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The ecological economics of land degradation: Impacts on ecosystem service values

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ABSTRACT

We use two datasets to characterize impacts on ecosystem services. The first is a spatially explicit measure of the impact of human consumption or 'demand' on ecosystem services as measured by the human appropriation of net primary productivity (HANPP) derived from population distributions and aggregate national statistics. The second is an actual measure of loss of productivity or a proxy measure of 'supply' of ecosystem services derived from biophysical models, agricultural census data, and other empirical measures. This proxy measure of land degradation is the ratio of actual NPP to potential NPP. The HANPP dataset suggests that current 'demand' for NPP exceeds 'supply' at a corresponding ecosystem service value of $10.5 trillion per year. The land degradation measure suggests that we have lost $6.3 trillion per year of ecosystem service value to impaired ecosystem function. Agriculture amounts to 2.8% of global GDP. With global GDP standing at $63 trillion in 2010, all of agriculture represents $1.7 Trillion of the world's GDP. Our estimate of lost ecosystem services represent a significantly larger fraction (~10%) of global GDP. This is one reason the economics of land degradation is about a lot more than the market value of agricultural products alone.

1. Introduction

It is becoming increasingly evident that land degradation is expensive, both to local owners and to society in general, over multiple time and space scales (Costanza et al., 1997; Bateman et al., 2013; Trucost, 2013; Von Braun et al., 2013; Costanza et al., 2014). The United Nations Convention to Combat Desertification (UNCCD), at RIO + 20, set a target of zero net land degradation (ELD-Initiative, 2013). The need to restore degraded lands and prevent further degradation is especially important now, as the demand for accessible productive land is increasing. These changes are projected to affect mainly tropical regions that are already vulnerable to other stresses, including the increasing unpredictability of rainfall patterns and extreme events as a result of climate change (IPCC, 2007; Foley et al., 2011).

Land degradation is a consequence of the poor management of natural capital (soils, water, vegetation, etc.). Better frameworks are needed to: (1) quantify the scale of the problem globally; (2) calculate the cost of business-as-usual (ELD-Initiative, 2013), and (3) assess the costs and benefits of restoration. Farmers and business leaders realize that ecosystem degradation is a material issue that affects their bottom line and future prosperity (ACCA et al., 2012). However, they lack the decision-making tools to develop robust and effective solutions to the problem. Modeling and simulation techniques enable the creation and evaluation of scenarios of alternative futures and decision tools to address this gap (Farley and Costanza, 2002; Costanza et al., 2006, 2013; Jarchow et al., 2012).

Managed land surface covers more than 60% of the Earth's total land surface. Approximately 60% of that is agricultural land use (Ellis et al., 2010; Foley et al., 2011). Ecosystems, including those from agricultural land, contribute to human well-being in a number of complex ways at multiple scales of space and time (Costanza and Daly, 1992; MEA, 2005, Dasgupta, 2008; Lal, 2012; UNEP, 2012; Costanza et al., 2013). Land degradation reduces the productivity of these ecosystems (Lal, 1997; MEA, 2005; DeFries et al., 2012) and results in "the reduction in the economic value of ecosystem services and goods derived from land as a result of anthropogenic activities or natural biophysical evolution" (ELD-Initiative, 2013). Ecosystem services, including, but not limited to, agricultural products, clean air, fresh water, disturbance regulation, climate regulation, recreational opportunities, and fertile soils are jeopardized by the effects of land degradation, globally (Walker et al., 2002; Foley et al., 2011; MEA, 2005; UNEP, 2012; Von Braun et al., 2013).

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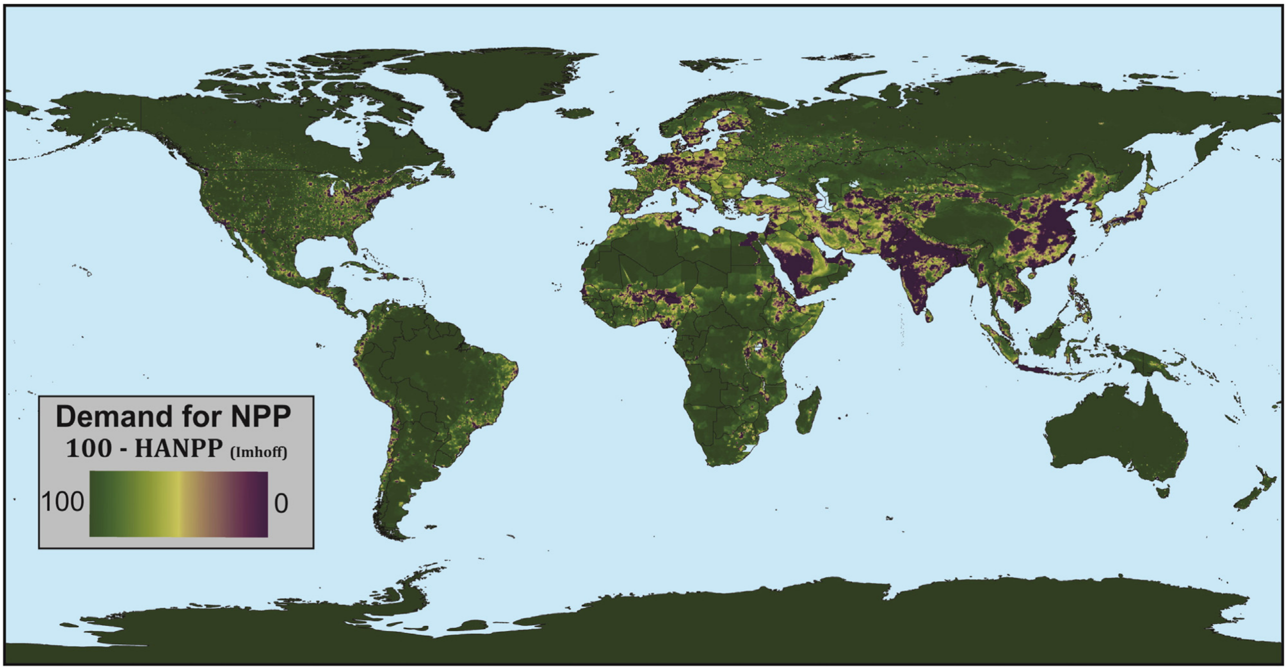


Fig. 1. A representation of Demand for NPP derived from Imhoff data.

In this paper, we investigate methods to assess the degree of global land degradation based on its effects on net primary productivity (NPP). We then derive the loss of ecosystem services value from land degradation globally. We pull out a few selected countries to see the spatially explicit results at a scale that allows them to be seen.

2. Data and Methods

Land degradation is a complex phenomenon that manifests in many ways. Numerous efforts using a variety of approaches have attempted to characterize the facets of land degradation over the last few decades. Gibbs and Salmon (2015) recently reviewed approaches to the development of land degradation indicators (e.g. expert opinion, satellite derived NPP, biophysical models, and abandoned cropland). The GLASOD project[1] (1987–1990) was a global assessment of human-induced soil degradation based primarily on expert opinion. The GLASOD effort separately characterized chemical deterioration, wind erosion susceptibility and damage, physical deterioration, and water erosion severity into categories of low, medium, high, and very high. An influential 1986 study estimated that humans were directly and indirectly appropriating 31% of the earth's NPP (Vitousek et al., 1986). A subsequent 2001 study arrived at a similar figure of 32% (Rojstaczer et al., 2011).

The FAO developed a map of land degradation represented by a loss of NPP. NPP is measured using a Rainfall Use Efficiency (RUE) adjusted Normalized Difference Vegetation Index (NDVI) derived from MODIS satellites as a proxy measure of land degradation[2] (Bai et al., 2008). There are many challenges associated with using satellite observations of NDVI as a proxy of NPP because of variability of rainfall and spatially varying agricultural and pastoral practices.

