20% in Oceania and 31% in the Neotropics (Figure 28).
- The values of **climate change/variability** may be masked by the high values of other drivers. In Africa is listed as a driver in 32% of the cases, where rainfall variability has a great impact in agricultural land, particularly in crop production (Figure 28).
- **Urbanization** effects are higher in Africa, where is a driver in 36% of the cases, than in the other regions. Urban expansion disproportionately damages wetlands, which tend to be in-filled, drained, or polluted (UNCCD, 2017) (Figure 28).

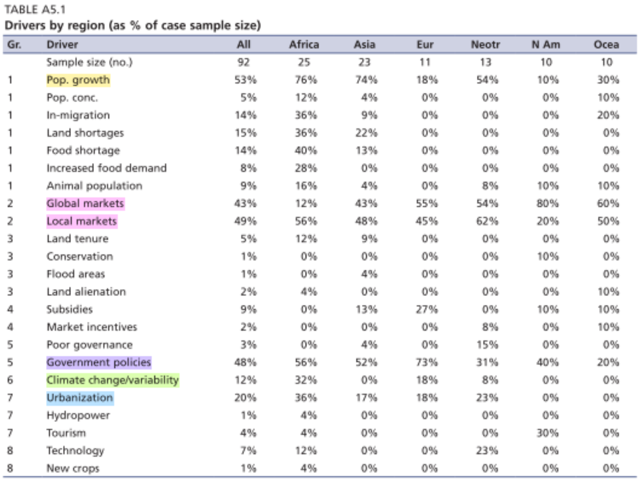


TABLE A5.1

Drivers by region (as % of case sample size)

Gr.	Driver	All	Africa	Asia	Eur	Neotr	N Am	Ocea
	Sample size (no.)	92	25	23	11	13	10	10
1	Pop. growth	53%	76%	74%	18%	54%	10%	30%
1	Pop. conc.	5%	12%	4%	0%	0%	0%	10%
1	In-migration	14%	36%	9%	0%	0%	0%	20%
1	Land shortages	15%	36%	22%	0%	0%	0%	0%
1	Food shortage	14%	40%	13%	0%	0%	0%	0%
1	Increased food demand	8%	28%	0%	0%	0%	0%	0%
1	Animal population	9%	16%	4%	0%	8%	10%	10%
2	Global markets	43%	12%	43%	55%	54%	80%	60%
2	Local markets	49%	56%	48%	45%	62%	20%	50%
3	Land tenure	5%	12%	9%	0%	0%	0%	0%
3	Conservation	1%	0%	0%	0%	0%	10%	0%
3	Flood areas	1%	0%	4%	0%	0%	0%	0%
3	Land alienation	2%	4%	0%	0%	0%	0%	10%
4	Subsidies	9%	0%	13%	27%	0%	10%	10%
4	Market incentives	2%	0%	0%	0%	8%	0%	10%
5	Poor governance	3%	0%	4%	0%	15%	0%	0%
5	Government policies	48%	56%	52%	73%	31%	40%	20%
6	Climate change/variability	12%	32%	0%	18%	8%	0%	0%
7	Urbanization	20%	36%	17%	18%	23%	0%	0%
7	Hydropower	1%	4%	0%	0%	0%	0%	0%
7	Tourism	4%	4%	0%	0%	0%	30%	0%
8	Technology	7%	12%	0%	0%	23%	0%	0%
8	New crops	1%	4%	0%	0%	0%	0%	0%

Figure 28. Indirect drivers of wetland decrease (Wood & van Halsema, 2008).

The wetland types considered by the study can be seen in Annex 4.
Natural wetland expansion due to sea-level rise can be found in Section 8.1.1.

5. DRYLANDS

Drylands are usually found in areas characterized by: (i) continentality[18]; (ii) rain shadow: location on the leeward side of mountain chains; (iii) latitude; (iv) proximity to cold ocean surfaces (Odorico et al., 2013). Furthermore, drylands suffer from strong seasonal and interannual variability, which is even more common in tropical drylands. Due to this, areas face conditions of limited water availability despite their relatively high rainfall values (Odorico et al., 2013).

(FAO, 2019)
Drylands cover about 41% of the Earth's land surface (6.1 billion ha). 32% of the world's total is in Africa, followed by Asia, North America, Oceania, South America and Europe. Climate change, unsustainable land use and management and inefficient water use are the main causes of dryland degradation. They are expected to expand by 10 to 23% by the end of the 21st century. Arid regions are expected to expand in southwestern North America, the northern fringe of Africa, Southern Africa and Australia, while the semi-arid regions are expected to do it in the northern Mediterranean, Southern Africa and North and South America (Feng and Fu, 2013 as cited in FAO, 2019).

5.1. Land uses distribution in drylands (FAO, 2019)

18% is forest and 10% other wooded-land[19]. The remaining 71% was classified as other land (39% bare soil/rock, 35% grassland, 19% cropland, 2% built-up land and 5% other or no identified).

By aridity (Figure 29)

---

[18] Continentality: distance from seas and oceans, major sources of atmospheric moisture.

[19] Wooded-land: Land not defined as "forest", more than 0.5 ha; with trees higher than 5m and a canopy cover of 5 to 10%, (or able to reach it); or with a combined cover of shrubs, bushes and trees above 10%. Nor land under urban nor agriculture.

The distribution of land uses is highly dependent on aridity. In hyper-arid zones 99% was identified as other land, 83% in the arid, 65% in the semi-arid and 43% in the dry sub-humid. Forests exhibit the opposite pattern, 43% in the dry sub-humid, 20% in the semi-arid, with rare occurrence in the arid and hyper-arid zones. Other wooded land, makes up 6% in dry sub-humid zone but only 1% of the hyper-arid zone.

By region

Other land accounts for the 85% of the drylands of Asia, 68% in Africa, 62% in Ocenia, 55% in Europe and 50% in South America and 42% in North, Central America and the Caribbean. 37% of drylands are forest in South America and 36% in Europe, while just 6% in Asia. 52% of the forests in drylands are in the dry sub-humid region, mostly in Southern Africa and western South America.

In Africa 66% of the "other-land" is barren land. 87% is grassland in Oceania and 57% croplands in Europe.

Non irrigated croplands represents a 48% of the total croplands, 33.8% of them are in Europe. A mention to irrigated croplands in arid zones was made in Section 3.2.

Inland water bodies just 1% of the dryland areas. 0.1% of the hyperarid zone, 1% of the semi-arid zone, 1% arid zone and 2% of the dry subhumid zone. The regions with more inland water bodies in drylands area are North and Central America and the Caribbean and Europe (Figure 30).

The study gives the distribution between land uses in drylands, Figure 29, specific for the following regions: Northern Africa, Western and Central Africa, Eastern Africa, Southern Africa, Western Asia, Central and Eastern Asia, Southern Asia, Oceania, South America, North and Central America and the Caribbean and Europe.

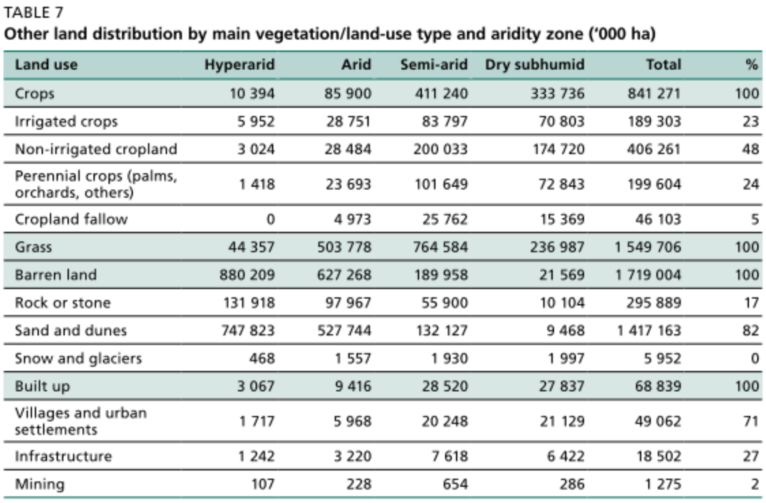


TABLE 7

Other land distribution by main vegetation/land-use type and aridity zone ('000 ha)

Land use	Hyperarid	Arid	Semi-arid	Dry subhumid	Total	%
Crops	10 394	85 900	411 240	333 736	841 271	100
Irrigated crops	5 952	28 751	83 797	70 803	189 303	23
Non-irrigated cropland	3 024	28 484	200 033	174 720	406 261	48
Perennial crops (palms, orchards, others)	1 418	23 693	101 649	72 843	199 604	24
Cropland fallow	0	4 973	25 762	15 369	46 103	5
Grass	44 357	503 778	764 584	236 987	1 549 706	100
Barren land	880 209	627 268	189 958	21 569	1 719 004	100
Rock or stone	131 918	97 967	55 900	10 104	295 889	17
Sand and dunes	747 823	527 744	132 127	9 468	1 417 163	82
Snow and glaciers	468	1 557	1 930	1 997	5 952	0
Built up	3 067	9 416	28 520	27 837	68 839	100
Villages and urban settlements	1 717	5 968	20 248	21 129	49 062	71
Infrastructure	1 242	3 220	7 618	6 422	18 502	27
Mining	107	228	654	286	1 275	2

Figure 29. % of each land use in drylands by aridity (FAO, 2019)

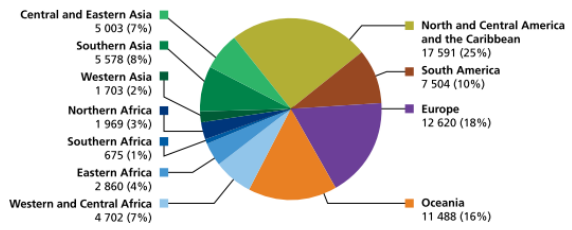


FIGURE 17

Distribution of inland water bodies among continents ('000 ha)

Figure 30. Water bodies in drylands, globally (FAO, 2019)

An estimated 44% of croplands and 50% of livestock worldwide are found in drylands (UNCCD, 2012, as cited in UNCCD, 2017). The extent of forests in the drylands has until now been underestimated by 40-47% (UNCCD, 2017).

Climate change is likely to lead to more water scarcity and reduced crop yields in drylands. It has been found that desertification can happen as a result of intensive management practices and efforts to increase productivity (UNCCD, 2017).
In Australia, as in other dryland countries, one of the most significant drivers of desertification is salinization (UNCCD, 2017).

6. WATER BODIES

Since the amount of water area that is gained or lost is relatively small compared to the changes in other land use types in many models is considered as a constant. However in the literature review have been seen that both water scarcity due to irrigation (Section 3.4.2.) and climate change (Section 8.2.) influence the state of water bodies.
As there have not been found studies about for to what land use type are water bodies converted to after drainage or what uses become new water bodies, there have been reviewed three studies about the land use changes in three regions (China, Tanzania and Shanghai), which were chosen because they do not consider water bodies as constant, they show the conversions suffered from this land use type (Section 9.1.). Especially in the study about Shanghai the interactions between wetland and water bodies are reviewed (Section 9.1.3.).

Water bodies in drylands Figure 30.

7. LAND FOR RES

(Perpiña Castillo et al., 2016)
Perpiña Castillo et al. carried and study to find out where are the most suitable[20] lands for solar infrastructures in Europe. The most interesting thing about this article is the factors that are considered to assess the suitability. Ideally, these installations should be located on unused, low productivity agricultural and/or pasture land and, in general, areas covered by grasslands or scrublands to minimise the impacts (Turney and Fthenakis, 2011 as cited in Perpiña Castillo et al., 2016).

7.1. Land suitability criterias for solar expansion (Perpiña Castillo et al., 2016).

Firstly the areas with strong restrictions to the development of large-scale solar installations were subtracted. Those are protected and sensitive natural areas, built-up areas, wetlands, water bodies and forest. Secondly, based on the suitability factors, a quantitative scoring was given to each class to rank their suitability to hold PV systems. All factors were assigned equal weights except for solar radiation, which was assigned double. The biophysical and socio-economic factors taken into consideration were:

---

[20] Suitability defined as the quantification of the appropriateness of each location to hold PV systems, determined by a set of biophysical and socio-economic factors.

- Solar radiation: defined as the solar energy (light) arriving at the surface of the Earth on a yearly basis (kWh/year). The least suitable are those that fall below 900 kWh/m2 (Šúri et al., 2007 as cited in Perpiña Castillo et al., 2016).
- Topographic parameters: Variability in elevation, surface orientation (slope and aspect), and shadows create strong local gradients of insolation. Slope ranging from 16% to 30% was considered as poorly suitable while greater than 30% as technically unviable (Šúri et al., 2007 as cited in Perpiña Castillo et al., 2016).
- Population: Locations at distances greater than 500 m from cities/residential areas were considered more suitable in order to avoid negative effects (pollution, visual intrusion) affecting cities' population.
- Transportation network: Since easy access is important for construction, operation and maintenance (Janke, 2010 as cited in Perpiña Castillo et al., 2016), locations closer to roads were considered more suitable, cut-off value of 5000 m for unfeasible locations.
- Electricity grid: The higher the proximity to the existing electricity grid, the lower transmission costs and power losses.

The authors also propose to integrate land degradation as a factor. So that medium to high saline concentration, severe erosion, or contamination by heavy metals lands could be the first areas to locate PV systems.
To validate the obtained suitability map it was compared with the locations of the solar systems that are currently being used. It was found that 75% of them are located on areas with suitability values from 79.8 to 100.

It was found that suitability increases from North to South, due to solar radiation, which is negatively correlated with latitude (Figure 31). The most suitable areas were located in Southern Europe (Mediterranean regions) where the highest levels of solar radiation occur. Some countries of Central and Eastern were characterized by low to moderate suitability. The less favourable group of countries were those of Northwest Europe, Northeast part of Central Europe and the Baltic States including Sweden and Finland. Furthermore there are some countries were the levels of suitability vary greatly within their borders (e.g. in Italy it goes from 46 to 99, in Spain from 52 to 95).

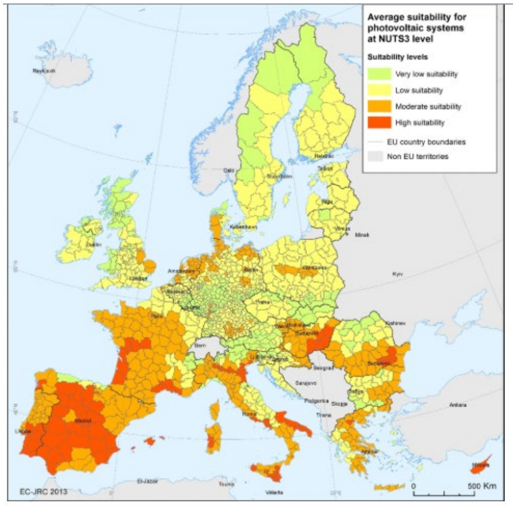


Fig. 5. Regional distribution of the average suitability levels for the installation of large-scale PV systems in Europe (NUTS3 level).

Figure 31. Suitability for solar land, Europe (Perpiña Castillo et al., 2016).

7.2. Land cover changes due to solar expansion (van de Ven et al., 2021a)

van de Ven et al. used GCAM as the base for their study, in which the land cover changes due to solar expansion in Europe, Japan and South Korea and India were reviewed. To find the suitable lands they took into consideration factors such as solar irradiance, geographical constraints (slope, current use of the land) and regulatory constraints (e.g. the protected status).
They found that due to the lower irradiance and higher latitude of Europe, the land use of per unit of solar output is almost twice as high as in Japan and South-Korea and three times higher as in India. With solar energy accounting for 25 to 80% of the electricity mix, land occupation is projected to be significant, ranging from 0.5 to 2.8% of total territory in the EU, 0.3 to 1.4% in India, and 1.2 to 5.2% in Japan and South-Korea.

Rooftop space is often used for smaller scale PV systems and has the advantage of not competing for space. However, only 2-3% of the urbanized area can be used.

Where available, **deserts and dry scrubland** with high solar irradiance and that are not suitable for human activities, are used or planned to be used for solar energy. However, features like the lack of road, electricity and water infrastructures, and the distance from human settlements complicate the large scale construction, operation and maintenance of solar power in these areas (Hernandez, R. R. et al., 2015 as cited in van de Ven et al., 2021).
By default, deserts are exempted from land competition in GCAM, and only 10% of current scrublands are included. Therefore, apart from this 10% of scrublands, we assumed no additional availability of suitable deserts and scrublands for solar energy. The EU, Japan and South-Korea have limited amounts of deserts and scrublands and a significant share is protected.

