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Supplementary Information for

Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy

Joep F. Schyns, Arjen Y. Hoekstra, Martijn J. Booij, Rick J. Hogeboom, Mesfin M. Mekonnen

Joep F. Schyns

Email: j.f.schyns@utwente.nl

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Supplementary Figures

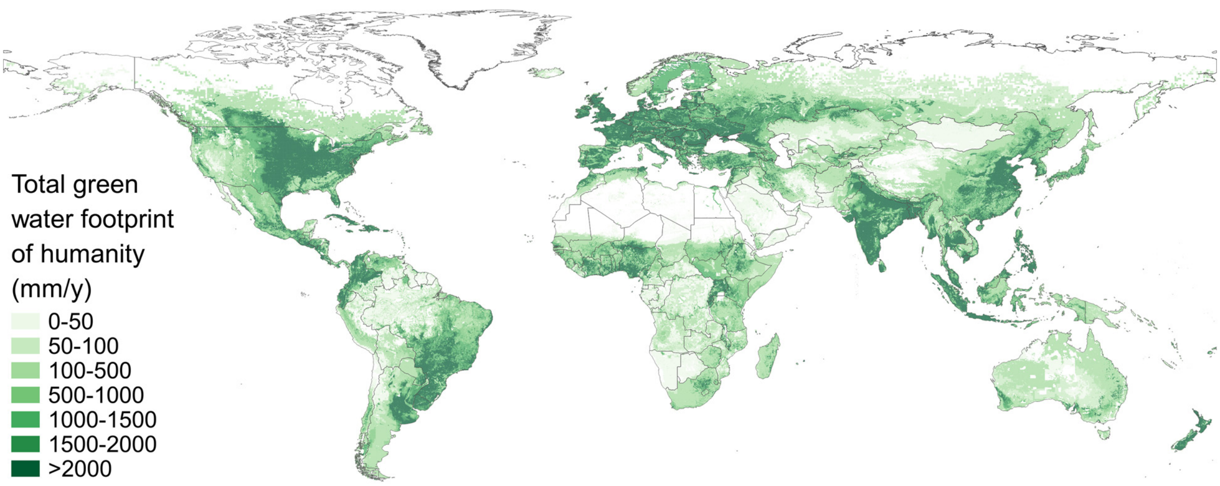

Figure S1. Total green water footprint of humanity in mm y^{-1} on a 5 x 5 arc minute grid. Sum of the green water footprints (in m^3 y^{-1}) of crop production, livestock grazing, wood production and urban areas, divided by the grid cell area.

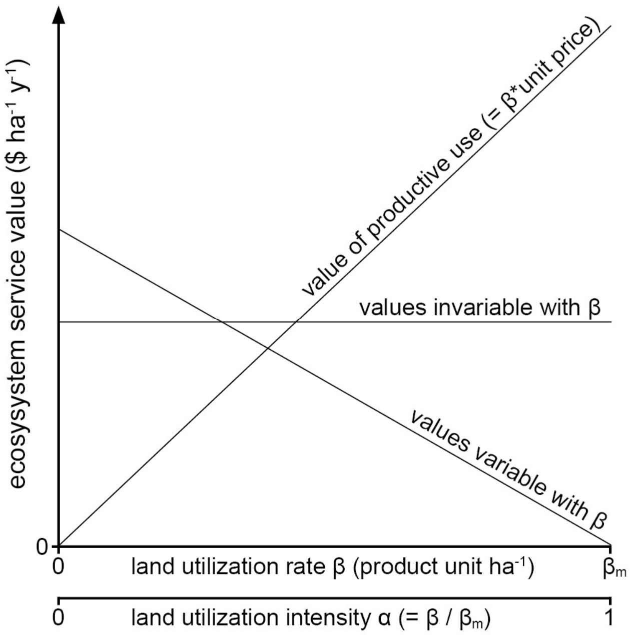

Figure S2. Conceptual relationships between the value of ecosystems services and the actual (β) and maximum sustainable (β_m) land utilization rate (following Schyns et al. (1), assumed to be linear in this study due to lack of data).

Supplementary Tables

Table S1. Green water scarcity and actual and maximum sustainable green water footprints per country.