We sought spatially explicit global datasets that provide simple and general measures of the drivers and impacts of land degradation to use as a factor to adjust ecosystem service values on a pixel-by-pixel basis. There is growing consensus that the Human Appropriation of Net Primary Productivity (HANPP) is a useful 'integrated socioecological indicator' to characterize human impacts on biomass flows, and by extension land degradation and ecosystem services (Haberl et al., 2014). There are two ways to look at this. One is based on effects on the supply of services at the site of their production and the other based on effects on the demand for services at the site of their use. In this paper, we characterize both the 'Supply' of NPP at the point of production and the 'Demand' on NPP at the point of consumption or use.

2.1. Mapping Degradation of Supply – Land Degradation

Haberl et al. (2007) made an assessment of HANPP as a measure of land use intensity using process models and agricultural statistics. This data enables the representation of land degradation by spatially allocating land degradation primarily to the agricultural and grazing areas where the land degradation is actually taking place. This is a spatially explicit proxy of land degradation and by implication the degradation of the 'supply' of ecosystem services at the site of their production.

The Haberl et al. database was easy to access.[3] It consisted of several datasets including the following: 1) NPPo - a dynamic global vegetation model (DGVM) which is used to represent potential NPP in terms of gC/m^2/yr (Gerten et al., 2004; Sitch et al., 2003); 2) NPPact – an actual NPP layer calculated from harvest statistics in agricultural areas and livestock statistics that are used in grazing areas; 3) NPPh – the NPP destroyed during harvest; 4) NPPt the NPP remaining on the land surface after harvest; and finally ΔNPPlc – the impact of human-induced land conversions such as land cover change, land use change, and soil degradation.

We created a data layer that varied in value from 0 to 100 as a percentage ratio of NPPactual (tnap_all_gcm) and NPP potential - NPPo (tn0_all_gsm) (Fig. 1). We call this layer "supply degradation". Note this is not identical to their measure of HANPP but is closer to what we want as a measure of land degradation based on the loss of potential NPP at the site where that loss occurs.

[1] http://www.isric.org/data/global-assessment-human-induced-soil-degradation-glasod.

[2] http://www.fao.org/geonetwork/srv/en/metadata.show?id=37055.

[3] https://www.uni-klu.ac.at/socec/inhalt/1191.htm

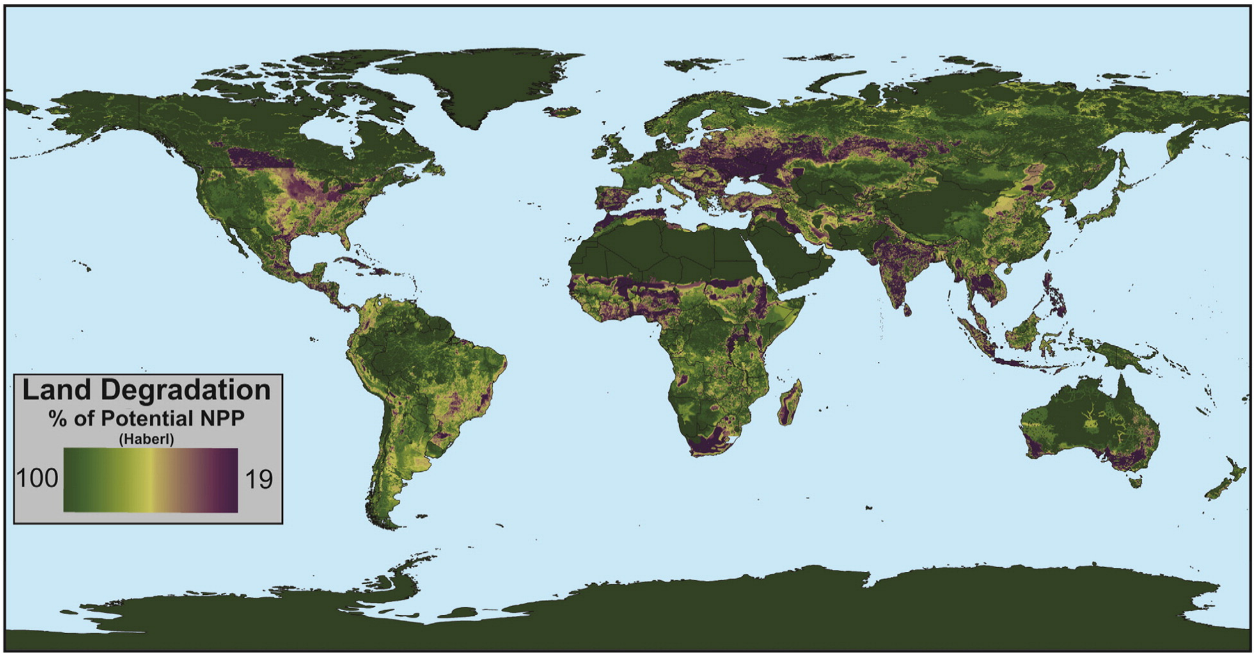
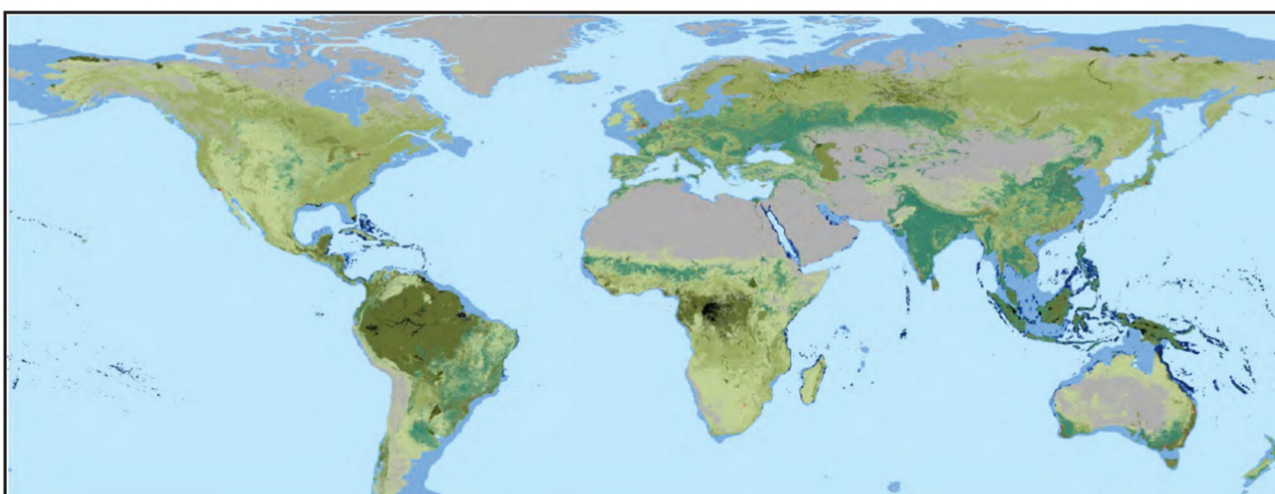


Fig. 2. A representation of land degradation derived from the Haberl data.