The optimal microclimate for solar energy production (insolation, air temperature, wind speed and humidity) is found over land that is currently used as cropland (Adeh, E. H. et al, 2019 as cited in van de Ven et al., 2021). This together with other factors like flatness and connectivity in terms of roads and electricity grids, will make investors have for croplands. Nevertheless, since land profitability is an important driver of land use decisions, high profitability of cropland could force investors to focus on other land types.

It was review the effect of solar energy expansion, both within the region (the transition it causes in the region where the expansion takes place) and across the world (how the expansion in a region affects the rest of the world). Within the region it predominantly replaces land used for commercial purposes, such as cropland or commercial forest but it does not affect directly to unmanaged land. However, the replacement of commercial land within the region is likely to would incentivise the use of currently unused arable land (unmanaged land), leading to loss of natural land cover. These impacts depend on the crop productivity of the region where the expansion takes place: the replacement of high productive croplands in the EU, Japan and South-Korea amplify the impact of solar expansion by 22%, as they are displacement to other regions with lower productivities. This effect is lower at lower solar energy penetration levels (even negative in the EU), as solar energy is projected to displace the most marginal cropland first. In India, where crop productivities are below the global average, the impact is less significant.

- For every 100 ha of solarland expansion in Europe 31 -43 ha of unmanaged forest may be cleared throughout all the world. In India 27 to 30 ha and in Japan and South-Korea 49 to 54 ha.

The allocation of the currently existent solar installations can be found in Annex 3.

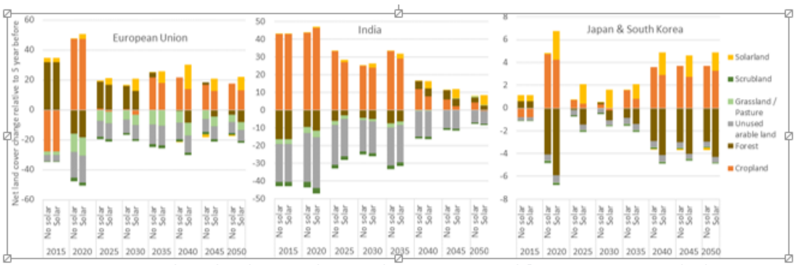


Figure S8: Projected net land cover changes by 5-year period for a scenario in which no new USSE is entering the electricity mix after 2015 ("No solar") and a scenario where USSE will account for 45-52% of the electricity mix by 2050 ("mid scenario" for PV module efficiencies). Different penetration and efficiency levels for solar energy lead to relatively proportional results as in this example.

Figure 32. Projected land cover changes in a no new solar scenario and a 45-52% solar use by 2050 (van de Ven et al., 2021a).

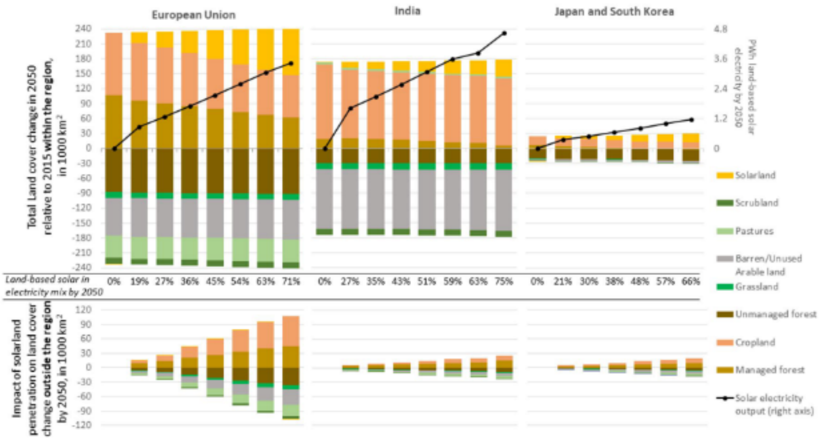


Figure 2. Global land-cover changes by 2050 due to solar expansion, for a range of solar energy penetration levels and for an average efficiency of installed solar modules of 24% by 2050. The upper graphs shows total land cover changes by 2050 relative to 2015 within each region and the lower side shows the land cover changes in the rest of the world (leaking), indirectly driven by the penetration of solarland within the region. Positive land cover changes refer to increases and negative to land cover loss. See Section 3b in the SM for aggregated global land cover changes. Note that land cover changes do not correspond with land use changes: this figure compares total land cover in different scenarios of land-based solar energy penetration, but does not show which specific types of land convert to solarland (or any other type of land). Note that these land cover changes are based on simulated land use decisions driven by economic optimisation. See "Methods" section for more details.

Figure 33. Direct and indirect land cover changes due to solar expansion by 2050 (van de Ven et al., 2021a)

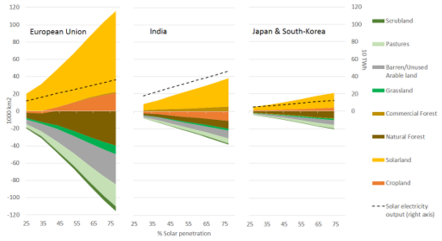


Figure S14: Total net global land cover changes by 2050 by type for each region (for scenarios reaching a 24% average PV module efficiency by 2050). See Figure 2 in main document for relative changes within each of the regions, and outside the regions.

Figure 34. Total cover change due to solar expansion by 2050 (van de Ven et al., 2021a).

8. CLIMATE CHANGE AS LAND USE CHANGE DRIVER

8.1. Sea-Level Rise

Between 1984 and 2015 the loss of permanent land in coastal areas has been of almost 28.000 km2 while the amount of land gained was about 14,000 km2. The region with the highest change per unit coast is the Caspian Sea (more than 50% of the overall global changes) followed by

Southern Asia. Pacific Asia, Southern America, Eastern Africa and Western Australia present much smaller changes (Mentaschi et al., 2018).

Dams are among the most prominent erosion factors, as they retain sediment that would normally feed the downdrift beaches (Bianchi, T. S. & Allison, M. A., 2009 as cited in Mentaschi et al., 2018). Erosion is usually more intense under El Niño conditions, when storms are more frequent, and La Niña typically favours beach recovery (Vousdoukas, M. I., et al., 2012 as cited in Mentaschi et al., 2018). Climate projections indicate that these phenomenon will intensify, as well as sea-level rise will increase due to global warming, which will increase sea level erosion.

8.1.1. Land changes due to sea-level rise (Kirwan & Gedan, 2019b)

Marshes, mangroves and oyster reefs are well known to resist sea level rise by growing vertically (Kirwan, M. L. & J. P. Megonigal, J. P., 2013; McKee, K. L. et al., 2007; Rodriguez, A. B. et al., 2014 as cited in Kirwan & Gedan, 2019). However, some studies suggest that terrestrial ecosystems lack mechanisms to do so (Smith, J. A., 2013; Raabe, E. A. & Stumpf, R. P., 2016; Schieder, N. W., 2018 as cited in Kirwan & Gedan, 2019).

Some of the effects of sea level rise are:

- **Creation of ghost forests:** dead trees and stumps surrounded by marshland, forestland that has been replaced by intertidal vegetation. The elevation (vertical growth) of coastal treelines has increased in parallel with late-Holocene sea level rise, and lateral rates of forest retreat are 2–14 times higher than pre-industrial rates (Schieder, N. W., 2017; Hussein, A. H., 2009 as cited in Kirwan & Gedan, 2019).
- The conversion of **agricultural fields to wetlands** (one plan community is replaced by another).
- Abandonment of agricultural land due to **salinization** in low elevation coastal regions around the world.

Ghost forest creation: When the salinization begins, sap flow and annual growth decrease. In the next phase young trees begin to die, and then old trees do the same as salt-tolerant species establish. Shrubs dominate the transition from forest to tidal wet- land (Langston, A. K., et al., 2017 as cited in Kirwan & Gedan, 2019).

Cropland abandonment: Most crops cannot tolerate sustained salinities over 2 ppt (Katerji, N. et al., 2012; Tanji, K. K. & Kielen, N. C., 2002 as cited in Kirwan & Gedan, 2019).

Wetland expansion: Although marshes and mangroves build soil vertically, there are limits to the rate of sea level rise that wetlands can survive in place, and some observations indicate that this limit has already been exceed in same regions (Lovelock, C. E. et al., 2015; Crosby, S. C. et al.,2016 as cited in Kirwan & Gedan, 2019) forcing wetlands to migrate. The formation of new wetlands in drowning uplands has the potential to compensate for even large losses of existing wetlands. The expansion of marshes into sloping uplands will be big under moderate rates of sea level rise and then it will decrease under higher rates due to widespread drowning of marshes (Kirwan, M. L., et al., 2016 as cited in Kirwan & Gedan, 2019). The formation of new wetlands in drowning uplands has the potential to compensate for even large losses of existing wetlands. Wetland migration into submerging uplands is the single biggest factor influencing wetland area through time. It is estimated that global wetland area could increase by up to 60% by 2100 for a 1.1m sea level rise (Schuerch, M. et al., 2018 as cited in Kirwan & Gedan, 2019).

The conversion of forests and croplands to tidal wetlands will increase total carbon sequestration.

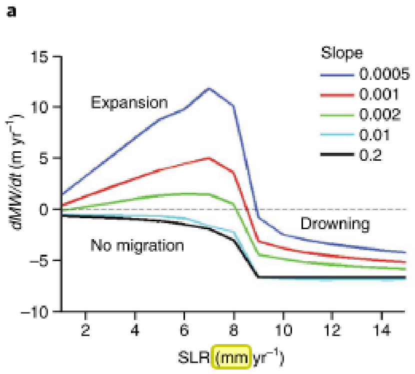


Figure 34 bis. Marsh variation with sea level rise (Kirwan & Gedan, 2019a)

Land submergence is most extensive within the mid-Atlantic sea-level rise hotspot (from North Carolina to Massachusetts), where relative sea level is rising three times faster than eustatic rates (Sallenger, A. H. et al., 2012 as cited in Kirwan & Gedan, 2019). Surprisingly, the phenomenon has not been widely documented on coastal plains outside of the United States, where the phenomenon would be predicted. The author points out that anthropogenic structures and coastal development may prevent land conversion. The south-eastern and mid-Atlantic United States are largely rural coastal regions devoid of large, systematic flood control structures. In contrast, Western Europe and China have extensive seawalls and dykes protecting uplands from sea level rise (Ma, Z. J. et al., 2014; Temmerman, S. et al., 2013 as cited in Kirwan & Gedan, 2019).

8.1.2. Agricultural land loss due to sea-level rise (WORLD BANK, 2016)

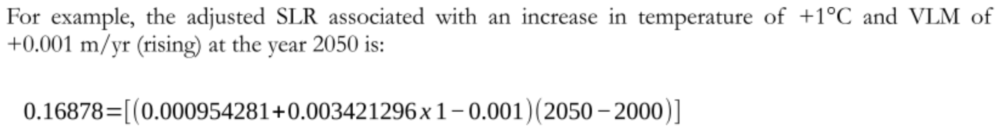
This study uses GTAP to evaluate the amount of land and agricultural land lost due to sea-level rise. Sea-level rise is generally turned by expansion of water bodies and glaciers' melting. The share of land that may be lost depends of: (i) its composition (rocky costs are less susceptible than sandy coast or wetlands); (ii) length of the coast; (iii) share of the coast suitable for agriculture; (iv) vertical movement, VLM, processes causing the land to move up and down (e.g. tectonic movements).

There exist a positive relation between sea-level rise ad global mean surface temperature, but also a time component, related to the substantial inertia of the physical processes involved.

$$SLR=[(\alpha+\beta\Delta t)(T-2000)]$$

Δt is the change in average global temperature with respect to the baseline [1985-2005], and T is the year period. A panel estimation gives α a value of 0.000954281 and for β is 0.003421296. To account for the vertical land movement (V), the equation can be modified as follows (aSLR is the adjusted sea level rise):

$$aSLR=[(\alpha+\beta\Delta t-V)(T-2000)]$$



For example, the adjusted SLR associated with an increase in temperature of +1°C and VLM of +0.001 m/yr (rising) at the year 2050 is:

$$0.16878=[(0.000954281+0.003421296\,x\,1-0.001)(2050-2000)]$$

For the European regions, the shares of erodible coast have been obtained from the Eurosion project (www.eurosion.org), while for the remaining countries we have adopted the 70% (Bird, 2010 as cited in WORLD BANK GROUP, 2016). The fraction of coastal land suitable for agricultural or other productive activities was obtained from UNEP 2005. Data on coastline length are provided by the CIA database (www.cia.gov).

They estimated the fraction of agricultural land which is lost when SLR equals 0.16 meters, and then scaling up, the share of productive land which is lost for one meter of SLR (LR) is obtained. LRT, percentage change in the land stock by year and country, it is computed by multiplying the percentage of effective land change by meter of SLR (LR) and the predicted adjusted SLR, as follows:

$$L_{RT}=L_R[(\alpha+\beta\Delta t-V_R)(T-2000)]$$

(α, β) are common across all regions, (LR, VR) are country/region specific. LR percentage loss of land by meter of SLR, VR vertical land motion (VLM). Table A1: % of land change by meter of SLR by country. Table A2: % of land loss for +1, 2, 3 ,4 or 5 ºC by 2050 and 2100 by country.

8.2. Water Bodies (Pekel et al., 2016)

In 2015 permanent bodies of water covered 2.78 million km2, and 86% (2.4 million km2) were geographically and temporally invariant. Conversely, over the past three decades, more than 162.000 km2 of water bodies previously thought of as permanent have proved not to be so: almost 90,000 km2 have vanished and over 72,000 km2 have transitioned to a seasonal state. And almost 213,000 km2 of new permanent water bodies came into existence: 29,000 km2 of these used to be seasonally flooded and 184,000 km2 came from devoid of surface water.

Geographically: Almost 52% of the planet’s truly permanent and 18% contemporary seasonal water occurs in North America. Between 1984 and 2015, North America’s permanent water area increased by 17,000 km2. Asia, accounts for only 9% of the truly permanent and 35% of the contemporary seasonal water. Asia has gained 71,000 km2 of permanent water, which is a 23% increase for the continent. Africa and Latin America have almost 9% of the world’s permanent water each. Europe, including Russia, has 22% of the permanent water and 18% of the contemporary seasonal. Oceania is the only continental region with a net loss of permanent water, albeit a tiny area at 229 km2.

Over 70% of global net permanent water loss is concentrated in five countries, centred at 45° N, 60° E. The rate of loss was greatest between 1994 and 2009, though lately this has slowed and even partially reversed. Most of the gains came from reservoir construction.

The supplementary information of the paper gives information about the transitions:

Always permanent	Not water to Permanent	Seasonal to Permanent	Permanent to Not water	Permanent to Seasonal	Always seasonal

8.3. Desertification

Desertification does not necessarily occur at the desert margins: even dryland areas that are not at the edges of existing deserts may be prone to desertification (Dregne HE., 1977 as cited in Odorico et al., 2013).

Global aridity[21] has increased since the middle of the 20th century mainly due to the rapid warming since the late 1970's caused by anthropogenic increases in greenhouse gas emissions (Dai A., 2011 as cited in Odorico et al., 2013). It is estimated that 50% of the earth's surface will be in drought at the end of the 21st century under a ''business as usual'' scenario. And while some regions have become drier, central Africa, eastern Asia and high latitudes of northern hemisphere will become wetter (Burke E.J. et al., 2016 as cited in Odorico et al., 2013). East and South Asia will experience larger variability in precipitation and an increase in drought occurrence (Kim D. et al., 2016 as cited in Odorico et al., 2013).

This changes will put agriculture at risk and cause the expansion of deserts (Burke EJ, 2016; Morton JF., 2007 as cited in Odorico et al., 2013). 20% of irrigated land are affected by increasing salt content (Rengasamy P., 2006 as cited in Odorico et al., 2013), which not only reduces crop growth but can leave the soil in a permanently degraded state. Nevertheless, satellite data show that some arid lands (e.g., the Sahel, the Mediterranean basin, southern Africa) are greening up (Helldén U. et al., 2008 as cited in Odorico et al., 2013).

8.3.1. Desertification and greening drivers (Burrell et al., 2015a)

Burrell et al., quantified the scale of global desertification[22]. They found that 6% of drylands have experienced desertification, 41% showed significant greening and the remaining 53% had no significant change between 1982 and 2015. It is also estimated that unsustainable LU practices or anthropogenic climate change[23] (ACC) has placed 20% of drylands at high risk of future desertification (Burrell et al., 2015b).

