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Joep F. Schyns
*University of Twente*, hoekstra@utwente.nl

Arjen Y. Hoekstra
*University of Twente & Lee Kuan Yew School of Public Policy*, a.y.hoekstra@utwente.nl

Martijn J. Booij
*University of Twente*

Rick J. Hogeboom
*University of Twente*

Mesfin Mekonnen
*University of Nebraska - Lincoln*, mmekonnen2@unl.edu

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

**Joep F. Schyns**[a,1], **Arjen Y. Hoekstra**[a,b,1], **Martijn J. Booij**[a], **Rick J. Hogeboom**[a], **and Mesfin M. Mekonnen**[c]

[a]Twente Water Centre, University of Twente, 7500 AE Enschede, The Netherlands; [b]Institute of Water Policy, Lee Kuan Yew School of Public Policy, National University of Singapore, 259770, Singapore; and [c]Robert B. Daugherty Water for Food Global Institute, University of Nebraska, Lincoln, NE 68583

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**Green water—rainfall over land that eventually flows back to the atmosphere as evapotranspiration—is the main source of water to produce food, feed, fiber, timber, and bioenergy. To understand how freshwater scarcity constrains production of these goods, we need to consider limits to the green water footprint ($WF_g$), the green water flow allocated to human society. However, research traditionally focuses on scarcity of blue water—groundwater and surface water. Here we expand the debate on water scarcity by considering green water scarcity ($WS_g$). At 5 × 5 arc-minute spatial resolution, we quantify $WF_g$ and the maximum sustainable level to this footprint ($WF_{g,m}$), while accounting for green water requirements to support biodiversity. We then estimate $WS_g$ per country as the ratio of the national aggregate $WF_g$ to the national aggregate $WF_{g,m}$. We find that globally $WF_g$ amounts to 56% of $WF_{g,m}$, and overshoots it in several places, for example in countries in Europe, Central America, the Middle East, and South Asia. The sustainably available green water flows in these countries are mostly or fully allocated to human activities (predominately agriculture and forestry), occasionally at the cost of green water flows earmarked for nature. By ignoring limits to the growing human $WF_g$, we risk further loss of ecosystem values that depend on the remaining untouched green water flows. We emphasize that green water is a critical and limited resource that should explicitly be part of any assessment of water scarcity, food security, or bioenergy potential.**

green water | water scarcity | water footprint | water consumption | water sustainability

Although water is a circulating resource, there are limits to freshwater availability for human appropriation (1). All freshwater stems from precipitation over land, which differentiates into a blue water flow—runoff via groundwater and surface water—and a green water flow—rainfall that infiltrates the soil or is intercepted by vegetation and eventually flows back to the atmosphere as evapotranspiration (2)*. Since the amount of precipitation is limited in time and space, so are the blue- and green water flows. Conventional water resource assessments focus on the availability of blue water and its allocation for use in the domestic, industrial, livestock, and irrigation sectors (3–5). To produce food, feed, fiber, timber, and bioenergy both green and blue (irrigation) water are used, but the largest part of water use is green (6–8).

Water scarcity assessments address the degree to which freshwater use approaches or exceeds limits to freshwater availability, which results in increased competition over water. Blue water scarcity refers to the competition over limited runoff and is often expressed as the ratio of blue water use to availability (5). It has been recognized as a global risk (9) and is thoroughly studied (10–13). However, given availability of green water is much larger than for blue water (1), the invisibility of green water in the landscape, and the indirectness of green water allocation through land-use decisions (2, 14), limits to green water appropriation are rarely considered. An illustrative example of the lack of recognition of limits to green water is seen in the water-energy debate. The International Energy Agency ignores green water in their World Energy Outlook (15), while their energy scenario with the smallest carbon footprint has a water footprint that quadruples due to the increased use of green water for biomass (16). As another example, in the United States, blue water constraints have been considered in the development and scale-up of biomass production, but green water has usually been taken for granted (17).