2.2. Mapping Demand - HANPP

Imhoff and Bounoua (2006) created what can be viewed as a demand-based measure of the driver of land degradation. They used demographic and economic data that is spatially mapped at the site of the demand and use of the NPP. They derived estimates of HANPP using models that employed empirical satellite observations of AVHRR and related statistical data (Imhoff et al., 2004; Cramer et al., 1999;



LandCover	Flow Value per Hectare per year	Legend	Area (millions of hectares)
Desert	$0		2159
Tundra	$0		433
Ice/Rock	$0		1640
Open Ocean	$491		33200
Marine Shelf	$2,222		2660
Grass/Rangelands	$2,871		4418
Temperate/Boreal Forest	$3,013		3003
Lakes/Rivers	$4,267		200
Tropical Forest	$5,264		1258
Cropland	$5,567		1672
Urban	$6,661		352
Swamps/Floodplains	$25,682		60
Tidal Marsh/Mangroves	$193,845		128
Coral Reefs	$352,249		28

Fig. 3. Ecosystem service values (adapted from Costanza et al., 2014).

Table 1
The total terrestrial ecosystem services value for each country before and after land degradation.
ESV terrestrial: The total ecosystem services value before land degradation.
ESV degraded: The total ecosystem services value after land degradation (% of potential NPP) is incorporated into the estimate.
% Degradation: Percent reduction in ecosystem services value between ESV Terrestrial and ESV Degraded.

Country	Population (in 2015)	Land Area (km2)	ESV Terrestrial (US$/yr)	ESV Degraded (US$/yr)	% Degradation
Afghanistan	27,101,365	641,358	125,604,005,570	107,437,394,250	14.5
Albania	2,893,005	28,798	13,342,184,554	9,301,152,510	30.3
Algeria	39,500,000	2,323,510	101,734,036,585	71,113,126,156	30.1
Andorra	76,949	336	223,529,166	221,310,650	1.0
Angola	24,383,301	1,252,935	554,607,181,753	517,469,927,495	6.7
Anguilla	13,452	74	88,400,970	87,877,400	0.6
Antigua & Barbuda	86,295	255	861,399,012	626,925,000	27.2
Argentina	43,131,966	2,776,913	2,134,944,725,840	1,945,834,216,540	8.9
Armenia	3,006,800	30,178	14,515,333,345	12,627,210,140	13.0
Aruba	107,394	140	588,301,896	376,692,900	36.0
Australia	23,846,700	7,694,273	3,290,360,649,480	3,066,790,443,510	6.8
Austria	8,602,112	82,869	34,955,562,713	31,785,458,841	9.1
Azerbaijan	9,636,600	164,056	46,312,333,886	40,902,056,654	11.7
Bahrain	1,316,500	236	292,018,573	289,582,900	0.8
Bangladesh	158,757,000	135,693	145,511,923,428	128,540,088,330	11.7
Belarus	9,481,000	205,964	131,703,050,541	102,380,018,155	22.3
Belgium	11,248,330	30,711	14,808,681,191	14,413,500,562	2.7
Belize	358,899	22,668	11,749,302,912	11,028,903,027	6.1
Benin	10,315,244	118,509	51,166,122,089	42,113,953,538	17.7
Bhutan	763,160	39,408	14,638,105,710	14,035,832,013	4.1
Bolivia	11,410,651	1,090,564	1,266,014,104,920	1,212,982,904,360	4.2
Bosnia & Herzegovina	3,791,622	51,366	20,963,567,418	16,259,075,274	22.4
Botswana	2,056,769	579,783	375,350,854,610	362,256,724,388	3.5
Brazil	204,671,000	8,493,132	6,806,175,667,670	6,352,281,515,570	6.7
British Virgin Is.	28,054	40	324,964,224	323,012,200	0.6
Brunei	393,372	6078	7,247,561,360	6,752,775,715	6.8
Bulgaria	7,202,198	110,523	49,875,530,520	37,284,470,551	25.2
Burkina Faso	18,450,494	274,056	131,690,280,755	101,942,349,319	22.6
Burundi	9,823,827	27,098	13,276,114,120	7,523,876,386	43.3
Cambodia	15,405,157	181,911	103,682,202,311	83,682,684,965	19.3
Cameroon	21,143,237	466,387	267,957,070,122	230,944,783,979	13.8
Canada	35,749,600	9,832,884	3,310,731,625,550	3,164,148,189,380	4.4
Cape Verde	518,467	2168	1,248,942,465	1,181,882,200	5.4
Cayman Is.	55,691	158	330,895,287	301,996,200	8.7
Central African Republic	4,803,000	619,933	238,962,420,945	232,040,357,207	2.9
Chad	13,606,000	1,270,759	300,166,987,967	273,138,458,551	9.0
Chile	18,006,407	722,511	256,151,917,823	242,298,715,358	5.4
China	1,371,210,000	9,402,887	3,149,889,472,520	2,941,508,831,470	6.6
Christmas I.	2072	99	32,100,096	30,621,600	4.6
Cocos Is.	550	10	385,810,908	326,093,100	15.5
Colombia	48,236,100	1,143,017	716,054,937,685	658,550,160,246	8.0
Comoros	784,745	1119	1,487,886,624	1,213,456,600	18.4
Congo	4,671,000	345,447	287,961,442,785	278,494,971,928	3.3
Congo, DRC	71,246,000	2,336,471	1,732,249,366,120	1,648,055,850,240	4.9
Costa Rica	4,773,130	52,894	42,277,286,901	35,485,475,508	16.1
Cote d'Ivoire	22,671,331	321,085	131,173,975,227	101,384,546,451	22.7
Croatia	4,267,558	53,541	24,838,916,955	19,195,106,082	22.7
Cuba	11,238,317	107,891	67,191,556,452	52,505,469,053	21.9
Cyprus	858,000	9894	4,186,790,682	3,428,043,223	18.1
Czech Republic	10,537,818	78,282	34,927,962,985	28,341,802,384	18.9
Denmark	5,668,743	41,103	27,586,694,805	27,010,572,172	2.1
Djibouti	900,000	20,503	3,145,713,144	2,900,751,059	7.8
Dominican Republic	10,652,000	47,266	25,297,893,069	18,786,808,261	25.7
Ecuador	15,538,000	254,767	159,133,422,199	144,593,225,833	9.1
Egypt	89,211,400	1,000,942	37,946,871,205	36,881,567,130	2.8
El Salvador	6,401,240	19,917	14,759,091,667	10,629,312,599	28.0
Equatorial Guinea	1,430,000	26,693	17,501,870,922	16,040,246,762	8.4
Eritrea	6,738,000	119,905	28,031,333,658	23,589,421,724	15.8
Estonia	1,313,271	45,515	60,700,981,423	50,545,493,215	16.7
Ethiopia	90,077,000	1,134,156	483,385,465,431	397,966,416,478	17.7
Falkland Is.	3000	10,217	8,021,687,736	7,508,688,700	6.4
Faroe Is.	48,846	710	472,114,397	465,394,100	1.4
Fiji	859,178	17,816	13,655,125,803	12,929,517,800	5.3
Finland	5,483,533	330,958	560,257,063,515	523,579,183,340	6.5
France	66,162,000	546,970	255,861,977,097	242,660,569,391	5.2
French Guiana	239,648	83,726	78,425,332,139	77,569,156,555	1.1
Gabon	1,751,000	262,971	167,492,911,054	162,391,225,102	3.0
Gaza Strip	1,816,000	228	6,434,257,968	6,149,800,873	4.4
Georgia	3,729,500	69,677	28,981,353,589	24,813,791,410	14.4
Germany	81,083,600	355,246	179,034,858,361	174,173,822,223	2.7
Ghana	27,043,093	240,310	105,370,419,169	83,921,874,285	20.4

(continued on next page)

Table 1 (*continued*)