Country	Actual green water footprint (km³ y^{-1})	Maximum sustainable green water footprint (km³ y^{-1})	Green water scarcity (-)*	Overshoot as % of the actual green water footprint (%)
Afghanistan	16	27	0.58	16
Albania	3.5	2.8	1.3	58
Algeria	22	47	0.46	5.0
American Samoa	0	0	1.0	0
Andorra	0.020	0.0046	4.5	86
Angola	17	170	0.098	13
Antigua and Barbuda	0.072	0.14	0.51	36
Argentina	260	460	0.58	6.7
Armenia	3.5	4.1	0.86	31
Australia	170	740	0.23	16
Austria	22	32	0.68	4.9
Azerbaijan	8.8	12	0.71	24
Bahamas	0.11	0.37	0.29	48
Bahrain	0.018	0.019	0.97	0
Bangladesh	70	67	1.0	13
Barbados	0.21	0.30	0.69	36
Belarus	34	58	0.58	7.2
Belgium	6.8	5.6	1.2	35
Belize	0.81	1.4	0.58	43
Benin	12	26	0.48	5.0
Bhutan	1.7	0.61	2.8	85
Bolivia	21	110	0.20	30
Bosnia and Herzegovina	8.9	18	0.50	13
Botswana	1.7	23	0.072	7.1
Brazil	870	1700	0.51	14
British Virgin Islands	0.0020	0.0020	1.0	0
Brunei	0.40	0.24	1.6	51
Bulgaria	22	29	0.76	13
Burkina Faso	25	68	0.37	7.6
Burundi	6.5	8.6	0.75	20
Cambodia	16	22	0.73	21
Cameroon	32	45	0.70	41
Canada	250	1000	0.25	6.2
Cape Verde	0.17	0.11	1.5	58
Cayman Islands	0.016	0.00059	27	96

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Table S1 (continued). Green water scarcity and actual and maximum sustainable green water footprints per country.

Country	Actual green water footprint ($km^3\ y^{-1}$)	Maximum sustainable green water footprint ($km^3\ y^{-1}$)	Green water scarcity (-)*	Overshoot as % of the actual green water footprint (%)
Central African Republic	7.5	45	0.17	8.9
Chad	16	82	0.19	6.6
Chile	27	42	0.63	21
China	950	1500	0.65	9.2
Colombia	160	230	0.68	55
Comoros	0.92	0.16	5.9	84
Congo	1.8	32	0.055	8.9
Congo, DRC	35	190	0.18	14
Cook Islands	0	0	1.0	0
Costa Rica	19	6.4	3.0	78
Côte d'Ivoire	49	77	0.64	16
Croatia	12	18	0.70	21
Cuba	27	23	1.2	41
Cyprus	0.43	0.19	2.3	72
Czech Republic	24	23	1.0	24
Denmark	9.1	6.3	1.4	43
Djibouti	0.15	0.13	1.2	29
Dominica	0.24	0.12	2.0	54
Dominican Republic	14	6.5	2.2	71
Ecuador	46	6.6	7.0	91
Egypt	7.5	6.3	1.2	17
El Salvador	9.5	11	0.88	16
Equatorial Guinea	0.96	2.2	0.43	47
Eritrea	2.6	7.2	0.37	2.6
Estonia	6.9	7.8	0.88	33
Ethiopia	97	150	0.64	21
Faroe Islands	0.0013	0.000058	23	96
Fiji	2.7	0.75	3.6	86
Finland	35	81	0.43	6.5
France	130	140	0.91	17
French Guiana	0.38	0.45	0.85	63
French Polynesia	0	0	1.0	0
Gabon	1.9	28	0.067	11
Georgia	8.6	18	0.47	21
Germany	92	52	1.8	60
Ghana	37	66	0.56	19
Greece	23	20	1.2	30

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Table S1 (continued). Green water scarcity and actual and maximum sustainable green water footprints per country.