CO2 fertilization was the largest absolute attributed driver of dryland vegetation change in 44.1% of areas, followed by land use, LU, (28.2%), climate variability, CV, (14.6%), and climate change, CC, (13.1%). Globally, ACC had a positive (greening effect) over the period (1982-2015) but it also had a desertifying effect across 12.55% of drylands areas.
Nevertheless, ACC negative effect does not guarantee desertification, only 13.8% of areas with a negative ACC forcing, experienced significant desertification and in only 2.27% of the areas experiencing desertification, climate was the sole negative driver.

a) Drivers of desertification: 2.70 km2 of drylands experience desertification in the period 1982-2015. In 79.9% of them a negative LU was the primary driver and it was a contributing factor across 99.0% of areas. Even though the average impact of CC and CV are much smaller than LU, climate remains an important driver, changes like decrease in rainfall caused by CC and negative phase of CV have damaging impacts. However, in 12.0 million km2 the desertifying effect of LU has been offset by a positive ACC signal. These regions, along with the 7.2% of areas with a negative CC but no significant vegetation change, are at the highest risk of future desertification.

- Examples of desertification: Central and Western Africa and South America.

b) Drivers of dryland greening: 18.0 million km2 of drylands had a significant positive vegetation change in the period 1982-2015. CO2 was the largest driver of this change (it was the largest attributed driver in ~40% of the areas experiencing greening) followed closely by LU (~38%), CV (~13%), and CC (~8%). The importance of CV and LU is especially apparent when considering regional drivers.

- Examples of greening: Sahel, India, Australia, Eastern Africa.

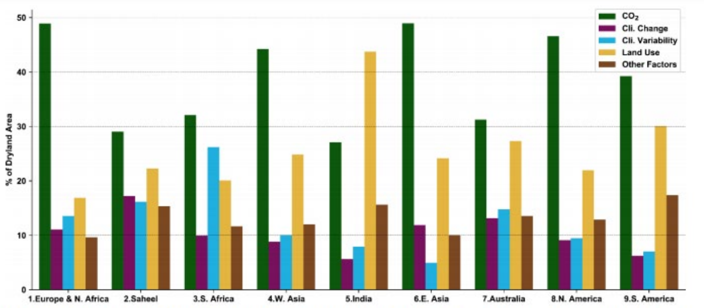
---

[21] In regions such as Africa, east and southern Asia, eastern Australia, and southern Europe.

[22] Desertification defined by the UNCCD and IPCC as land degradation in arid, semi- arid, and dry sub-humid areas (IPCC, 2019 as cited in Burrell et al., 2015).

[23] Anthropogenic climate change[23] (ACC), in the text refers to the combination of CO2 fertilization and climate change (CC) (Burrell et al., 2015b).

The contribution of each driver in each studied region can be seen in Figure 35.



Supplementary Figure 9 Primary regional drivers of vegetation change. Largest absolute driver by percentage of regional dryland area assuming a mixed C3/C4 photosynthetic mechanism. This figure is a regional breakdown of the information show in Supplementary Figure 3a.

Figure 35. Drivers of vegetation change in drylands by region (Burrell et al., 2015b)

8.3.2. Biophysical feedbacks of desertification (Odorico et al., 2013)

a) Land degradation feedbacks:

- Soil erosion: removal of nutrient-rich soil particles caused by wind and water erosion. Intensive agriculture favours soil erosion, which leads to desertification. 15% of drylands previously used for pasture has been converted to cropland within the first half of the 20th century (MEA, 2015 as cited in Odorico et al., 2013).
- Decrease in soil moisture: Plant cover increases soil infiltration capacity, therefore, its loss is associated with losses of soil water and the inability for plants to re-establish. The strength of this feedback increases with decreasing mean annual rainfall (D'Odorico P. et al., as cited in Odorico et al., 2013).
- Soil salinization: Accumulation of salts and other toxic substances, which prevent vegetation re-establishment and growth. The replacement of native vegetation with cropland led to a water table rise thereby enhancing salt deposition (Walker BH., 2006 as cited in Odorico et al., 2013)

b) Vegetation-climate feedbacks: Changes in land cover may reduce or suppress precipitation, preventing vegetation re-establishment and growth.

- precipitation recycling[24]: A decrease in evapotranspiration induced by vegetation loss is expected to cause a decrease in precipitation recycling. This effect may lead to desertification if precipitation recycling is a substantial fraction of total precipitation. The value is usually 10- 30%.
- surface energy balance: modification of surface attributes crucial in energy fluxes: (i) removal of desert margins' vegetation increase albedo, which may cause surface cooling ability and precipitation decrease (Charney JG., 1975 as cited in Odorico et al., 2013). Nevertheless many studies state the opposite, land degradation tend to cause an increase in surface temperatures. (ii) in some regions moister land surface conditions enhance precipitation, while in others wetter soil may induce surface cooling and inhibit precipitation (Cook BI. et al., 2006 as cited in Odorico et al., 2013). (iii) decrease in

---

[24] Precipitation recycling: fraction of precipitation contributed by moisture coming from regional evapotranspiration.

roughness associated with vegetation removal may cause a decrease in moisture, reducing precipitation (Sud YC. Et al, 1988 as cited in Odorico et al., 2013).

- Dust emissions: Loss of vegetation cover causes an intensification of dust emissions, which may cause a reduction of precipitation and surface cooling impeding plants to grow (Ravi S. et al., 2009, Kaufman YJ. et al., 2002 as cited in Odorico et al., 2013).

c) Feedbacks involving shifts in plant community composition:

- Shrub encroachment (Ravi S. et al., 2009): Since it increases bare soil area it is often considered as a desertification process, nevertheless, some shrublands can be more productive than the native grassland (Eldridge DJ. et al.,2011). The shift grass to shrub, both stable states, may be caused by: (i) erosion feedbak; (ii) fire-vegetation feedback, the change from grass to shrubs decreases fires' frequency enhancing shrubs' growth (D'Odorico P. et al., 2006) [37]; (iii) vegetation-climate feedback shrub encroachment causes an increase in nocturnal temperatures, reducing its exposition to frost-induced mortality (D'Odorico P. et al., 2005) (all as cited in Odorico et al., 2013).
- Grasses invasion of shrubland desserts: It causes an increase in fire frequency, killing the shrubs and promoting grasses' establishment. Even though the ground cover can be similar during wet growing seasons, during droughts and the dry season grasses provide just a sparse vegetation, which makes erosion more likely (Ravi S. et al., 2009 as cited in Odorico et al., 2013).

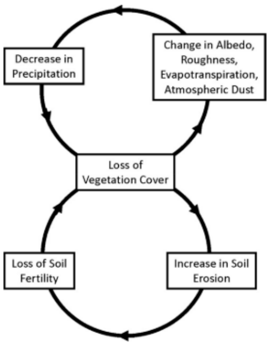


Fig. 4. Examples of desertification feedbacks. Bottom loop: the typical land degradation feedback. The exposure of the soil surface to wind and water erosion causes substantial losses of soil nutrients thereby preventing the re-establishment of vegetation (e.g., [29,187]). This type of feedback invokes the ability of vegetation to stabilize the soil surface as the mechanism that allows the system to persist either in a vegetated or in a bare soil state. Top loop: vegetation-atmosphere feedbacks.

Figure 36. Desertification drivers (Odorico et al., 2013).

The graph in Figure 37 shows the major transitions between rangeland, cropland and urban are shown, as well as what drives to desertification ("degraded soil").

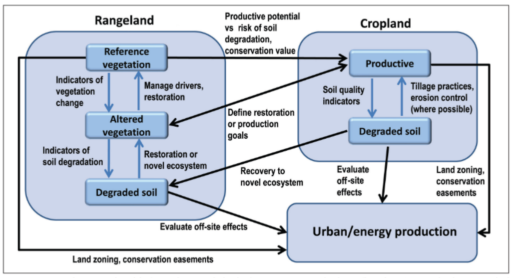


Figure 6. General conceptual model of state change in drylands, featuring prominent land uses (large boxes), generalized vegetation/soil states (small boxes), considerations for managing state change and regime shifts within a land use (blue arrows), and considerations for managing land-use change (black arrows).

Figure 37. Rangeland/Cropland/Urban transitions driving desertification (Bestelmeyer et al., 2015).

8.4. Other changes (Bjørn et al., 2019)

The study focuses on the effect of surface air temperature (SAT; defined as the temperature two meters above vegetation (Zhao and Jackson, 2014)) and precipitation as regime state shifts drivers (Figure 38).

Tropical and subtropical biomes (Amazonia, Africa, Southeast Asia): Several studies point out that reduction in precipitation and increase in surface air temperature (SAT) are decisive drivers of shifts from a forest to a savanna or a grassland state.
Boreal and tundra biomes: Tundra (a type of shrubland) and steppe (a type of grassland) constitute alternative stable states to boreal forest at the lower and higher temperature range (Scheffer et al.,2012 as cited in Bjørn et al., 2019).
Temperate biomes: There is evidence of the response to unusually severe drought, driven by climate change, which suggests that there may be several thresholds linked to increase in wildfires, drought-stress and pest outbreak. Once a forest state is shifted to a shrubland or grassland state, reversing the shift can be difficult.
Drylands: Areas where the aridity index (precipitation/potential evapotranspiration) is below 0.65. Dryland degradation (desertification) is often a highly persistent state shift. A major driver is increased aridity, which can be caused by a combination of decrease in precipitation and increase in SAT. Once grassland or other land cover types have undergone a state shift to desert, feedbackmechanisms stabilise the new state (Section 8.3.2.) (Peters et al., 2004 as cited in Bjørn et al., 2019).

Deeper investigation about tropical/subtropical biomes:

- **Cox et al. (2004)** used a coupled climate-carbon cycle model to simulate the response of Amazonia to a future warmer and drier climate. His found a threshold (after which forest cannot (re)growth) in the broadleaf tree fraction when precipitation decreases to around 1,100 mm/year (approximately half of the current mean annual precipitation level) and surface air temperatures (SAT) increase to around 305 K (5-6 degrees above the 1990 level).
- **Jones et al., 2009** used a general circulation model coupled with a dynamic vegetation model and predicted forest dieback in Amazonia to start happening at around a global warming of 3 °C above pre-industrial temperatures.
- According to **Hirota et al. ,2011 and Xu et al., 2016**, there might be three alternative stable states: forest, savanna, and “treeless”, while, between the stable states forest and savanna there is an unstable state, characterized by a tree cover around 30-60% and a canopy height around 20-30 m. They observed that a savannah and forest state are both common at 1,500–2,000 mm/year of precipitation, whereas a savannah state is most common below that range and a tree state is most common above it. This means that a forest is likely to be pushed into a savannah state when precipitation decreases to 1,500–2,000 mm/year.
- **Staal et al., 2016** used the same dataset as Hirota et al. (2011) and a similar analysis but he considered, but in addition to mean annual rainfall, they considered seasonality (inequal distribution of rainfall over a year’s). They found that savanna was more likely than forest in locations with high seasonality. Long periods of low rainfall (dry seasons) are associated with low tree cover. The study also suggests that rainfall seasonality affects the South American forest-savanna more strongly than absolute quantities of precipitation (measured in mm/year), while the opposite happens in Africa. He stated that forest and savanna are equally likely to occur in South America at a MSI (Markham's

Seasonality Index) value of 50%, forest is likely to be pushed to a savanna state when changes in precipitation leads to a MSI value above 50%.

Deeper investigation about boreal biomes:

- **Scheffer et al., 2012** states that treeless tundra dominates at low temperatures, whereas a distinct treeless steppe dominates at high temperatures. The probability of finding boreal forest increases with precipitation. The combination of temperature and precipitation explains the distribution of boreal forest better than either of those factors alone. In the study, tree cover is a smooth function of temperature, precipitation, and their interaction (Figure A7a; Figure A7b).

Deeper investigation about temperate biomes:

- Even though **Millar & Stephenson, 2021** stated that increasing temperatures can also result in long-term chronic increases in drought stress, which elevates forest mortality, even when precipitation remains average or increases there have not been found conclusive thresholds neither for temperature nor for precipitation (Figure A7c).

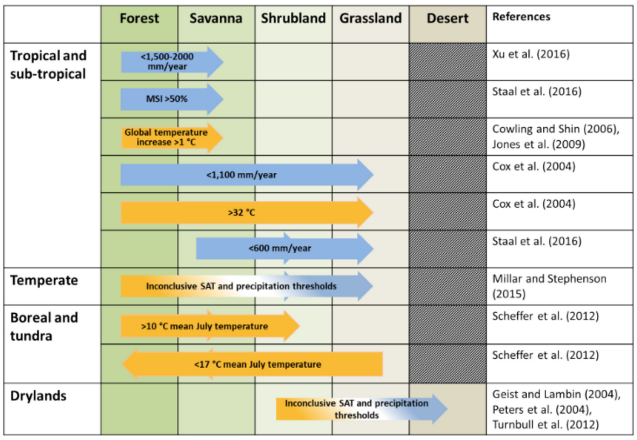


Fig. 2. Thresholds separating five alternative land-system states in four biome categories. Each arrow starts at the original state and leads to one or more potential new states. Associated threshold values are indicated for precipitation (blue) and surface air temperature (orange). MSI = Markham's Seasonality Index, a precipitation-related measure (see SM2 for details). Additional details on each identified threshold is given in SM1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Figure 38. Main land cover changes driven by climate change (Bjørn et al., 2019).

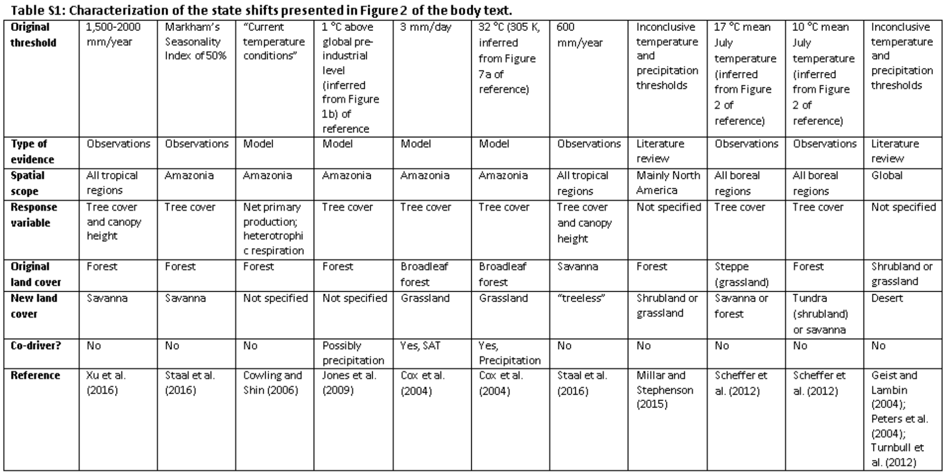


Table S1: Characterization of the state shifts presented in Figure 2 of the body text.

Original threshold	1,500-2000 mm/year	Markham's Seasonality Index of 50%	"Current temperature conditions"	1 °C above global pre-industrial level (inferred from Figure 1b) of reference	3 mm/day	32 °C (305 K, inferred from Figure 7a of reference)	600 mm/year	Inconclusive temperature and precipitation thresholds	17 °C mean July temperature (inferred from Figure 2 of reference)	10 °C mean July temperature (inferred from Figure 2 of reference)	Inconclusive temperature and precipitation thresholds
Type of evidence	Observations	Observations	Model	Model	Model	Model	Observations	Literature review	Observations	Observations	Literature review
Spatial scope	All tropical regions	Amazonia	Amazonia	Amazonia	Amazonia	Amazonia	All tropical regions	Mainly North America	All boreal regions	All boreal regions	Global
Response variable	Tree cover and canopy height	Tree cover	Net primary production; heterotrophic respiration	Tree cover	Tree cover	Tree cover	Tree cover and canopy height	Not specified	Tree cover	Tree cover	Not specified
Original land cover	Forest	Forest	Forest	Forest	Broadleaf forest	Broadleaf forest	Savanna	Forest	Steppe (grassland)	Forest	Shrubland or grassland
New land cover	Savanna	Savanna	Not specified	Not specified	Grassland	Grassland	"treeless"	Shrubland or grassland	Savanna or forest	Tundra (shrubland) or savanna	Desert
Co-driver?	No	No	No	Possibly precipitation	Yes, SAT	Yes, Precipitation	No	No	No	No	No
Reference	Xu et al. (2016)	Staal et al. (2016)	Cowling and Shin (2006)	Jones et al. (2009)	Cox et al. (2004)	Cox et al. (2004)	Staal et al. (2016)	Millar and Stephenson (2015)	Scheffer et al. (2012)	Scheffer et al. (2012)	Geist and Lambin (2004); Peters et al. (2004); Turnbull et al. (2012)

Figure 39. Main land cover changes driven by climate change, extended (Bjørn et al., 2019).