Country	Population (in 2015)	Land Area (km2)	ESV Terrestrial (US$/yr)	ESV Degraded (US$/yr)	% Degradation
Glorioso Is.	0	5	1,532,869,636	1,328,358,500	13.3
Greece	10,903,704	125,515	58,193,849,117	52,275,916,398	10.2
Greenland	55,984	2,118,140	16,108,997,747	15,957,570,000	0.9
Grenada	103,328	179	371,044,884	339,403,700	8.5
Guadeloupe	405,739	1120	1,485,997,432	1,044,958,900	29.7
Guatemala	16,176,133	109,829	57,092,842,827	48,041,768,447	15.9
Guernsey	65,150	46	31,308,536	31,052,600	0.8
Guinea	10,628,972	245,517	154,882,657,107	136,827,275,800	11.7
Guinea-Bissau	1,788,000	31,398	107,728,807,704	89,287,644,228	17.1
Guyana	746,900	210,336	185,657,415,526	179,451,230,494	3.3
Haiti	10,911,819	27,949	15,365,266,431	7,865,903,042	48.8
Honduras	8,725,111	113,029	68,706,871,037	56,225,360,370	18.2
Hungary	9,849,000	92,174	48,413,573,141	40,637,594,875	16.1
Iceland	330,610	99,900	116,306,950,961	93,015,419,729	20.0
India	1,274,830,000	3,153,010	1,777,194,322,420	1,416,469,457,420	20.3
Indonesia	255,770,000	1,847,033	1,654,724,361,960	1,426,984,106,250	13.8
Iran	78,521,000	1,680,136	245,139,136,130	219,928,651,744	10.3
Iraq	36,004,552	434,754	46,556,282,387	27,604,710,136	40.7
Ireland	4,609,600	67,565	33,415,694,386	31,682,274,562	5.2
Isle of Man	84,497	290	235,599,950	230,193,200	2.3
Israel	8,358,100	22,671	6,434,257,968	6,149,800,873	4.4
Italy	60,788,245	301,101	141,511,690,207	119,861,277,752	15.3
Jamaica	2,717,991	10,992	5,633,821,483	4,676,462,478	17.0
Jan Mayen	20	470	46,264,110	41,262,500	10.8
Japan	126,865,000	370,727	149,230,560,387	134,483,597,123	9.9
Jersey	99,000	110	56,099,736	55,837,600	0.5
Jordan	6,759,300	87,399	4,317,802,912	3,626,423,738	16.0
Juan De Nova I.	0	5	1,532,869,636	1,328,358,500	13.3
Kazakhstan	17,519,000	2,832,826	1,007,663,857,170	896,146,652,513	11.1
Kenya	46,749,000	584,683	232,580,510,608	205,618,967,358	11.6
Kyrgyzstan	5,944,400	200,634	67,131,373,376	64,022,028,135	4.6
Laos	6,802,000	231,035	110,805,683,156	99,941,930,696	9.8
Latvia	1,980,700	64,745	53,549,724,621	40,782,027,286	23.8
Lebanon	4,104,000	10,808	4,724,136,687	4,056,179,385	14.1
Lesotho	2,120,000	30,800	11,770,323,259	8,750,726,434	25.7
Liberia	4,503,000	95,659	50,294,224,586	46,103,677,437	8.3
Libya	6,317,000	1,626,966	7,470,804,809	4,209,316,004	43.7
Liechtenstein	37,370	112	66,211,756	64,920,538	2.0
Lithuania	2,904,391	64,439	32,184,929,072	22,601,838,129	29.8
Luxembourg	562,958	2578	1,027,792,692	1,014,842,369	1.3
Macedonia	2,065,769	25,272	11,184,225,370	8,659,776,258	22.6
Madagascar	24,235,000	591,713	285,539,677,789	231,744,229,750	18.8
Malawi	16,310,431	117,440	67,943,987,307	62,888,020,250	7.4
Malaysia	30,657,700	328,536	233,773,982,290	201,539,949,449	13.8
Mali	16,259,000	1,258,013	368,982,387,012	306,929,750,476	16.8
Martinique	381,326	780	741,585,744	660,934,600	10.9
Mauritania	3,631,775	1,038,293	84,313,981,062	66,139,471,048	21.6
Mauritius	1,261,208	1413	4,408,485,986	3,871,917,300	12.2
Mayotte	212,645	268	886,407,732	758,904,300	14.4
Mexico	121,470,000	1,953,851	831,883,939,928	745,221,250,753	10.4
Micronesia	101,351	156	2,046,907,355	1,745,195,000	14.7
Moldova	3,555,200	33,548	18,002,628,428	11,239,488,385	37.6
Monaco	37,800	5	5,158,276	5,022,836	2.6
Mongolia	3,028,222	1,557,318	315,058,346,109	298,505,444,086	5.3
Morocco	33,337,529	406,452	103,057,948,860	71,172,474,630	30.9
Mozambique	25,727,911	793,980	294,631,960,656	273,601,927,801	7.1
Myanmar	54,164,000	659,592	369,854,638,360	314,097,712,461	15.1
Namibia	2,280,700	827,897	308,542,783,163	299,166,531,928	3.0
Nepal	28,037,904	148,253	61,433,193,925	57,162,076,130	7.0
Netherlands	16,913,100	34,691	16,808,004,168	16,558,247,881	1.5
Netherlands Antilles	227,049	440	828,402,876	692,714,400	16.4
New Caledonia	268,767	17,946	14,994,039,242	13,966,543,900	6.9
New Zealand	4,603,530	267,214	116,184,352,404	109,672,447,619	5.6
Nicaragua	6,134,270	129,796	87,319,317,035	74,705,072,802	14.4
Niger	19,268,000	1,184,364	145,522,881,758	115,110,183,689	20.9
Nigeria	183,523,000	913,388	483,684,347,551	371,659,506,206	23.2
North Korea	25,155,000	122,847	39,562,403,102	34,683,099,813	12.3
Northern Mariana Is.	53,883	73	482,246,849	460,964,800	4.4
Norway	5,176,998	305,866	516,752,911,018	475,694,325,365	7.9
Oman	4,163,869	310,328	4,799,186,314	4,537,996,391	5.4
Pakistan	190,476,000	880,203	215,598,474,382	209,384,732,993	2.9
Palau	20,901	231	360,091,025	290,916,600	19.2
Panama	3,764,166	73,680	50,932,961,350	40,143,737,324	21.2
Papua New Guinea	7,398,500	458,666	382,426,184,286	365,964,707,656	4.3
Paraguay	7,003,406	401,191	497,135,043,355	479,604,107,999	3.5
Peru	31,151,643	1,296,605	895,343,136,380	839,787,366,767	6.2

Table 1 (*continued*)