Country	Actual green water footprint (km³ y^{-1})	Maximum sustainable green water footprint (km³ y^{-1})	Green water scarcity (-)*	Overshoot as % of the actual green water footprint (%)
Grenada	0.15	0.0013	110	99
Guadeloupe	0.47	0.11	4.4	89
Guam	0.13	0.083	1.6	36
Guatemala	22	14	1.5	70
Guinea	19	61	0.31	14
Guinea-Bissau	2.8	7.3	0.39	18
Guyana	2.7	29	0.095	5.8
Haiti	8.9	3.3	2.7	65
Honduras	15	11	1.4	59
Hungary	26	30	0.86	5.3
Iceland	0.59	5.8	0.10	9.5
India	810	890	0.92	11
Indonesia	340	320	1.1	33
Iran	72	100	0.69	10
Iraq	11	17	0.66	8.3
Ireland	14	19	0.78	6.3
Israel	2.5	2.5	0.99	23
Italy	69	77	0.90	20
Jamaica	4.2	0.86	4.9	83
Japan	51	130	0.40	27
Jordan	1.1	0.96	1.1	31
Kazakhstan	72	270	0.27	2.6
Kenya	56	75	0.74	21
Kuwait	0.16	0.12	1.4	33
Kyrgyzstan	11	23	0.46	11
Laos	6.9	13	0.53	40
Latvia	12	14	0.85	23
Lebanon	1.2	1.2	0.99	26
Lesotho	1.7	7.1	0.24	27
Liberia	4.8	11	0.43	27
Libya	3.0	6.4	0.47	2.3
Liechtenstein	0.056	0.028	2.0	78
Lithuania	14	15	0.94	23
Luxembourg	0.76	0.89	0.86	11
Macedonia	3.8	6.6	0.57	13
Madagascar	29	100	0.29	49
Malawi	13	17	0.75	43

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Table S1 (continued). Green water scarcity and actual and maximum sustainable green water footprints per country.

Country	Actual green water footprint (km^3 y^{-1})	Maximum sustainable green water footprint (km^3 y^{-1})	Green water scarcity (-)*	Overshoot as % of the actual green water footprint (%)
Malaysia	89	54	1.6	49
Mali	26	90	0.29	6.6
Malta	0.056	0.030	1.9	70
Martinique	0.41	0.22	1.9	72
Mauritania	3.6	6.7	0.54	0
Mauritius	0.80	0.46	1.7	69
Mexico	180	230	0.77	39
Micronesia	0	0	1.0	0
Moldova	7.9	9.1	0.87	2.7
Monaco	0.0024	0.0024	1.0	0
Mongolia	2.4	48	0.049	9.9
Montenegro	3.4	3.8	0.90	29
Montserrat	0.014	0.014	1.0	0
Morocco	30	42	0.73	14
Mozambique	26	210	0.12	12
Myanmar	81	95	0.85	24
Namibia	2.4	28	0.085	3.5
Nepal	27	15	1.8	51
Netherlands	8.7	3.4	2.5	67
New Caledonia	0.17	0.22	0.77	71
New Zealand	66	40	1.6	52
Nicaragua	16	27	0.61	33
Niger	48	54	0.89	1.1
Nigeria	210	300	0.70	11
Niue	0	0	1.0	0
North Korea	18	45	0.41	3.9
Norway	9.3	43	0.22	25
Oman	0.57	0.43	1.3	37
Pakistan	57	62	0.91	8.6
Palau	0	0.0092	0	0
Panama	7.5	5.4	1.4	71
Papua New Guinea	8.9	21	0.42	56
Paraguay	42	130	0.32	3.6
Peru	29	91	0.32	55
Philippines	120	44	2.6	67
Poland	84	100	0.83	14
Portugal	15	15	1.0	15

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Table S1 (continued). Green water scarcity and actual and maximum sustainable green water footprints per country.