Green water scarcity refers to the competition over limited green water flows, which can either support a natural ecosystem or the production of biomass for various purposes in the human economy (18). Increasing green water scarcity means that reduced green water flows remain for nature and for fulfilling additional biomass demands for the human economy. This resource allocation problem has been recognized by a few scholars (19–22). Postel et al. (19) made a first attempt to estimate the share of ET appropriated by human activity (26%). Shortly after, Rockström et al. (20) and Rockström and Gordon (21) warned that mankind's reliance on green-water–dependent biomes is much larger, and furthermore, that there are critical trade-offs between green water allocation to food production versus other welfare-supporting ecosystem services. To date, however, appropriate incorporation of green water in water scarcity assessments still remains a key challenge (5). Previous attempts to assess green–blue water scarcity (23–25) suffer from an incomplete

## Significance

**Precipitation over land partitions into runoff via surface water and groundwater (blue water) and evapotranspiration (green water). We expand the traditional debate on water scarcity, which solely focuses on blue water, by assessing green water scarcity. The current debate on water scarcity is heavily skewed, since it leaves unnoticed the bulk of water availability—which is green—and the bulk of water use—which is also green. Green water is the main source of water to produce food, feed, fiber, timber, and bioenergy. Thus, to understand how freshwater scarcity constrains the production of these vital goods, explicating and including (limits to) green water use is imperative.**

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[1]To whom correspondence may be addressed. Email: j.f.schyns@utwente.nl or a.y.hoekstra@utwente.nl.

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*Blue water can be withdrawn from groundwater or surface water to be added to the green water in the soil by means of irrigation. The resulting evapotranspiration (ET) will then have a green component ($ET_g$) as well as a blue component ($ET_b$). In this paper we stick to the definition by Falkenmark and Rockström (2). To be concise, when we speak of "ET" in this paper we refer to the ET of green water ($ET_g$).

quantification of green water availability and use: by excluding ET from nonagricultural lands they underrepresent green water availability (5) and by excluding the forestry sector they underrepresent green water use (18).

The objective of this study is to quantify the degree of human appropriation of the world's limited green water flow. We answer three questions: What is the appropriation of green water by the human economy, specified geographically? What are the geographically explicit limits to the human appropriation of green water? Where are these limits approached or exceeded?

Regarding the first question, we estimate the human appropriation of green water flows as the sum of the green water footprints ($WF_g$) of crop production, livestock grazing, wood production, and urban areas at a 5 × 5 arc-minute grid cell spatial resolution. By doing so, we provide a more comprehensive, spatially explicit estimate of the $WF_g$ of humanity than was previously shown by Hoekstra and Mekonnen (8) (which included crop production only).

Regarding the second question, the limits to the $WF_g$ are estimated at 5 × 5 arc-minute resolution by quantifying the maximum sustainable $WF_g$ ($WF_{g,m}$) as the total available green water flow minus the green water flow to be reserved for nature (22). In estimating $WF_{g,m}$ we consider agroecological suitability and accessibility of land, biophysical constraints to intensifying land use, and biodiversity conservation needs. For the latter, we subtract the green water flow from land needed to support biodiversity, using a spatially explicit map of biodiversity conservation areas to achieve the Aichi Biodiversity Target (ABT) 11—which entails expanding the protected area network to at least 17% of the terrestrial world by 2020 (www.cbd.int/sp/targets)—with maximum conservation outcome (26). In doing so, we innovate upon ecological footprint studies, which do not account for conservation needs in the assessment of "biocapacity" (27, 28).

Regarding the third question, we present the global allocation of the green water flow to human activities versus ecosystem services and show the degree of human appropriation and overshoot of the $WF_{g,m}$ on the level of 5 × 5 arc-minute grid cells. Next, we assess green water scarcity ($WS_g$) per country—in a complementary way to common blue water scarcity indicators—as the ratio of the national aggregate $WF_g$ to the national aggregate $WF_{g,m}$, which reflects the degree to which the sustainably available green water flow in a country has already been allocated to human activities. In doing so, we make a contribution to the incorporation of green water in water scarcity assessments.

## Results

**Human Appropriation and Overshoot of the Limited Green Water Flow.** Fig. 1 shows the allocation of the limited green water flow to human activities and ecosystem services. About 22% of the global green water flow is from land that is set aside for nature so as to effectively achieve ABT 11, while 17% is from nonutilizable lands that are too cold for cropping or grazing, have too steep terrain slopes, or are far from human settlement and infrastructure. The green water flow from the remaining utilizable land (62%) is in part allocated to human activities and in part to ecosystem services like habitat, climate regulation, erosion control, and others (see refs. 29 and 30 for the full list of ecosystem services and descriptions).

The $WF_g$ reflects the human appropriation of the green water flow and is made up of $5.7 \times 10^3$ km$^3$ y$^{-1}$ for crop production (58%), $2.9 \times 10^3$ km$^3$ y$^{-1}$ for livestock grazing (30%), $0.9 \times 10^3$ km$^3$ y$^{-1}$ for wood production (9%), and $0.3 \times 10^3$ km$^3$ y$^{-1}$ for urban areas (3%). A spatially explicit map of the $WF_g$ of humanity is included in *SI Appendix*, Fig. S1.