Country	Population (in 2015)	Land Area (km2)	ESV Terrestrial (US$/yr)	ESV Degraded (US$/yr)	% Degradation
Philippines	101,816,000	280,958	187,631,541,215	133,036,117,065	29.1
Poland	38,484,000	312,136	150,781,294,242	110,867,520,190	26.5
Portugal	10,477,800	90,411	39,854,111,835	30,351,239,117	23.8
Puerto Rico	3,548,397	9084	4,765,444,725	3,918,165,168	17.8
Qatar	2,344,005	10,621	263,008,968	247,938,500	5.7
Reunion	844,944	2230	1,532,869,636	1,328,358,500	13.3
Romania	19,942,642	237,076	162,276,500,633	123,778,519,131	23.7
Russia	146,531,140	16,897,294	14,148,651,821,100	13,101,177,838,500	7.4
Rwanda	10,996,891	25,036	11,513,699,608	6,582,060,155	42.8
Sao Tome & Principe	187,356	708	1,382,025,848	1,323,907,500	4.2
Saudi Arabia	31,521,418	1,936,713	28,789,030,111	27,870,811,565	3.2
Senegal	13,508,715	197,396	165,340,510,453	135,169,597,754	18.2
Serbia & Montenegro	10,830,000	102,667	45,891,606,736	33,370,985,034	27.3
Seychelles	89,949	222	839,646,528	592,080,100	29.5
Sierra Leone	6,319,000	73,113	49,346,128,568	43,092,200,752	12.7
Slovakia	5,421,349	48,560	21,132,915,391	16,804,736,591	20.5
Slovenia	2,067,452	20,625	7,664,569,273	6,720,506,703	12.3
Solomon Is.	581,344	21,573	20,149,908,224	18,128,421,600	10.0
Somalia	11,123,000	637,888	237,589,530,224	222,276,331,149	6.4
South Africa	54,002,000	1,219,930	460,032,415,732	349,655,148,375	24.0
South Korea	51,431,100	94,773	34,290,170,182	33,925,123,042	1.1
Spain	46,439,864	503,250	225,871,319,918	174,941,008,537	22.5
Sri Lanka	20,675,000	64,665	33,704,825,005	24,281,749,087	28.0
St. Kitts & Nevis	55,000	165	453,596,858	415,176,200	8.5
St. Lucia	185,000	321	431,649,302	366,389,100	15.1
St. Pierre & Miquelon	6069	286	166,747,493	160,280,000	3.9
St. Vincent & the Grenadines	109,000	237	653,252,979	580,307,800	11.2
Sudan	38,435,252	2,496,340	1,357,783,593,060	1,205,412,282,940	11.2
Suriname	534,189	143,155	142,145,073,413	139,723,218,870	1.7
Svalbard	2562	60,119	46,264,110	41,262,500	10.8
Swaziland	1,119,375	16,823	6,552,971,715	6,438,764,831	1.7
Sweden	9,784,445	442,246	696,318,638,583	656,301,572,980	5.7
Switzerland	8,256,000	41,854	17,531,017,091	16,331,837,966	6.8
Syria	23,307,618	190,030	31,811,426,773	21,570,707,029	32.2
Tajikistan	8,354,000	143,924	37,547,875,382	33,598,374,813	10.5
Tanzania	48,829,000	942,536	470,259,561,299	435,374,964,270	7.4
Thailand	65,104,000	515,357	278,217,006,344	189,920,967,664	31.7
The Bahamas	368,390	10,714	26,834,976,107	23,697,360,900	11.7
The Gambia	1,882,450	9970	34,830,546,465	29,593,996,254	15.0
Timor Leste	1,212,107	15,496	8,739,535,440	7,237,456,206	17.2
Togo	7,171,000	56,187	23,658,437,294	15,729,364,925	33.5
Trinidad & Tobago	1,328,019	4421	5,896,615,368	4,124,821,629	30.0
Tunisia	10,982,754	156,669	28,377,378,458	13,106,917,361	53.8
Turkey	77,695,904	778,602	352,510,270,023	276,212,101,216	21.6
Turkmenistan	4,751,120	552,479	70,421,423,516	68,189,735,380	3.2
Turks & Caicos Is.	31,458	163	531,984,720	480,144,400	9.7
Uganda	34,856,813	245,631	139,726,325,318	108,996,141,195	22.0
Ukraine	42,836,922	593,788	339,916,939,287	210,981,130,860	37.9
United Arab Emirates	9,577,000	68,172	710,124,052	696,125,158	2.0
United Kingdom	64,800,000	238,074	106,563,514,916	102,014,440,151	4.3
United States	321,504,000	9,426,295	5,212,482,947,600	4,794,246,500,410	8.0
Uruguay	3,415,866	178,438	126,020,633,160	120,116,484,754	4.7
Uzbekistan	31,022,500	446,633	89,865,211,619	85,847,120,933	4.5
Vanuatu	264,652	8457	9,595,348,990	8,915,714,000	7.1
Venezuela	30,620,404	913,485	687,905,093,658	647,445,345,281	5.9
Vietnam	91,812,000	322,743	162,603,792,051	132,965,385,577	18.2
Virgin Is.	106,405	178	169,419,874	157,442,200	7.1
West Bank	1,715,000	4861	6,434,257,968	6,149,800,873	4.4
Western Sahara	510,713	268,179	418,429,456	407,974,300	2.5
Yemen	25,956,000	455,126	24,962,733,913	24,297,086,955	2.7
Zambia	15,473,905	753,941	488,217,658,883	458,222,575,968	6.1
Zimbabwe	13,061,239	391,456	155,663,001,987	143,702,164,405	7.7
World Totals	7,192,307,915	134,477,937	68,782,784,666,249	62,462,358,238,329	**9.2**

Potter et al., 1993). This approach spatially allocates the HANPP to the location of its consumption, which identifies the spatial location of 'demand' on the land or the consumption of the products that caused the land degradation in the first place (Fig. 2).

Comparison of the supply and demand maps show significant differences, as one would expect (Figs. 1 & 2). For example, India and China show that they are the significant sources of the demand for NPP, particularly relative to local supply. Meanwhile the mid-west of the United States and central Canada show much more significant levels of impacts to the supply of NPP. It should be noted that these differences do not suggest inaccuracy on the part of either dataset. These datasets are representative of two connected but distinct phenomena. We chose to show both because their juxtaposition is an interesting exploration of the spatial separation of consumption (demand) from production (supply). The land degradation map (Fig. 1) shows the actual degradation of the supply of NPP, while the demand map (Fig. 2) shows the