Country	Actual green water footprint (km³ y^{-1})	Maximum sustainable green water footprint (km³ y^{-1})	Green water scarcity (-)*	Overshoot as % of the actual green water footprint (%)
Puerto Rico	2.5	1.0	2.4	66
Qatar	0.056	0.062	0.90	0
Réunion	0.35	0.12	2.9	80
Romania	60	73	0.83	7.9
Russia	520	1900	0.27	6.6
Rwanda	9.5	7.2	1.3	37
Saint Pierre et Miquelon	0.00040	0.00040	1.0	0
Samoa	0	0.070	0	0
San Marino	0.0038	0.019	0.20	0
Sao Tome and Principe	0.22	0.13	1.7	51
Saudi Arabia	5.5	5.2	1.1	15
Senegal	10	24	0.42	4.2
Serbia	17	25	0.69	3.8
Seychelles	0.012	0	1.0	100
Sierra Leone	5.7	13	0.43	17
Singapore	0.31	0.31	0.99	0
Slovakia	10	12	0.85	18
Slovenia	5.1	6	0.85	40
Solomon Is.	0.75	0.94	0.80	68
Somalia	20	30	0.65	7.3
South Africa	65	150	0.43	20
South Korea	18	36	0.50	25
South Sudan	51	150	0.34	8.0
Spain	83	89	0.93	11
Sri Lanka	21	7.8	2.7	73
St. Kitts and Nevis	0.064	0.00069	92	99
St. Lucia	0.016	0.063	0.25	0
St. Vincent and the Grenadines	0.13	0.14	0.91	0
Sudan	67	140	0.47	2.0
Suriname	0.57	7.2	0.080	56
Swaziland	1.6	5.2	0.31	16
Sweden	52	110	0.47	9.8
Switzerland	9.7	8.0	1.2	46
Syria	21	23	0.91	3.6
Taiwan	5.6	4.2	1.3	53
Tajikistan	4.9	8.6	0.57	7.5
Tanzania	52	170	0.31	31

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Table S1 (continued). Green water scarcity and actual and maximum sustainable green water footprints per country.

Country	Actual green water footprint (km³ y^{-1})	Maximum sustainable green water footprint (km³ y^{-1})	Green water scarcity (-)*	Overshoot as % of the actual green water footprint (%)
Thailand	120	120	1.0	24
The Gambia	1.3	3.0	0.41	0
Timor Leste	1.2	0.24	5.0	90
Togo	7.2	13	0.55	13
Tonga	0	0.083	0	0
Trinidad and Tobago	0.90	0.43	2.1	70
Tunisia	19	22	0.86	3.9
Turkey	120	170	0.74	13
Turkmenistan	9.5	24	0.40	10
Uganda	52	66	0.78	13
Ukraine	130	160	0.83	5.6
United Arab Emirates	2.6	2.6	1.0	3.3
United Kingdom	61	48	1.3	42
United States	1300	1900	0.71	11
United States Virgin Islands	0.061	0.10	0.59	0
Uruguay	37	68	0.54	9.4
Uzbekistan	27	29	0.91	5.8
Vanuatu	1.0	0.46	2.2	78
Venezuela	47	110	0.43	33
Vietnam	76	59	1.3	37
Wallis and Futuna	0	0	1.0	0
Yemen	4.5	4.1	1.1	24
Zambia	12	79	0.15	16
Zimbabwe	18	67	0.26	13

* If the maximum sustainable green water footprint is zero, green water scarcity is mathematically undefined. Since in such cases no green water remains to be allocated to human activities, we then set green water scarcity to 1.0.

Table S2. Materials used for estimating the green water footprint of livestock grazing.

Variable	Source dataset(s)	Operation(s)/remarks
Area of permanent meadows and pastures (5 x 5 arc minute)	Klein Goldewijk et al. (2)	Linear interpolation between 2000 and 2005 and constant for 2005-2009.
Area of harvested fodder grasses (5 x 5 arc minute)	Portmann et al. (3)	Clipped with the area of permanent meadows and pastures and then scaled to national annual statistics on harvested area of fodder grasses.
National annual statistics on harvested area of fodder grasses	FAOSTAT (http://www.fao.org/faostat/en/#data/QC)	Sum of FAOSTAT crop codes: 639 (grasses, nes), 640 (clover), and 50% of 651 (mixed grasses and legumes).
Density of cattle, goats and sheep representative of the year 2006 (0.5 x 0.5 arc minute)	Robinson et al. (4)	See section S3.1. For asses, camels, horses, llamas and mules, we used the distribution of cattle due to lack of animal-specific distribution maps.
Density of buffaloes representative of the year 2005 (3 x 3 arc minute)	Wint & Robinson (5)	See section S3.1.
Ruminant production systems representative of the year 2011 (0.5 x 0.5 arc minute)	Bouwman et al. (6)	The production systems are grouped into the two systems (pastoral and mixed/landless) as distinguished by Bouwman et al. (6).
Production per system in 1970 and 1995 (per animal category, per world region)	Bouwman et al. (6)	Annual rate of change of the fraction of production in the pastoral system is derived. This rate is applied to the estimated livestock distribution map, assuming no change if a grid cell is classified as either 100% pastoral or 100% mixed/landless by Robinson et al. (7).
Actual annual evapotranspiration rate of grazed grass (30 x 30 arc minute)	Rolinski et al. (8)	Daily grazing option under livestock density that results in the highest grass yield. Assumed to be fully green (no irrigation).