The $WF_{g,m}$ is estimated at $18 \times 10^3$ km$^3$ y$^{-1}$. Comparing the global sum of $WF_g$ to the global sum of $WF_{g,m}$, we find that 56%

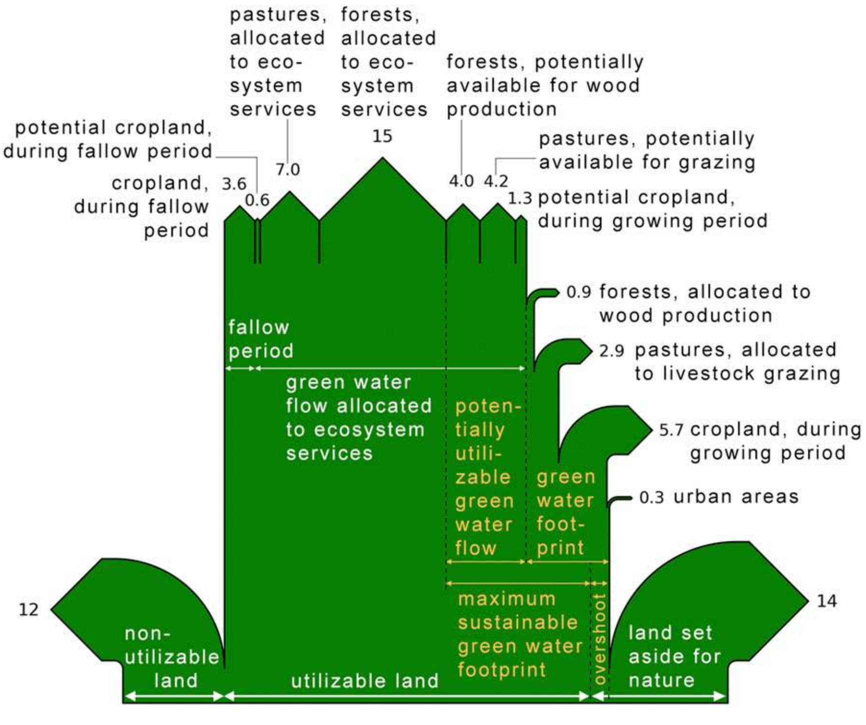

**Fig. 1.** Allocation of the total green water flow from the terrestrial Earth surface ($72 \times 10^3$ km$^3$ y$^{-1}$). Values are in 1,000 km$^3$ y$^{-1}$. Arrows represent green water flows from different sorts of land, as indicated by the labels. Overshoot amounts to $1.8 \times 10^3$ km$^3$ y$^{-1}$ and relates to overuse of green water resources in crop production ($0.9 \times 10^3$ km$^3$ y$^{-1}$), grazing ($0.6 \times 10^3$ km$^3$ y$^{-1}$), wood production ($0.2 \times 10^3$ km$^3$ y$^{-1}$), and urban areas ($0.1 \times 10^3$ km$^3$ y$^{-1}$).