9. GENERAL LAND USE CONSIDERATION

9.1. Countries

Even though these studies were chosen because they do not consider water bodies as constant, a summary of the whole study (land-use changes) is presented.

9.1.1. China (Ning et al., 2018)

To evaluate the land use/cover changes China is divided in four regions: (i) eastern coastal region (ECR)[25]; (ii) central region (CR)[26]; (iii) western region (WR)[27]; (iv) northeastern region (NER)[28].

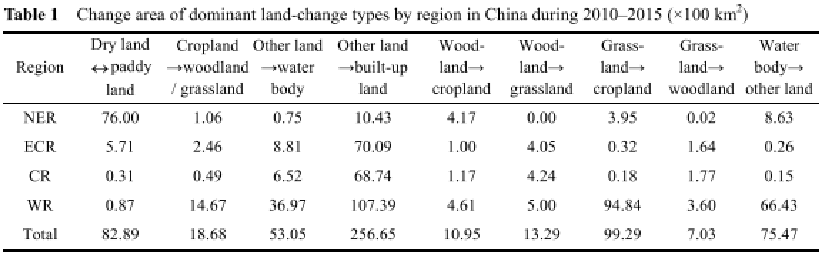


Table 1 Change area of dominant land-change types by region in China during 2010–2015 (×100 km^2)

Region	Dry land ↔paddy land	Cropland →woodland / grassland	Other land →water body	Other land →built-up land	Wood-land→ cropland	Wood-land→ grassland	Grass-land→ cropland	Grass-land→ woodland	Water body→ other land
NER	76.00	1.06	0.75	10.43	4.17	0.00	3.95	0.02	8.63
ECR	5.71	2.46	8.81	70.09	1.00	4.05	0.32	1.64	0.26
CR	0.31	0.49	6.52	68.74	1.17	4.24	0.18	1.77	0.15
WR	0.87	14.67	36.97	107.39	4.61	5.00	94.84	3.60	66.43
Total	82.89	18.68	53.05	256.65	10.95	13.29	99.29	7.03	75.47

Figure 40. Dominant land use transition in China (Ning et al., 2018).

The changes are greatly dependent on the region:

- The major land-use change was built-up expansion (increase of 25.700 km2) and ~41.8% of it occurred in WR. 67.5% of the new built-up land came from croplands, 14% from woodlands and 15.6% from grassland. It happened in economically developed and densely populated areas. The new built up area shifted from growing in ECR and CR in 2000/10 to doing so in WR and NR between 2010/15.
- Cropland expansion (11.000 km2) came from grassland (64%), unused land (21.9%) and woodland. More than 80% of the national change of woodland to cropland happened in NER and WR and over 95.5% of the national change of grassland into cropland occurred in the northwest Xinjiang oasis area (WR).
- The total cropland area in China decreased, mainly due to built-up expansion (81,5%). 80% of the national cropland into grassland and woodland change occurred in WR. In CR the conversion of cropland to grassland and woodland (national ecological projects) played a major role too. However the reclamation of cropland was much greater than the returning cropland.
- The area of woodland and grassland in China decreased. The main decline occur in WR (much bigger than in the other three). It was mainly due to cropland (53,2%) and built-up (35,2%) expansion.
- 8.290 km2 were converted from dry land to paddy land and ~91.7% of the changes were in NER.
- Water body shrinkage and expansion was also substantial and mainly occurred in WR.

1. NER

---

[25] ECR: Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Hainan, Hong Kong, Macao, and Taiwan, with an area of ~955.000 km2.

[26] CR: Shanxi, Henan, Anhui, Hubei, Hunan and Jiangxi, with an area of ~1028.000 km2.

[27] WR: Inner Mongolia, Shaanxi, Gansu, Ningxia, Qinghai, Xinjiang, Chongqing, Sichuan, Guizhou, Yunnan, Guangxi, and Tibet, with an area of ~6827.000 km2.

[28] NER: Heilongjiang, Jilin and Liaoning provinces, and has an area of ~790.000 km2.

Main land uses: woodland (42,7%) and cropland (39,5%). Built-up was 3,9%. Land-use change was 0,4% of its total area.

Main dynamics: Cropland area continued to increase, woodland and grassland slightly decreased. The expansion of built-up land was 1.000 km2, even if the number of km2 exceeded those of other land use changes within NER, compared to the expansion in other regions it is relatively small.

Main conversions: cropland->built-up (28,6% of LUC); unused land->cropland (21,6%); woodland->cropland(14,2%); grassland->cropland(13,5%).

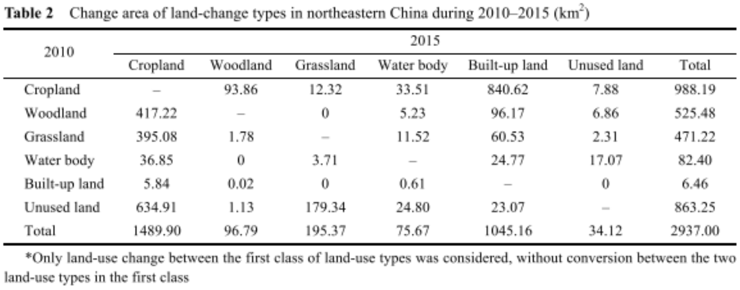


Table 2 Change area of land-change types in northeastern China during 2010–2015 (km^2)

2010	2015						
	Cropland	Woodland	Grassland	Water body	Built-up land	Unused land	Total
Cropland	–	93.86	12.32	33.51	840.62	7.88	988.19
Woodland	417.22	–	0	5.23	96.17	6.86	525.48
Grassland	395.08	1.78	–	11.52	60.53	2.31	471.22
Water body	36.85	0	3.71	–	24.77	17.07	82.40
Built-up land	5.84	0.02	0	0.61	–	0	6.46
Unused land	634.91	1.13	179.34	24.80	23.07	–	863.25
Total	1489.90	96.79	195.37	75.67	1045.16	34.12	2937.00

*Only land-use change between the first class of land-use types was considered, without conversion between the two land-use types in the first class

Figure 41. Transition matrix 2010-2015 in NER, China (Ning et al., 2018).

2. ECR

Main land uses: cropland (41,3%) and woodland (34,8%). Built-up (11,3%). 1% of the total land suffered LUC.

Main dynamics: Built-up land continued to increase, cropland to decrease.

Main changes: cropland->built-up (57,4% of total LUC), woodland->built-up (9,1%), woodland->grassland (4,2%).

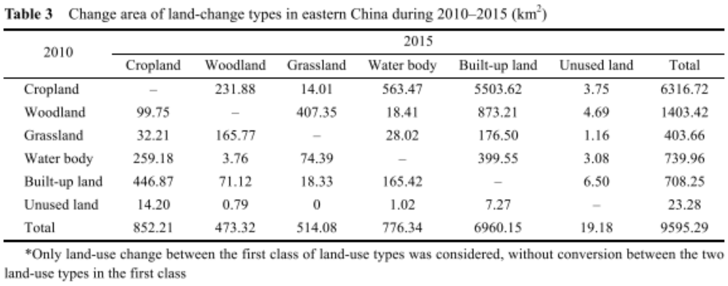


Table 3 Change area of land-change types in eastern China during 2010–2015 (km^2)

2010	2015						
	Cropland	Woodland	Grassland	Water body	Built-up land	Unused land	Total
Cropland	–	231.88	14.01	563.47	5503.62	3.75	6316.72
Woodland	99.75	–	407.35	18.41	873.21	4.69	1403.42
Grassland	32.21	165.77	–	28.02	176.50	1.16	403.66
Water body	259.18	3.76	74.39	–	399.55	3.08	739.96
Built-up land	446.87	71.12	18.33	165.42	–	6.50	708.25
Unused land	14.20	0.79	0	1.02	7.27	–	23.28
Total	852.21	473.32	514.08	776.34	6960.15	19.18	9595.29

*Only land-use change between the first class of land-use types was considered, without conversion between the two land-use types in the first class

Figure 42. Transition matrix 2010-2015 in ECR, China (Ning et al., 2018).

3. CR

Main land uses: woodland (41,9%) and cropland (39,8%). Built-up (6,18%). 0.8% of the total land of the region suffered from LUC.

Main dynamics: Built-up land continued to increase, cropland to decrease.

Main changes: cropland->built-up (57,0%), woodland->built-up (18,2%).

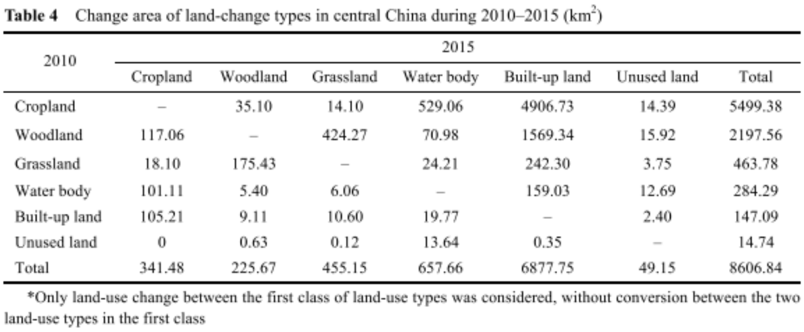


Table 4 Change area of land-change types in central China during 2010–2015 (km^2)

2010	2015						
	Cropland	Woodland	Grassland	Water body	Built-up land	Unused land	Total
Cropland	–	35.10	14.10	529.06	4906.73	14.39	5499.38
Woodland	117.06	–	424.27	70.98	1569.34	15.92	2197.56
Grassland	18.10	175.43	–	24.21	242.30	3.75	463.78
Water body	101.11	5.40	6.06	–	159.03	12.69	284.29
Built-up land	105.21	9.11	10.60	19.77	–	2.40	147.09
Unused land	0	0.63	0.12	13.64	0.35	–	14.74
Total	341.48	225.67	455.15	657.66	6877.75	49.15	8606.84

*Only land-use change between the first class of land-use types was considered, without conversion between the two land-use types in the first class

Figure 43. Transition matrix 2010-2015 in CR, China(Ning et al., 2018)

4. WR

Main land use: grassland (36,6%) and unused land (32,3%). Built-up (0,9%). 0.5% of the total land of the region suffered from LUC.
Main dynamics: Built-up and cropland areas increased, while woodland and grassland areas continued to decrease.
Main changes: grassland->cropland (28,0%), cropland->built-up (16,0%).

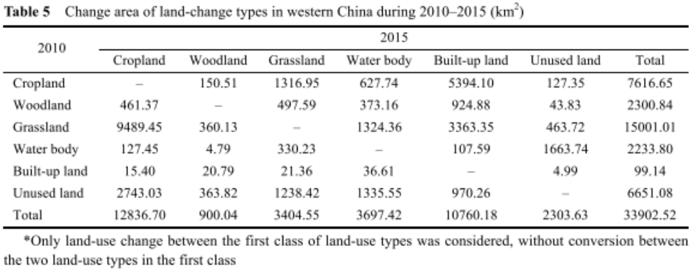


Table 5 Change area of land-change types in western China during 2010–2015 (km^2)

2010	2015						
	Cropland	Woodland	Grassland	Water body	Built-up land	Unused land	Total
Cropland	–	150.51	1316.95	627.74	5394.10	127.35	7616.65
Woodland	461.37	–	497.59	373.16	924.88	43.83	2300.84
Grassland	9489.45	360.13	–	1324.36	3363.35	463.72	15001.01
Water body	127.45	4.79	330.23	–	107.59	1663.74	2233.80
Built-up land	15.40	20.79	21.36	36.61	–	4.99	99.14
Unused land	2743.03	363.82	1238.42	1335.55	970.26	–	6651.08
Total	12836.70	900.04	3404.55	3697.42	10760.18	2303.63	33902.52

*Only land-use change between the first class of land-use types was considered, without conversion between the two land-use types in the first class

Figure 44. Transition matrix 2010-2015 in WR, China (Ning et al., 2018).

9.1.2. Tanzania (Msofe et al., 2019)

Summary in Figure 45

- Agricultural land: Main transformation happened between 1990 and 2010 and from forest and bushland.
    - 1990-2010: it increased by 26.741 km2, 38.4% from bushland, 30.3% from forest, 21.0% from grassland and 8.76% from wetland.
    - 2010-2016, it increased by 789 km2, 42% forest, 38.4% bushland, 13.7% grassland and 6.1% wetland.
- Grassland: Bigger increase between 2010 and 2016.
    - 1990-2010, it increased by 290 km2, of which 53.6% from forest, 30.0% from bushland.
    - 2010-2016, it increased by 3.765 km2, 34% from bushland, 32.5% from forest.
    - In addition, it gained 20.6% from agricultural land as they were left.
- Forest: Bigger decrease between 1990 and 2010
    - 1990-2010, forest decreased by 2.752 km2, 56% changed to bushland, 23.2% to grassland and 18.9% to agriculture.
    - 2010-2016, forest decreased by 377 km2, 39.5% changed to grassland, 30.5% to bushland and 27.0% to agricultural land.
- Bushland :
    - 1990-2010, showed an increased trend associated with massive deforestation, (56% of the forest was converted to bushland).
    - 2010-2016, it decreased by 3.483 km2, 44,7% changed to forest, 34,1% grassland and 20,5% agriculture.
    - An area of 1359 km2 of bushland changed into forest in 2010 while 2430 km2 of forest changed back to bushland in 2016.
- Wetland:
    - 1990-2010, it decreased by 449 km2 with 27.8% changed to grassland, 23.9% to agricultural land.
    - 2010-2016, it was reduced by 705 km2, 72.6% change to grassland, 18.9% to agricultural land.
- Water bodies
    - 1990-2010, it decreased by 165 km2, 24.8% change to agriculture land, 23.44% to forest, 19.14% to wetland and grassland each and the remaining 14.35% to bushland.
    - 2010-2016, it decreased by 31 km2. 39% to forest and grassland each and 14.28% to wetlands.

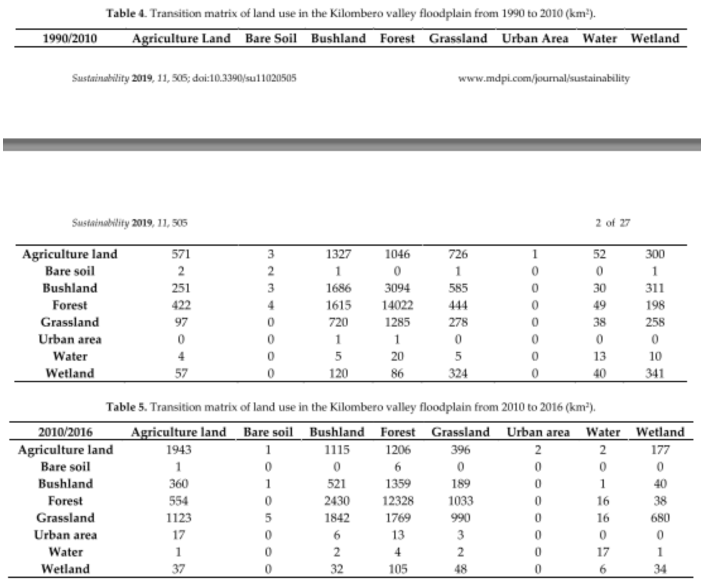


Table 4. Transition matrix of land use in the Kilombero valley floodplain from 1990 to 2010 (km²).

1990/2010	Agriculture Land	Bare Soil	Bushland	Forest	Grassland	Urban Area	Water	Wetland
Agriculture land	571	3	1327	1046	726	1	52	300
Bare soil	2	2	1	0	1	0	0	1
Bushland	251	3	1686	3094	585	0	30	311
Forest	422	4	1615	14022	444	0	49	198
Grassland	97	0	720	1285	278	0	38	258
Urban area	0	0	1	1	0	0	0	0
Water	4	0	5	20	5	0	13	10
Wetland	57	0	120	86	324	0	40	341

Sustainability **2019**, *11*, 505; doi:10.3390/su11020505 www.mdpi.com/journal/sustainability

Sustainability **2019**, *11*, 505 2 of 27

Table 5. Transition matrix of land use in the Kilombero valley floodplain from 2010 to 2016 (km²).