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Table S2 (continued). Materials used for estimating the green water footprint of livestock grazing.

Variable	Source dataset(s)	Operation(s)/remarks
Sustainable grass yield (30 x 30 arc minute)	Rolinski et al. (8)	Daily grazing option under livestock density that results in the highest grass yield. Conversion from carbon mass units (C) to grass dry matter (DM) using C = 0.45DM. If in a grid cell that is grazed according to our estimates the sustainable grass yield is zero, we set it to 0.0001 t dry matter ha^{-1} y^{-1}.
National annual statistics on meat/milk production (per animal category)	FAOSTAT (http://www.fao.org/ faostat/en/#data/QL)	The total meat/milk production per animal category is distributed over the two production systems based on the number of heads per system.
Feed conversion efficiencies (per world region, per animal category, per production system)	Bouwman et al. (6)	Linear interpolation between values reported for 1995 and 2030.
Fraction of grass in animal feed (per world region, per animal category, per production system)	Bouwman et al. (6)	Linear interpolation between values reported for 1995 and 2030.
National annual statistics on production of fodder grasses	FAOSTAT (http://www.fao.org/ faostat/en/#data/QC)	Sum of FAOSTAT crop codes: 639 (grasses, nes), 640 (clover), and 50% of 651 (mixed grasses and legumes). Assuming that reported weights represent fresh weight incl. 15% moisture.
Value fraction of meat and milk production from grazing pastures	Costanza et al. (9)	See section S2.

Table S3. Ecosystem service values for the reference year 2011. Values are in 2007 US dollars.

	Grasslands[a]	Grazed grasslands	Non-grazed grasslands
Area in 2011 (10^6 ha)	4,418	3,111	1,307
Average intensity of grazing (α) in 2011 (-)	-	0.35	-
Actual meat and milk production from grazing livestock in 2011 (10^6 t y^{-1})	-	820	-
Ecosystem values that are invariable with α[b] (V_1) ($ ha^{-1} y^{-1})	1,603	1,569	1,569
Ecosystem values that are inversely proportional to α[c] (V_2) ($ ha^{-1} y^{-1})	1,317	1,168[d]	1,788[d]
Value of meat and milk production[e] (V_3) ($ ha^{-1} y^{-1})	1,246	1,769[f]	-
Value of meat and milk production (V_3^*) ($ t^{-1} y^{-1})		6,682[g]	-

[a] Data from Costanza et al. (9) for 2011.

[b] Services included in this category: gas regulation, climate regulation, water regulation, water supply, nutrient cycling, waste treatment, genetic resources, cultural.

[c] Services included in this category: erosion control, soil formation, pollination, biological control, habitat/refugia, recreation.

[d] Estimated based on the average α in 2011 – assuming a linear relation between V_2 and β and furthermore assuming that $V_2 = 0$ when $\alpha = 1$ – such that the area-weighted average of V_2 for grazed and non-grazed lands equals V_2 for the entire biome (column 2), resulting in the relationship: $V_2 = -\delta\alpha + \delta$ with $\delta = 1{,}788$. This equation is used to estimate V_2 per country per year.

[e] We assume that the value of the services food production and raw materials on grasslands primarily reflect the value of meat and milk production.

[f] Estimated by first calculating the total value of V_3 ($ y^{-1}) for the reference year according to Costanza et al. (9), by multiplying the value per ha with the area (both as reported by Costanza et al. (9)) and subsequently dividing the total value of V_3 by the estimated grazed land area in 2011. We estimate V_3 per country per year as $[V_3^*]*Q/A$ where A is the grazed pasture area (ha) and Q is the country total meat and milk production (t y^{-1}).

[g] Estimated by first calculating the total value of V_3 ($ y^{-1}) for the reference year and subsequently dividing the total value of V_3 by the actual meat and milk production from grazing livestock in 2011.

Table S4. Global total water footprint of grazing of this study (column on right hand side) compared to estimates from previous studies.