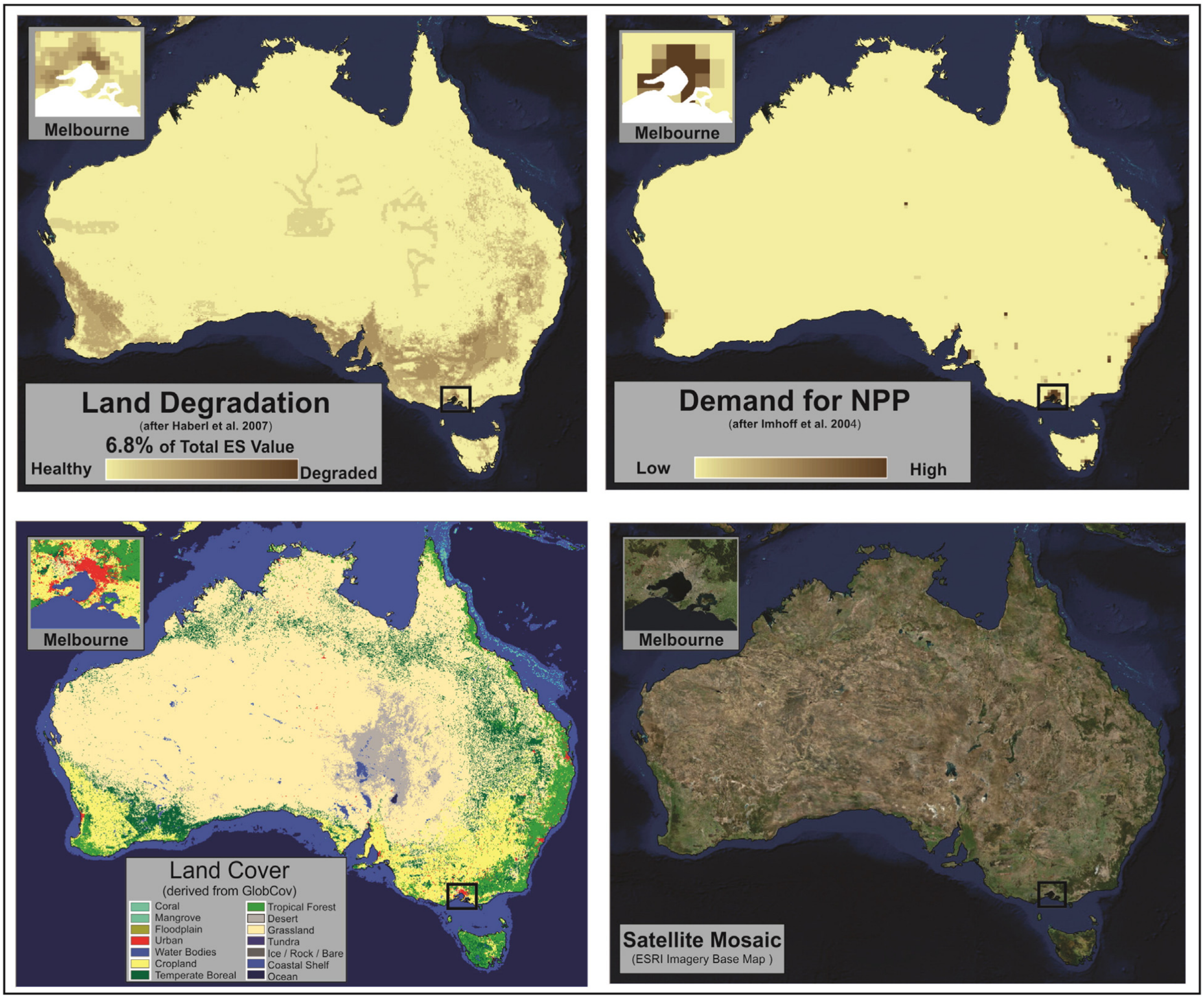


Fig. 4. Representations of land degradation and land cover for Australia.

consumption or demand for NPP that is driving the land degradation. Supply and demand for NPP are often in different parts of the world.

2.3. Ecosystem Service Losses from Land Degradation

The third dataset used in this analysis was a representation of ecosystem service values based on land cover (Costanza et al., 2014) (Fig. 3). For this study we only used terrestrial values because our representation of land degradation did not include coastal estuaries, coral reefs, and ocean areas. These figures present the data products as they were obtained (i.e. in an unprojected geographic or platte carre equi-rectangular projection). Our calculations assume ecosystem service values are a function of areal extent and consequently our analyses have all been converted to their corresponding area. We mapped the effects of land degradation on ecosystem services via the simple process of multiplying three raster representations as follows:

$$\mathbf{ESV\_Supply} = \mathbf{ESV}(\mathbf{Figure\ 3}) * \mathbf{Land\ Degradation}(\mathbf{Figure\ 2}) * \mathbf{Area\ in\ Hectares}$$

This results in a spatially explicit representation of ecosystem service value as adjusted by the measure of 'land degradation'. Global and national aggregations of these are presented as results.

We emphasize that this is a global study and our results are estimates. We merely pull out specific countries for better viewing of the results. It is not an aggregation of individual country studies. Therefore, this study uses simple benefit transfer methods, based on global averages, to estimate the effects on ecosystem service values. As more and better information becomes available, or if one wanted to do a more detailed regional scale study, more sophisticated benefit transfer methods or other modeling methods can be used (Bateman et al., 2013; Schmidt et al., 2016; Turner et al., 2016). However, a recent study comparing country level analysis and a global analysis for the same countries, showed that higher resolution land use data and more country specific unit values resulted in total values that are within 10% of the estimates using global averages the way we are doing here (Kubiszewski et al., 2016).

3. Results

The estimated impacts on the total value of ecosystem services for each nation were obtained using this proxy measure of land degradation (Table 1). Globally this proxy estimates a 9.2% weighted average decrease in the global annual value of ecosystem services from land degradation. Russia, the largest nation of the world in terms of areal extent (just under 17 million km^2) has a total terrestrial ecosystem service value (ESV Terrestrial) of \$14.1 trillion/year. We estimate that Russia's land

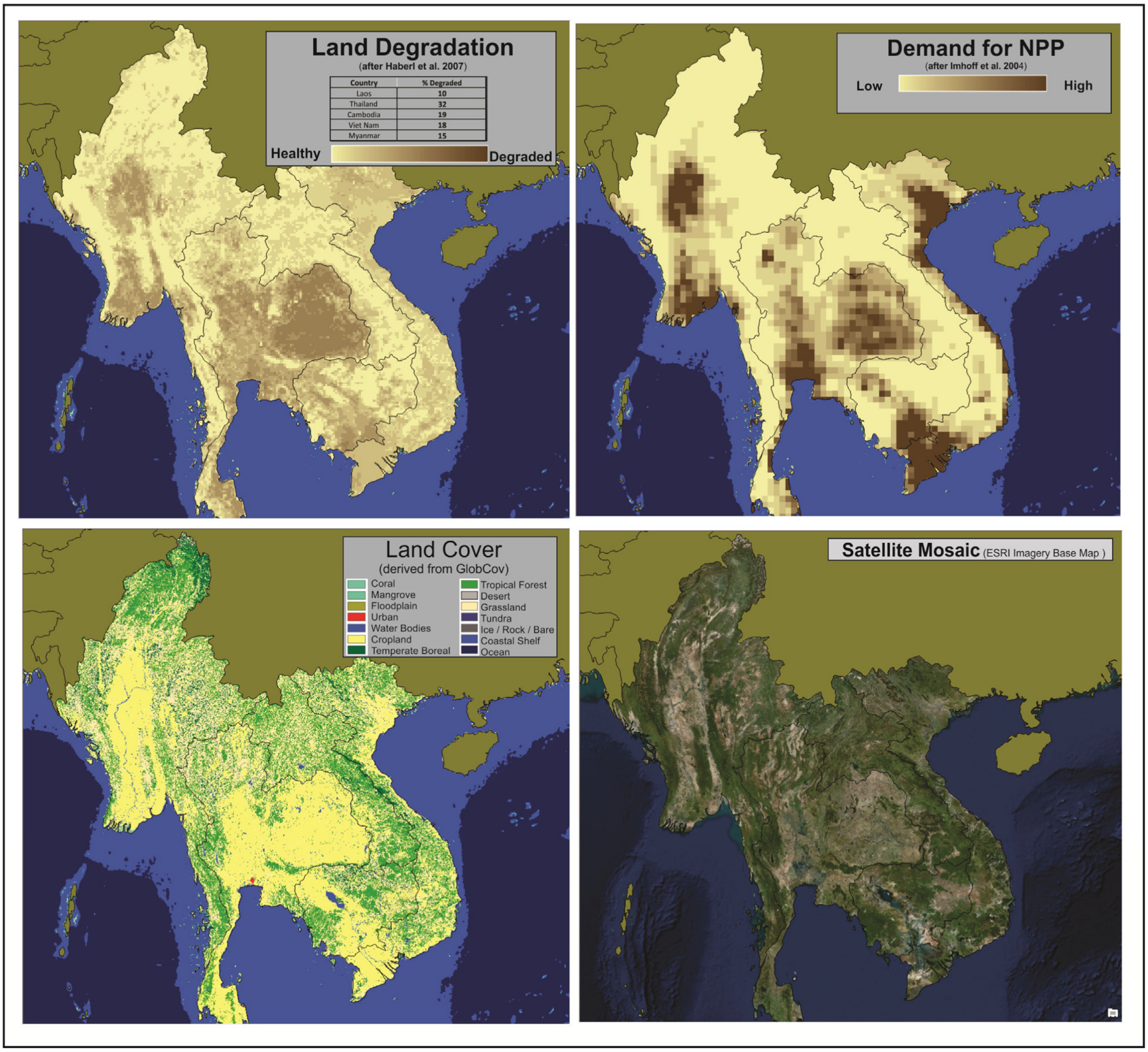


Fig. 5. Representations of land degradation and land cover for Southeast Asia.

degradation has resulted in a 7.4% loss, reducing the total value of its ecosystem services to $13.1 trillion/year. In India, the impact is a 20.3% loss of ecosystem service value (ESV). Our estimate for China is a loss of 6.6% of total ESV. In the United States, the loss is estimated to be 8%.