2010/2016	Agriculture land	Bare soil	Bushland	Forest	Grassland	Urban area	Water	Wetland
Agriculture land	1943	1	1115	1206	396	2	2	177
Bare soil	1	0	0	6	0	0	0	0
Bushland	360	1	521	1359	189	0	1	40
Forest	554	0	2430	12328	1033	0	16	38
Grassland	1123	5	1842	1769	990	0	16	680
Urban area	17	0	6	13	3	0	0	0
Water	1	0	2	4	2	0	17	1
Wetland	37	0	32	105	48	0	6	34

Figure 45. Tanzania transition matrix 1990-2010 2010-2016 (Msofe et al., 2019).

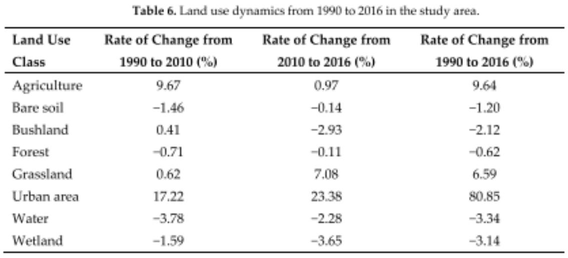


Table 6. Land use dynamics from 1990 to 2016 in the study area.

Land Use Class	Rate of Change from 1990 to 2010 (%)	Rate of Change from 2010 to 2016 (%)	Rate of Change from 1990 to 2016 (%)
Agriculture	9.67	0.97	9.64
Bare soil	−1.46	−0.14	−1.20
Bushland	0.41	−2.93	−2.12
Forest	−0.71	−0.11	−0.62
Grassland	0.62	7.08	6.59
Urban area	17.22	23.38	80.85
Water	−3.78	−2.28	−3.34
Wetland	−1.59	−3.65	−3.14

Figure 46. Rates of land use change, Tanzania (Msofe et al., 2019)

9.1.3. Shanghai (Shi et al., 2018)

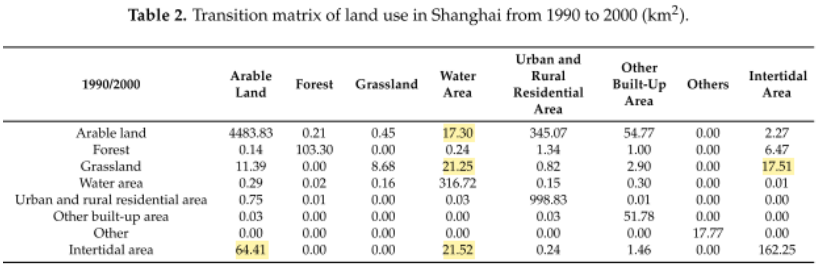


Table 2. Transition matrix of land use in Shanghai from 1990 to 2000 (km^2).

1990/2000	Arable Land	Forest	Grassland	Water Area	Urban and Rural Residential Area	Other Built-Up Area	Others	Intertidal Area
Arable land	4483.83	0.21	0.45	17.30	345.07	54.77	0.00	2.27
Forest	0.14	103.30	0.00	0.24	1.34	1.00	0.00	6.47
Grassland	11.39	0.00	8.68	21.25	0.82	2.90	0.00	17.51
Water area	0.29	0.02	0.16	316.72	0.15	0.30	0.00	0.01
Urban and rural residential area	0.75	0.01	0.00	0.03	998.83	0.01	0.00	0.00
Other built-up area	0.03	0.00	0.00	0.00	0.03	51.78	0.00	0.00
Other	0.00	0.00	0.00	0.00	0.00	0.00	17.77	0.00
Intertidal area	64.41	0.00	0.00	21.52	0.24	1.46	0.00	162.25

Figure 47. Transition matrix 1990-2000, Shanghai (Shi et al., 2018).

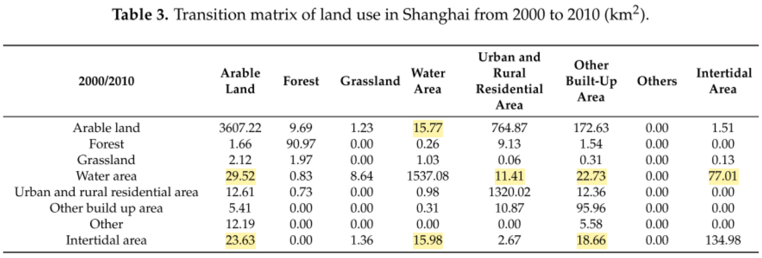


Table 3. Transition matrix of land use in Shanghai from 2000 to 2010 (km^2).

2000/2010	Arable Land	Forest	Grassland	Water Area	Urban and Rural Residential Area	Other Built-Up Area	Others	Intertidal Area
Arable land	3607.22	9.69	1.23	15.77	764.87	172.63	0.00	1.51
Forest	1.66	90.97	0.00	0.26	9.13	1.54	0.00	0.00
Grassland	2.12	1.97	0.00	1.03	0.06	0.31	0.00	0.13
Water area	29.52	0.83	8.64	1537.08	11.41	22.73	0.00	77.01
Urban and rural residential area	12.61	0.73	0.00	0.98	1320.02	12.36	0.00	0.00
Other build up area	5.41	0.00	0.00	0.31	10.87	95.96	0.00	0.00
Other	12.19	0.00	0.00	0.00	0.00	5.58	0.00	0.00
Intertidal area	23.63	0.00	1.36	15.98	2.67	18.66	0.00	134.98

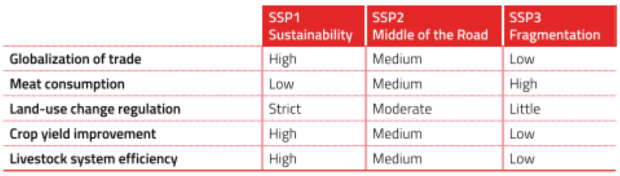
Figure 48. Transition matrix 2000-2010, Shanghai (Shi et al., 2018).

From 1990 to 2000, intertidal area[29] was converted into arable land (73.5%) and water area. From 2000 to 2010, the intertidal area mainly changed into arable land (37.9%), other built-up land, and water area. During the 20-year time period, 88.0 km2 of intertidal area were reclaimed into arable land. Intertidal areas changed from decreasing in 1990-2000 to increasing in 2000-2010, the increases came completely from water areas. From 1990 to 2000 some grasslands changed into water area and intertidal area, because the Shanghai government promoted the building of some parks within the urban area and along the Yangtze River, which had some collapsed area.

From 1990 to 2000 the transitions from water areas to other were negligible while the gains came mostly from arable land, grasslands and intertidal areas. From 2000 to 2010 water areas were lost to arable land and built-up area. The gains were smaller and came from arable land and intertidal area.

9.2. Scenarios of change (UNCCD, 2017)

'Middle of the Road' scenario (SSP2) is characterized by the continuation of current trends (business as usual); the 'Sustainability' scenario (SSP1) depicts a more equitable and prosperous world striving for sustainable development; and the 'Fragmentation' scenario (SSP3) portrays a divided world with low economic development, high population growth, and limited environmental concern.



	SSP1 Sustainability	SSP2 Middle of the Road	SSP3 Fragmentation
Globalization of trade	High	Medium	Low
Meat consumption	Low	Medium	High
Land-use change regulation	Strict	Moderate	Little
Crop yield improvement	High	Medium	Low
Livestock system efficiency	High	Medium	Low

Figure 49. Considered scenarios (UNCCD, 2017).

In all three scenarios, the demand for land-based goods and services will continue to grow rapidly over the coming decades, in addition to this demand, cities and infrastructures and conservation of forests also require land. However the demand is much smaller in SSP1 and as SPP3 has higher population, the demand is higher than in SS2.

Since much of the land suitable for agriculture is already being used (crops/urban/livestock), agriculture is likely expand into less productive areas, which requires bigger shares of land and are more prone to degradation.

SSP2 and SSP3 expect an increase of agricultural land, 50% (SSP3) and 80% (SSP2) will be established in low/moderate productive lands. SSP1 accounts for a decrease in agricultural land due to low population growth, sustainable consumption and production and increased efficiencies. Under SSP2 an increase of 0.9 million km2 of cropland expansion plus 1.2 km2 cropland for energy crops and 1.6 million km2 of pastures is expected by 2050 (Figure 50). SSP3 shows bigger increase than SSP2 (40% bigger) mainly because of slow technological development and slow crop yields improvements.

All scenarios show expansion of agriculture on tropical soils, vulnerable to erosion. Continuing productivity loss may require cropland expansion. Indeed, in SSP2 it is expected a 5% larger cropland area by 2050 on top of the 8% expansion produced by the scenario.

Under SSP2 total water demand increased.

SSP1 rate of biodiversity loss slowed down. SSP2 and SSP3 show the biggest biodiversity losses as effect of increase in cropland, infrastructure and climate change. In all three scenarios loss of biodiversity continues beyond 2050 and the impacts of climate change accelerate.

---

[29] Intertidal area = Land exposed to water that has not been used for years (Shi et al., 2018)

Climate change is likely to decrease yields and suitable available land for agriculture in some regions, while increase yields (due to warming) in others. Temperate regions may benefit while in Sub-Saharan Africa and India yields will decline as a result of water limitation and higher temperatures.

As urban land establish in the most fertile lands it enhances the trend of displacing agriculture to less productive locations. SSP2 projected an increase by 0.4 million km2, mainly taking place in productive agricultural areas.

Figure 50. Expected land cover changes under the scenarios (UNCCD, 2017).

ANNEX

ANNEX 1.

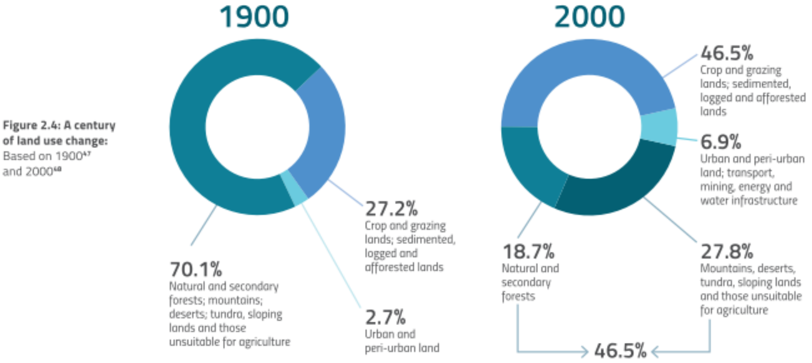
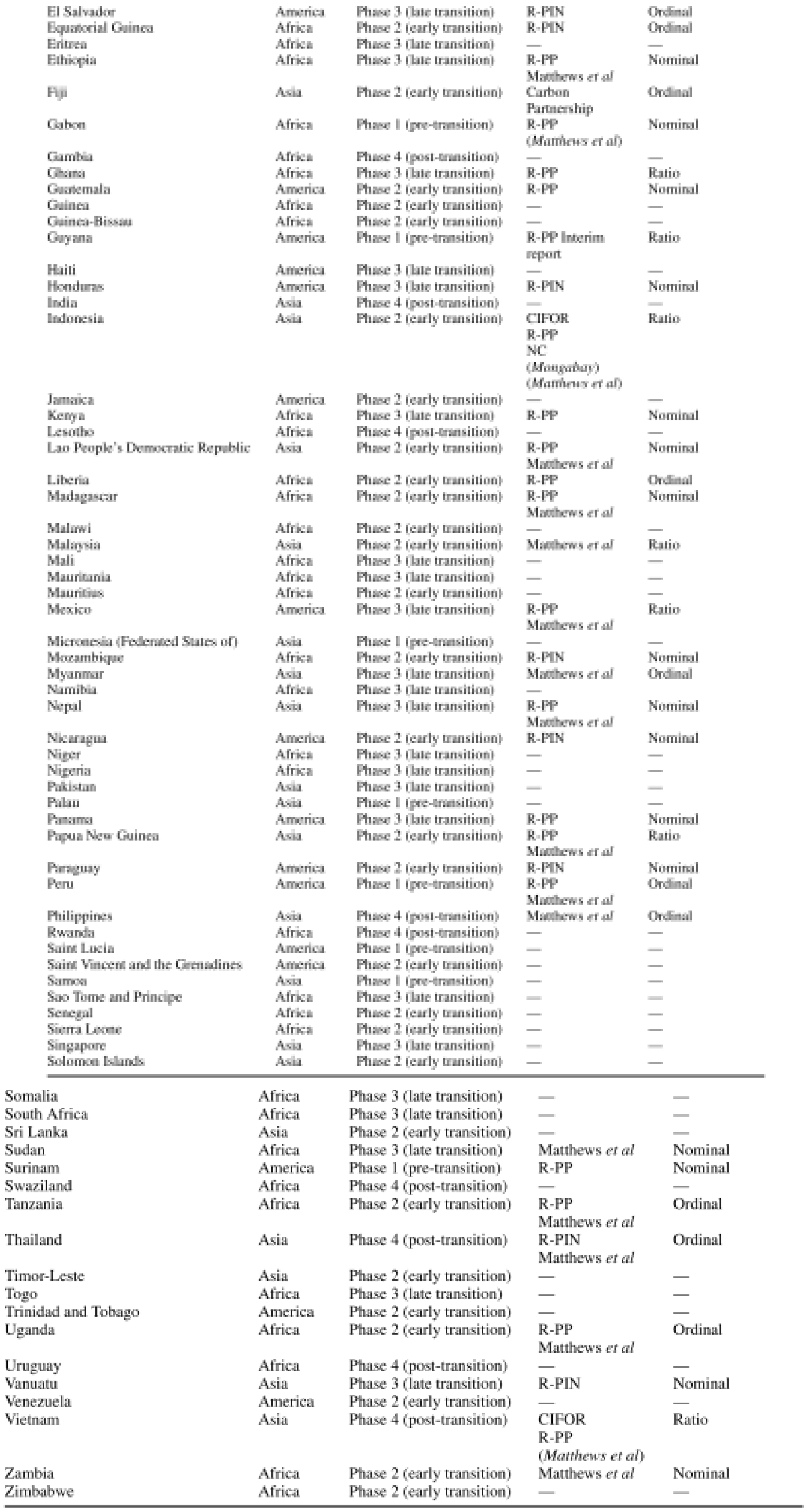


Figure A1. Land use change 1900-2000 (UNCCD, 2017).

ANNEX 2.