		Total green water footprint of grazing ($km^3\ y^{-1}$)	
Previous studies	**Period**	Previous study	This study[b]
Postel et al. (10)[a]	1995	5,800	2,413
De Fraiture et al. (11)[b]	2000	840	2,620
Rost et al. (12)[a]	1971-2002	8,258	2,200
Hanasaki et al. (13)[a]	1985-1999	12,960	2,323
Mekonnen and Hoekstra (14)[b]	1996-2005	913	2,683

[a] Refers to total evapotranspiration from grazing lands.

[b] Relates to the grass actually consumed.

Supplementary Materials and Methods

S1. Human appropriation of the green water flow

We estimated the human appropriation of the green water flow as the sum of the green water footprints (WF_g) of crop production, wood production, livestock grazing and urban areas at a 5 x 5 arc minute grid cell spatial resolution. WF_g of crop production is estimated for 126 crops with a grid-based soil water balance model at 5 x 5 arc minute spatial resolution taken from Mekonnen & Hoekstra (15). We averaged WF_g of wood production for 2000-2009 at 30 x 30 arc minute from Schyns et al. (1) and downscaled this to 5 x 5 arc minute. We estimated WF_g of livestock grazing per year at 5 x 5 arc minute resolution and then averaged it for 2000-2009. A full description of the method to is included in section S3 below. We estimated the WF_g of urban areas at 5 x 5 arc minute resolution by multiplying the extent of urban areas (16, 17) with the average annual ET rate from urban areas for 2000-2009. The annual ET rate from urban area in grid cell *x* is estimated using the formula by Zhang et al. (18) based on the average annual P and potential ET for the period 2000-2009 – both estimated from daily climate data at 30 x 30 arc minute resolution (19) – and a dimensionless coefficient representing plant water availability *w*. Based on an average for 386 European cities (20), we assumed urban area is made up of 20%

S2. Maximum sustainable levels to the human appropriation of the green water flow

Limits to the WF_g are expressed by maximum sustainable green water footprints ($WF_{g,m}$), which we estimate at 5 x 5 arc minute resolution. To estimate $WF_{g,m}$ we translate limits to land use into limits to the use of the green water flow. We set aside the green water flow ($WF_{g,m}$ = 0) from lands that should be maintained to support natural terrestrial ecosystems (section S2.1), which is similar to the practice of accounting for environmental flow requirements to support natural aquatic ecosystems (21). Furthermore, we estimate $WF_{g,m}$ based on agro-ecological suitability and accessibility of land, and biophysical constraints to intensifying land-use (section S2.2).

<u>S2.1. Land and associated green water flows reserved to maintain terrestrial ecosystems</u>

We set aside lands ($WF_{g,m}$ = 0) that have a protected status or have priority to receive that status to achieve the Aichi Biodiversity Target 11. This target has been adopted by the Convention on Biological Diversity and states that the protected area network should be expanded to at least 17% of the terrestrial world by 2020 (https://www.cbd.int/sp/targets).

We translate the polygon map of the current protected area network (22) to a 5 x 5 arc minute grid of protected cells (grid cell is considered fully protected if >50% is covered by a protected area polygon). Following Smith et al. (23), we only considered strictly protected areas, including strict nature reserves (IUCN category Ia), wilderness areas (IUCN category Ib) and national parks (IUCN category II). Priority areas for protection, representing the most suitable 17% of the terrestrial land for protection based on conservation value, were obtained from Montesino Pouzols et al. (24) using the map for present land-use conditions.

To complete Fig. 1 in the main manuscript we also estimated the total green water flow from land set aside for nature and non-utilizable lands. We did this using the method proposed by Zhang et al. (18) with $w = 2.0$ for forest cover and $w = 0.5$ for grass-like cover (we assumed there is no green water flow from the land cover types permanent wetlands, and snow and ice).

S2.2. Maximum sustainable green water footprints

We distinguish between lands that are currently utilized to some extent for agriculture, forestry or urban areas, and those lands that are non-utilized at the moment but do have the potential to be used considering a range of constraints.

On lands currently utilized for grazing, we estimate $WF_{g,m}$ as the green water footprint in the hypothetical situation that the grass consumed by the animals equals the sustainable grass production (8) (Table S2). Similarly, on lands currently utilized for wood production, we estimate $WF_{g,m}$ as the green water footprint for the case that the actual wood extraction equals the sustainable wood production (1). For current cropland and urban areas, we assume $WF_{g,m}$ equals the current WF_g.