The ten countries with the highest percentage levels of degradation were: Tunisia (53.8%), Haiti (48.8%), Libya (43.7%), Burundi (43.3%), Rwanda (42.8%), Iraq (40.7%), Ukraine (37.9%), Moldova (37.6%), and Aruba (36.0%). At the national level, the spatial patterns of land degradation and their impacts on the loss of ESV varied dramatically from one country to another.

Australia provides an interesting example of striking differences in the spatial pattern of land degradation relative to the location of demand for NPP (Fig. 4). The total value of terrestrial ecosystem services in Australia is roughly $3.2 trillion/year (Costanza et al., 2014). The land degradation for Australia includes most of Australia's agricultural areas and some central shrublands. The demand for NPP is much more focused on areas of intense human settlement in and around the capital cities (Fig. 4). The loss of ecosystem services from land degradation is estimated at $224 billion/year. These results are likely a consequence of the highly urbanized and spatially concentrated population of Australia and the fact that Australia is a net exporter of food and ecosystem service value.

Southeast Asia diverges from the findings for Australia (Fig. 5). The total annual value of ecosystem services for this region is roughly $1 trillion/year (Costanza et al., 2014). The overall spatial patterns of land degradation and demand for NPP generally agree because these countries have significant rural populations. We estimate losses to annual value of ecosystem services as a result of land degradation for this region to be $100 billion/year (Fig. 5). The overall losses presented here respectively represent a 10% annual loss of ecosystem service value. In contrast to Australia this region of the world is likely in some sort of ecological deficit (Wackernagel et al., 2002; Sutton et al., 2012).

Germany provides a striking contrast to the patterns seen in Australia as well (Fig. 6). In Germany the demand for NPP shows widespread demand for ecosystem services throughout the nation, while the land degradation shows degradation as much more concentrated in and around the urban centers (Fig. 6). The annual value of ecosystem services from German lands is estimated to be $179 billion/year (Costanza et al., 2014). The losses to land degradation impacts on ecosystem service value are around 3% or $4.8 billion/year. The demand for NPP is a result of the high levels of consumption characteristic of the population of a western European nation. The land degradation is nonetheless not very extensive or severe and likely results from significant soil inputs and a highly regulated agricultural industry.

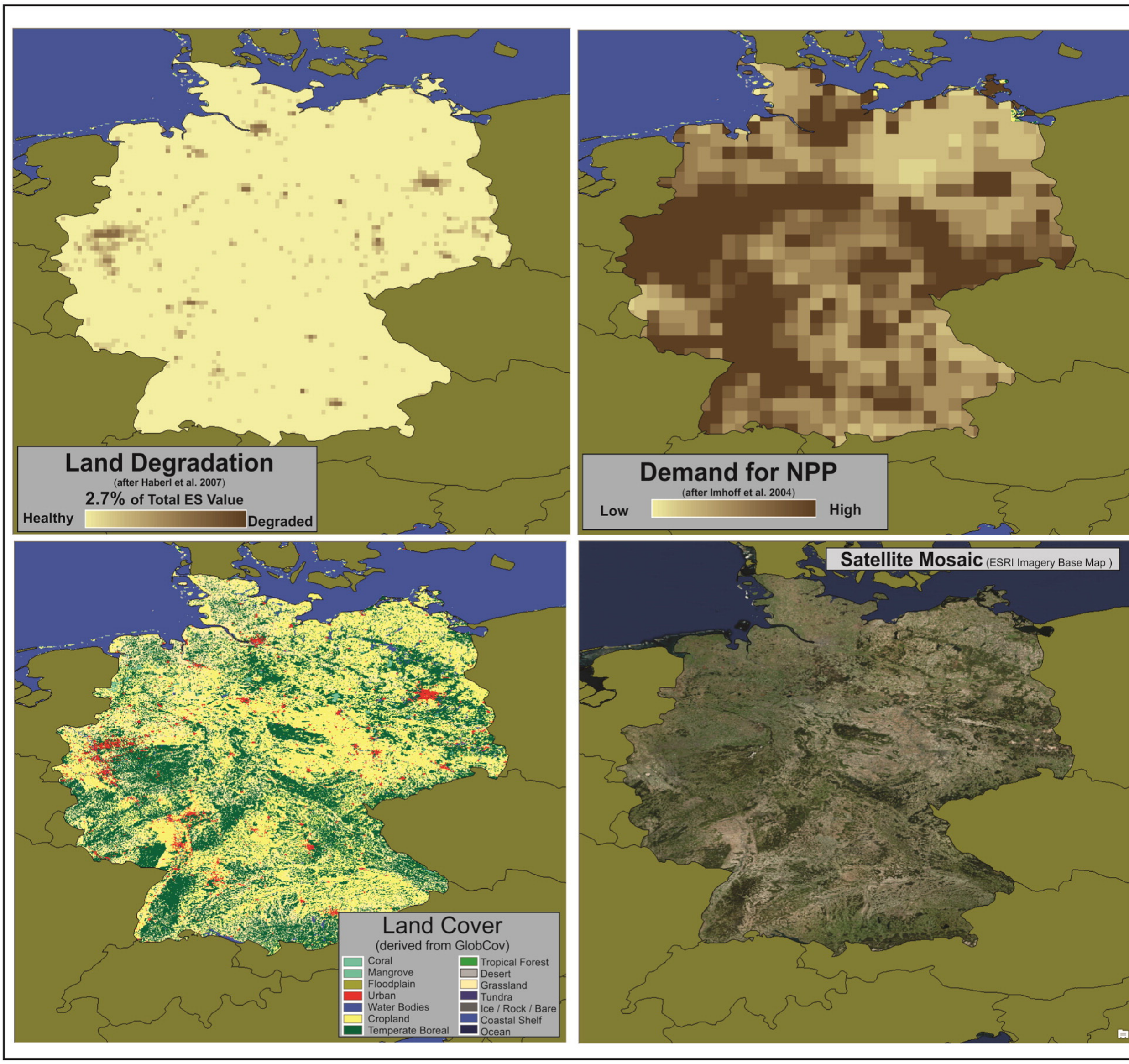


Fig. 6. Representations of land degradation and land cover for Germany.

Bolivia is a nation that appears to have navigated the challenges of land degradation fairly well so far (Fig. 7). We estimate the annual value of ecosystem services in Bolivia to be $1.266 trillion/year (Costanza et al., 2014). Here the patterns of demand for NPP and land degradation look similar to Australia in that the impacted areas are concentrated in and around human settlements whereas the land degradation is more widespread throughout the agricultural areas. The percentage loss of annual ecosystem service values for Bolivia is estimated to be 2% ($21 billion/year).

4. Discussion

Characterizing, measuring, and mapping land degradation has long been recognized as a challenging task. In this paper, we present a simplifying approach to collapse the multivariate phenomena of land degradation into a single spatially varying number. We use this simplification as a proxy measure of land degradation to make an estimate of the impact of land degradation on ecosystem function, which is in turn converted into a loss of ecosystem service value. We also looked at the spatial patterns of 'demand' for ecosystem services via the proxy measure of HANPP (Imhoff et al., 2004) and the relationship of this demand to the location of land degradation (Haberl et al., 2007).