Country	Continent	Forest transition phase	Data source	Scale of data source
Angola	Africa	Phase 2 (early transition)	Matthews *et al*	Nominal
Antigua and Barbuda	America	Phase 3 (late transition)	—	—
Argentina	America	Phase 3 (late transition)	R-PP Matthews *et al*	Ratio
Bahamas	America	Phase 1 (pre-transition)	—	—
Bangladesh	Asia	Phase 3 (late transition)	—	—
Belize	America	Phase 2 (early transition)	—	—
Benin	Africa	Phase 3 (late transition)	—	—
Bhutan	Asia	Phase 1 (pre-transition)	—	—
Bolivia	America	Phase 2 (early transition)	R-PIN CIFOR (*Matthews et al*)	Ratio
Botswana	Africa	Phase 2 (early transition)	—	—
Brazil	America	Phase 2 (early transition)	NC Mongabay (*Matthews et al*) *CIFOR*	Ratio
Burkina Faso	Africa	Phase 2 (early transition)	—	—
Burundi	Africa	Phase 3 (late transition)	—	—
Cambodia	Asia	Phase 2 (early transition)	R-PP Matthews *et al*	Ordinal
Cameroon	Africa	Phase 2 (early transition)	CIFOR Mongabay (*R-PIN*) (*Matthews et al*)	Ratio
Cape Verde	Africa	Phase 4 (post-transition)	—	—
Central African Republic	Africa	Phase 2 (early transition)	R-PP	Ordinal
Chad	Africa	Phase 3 (late transition)	—	—
Chile	America	Phase 4 (post-transition)	R-PIN	Nominal
China	Asia	Phase 4 (post-transition)	—	—
Colombia	America	Phase 1 (pre-transition)	R-PP	Ratio
Comoros	Africa	Phase 3 (late transition)	—	—
Congo	Africa	Phase 1 (pre-transition)	R-PP	Ordinal
Costa Rica	America	Phase 4 (post-transition)	R-PP	Nominal
Cote d'Ivoire	Africa	Phase 4 (post-transition)	—	—
Cuba	America	Phase 4 (post-transition)	—	—
Democratic Republic of the Congo	Africa	Phase 1 (pre-transition)	R-PP Matthews *et al*	Ordinal
Dominica	America	Phase 3 (late transition)	—	—
Dominican Republic	America	Phase 3 (late transition)	—	—
Ecuador	America	Phase 2 (early transition)	Matthews *et al*	Nominal



El Salvador	America	Phase 3 (late transition)	R-PIN	Ordinal
Equatorial Guinea	Africa	Phase 2 (early transition)	R-PIN	Ordinal
Eritrea	Africa	Phase 3 (late transition)	—	—
Ethiopia	Africa	Phase 3 (late transition)	R-PP Matthews *et al*	Nominal
Fiji	Asia	Phase 2 (early transition)	Carbon Partnership	Ordinal
Gabon	Africa	Phase 1 (pre-transition)	R-PP (*Matthews et al*)	Nominal
Gambia	Africa	Phase 4 (post-transition)	—	—
Ghana	Africa	Phase 3 (late transition)	R-PP	Ratio
Guatemala	America	Phase 2 (early transition)	R-PP	Nominal
Guinea	Africa	Phase 2 (early transition)	—	—
Guinea-Bissau	Africa	Phase 2 (early transition)	—	—
Guyana	America	Phase 1 (pre-transition)	R-PP Interim report	Ratio
Haiti	America	Phase 3 (late transition)	—	—
Honduras	America	Phase 3 (late transition)	R-PIN	Nominal
India	Asia	Phase 4 (post-transition)	—	—
Indonesia	Asia	Phase 2 (early transition)	CIFOR R-PP NC (*Mongabay*) (*Matthews et al*)	Ratio
Jamaica	America	Phase 2 (early transition)	—	—
Kenya	Africa	Phase 3 (late transition)	R-PP	Nominal
Lesotho	Africa	Phase 4 (post-transition)	—	—
Lao People's Democratic Republic	Asia	Phase 2 (early transition)	R-PP Matthews *et al*	Nominal
Liberia	Africa	Phase 2 (early transition)	R-PP	Ordinal
Madagascar	Africa	Phase 2 (early transition)	R-PP Matthews *et al*	Nominal
Malawi	Africa	Phase 2 (early transition)	—	—
Malaysia	Asia	Phase 2 (early transition)	Matthews *et al*	Ratio
Mali	Africa	Phase 3 (late transition)	—	—
Mauritania	Africa	Phase 3 (late transition)	—	—
Mauritius	Africa	Phase 2 (early transition)	—	—
Mexico	America	Phase 3 (late transition)	R-PP Matthews *et al*	Ratio
Micronesia (Federated States of)	Asia	Phase 1 (pre-transition)	—	—
Mozambique	Africa	Phase 2 (early transition)	R-PIN	Nominal
Myanmar	Asia	Phase 3 (late transition)	Matthews *et al*	Ordinal
Namibia	Africa	Phase 3 (late transition)	—	
Nepal	Asia	Phase 3 (late transition)	R-PP Matthews *et al*	Nominal
Nicaragua	America	Phase 2 (early transition)	R-PIN	Nominal
Niger	Africa	Phase 3 (late transition)	—	—
Nigeria	Africa	Phase 3 (late transition)	—	—
Pakistan	Asia	Phase 3 (late transition)	—	—
Palau	Asia	Phase 1 (pre-transition)	—	—
Panama	America	Phase 3 (late transition)	R-PP	Nominal
Papua New Guinea	Asia	Phase 2 (early transition)	R-PP Matthews *et al*	Ratio
Paraguay	America	Phase 2 (early transition)	R-PIN	Nominal
Peru	America	Phase 1 (pre-transition)	R-PP Matthews *et al*	Ordinal
Philippines	Asia	Phase 4 (post-transition)	Matthews *et al*	Ordinal
Rwanda	Africa	Phase 4 (post-transition)	—	—
Saint Lucia	America	Phase 1 (pre-transition)	—	—
Saint Vincent and the Grenadines	America	Phase 2 (early transition)	—	—
Samoa	Asia	Phase 1 (pre-transition)	—	—
Sao Tome and Principe	Africa	Phase 3 (late transition)	—	—
Senegal	Africa	Phase 2 (early transition)	—	—
Sierra Leone	Africa	Phase 2 (early transition)	—	—
Singapore	Asia	Phase 3 (late transition)	—	—
Solomon Islands	Asia	Phase 2 (early transition)	—	—
Somalia	Africa	Phase 3 (late transition)	—	—
South Africa	Africa	Phase 3 (late transition)	—	—
Sri Lanka	Asia	Phase 2 (early transition)	—	—
Sudan	Africa	Phase 3 (late transition)	Matthews *et al*	Nominal
Surinam	America	Phase 1 (pre-transition)	R-PP	Nominal
Swaziland	Africa	Phase 4 (post-transition)	—	—
Tanzania	Africa	Phase 2 (early transition)	R-PP Matthews *et al*	Ordinal
Thailand	Asia	Phase 4 (post-transition)	R-PIN Matthews *et al*	Ordinal
Timor-Leste	Asia	Phase 2 (early transition)	—	—
Togo	Africa	Phase 3 (late transition)	—	—
Trinidad and Tobago	America	Phase 2 (early transition)	—	—
Uganda	Africa	Phase 2 (early transition)	R-PP Matthews *et al*	Ordinal
Uruguay	Africa	Phase 4 (post-transition)	—	—
Vanuatu	Asia	Phase 3 (late transition)	R-PIN	Nominal
Venezuela	America	Phase 2 (early transition)	—	—
Vietnam	Asia	Phase 4 (post-transition)	CIFOR R-PP (*Matthews et al*)	Ratio
Zambia	Africa	Phase 2 (early transition)	Matthews *et al*	Nominal
Zimbabwe	Africa	Phase 2 (early transition)	—	—

Figure A2a. Classification of countries (Hosonuma et al., 2012).

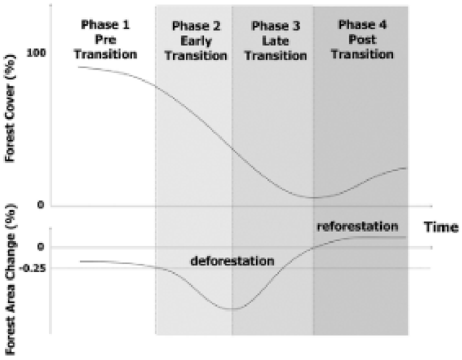


Figure 1. Four phases of the FT model as applied in this study.

Figure A2b. Forest curves (Hosonuma et al., 2012).

ANNEX 3.

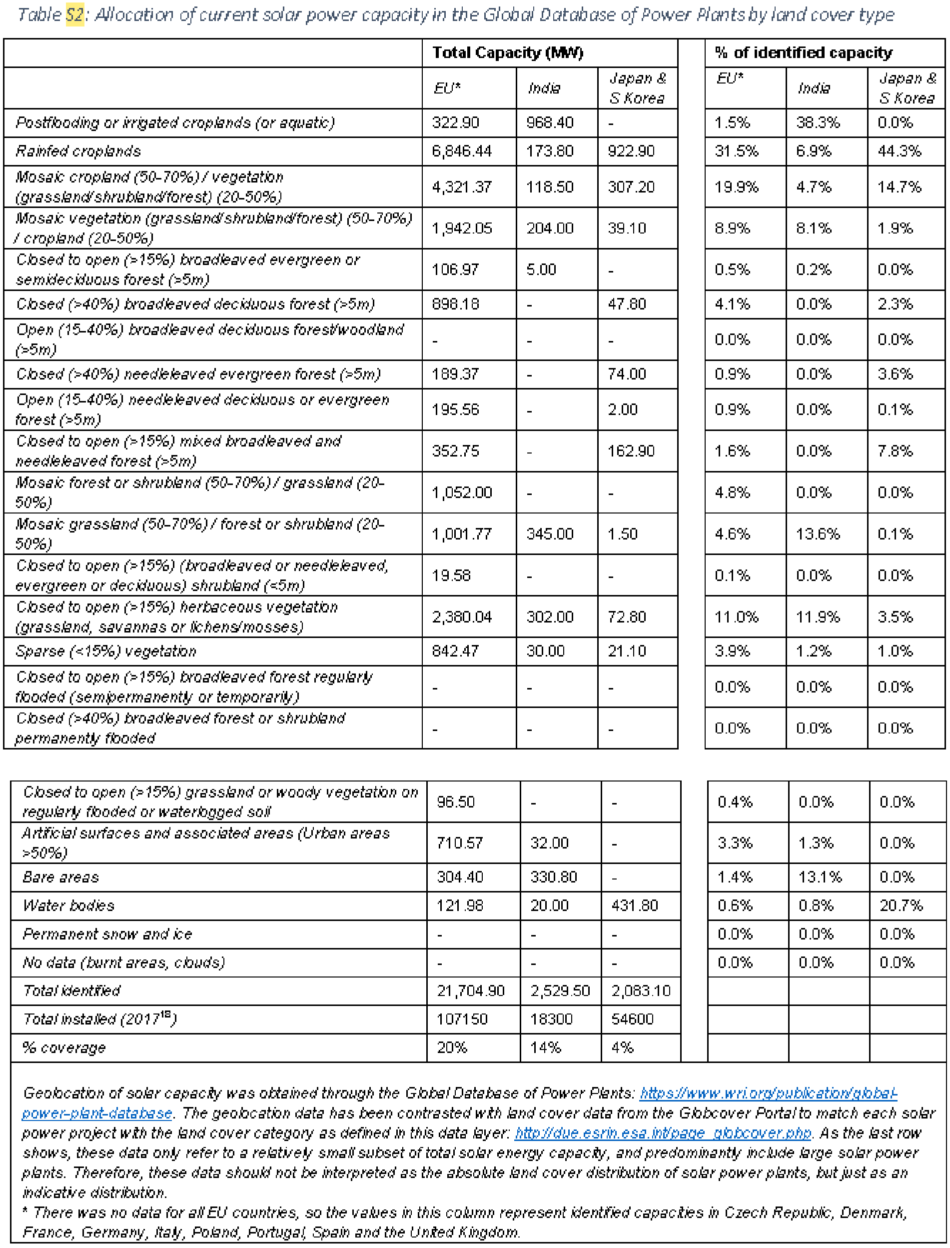


Table S2: Allocation of current solar power capacity in the Global Database of Power Plants by land cover type

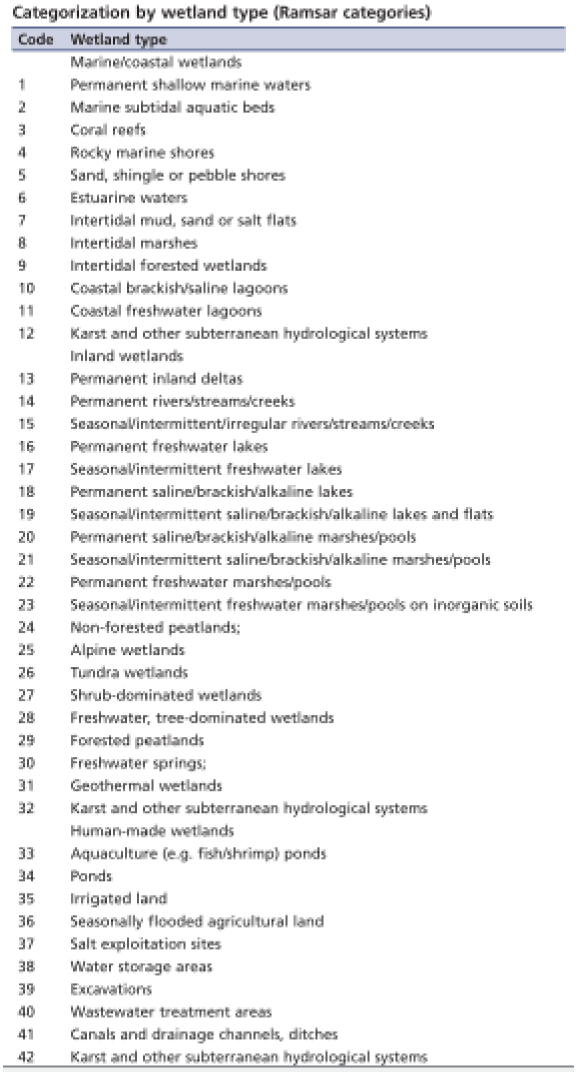
	Total Capacity (MW)			**% of identified capacity**		
	*EU**	*India*	*Japan & S Korea*	*EU**	*India*	*Japan & S Korea*
Postflooding or irrigated croplands (or aquatic)	322.90	968.40	-	1.5%	38.3%	0.0%
Rainfed croplands	6,846.44	173.80	922.90	31.5%	6.9%	44.3%
Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)	4,321.37	118.50	307.20	19.9%	4.7%	14.7%
Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	1,942.05	204.00	39.10	8.9%	8.1%	1.9%
Closed to open (>15%) broadleaved evergreen or semideciduous forest (>5m)	106.97	5.00	-	0.5%	0.2%	0.0%
Closed (>40%) broadleaved deciduous forest (>5m)	898.18	-	47.80	4.1%	0.0%	2.3%
Open (15-40%) broadleaved deciduous forest/woodland (>5m)	-	-	-	0.0%	0.0%	0.0%
Closed (>40%) needleleaved evergreen forest (>5m)	189.37	-	74.00	0.9%	0.0%	3.6%
Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	195.56	-	2.00	0.9%	0.0%	0.1%
Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	352.75	-	162.90	1.6%	0.0%	7.8%
Mosaic forest or shrubland (50-70%) / grassland (20-50%)	1,052.00	-	-	4.8%	0.0%	0.0%
Mosaic grassland (50-70%) / forest or shrubland (20-50%)	1,001.77	345.00	1.50	4.6%	13.6%	0.1%
Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)	19.58	-	-	0.1%	0.0%	0.0%
Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	2,380.04	302.00	72.80	11.0%	11.9%	3.5%
Sparse (<15%) vegetation	842.47	30.00	21.10	3.9%	1.2%	1.0%
Closed to open (>15%) broadleaved forest regularly flooded (semipermanently or temporarily)	-	-	-	0.0%	0.0%	0.0%
Closed (>40%) broadleaved forest or shrubland permanently flooded	-	-	-	0.0%	0.0%	0.0%
Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil	96.50	-	-	0.4%	0.0%	0.0%
Artificial surfaces and associated areas (Urban areas >50%)	710.57	32.00	-	3.3%	1.3%	0.0%
Bare areas	304.40	330.80	-	1.4%	13.1%	0.0%
Water bodies	121.98	20.00	431.80	0.6%	0.8%	20.7%
Permanent snow and ice	-	-	-	0.0%	0.0%	0.0%
No data (burnt areas, clouds)	-	-	-	0.0%	0.0%	0.0%
Total identified	21,704.90	2,529.50	2,083.10			
Total installed (2017[18])	107150	18300	54600			
% coverage	20%	14%	4%			

Geolocation of solar capacity was obtained through the Global Database of Power Plants: https://www.wri.org/publication/global-power-plant-database. The geolocation data has been contrasted with land cover data from the Globcover Portal to match each solar power project with the land cover category as defined in this data layer: http://due.esrin.esa.int/page_globcover.php. As the last row shows, these data only refer to a relatively small subset of total solar energy capacity, and predominantly include large solar power plants. Therefore, these data should not be interpreted as the absolute land cover distribution of solar power plants, but just as an indicative distribution.

** There was no data for all EU countries, so the values in this column represent identified capacities in Czech Republic, Denmark, France, Germany, Italy, Poland, Portugal, Spain and the United Kingdom.*

Figure A3. Allocation of current solar systems (van de Ven et al., 2021b).

ANNEX 4.