We identify non-utilized lands that have the potential to be used for agriculture by checking where all of the following conditions are met: the current land cover (17) is open shrublands, savannas, grasslands, croplands, cropland/natural vegetation, or barren/sparse vegetation (similar to previous studies (23, 25, 26) we do not consider the possibility of agricultural expansion into forests); the land is not set aside for nature; the land is not classified as non-accessible or non-productive (27); the land is agro-ecologically suitable (28); and the land is not already in use (29). After applying these constraints we reduced the resulting area per grid cell by 15% to account for previously unaccounted land uses that reduce the potentially utilizable area (26). We have considered grid cells with a suitability index ≥40 (range is 0-100; ref. (28)) to be suitable for crop production, the rest is considered suitable for grazing.

In a similar manner and using the same datasets we identify non-utilized lands which have the potential to be used for wood production, in cases where all of the following conditions are met: the current land cover is evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, mixed forest, closed shrublands or woody savannas; the land is not set aside for nature; the land is not classified as non-accessible or non-productive; the average annual forest ET rate ≥100 mm y^{-1} (1); and the land is not already in use (1). Also here we apply the 15% area reduction per grid cell (see above).

We estimated $WF_{g,m}$ for potentially utilizable land as the fraction of the annual green water flow (ET) that can be appropriated for human activities. For potentially utilizable cropland, ET is estimated using the method by Zhang et al. (18) with potential crop ET for the FAO reference crop (assuming a crop factor of 1.0) and w = 0.5. Subsequently, we estimate $WF_{g,m}$ as the fraction of ET that takes places during the crop growing period. We estimate this fraction at 0.7 based on what previous studies found for the major crops (ref. (13): ~0.6; ref. (30): ~0.8). For potentially utilizable forest, ET is estimated using the method by Zhang et al. (18) with potential forest ET estimated according to Komatsu et al. (31) and w = 2.0. For potentially utilizable grazing land, actual pasture ET is obtained from Rolinski et al. (8). For potentially utilizable forest and grazing land, we estimate $WF_{g,m}$ as the green water footprint in the case of full utilization of the local sustainable wood and grass production, respectively.

S3. Green water footprint of livestock grazing

We estimated the WF_g of livestock grazing per year at 5 x 5 arc minute resolution and then averaged it for 2000-2009. First, for the locations where livestock is present (section S3.1) we estimated the area used for grazing as the area of permanent meadows and pastures minus the area of harvested fodder grasses (which are included in WF_g of crop production, just like crops used for animal feed). Second, we estimated the total green water flow from grazed pastures using the evapotranspiration (ET) rate from grassland under a daily grazing scheme as modelled by Rolinski et al. (8). Third, we attribute only a fraction of the total green water flow from grazed pastures to livestock grazing. We do this using the method by Schyns et al. (1) based on the value of food production on grazed lands with respect to other ecosystem service values generated by pastures (section S3.2), which depends on the intensity of grazing (section S3.3). General data sources and operations are described in Table S2. In section S3.4 we discuss our estimate of WF_g of livestock grazing in the context of previous lower-resolution assessments.

S3.1. Spatiotemporal distribution of animal heads per production system

First, we estimated the number of grazing animals at 5 x 5 arc minute resolution for each year in 2000-2009. Second, we determined per grid cell per year the spread of these animals over these two production systems: pastoral and mixed/landless. We considered the following grazing animal categories: dairy cattle, non-dairy cattle, asses, buffaloes, camels, horses, mules, llamas, sheep and goats. We disaggregated national annual statistics on stocks of these animal categories (FAOSTAT; http://www.fao.org/faostat/en/#data/TA) to a 5 x 5 arc minute grid, using weights derived from livestock distribution data (4, 5). To obtain the weight per 5 x 5 arc minute grid cell, we first converted livestock densities from these sources – available at a finer resolution – to absolute heads by multiplying density with the grid cell area, and aggregated those numbers to 5 x 5 arc minute resolution. Second, we calculated from this map the weight per grid cell as the ratio of animal heads in the grid cell to the total animals heads present in the country. The spread of the animals over the two production systems per grid cell is based on Robinson et al. (7) and the change in production over these two systems during our study period is estimated based on a an annual rate of change derived from Bouwman et al. (6) (Table S2).