The Haberl and Imhoff datasets were both originally used to estimate HANPP in terms of Pg C/year (Haberl 15.6 Pg or 24% of NPP vs. Imhoff 11.5 Pg or 20% of NPP). These representations of impact on ecosystem services are not measuring the same thing. The Haberl data is used as a proxy measure of land degradation that is simply the percentage of potential NPP (e.g. Actual NPP / Potential NPP), which is representative of the fundamental productivity of an ecosystem from the perspective of energy transformation via photosynthesis. The Imhoff data was used to create a 'demand for NPP' map that was derived from an allocation of harvest processing and efficiency multipliers applied to national level FAO data from seven categories (vegetal foods, meat, milk, eggs, wood, paper and fibre) and spatially allocated to a global representation of the human population distribution. The percent loss of potential NPP is the most valid 'map' of land degradation in terms of spatial patterns. However, the 'demand for NPP' map augments this assessment from the perspective of separating production and consumption. A country that imports food contributes to agricultural land degradation of the countries it imports food from. Juxtapositions of this nature raise interesting and challenging questions about spatial

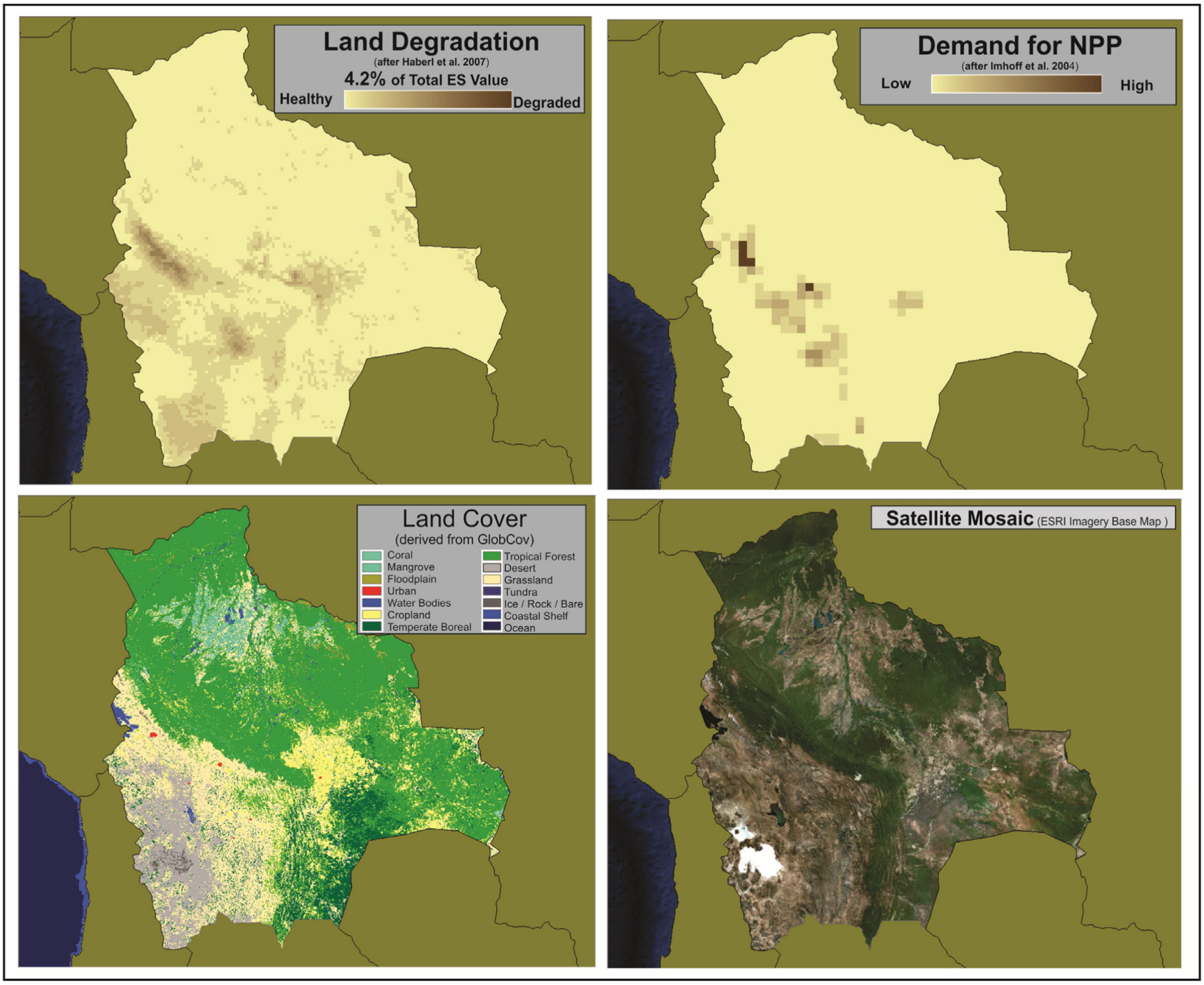


Fig. 7. Representations of land degradation and land cover for Bolivia.

and national patterns of sustainability and land degradation that are beyond the scope of this paper. Future research may explore the extent to which some countries of the world are appropriating the NPP of other countries of the world in order to survive. One study by Coscieme et al. (2016) suggests that high GDP countries are more likely to be in ecological deficit and more likely to engage in 'Land Grabbing' from low GDP countries that are not in ecological deficit.

These simplified representations of impacts on ecosystem service value are nonetheless relevant to our understanding of the ecological economics of land degradation. Our approach of using simple benefits transfer methods to estimate the impacts on the value of ecosystem services has myriad drawbacks and shortcomings including (Schmidt et al., 2016): 1) the ESVs used are not influenced by the spatial and non-spatial interactions of natural, social, human, and built capital; 2) the land cover classification scheme is limited to a very small number of classes which is only one oversimplification of ecological reality; and 3) the value of some ecosystem services (particularly those involving exchange values) vary dramatically with levels of economic development. However, the simplicity of this approach allows for a common methodology for all nations of the world, enabling reasonable comparisons of relative differences. This approach provides a first approximation of both the magnitude of 'demand' for ecosystem services at a national level and a map of the impacts of this demand in terms of land degradation. The spatial separation of the 'demand' and 'impacts' is quite significant. It invites further research exploring more detailed studies of the spatially explicit variability of ecosystem service value and the spatially variable nature of both demand driven impacts and land degradation's impacts on ecosystem function and services.

Agricultural lands provide a significant output of ecosystem services that are not accounted for if only dollar values of agricultural products are included (roughly $1.7 trillion/year or 2.8% of the global annual GDP). We make the simplifying assumption that this representation of land degradation can be used as a linear factor that reduces ecosystem function and consequently the dollar value of the ecosystem services provided. This approach produces an estimate of lost ecosystem services of $6.3 trillion/year globally.

There are, of course, other ongoing forms of land degradation not being accounted for using this approach, such as the potential extinction of pollinating species that are arguably another serious manifestation of land degradation. How phenomena such as species extinction interact with land degradation, which in turn interact with biogeochemical cycles, are some of the questions raised with respect to ideas of 'planetary boundaries' (Rockström et al., 2009) and that require much further modeling and analysis.

5. Conclusions

Natural capital annually generates ecosystem services valued at more than twice the world's marketed economy or global GDP. Changes in land cover over the past fifteen years have resulted in a loss of roughly $20 trillion/year because of land cover change alone (Costanza et al., 2014), assuming that ecosystems are functioning at 100%. However, the world's land surfaces and associated ecosystems are not functioning at 100%. We have lost ecosystem service value as a result of reduced or impaired ecological function. In this paper, we used a simplified representation of land degradation as a proxy measure of impaired or reduced ecological function in order to estimate of the reduced value of ecosystem services caused by land degradation. Our estimate of impacts to ecosystem service value from land degradation is $6.3 trillion/year. This suggests that the ESV losses are roughly 30% of the losses from land cover changes over the last 15 years. These measures are mostly associated with changes to agricultural lands around the world, but forests, grasslands, and shrublands are also affected. This estimate of lost ESV is more than three times larger than the entire value of agriculture in the market economy. The ecological economics of land degradation suggests that the economics of land degradation is about a lot more than the market value of agricultural products.

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