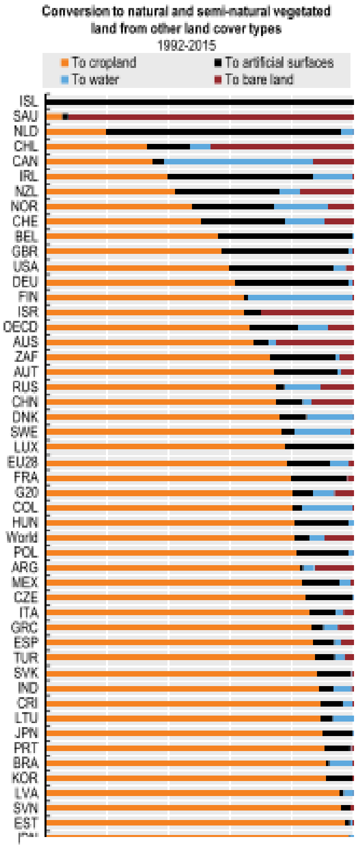
Categorization by wetland type (Ramsar categories)

Code	Wetland type
	Marine/coastal wetlands
1	Permanent shallow marine waters
2	Marine subtidal aquatic beds
3	Coral reefs
4	Rocky marine shores
5	Sand, shingle or pebble shores
6	Estuarine waters
7	Intertidal mud, sand or salt flats
8	Intertidal marshes
9	Intertidal forested wetlands
10	Coastal brackish/saline lagoons
11	Coastal freshwater lagoons
12	Karst and other subterranean hydrological systems
	Inland wetlands
13	Permanent inland deltas
14	Permanent rivers/streams/creeks
15	Seasonal/intermittent/irregular rivers/streams/creeks
16	Permanent freshwater lakes
17	Seasonal/intermittent freshwater lakes
18	Permanent saline/brackish/alkaline lakes
19	Seasonal/intermittent saline/brackish/alkaline lakes and flats
20	Permanent saline/brackish/alkaline marshes/pools
21	Seasonal/intermittent saline/brackish/alkaline marshes/pools
22	Permanent freshwater marshes/pools
23	Seasonal/intermittent freshwater marshes/pools on inorganic soils
24	Non-forested peatlands;
25	Alpine wetlands
26	Tundra wetlands
27	Shrub-dominated wetlands
28	Freshwater, tree-dominated wetlands
29	Forested peatlands
30	Freshwater springs;
31	Geothermal wetlands
32	Karst and other subterranean hydrological systems
	Human-made wetlands
33	Aquaculture (e.g. fish/shrimp) ponds
34	Ponds
35	Irrigated land
36	Seasonally flooded agricultural land
37	Salt exploitation sites
38	Water storage areas
39	Excavations
40	Wastewater treatment areas
41	Canals and drainage channels, ditches
42	Karst and other subterranean hydrological systems

Figure A4. Wetlands types considered (Wood & van Halsema, 2008)

ANNEX 5. (OECD, 2018)

Figure 4.5. The greatest share of natural and semi-natural vegetated land is converted to cropland



Source: OECD calculations using data from ESA/UCL-Geomatics (2017a) *Annual land cover state maps*

Figure A5a. Conversions from natural land to other uses by country (OECD, 2018).

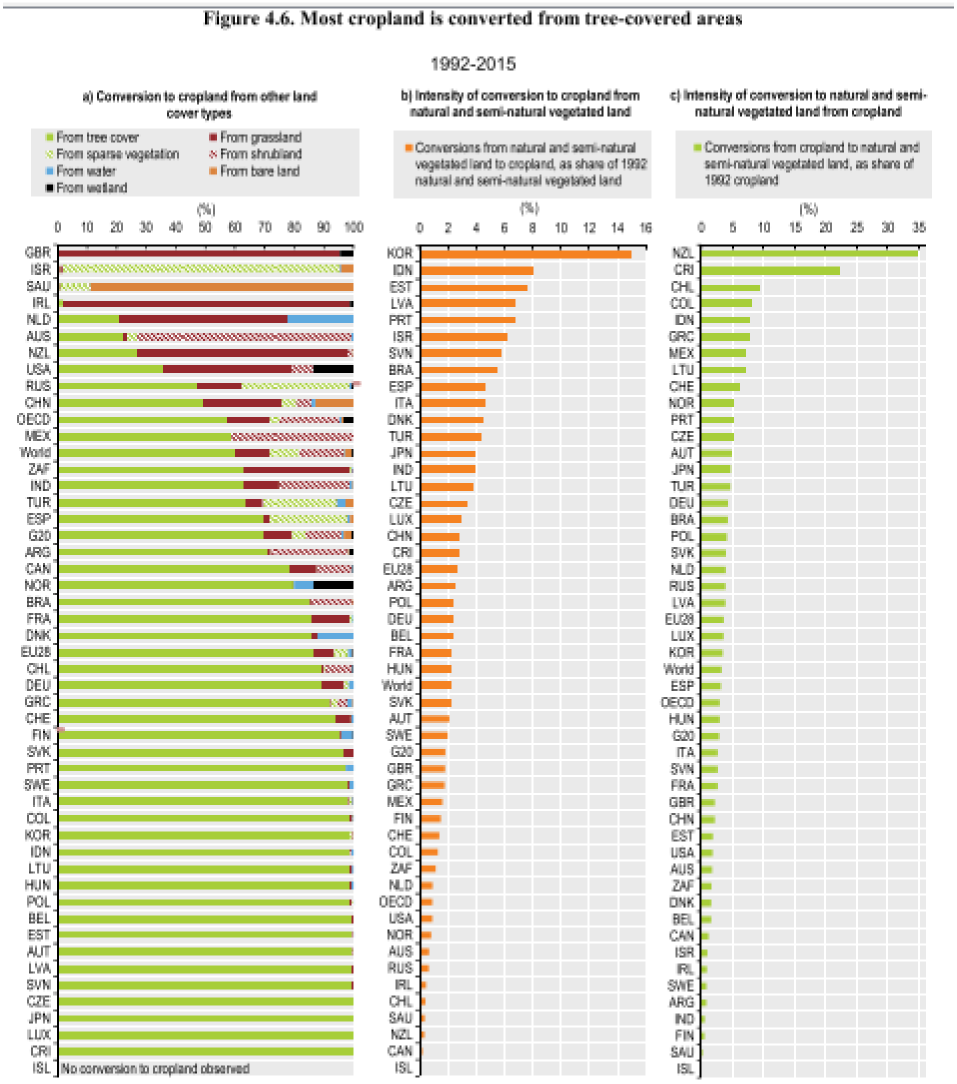


Figure A5b. Conversions to cropland from other land uses by country (OECD, 2018).

Figure 4.7. Most urban development occurs on cropland, 1992-2015

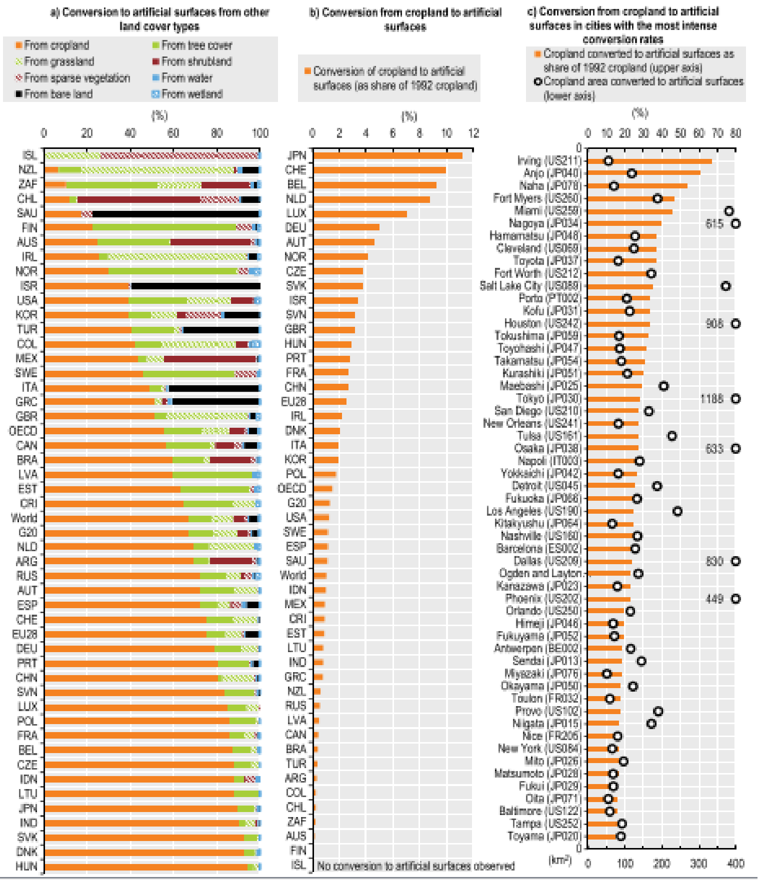


Figure A5c. Conversions to urban land from other land uses by country (OECD, 2018).

ANNEX 6. (Fischer et al., 2011)

TABLE 1: REGIONAL DISTRIBUTION OF MAIN LAND-USE/COVER CATEGORIES AROUND 2000

	Cultivated land		Grassland and woodland ecosystems		Forest land		Sparsely vegetated and barren land		Settlement and infrastucture		Inland water		Total
	Million ha	%	Million ha	%	Million ha	%	Million ha	%	Million ha	%	Million ha	%	Million ha
Northern America	230	11	673	32	609	29	451	22	15	0.7	112	5.4	2 090
Eastern Europe & Russia	205	11	604	33	850	46	142	8	10	0.6	27	1.5	1 838
Northern Europe	20	12	61	36	70	41	7	4	3	1.9	7	4.4	168
Southern Europe	44	34	37	29	43	33	1	1	3	2.6	2	1.2	129
Western Europe	35	33	34	31	32	30	0	0	6	5.3	1	0.6	108
Caribbean	7	32	7	34	5	24	0	1	1	3.5	1	5.8	22
Central America	36	15	99	40	89	36	16	6	3	1.1	4	1.6	246
South America	129	7	657	37	851	48	96	5	10	0.5	26	1.4	1 768
Australia & New Zealand	51	6	510	65	98	12	127	16	1	0.2	3	0.4	790
Melanesia	1	3	15	29	34	65	0	0	0	0.5	1	2.8	52
Eastern Africa	83	9	478	54	138	16	156	18	10	1.1	19	2.2	884
Central Africa	38	6	229	35	305	46	75	11	4	0.6	5	0.8	657
Northern Africa	19	3	33	6	5	1	514	89	3	0.5	2	0.3	575
Southern Africa	18	7	176	66	15	6	54	21	2	0.8	0	0.1	265
Western Africa	86	14	202	33	56	9	251	41	7	1.2	3	0.5	605
Western Asia	40	9	56	13	11	3	318	74	4	0.9	2	0.5	431
Southeastern Asia	97	22	111	25	210	48	0	0	11	2.5	7	1.6	436
Southern Asia	229	35	118	18	83	13	193	29	29	4.4	8	1.2	659
Eastern Asia	151	13	386	33	224	19	359	31	29	2.5	8	0.7	1 156
Central Asia	41	10	125	30	9	2	229	55	2	0.5	7	1.8	414
More developed	590	11	1 923	37	1 726	33	728	14	40	0.8	152	2.9	5 160
Less developed	969	12	2 689	33	2 009	25	2 261	28	112	1.4	94	1.2	8 135
World total	1 559	12	4 612	35	3 736	28	2 989	22	152	1.1	246	1.9	13 295

Source: GAEZ 2009; data compiled by authors.

Figure A6a. Land distribution by classes (%) by region (Fischer et al., 2011).

TABLE 3: PROTECTED LAND BY BROAD LAND USE / COVER CATEGORIES

Regions	Total land	Protected land			Grassland and woodland ecosystems	Forest ecosystems	Barren and sparsely vegetated ecosystems
	Million ha	Total Million ha	Protected (%)	Strictly protected (%)	Protected and strictly protected (%)	Protected and strictly protected (%)	Protected and strictly protected (%)
Northern America	2 090	271	1	12	12	8	29
Eastern Europe & Russia	1 838	180	1	9	10	10	15
Northern Europe	168	18	1	10	14	9	22
Southern Europe	129	24	4	14	25	28	24
Western Europe	108	13	2	10	16	19	36
Caribbean	22	2	3	7	11	19	7
Central America	246	25	5	5	7	13	30
South America	1 768	231	6	7	7	19	10
Australia & New Zealand	790	88	3	8	8	22	18
Melanesia	52	1	0	3	4	2	0
Eastern Africa	884	117	4	10	15	24	1
Central Africa	657	73	1	10	14	10	12
Northern Africa	575	19	1	3	0	3	4
Southern Africa	265	42	0	15	15	20	22
Western Africa	605	38	0	6	9	13	4
Western Asia	431	64	13	2	0	1	20
Southeastern Asia	436	60	2	12	16	19	49
Southern Asia	659	40	1	5	10	10	7
Eastern Asia	1 156	155	11	2	17	9	18
Central Asia	414	11	0	3	3	6	2
More developed	5 160	598	1	10	11	11	24
Less developed	8 135	874	4	6	11	16	9
World total	13 295	1 472	3	8	11	13	13

Source: GAEZ 2009; data compiled by authors.

Figure A6b. % of land in protected areas by land use by regions (Fischer et al., 2011).

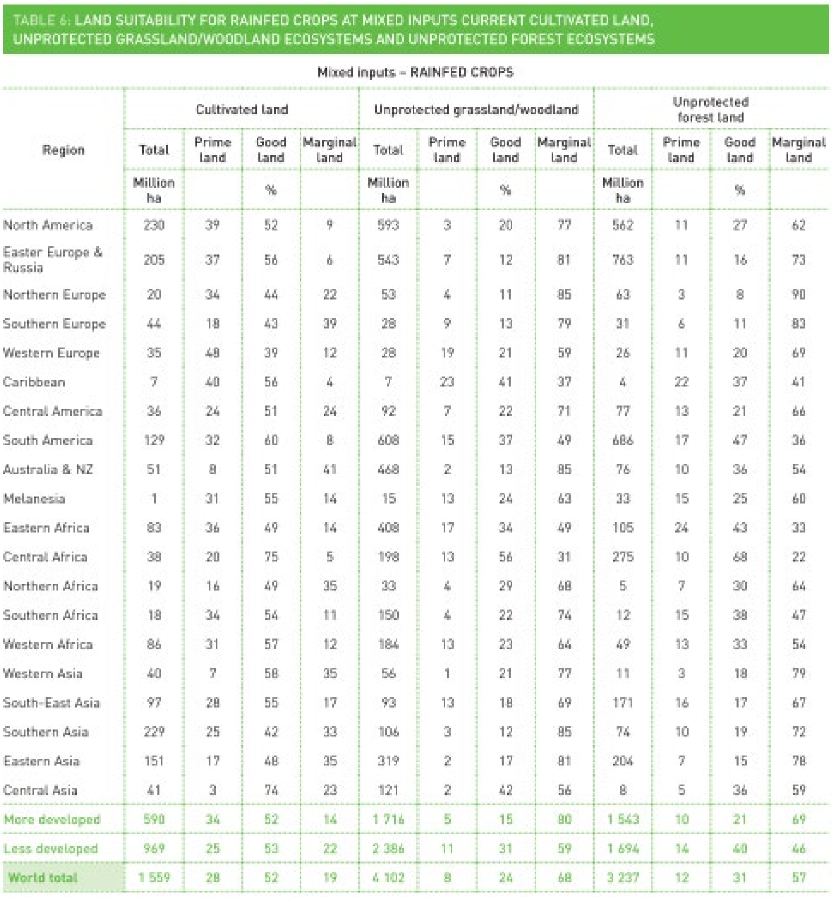


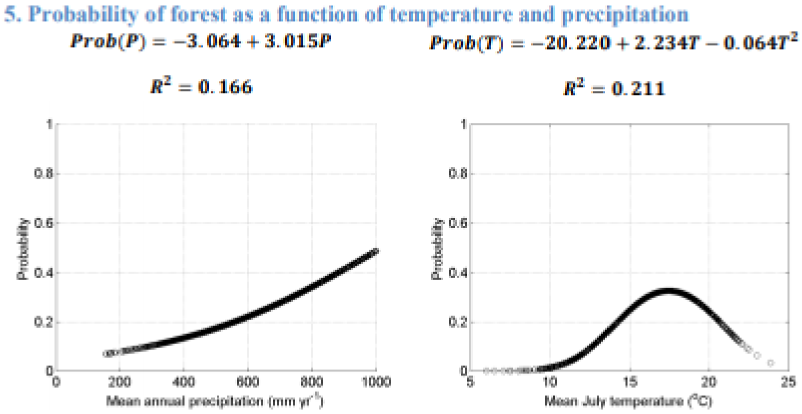
TABLE 6: LAND SUITABILITY FOR RAINFED CROPS AT MIXED INPUTS CURRENT CULTIVATED LAND, UNPROTECTED GRASSLAND/WOODLAND ECOSYSTEMS AND UNPROTECTED FOREST ECOSYSTEMS

Mixed inputs – RAINFED CROPS

Region	Cultivated land				Unprotected grassland/woodland				Unprotected forest land			
	Total	Prime land	Good land	Marginal land	Total	Prime land	Good land	Marginal land	Total	Prime land	Good land	Marginal land
	Million ha		%		Million ha		%		Million ha		%	
North America	230	39	52	9	593	3	20	77	562	11	27	62
Easter Europe & Russia	205	37	56	6	543	7	12	81	763	11	16	73
Northern Europe	20	34	44	22	53	4	11	85	63	3	8	90
Southern Europe	44	18	43	39	28	9	13	79	31	6	11	83
Western Europe	35	48	39	12	28	19	21	59	26	11	20	69
Caribbean	7	40	56	4	7	23	41	37	4	22	37	41
Central America	36	24	51	24	92	7	22	71	77	13	21	66
South America	129	32	60	8	608	15	37	49	686	17	47	36
Australia & NZ	51	8	51	41	468	2	13	85	76	10	36	54
Melanesia	1	31	55	14	15	13	24	63	33	15	25	60
Eastern Africa	83	36	49	14	408	17	34	49	105	24	43	33
Central Africa	38	20	75	5	198	13	56	31	275	10	68	22
Northern Africa	19	16	49	35	33	4	29	68	5	7	30	64
Southern Africa	18	34	54	11	150	4	22	74	12	15	38	47
Western Africa	86	31	57	12	184	13	23	64	49	13	33	54
Western Asia	40	7	58	35	56	1	21	77	11	3	18	79
South-East Asia	97	28	55	17	93	13	18	69	171	16	17	67
Southern Asia	229	25	42	33	106	3	12	85	74	10	19	72
Eastern Asia	151	17	48	35	319	2	17	81	204	7	15	78
Central Asia	41	3	74	23	121	2	42	56	8	5	36	59
More developed	590	34	52	14	1 716	5	15	80	1 543	10	21	69
Less developed	969	25	53	22	2 386	11	31	59	1 694	14	40	46
World total	1 559	28	52	19	4 102	8	24	68	3 237	12	31	57

Figure A6c. Land suitable for agriculture by land use by regions (Fischer et al., 2011).