S3.2. Attribution of the green water flow to the productive use based on a value fraction

We follow the value fraction method by Schyns et al. (1) (applied to wood production in forests) to attribute only a part of the annual green water flow to the productive use of grazed pastures, i.e. food production. In general terms, the value fraction is defined as the ratio of the monetary value of the productive use to the total monetary value of the ecosystem services generated on a unit of land. As the land utilization rate (β) approaches the maximum sustainable land utilization rate (β_m), the value of the productive use increases, but the value of some of the ecosystem services get reduced, while some other ecosystem services maintain their value irrespective of β. The shape of this relationship (Fig. S2) for various land uses is clearly an avenue of further research. Due to lack of data, we follow Schyns et al. (1) and assume it to be linear for now.

For livestock grazing, we estimated the value fraction of meat and milk production from grazing pastures per country (the uncertainty in the data does justify gridded estimate) for each year in the period 2000-2009. We use global ecosystem service values of grasslands for 2011 (9), which we distribute over grazed and non-grazed grasslands. We then estimate per country per year the value of meat and milk production and the value of ecosystem services that are inversely proportional to the intensity of grazing (section S3) as described in Table S3.

S3.3. Grazing intensity

The intensity of grazing (α) in a country is estimated per year as the ratio of the total grass consumed through grazing by animals to the sustainable grass production on grazed pastures. The total grass consumed through grazing by animals is estimated backwards from national annual statistics on meat and milk production in two steps. First, we converted meat and milk production per animal category per production system to the associated total grass consumed (including fodder grasses that are not directly grazed, but harvested and fed to livestock later) using feed conversion efficiencies and the fraction of grass in feed (Table S2). Second, we estimated the grass consumed by all animals in a production system and subtracted the production of fodder grasses from the total grass consumed in the intensive system (assuming that fodder grasses are fed to livestock in this system within the country in that year). The sustainable grass production on grazed pastures is estimated by multiplying the area used for grazing with the sustainable grass yield. In cases where α exceeds one – i.e. grazed grass consumption is larger than the sustainable grass production on grazed pastures – we assumed fully intensive use of the grazed pastures, but limited the grass consumed through grazing to the sustainable grass production on grazed pastures. This happens in small and arid countries with a substantial livestock sector that in practice relies on imported animal feed.

S3.4. A comparison of this study's estimate of WF_g of livestock grazing with previous work

Our global estimate of WF_g of livestock grazing falls between previous estimates that considered the total ET from grazing lands and those that take only the fraction of this total that relates to the grass actually consumed (see Table S4). Although our estimate of the total grazed grass consumed is comparable to the one by Mekonnen & Hoekstra (14) (2,660x10^6 t dry matter y^{-1} in our study vs. 2,768x10^6 t dry matter y^{-1} in theirs), we estimated the WF per unit of grass grazed to be nearly three times larger (857 m^3 t^{-1} in our study vs. 297 m^3 t^{-1} in theirs). Mekonnen & Hoekstra (14) probably underestimated the WF per unit of grass grazed, because they used an average ET rate per country for pasture area and assumed the pasture yield to be 80% of the yield of fodder crops. De Fraiture et al. (11) assumed the WF per unit of grass consumed to be 750 m^3 t^{-1} dry matter (882 m^3 t^{-1}), but seem to have estimated a much lower total grass consumption when derived backwards from their global WF_g of grazing (840 km^3 y^{-1} / 750 m^3 t^{-1} dry matter * 1000 = 1,120x10^6 t dry matter y^{-1}). Our estimate of total grass consumption seems to be more reasonable, since it not only compares well to Mekonnen & Hoekstra (14), but to

Bouwman et al. (6) for the year 1995 as well (2,445x10^6 t dry matter y^{-1} in our study vs. 2,400x10^6 t dry matter y^{-1} in theirs). Furthermore, our global estimate of WF_g of grazing might be higher than the estimates by De Fraiture et al. (11) and Mekonnen & Hoekstra (14), because our estimate of the total ET from grazing lands (12.5x10^3 km^3 y^{-1} for 1985-1999) is on the high side of the spectrum, similar to that by Hanasaki et al. (13).

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