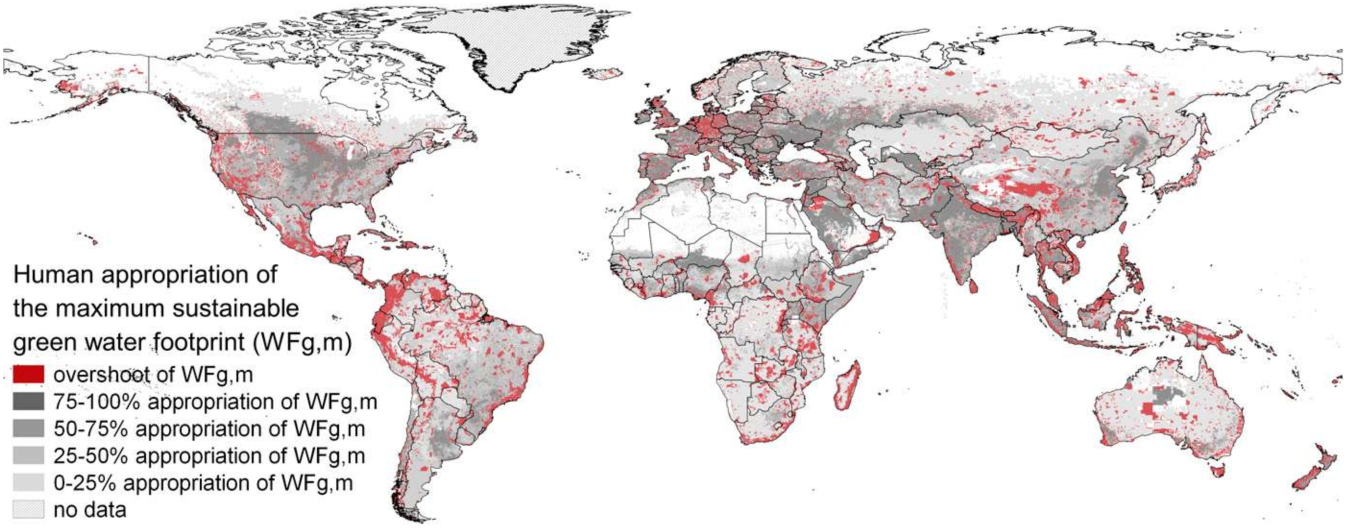

**Fig. 2.** The degree of human appropriation of the $WF_{g,m}$, at 5 × 5 arc-minute grid cell resolution, expressed as the ratio of the total $WF_g$ to the total $WF_{g,m}$. Overshoot occurs where $WF_g$ is located in biodiversity conservation areas to effectively achieve the ABT 11.

the world's sustainably available green water flow has already been allocated to human activities.

Although on a global level 56% of the sustainably available green flow has been appropriated for human use, locally the ratio of $WF_g$ to $WF_{g,m}$ can be much higher or lower (Fig. 2). In places on the map occurring in the darker shades of gray, $WF_g$ is close to $WF_{g,m}$, meaning that nearly all of the sustainable available green water flow has been allocated to human use. In places showing lighter shades of gray, $WF_g$ is still below $WF_{g,m}$ (Australia, Africa, Canada, Scandinavia, North Eurasia), indicating possibilities to locally increase $WF_g$ if local trade-offs with loss in ecosystem service values are deemed acceptable (*Discussion*).

Furthermore, we find that 18% of the total $WF_g$ overshoots $WF_{g,m}$ by being located in biodiversity conservation areas to effectively achieve the ABT 11 (i.e., the red areas in Fig. 2). Overshoot of $WF_g$ ($1.8 \times 10^3$ $km^3$ $y^{-1}$ globally) is mainly related to overshoot of the $WF_g$ of crop production (51%) and grazing (35%), followed by wood production (11%) and urban areas (3%). Over half the overshoot occurs in just 10 countries: United States (8.6%), Brazil (6.9%), Indonesia (6.4%), India (5.2%), China (5.0%), Colombia (4.9%), Philippines (4.4%), Mexico (4.0%), Germany (3.1%), and Malaysia (2.5%).

**$WS_g$ of Nations.** To assess $WS_g$ per country, we calculate the ratio of the national aggregate $WF_g$ to the national aggregate $WF_{g,m}$ (Fig. 3). $WS_g$ expresses the degree to which the sustainably available green water flow has already been allocated to human activities. Countries in which $WF_g$ closely approaches or exceeds $WF_{g,m}$—i.e., where $WS_g$ is close to or beyond 1—are predominantly found in Europe, Central America, the Middle East, and South Asia (Fig. 3). These include countries known for ample rainfall—and consequently a large green water flow, such as the United Kingdom, Germany, Indonesia, and New Zealand—where presence of $WS_g$ may sound counterintuitive. However, we show that the sustainably available green water