ANNEX 7. BOREAL AND TEMPERATE FORESTS.



5. Probability of forest as a function of temperature and precipitation

$$Prob(P) = -3.064 + 3.015P$$

$$R^2 = 0.166$$

$$Prob(T) = -20.220 + 2.234T - 0.064T^2$$

$$R^2 = 0.211$$

$$Prob(P,T) = -21.088 + 2.947P + 2.099T - 0.058T^2$$

$$R^2 = 0.321$$

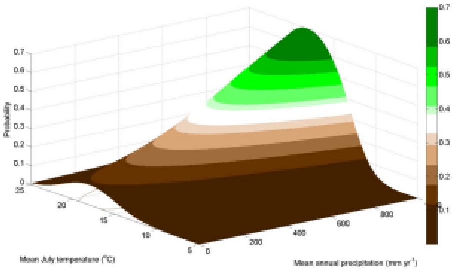


Figure S5 - Logistic regression models of the probability that a 500x500m grid-cell has boreal forest (tree cover >= 60%) as a function of mean annual precipitation (P, panel a), mean July temperature (T, panel b) (both averaged for the period 1961-2002), and the combination of the two (panel c). All terms in the logistic regression equations depicted in panels a, b and c are highly significant ($p < 0.05$).

Figure A7a. Boreal forest changes with temperature and precipitation (Scheffer et al., 2012)

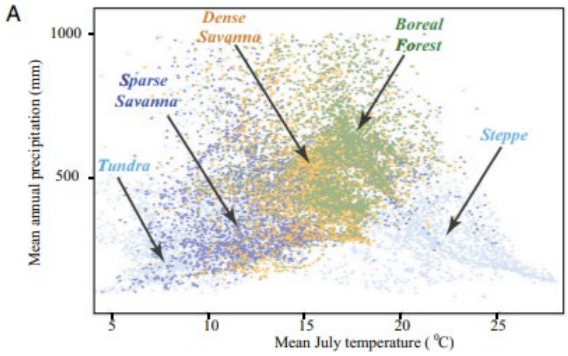


Figure A7b. Boreal vegetation depending on temperature and precipitation(Scheffer et al., 2012)

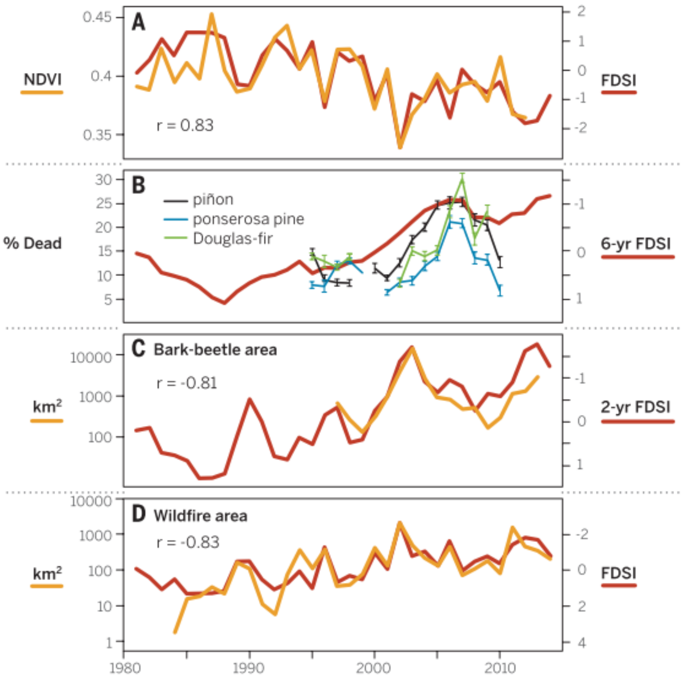


Fig. 3. Effects of hotter drought in the American Southwest. The forest drought-stress index (FDSI) integrates the effects of warm-season water deficit (controlled mostly by high temperature) and cold-season precipitation. Declining values of FDSI correspond to increasing drought. In the Southwest, increasing drought has been accompanied by (**A**) declining vegetation greenness [normalized difference vegetation index (NDVI)], a remotely sensed index of greenness; (**B**) increasing mortality of the three most common conifers; (**C**) increasing area affected by bark-beetle outbreaks; and (**D**) increasing area affected by wildfires. [Adapted by A. P. Williams (July 2015) with permission from Macmillan Publishers Ltd. (*15*)]

Figure A7c. Temperate forest variations (Millar & Stephenson, 2021)

REFERENCES

Bastin, J. F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C. M., & Crowther, T. W. (2019). The global tree restoration potential. *Science*, *364*(6448), 76–79. https://doi.org/10.1126/science.aax0848

Bestelmeyer, B. T., Okin, G. S., Duniway, M. C., Archer, S. R., Sayre, N. F., Williamson, J. C., & Herrick, J. E. (2015). Desertification, land use, and the transformation of global drylands. *Frontiers in Ecology and the Environment*, *13*(1), 28–36. https://doi.org/10.1890/140162

Bjørn, A., Sim, S., King, H., Keys, P., Wang-Erlandsson, L., Cornell, S. E., Margni, M., & Bulle, C. (2019). Challenges and opportunities towards improved application of the planetary boundary for land-system change in life cycle assessment of products. *Science of the Total Environment*, *696*(August). https://doi.org/10.1016/j.scitotenv.2019.133964

Burrell, A. L., Evans, J. P., & Kauwe, M. G. De. (2015a). Anthropogenic climate change has driven over 5 million km2 of drylands towards desertification. *Nature Communications*, *2020*, 1–11. https://doi.org/10.1038/s41467-020-17710-7

Burrell, A. L., Evans, J. P., & Kauwe, M. G. De. (2015b). Anthropogenic climate change has driven over 5 million km2 of drylands towards desertification. *Nature Communications*, *2020*, 1–11. https://doi.org/10.1038/s41467-020-17710-7

Cox, P. M., Betts, R. A., Collins, M., Harris, P. P., Huntingford, C., & Jones, C. D. (2004). Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theoretical and Applied Climatology*, *78*, 137–156. https://doi.org/10.1007/s00704-004-0049-4

FAO. (2016). Forests and agriculture: land-use challenges and opportunities. In *State of the World's Forests* (Vol. 45, Issue 12).

FAO. (2019). Trees, forests and land use in drylands: the first global assessment-Full report. FAO Forestry Paper No. 184. Rome. In *FAO Forestry Paper* (Issue 184). www.fao.org/%0Awww.fao.org/publications

FAO and UNEP. (2020). *The State of the World's Forests 2020. Forests, biodiversity and people.* FAO and UNEP. https://doi.org/10.4060/ca8642en

Fischer, G., Hizsnyik, E., Prieler, S., & Wiberg, D. (2011). *Scarcity and abundance of land resources: competing uses and the shrinking land resource base. SOLAW Background Thematic Report - TR02.* http://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/TR_02_light.pdf

Gaveau, D. L. A., Sheil, D., Husnayaen, Salim, M. A., Arjasakusuma, S., Ancrenaz, M., Pacheco, P., & Meijaard, E. (2016). Rapid conversions and avoided deforestation: Examining four decades of industrial plantation expansion in Borneo. *Scientific Reports*, *6*(June), 1–13. https://doi.org/10.1038/srep32017

Gerber, J. F. (2011). Conflicts over industrial tree plantations in the South: Who, how and why? *Global Environmental Change*, *21*(1), 165–176. https://doi.org/10.1016/j.gloenvcha.2010.09.005

Ghazoul, J. (2013). Deforestation and Land Clearing. In *Encyclopedia of Biodiversity: Second Edition* (Issue December 2013). Elsevier Ltd. https://doi.org/10.1016/B978-0-12-384719-5.00281-1

Gibbs, H. K., Ruesch, A. S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N., & Foley, J. A. (n.d.). *Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s*. https://doi.org/10.1073/pnas.0910275107

Graesser, J., Aide, T. M., Grau, H. R., & Ramankutty, N. (2015). Cropland/pastureland dynamics and the slowdown of deforestation in Latin America. *Environmental Research Letters*, *10*(3). https://doi.org/10.1088/1748-9326/10/3/034017

Heilmayr, R. (2014). Conservation through intensification? The effects of plantations on natural forests. *Ecological Economics*, *105*, 204–210. https://doi.org/10.1016/j.ecolecon.2014.06.008

Hirota, M., Holmgren, M., Nes, E. H. Van, & Scheffer, M. (2011). Global Resilience of Tropical Forest and Savanna to Critical Transitions. *Science*, *334*(October), 232–235. https://doi.org/10.1126/science.1210657

Hosonuma, N., Herold, M., De Sy, V., De Fries, R. S., Brockhaus, M., Verchot, L., Angelsen, A., & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, *7*(4). https://doi.org/10.1088/1748-9326/7/4/044009

Jones, C., Lowe, J., Liddicoat, S., & Betts, R. (2009). Committed terrestrial ecosystem changes due to climate change. *Nature Geoscience*, *2*(7), 484–487. https://doi.org/10.1038/ngeo555

Kirwan, M. L., & Gedan, K. B. (2019a). Sea-level driven land conversion and the formation of ghost forests. In *Nature Climate Change* (Vol. 9, Issue 6, pp. 450–457). Springer US. https://doi.org/10.1038/s41558-019-0488-7

Kirwan, M. L., & Gedan, K. B. (2019b). Sea-level driven land conversion and the formation of ghost forests. In *Nature Climate Change* (Vol. 9, Issue 6, pp. 450–457). Nature Publishing Group. https://doi.org/10.1038/s41558-019-0488-7

Mentaschi, L., Vousdoukas, M. I., Pekel, J. F., Voukouvalas, E., & Feyen, L. (2018). Global long-term observations of coastal erosion and accretion. *Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-018-30904-w

Millar, C. I., & Stephenson, N. L. (2021). *Temperate forest health in an era of emerging megadisturbance Downloaded from*. http://science.sciencemag.org/

Morales-Hidalgo, D., Oswalt, S. N., & Somanathan, E. (2015). Status and trends in global primary forest, protected areas, and areas designated for conservation of biodiversity from the Global Forest Resources Assessment 2015. *Forest Ecology and Management*, *352*, 68–77. https://doi.org/10.1016/j.foreco.2015.06.011

Msofe, N. K., Sheng, L., & Lyimo, J. (2019). Land use change trends and their driving forces in the Kilombero Valley Floodplain, Southeastern Tanzania. *Sustainability (Switzerland),* *11*(2). https://doi.org/10.3390/su11020505

Nahuelhual, L., Carmona, A., Lara, A., Echeverría, C., & González, M. E. (2012). Land-cover change to forest plantations: Proximate causes and implications for the landscape in south-central Chile. *Landscape and Urban Planning*, *107*(1), 12–20. https://doi.org/10.1016/j.landurbplan.2012.04.006

Ning, J., Liu, J., Kuang, W., Xu, X., Zhang, S., Yan, C., Li, R., Wu, S., Hu, Y., Du, G., Chi, W., Pan, T., & Ning, J. (2018). Spatiotemporal patterns and characteristics of land-use change in China during 2010–2015. *Journal of Geographical Sciences*, *28*(5), 547–562. https://doi.org/10.1007/s11442-018-1490-0

Odorico, P. D., Bhattachan, A., Davis, K. F., Ravi, S., & Runyan, C. W. (2013). Advances in Water Resources Global desertification : Drivers and feedbacks. *Advances in Water Resources*, *51*, 326–344. https://doi.org/10.1016/j.advwatres.2012.01.013

OECD. (2018). *Land Cover Change and Conversions: Methodology and Results for OECD ad G20 Countries*. *May*.

Pekel, J. F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, *540*(7633), 418–422. https://doi.org/10.1038/nature20584

Pendrill, F., Persson, U. M., Godar, J., & Kastner, T. (2019). Deforestation displaced: Trade in forest-risk commodities and the prospects for a global forest transition. *Environmental Research Letters*, *14*(5). https://doi.org/10.1088/1748-9326/ab0d41

Perpiña Castillo, C., Batista e Silva, F., & Lavalle, C. (2016). An assessment of the regional potential for solar power generation in EU-28. *Energy Policy*, *88*(2016), 86–99. https://doi.org/10.1016/j.enpol.2015.10.004

Scheffer, M., Hirota, M., Holmgren, M., Van Nes, E. H., & Chapin, F. S. (2012). Thresholds for boreal biome transitions. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(52), 21384–21389. https://doi.org/10.1073/pnas.1219844110

Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(40), 16083–16088. https://doi.org/10.1073/pnas.1211658109

Shi, G., Jiang, N., & Yao, L. (2018). Land use and cover change during the rapid economic growth period from 1990 to 2010: A case study of Shanghai. *Sustainability (Switzerland)*, *10*(2). https://doi.org/10.3390/su10020426

Staal, A., Dekker, S. C., Xu, C., & van Nes, E. H. (2016). Bistability, Spatial Interaction, and the Distribution of Tropical Forests and Savannas. *Ecosystems*, *19*(6), 1080–1091. https://doi.org/10.1007/s10021-016-0011-1

UNCCD. (2017). *Global Land Outlook: Secretariat of the United Nations Convention to Combat Desertification*.

United Nations. (2016). *The state of the World's Land and Water resources for food and agriculture. Managing systems at risk.*

van de Ven, D. J., Capellan-Peréz, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., & Gonzalez-Eguino, M. (2021a). The potential land requirements and related land use change emissions of solar energy. *Scientific Reports*, *11*(1), 1–12. https://doi.org/10.1038/s41598-021-82042-5

van de Ven, D. J., Capellan-Peréz, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., & Gonzalez-Eguino, M. (2021b). The potential land requirements and related land use change emissions of solar energy. *Scientific Reports*, *11*(1), 1–12. https://doi.org/10.1038/s41598-021-82042-5

van Vliet, J. (2019). Direct and indirect loss of natural area from urban expansion. *Nature Sustainability*, *2*(8), 755–763. https://doi.org/10.1038/s41893-019-0340-0

Wood, A., & van Halsema, G. E. (2008). Scoping agriculture – wetland interactions. In *FAO Water Reports* (Issue 33).

WORLD BANK. (2016). *Estimation of Climate Change Damage Functions for 140 Regions in the GTAP9 Database*. *June*.

Xu, C., Hantson, S., Holmgren, M., van Nes, E. H., Staal, A., & Scheffer, M. (2016). Remotely sensed canopy height reveals three pantropical ecosystem states. *Ecology*, *97*(9), 2518–2521. https://doi.org/10.1002/ecy.1470

Zomer, R. J., Trabucco, A., Bossio, D. A., & Verchot, L. V. (2008). Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agriculture, Ecosystems and Environment*, *126*(1–2), 67–80. https://doi.org/10.1016/j.agee.2008.01.014