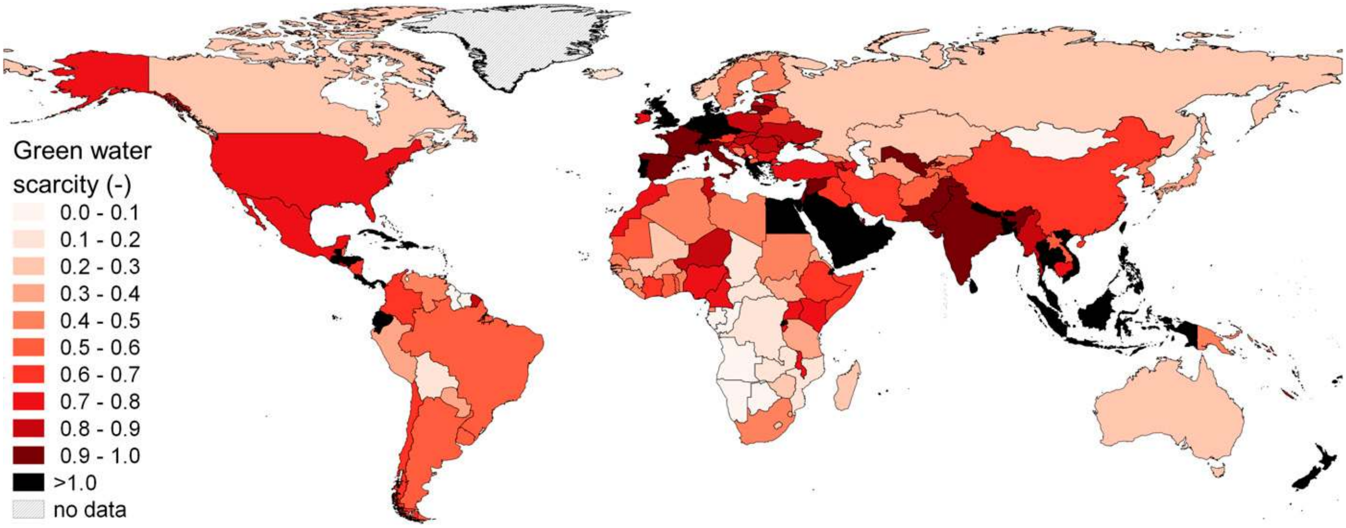

**Fig. 3.** $WS_g$ per country, expressed as the ratio of the national aggregate $WF_g$ to the national aggregate $WF_{g,m}$. Countries with $WS_g = 1$ have fully allocated their sustainably available green water flow to human activities (or overshoot is canceled out by remaining potential in another part of the country). Country-specific estimates of $WF_g$, $WF_{g,m}$, $WS_g$, and overshoot as percentage of $WF_g$ are included in *SI Appendix*, Table S1.

flow in these countries is limited and mostly or fully allocated to human activities, with even green water flows to be reserved for nature being appropriated already (mainly for agriculture).

## Discussion

The world's limited green water flow is shared by humans and nature. We have made its allocation explicit and provide an attempt to quantify $\mathrm{WS_g}$ as the ratio of actual to maximum sustainable $\mathrm{WF_g}$. The value of our assessment lies in raising awareness for the fact that there are limits to the human $\mathrm{WF_g}$. We show where these limits are approached or exceeded, i.e., where there is a high degree of $\mathrm{WS_g}$.

**Uncertainties.** Our results should be interpreted with care as they are subject to uncertainties in the estimates of both $\mathrm{WF_g}$ and $\mathrm{WF_{g,m}}$ (and hence in the $\mathrm{WS_g}$ ratio). Uncertainties can be particularly significant at the grid cell level, since uncertainties from random errors tend to reduce when averaged over larger scales (31). Uncertainties in the $\mathrm{WF_g}$ of crop production can range in the order of ±20% (32, 33). Our estimate of the $\mathrm{WF_g}$ of livestock grazing is within the range of estimates from previous studies (*SI Appendix*), but nevertheless subject to uncertainties, especially in the estimates of the grazed areas and the value of ecosystems services generated by pastures. Similar uncertainties in the areas used for wood production and the value of forests apply to the $\mathrm{WF_g}$ of wood production (see ref. 34). The $\mathrm{WF_g}$ of urban areas is so small that any uncertainties hardly affect our total $\mathrm{WF_g}$ estimate. The estimates of $\mathrm{WF_{g,m}}$ are uncertain (particularly at the smaller scales) due to uncertainties in the land that is set aside for nature ($\mathrm{WF_{g,m}}$ equals zero), which we will reflect upon below in *Trade-Offs Between Allocating Green Water to Humans Versus Nature*.

**Implications and Alleviation of $\mathrm{WS_g}$.** Tensions and trade-offs between green water allocation to humans versus nature are widespread. With our analysis we aim to make these issues part of the debate on water scarcity. For example, to become the European leader in biofuel production, Germany has reconverted vast areas of land to monocultures of bioenergy crops, rapeseed in particular (35). Germany has already reached the maximum use of grasslands according to Common Agricultural Policy regulations (35) and agricultural intensification is a prime suspect for the major decline in flying insects in protected areas in Germany (36). Also in the United States, bioenergy crops have expanded into previously set-aside land (35) and uncultivated grasslands (37), at the cost of plant, insect, and bird diversity (38). The strong irrigation dependence in the Middle East can be explained by the fact that green water flows for crop production are fully utilized already. The region has seen a huge increase in livestock grazing and associated environmental impacts over the past century (39). Grazing is now a major contributor to rangeland degradation in Saudi Arabia (40) and desertification in Israel (41).

Globally, deforestation is primarily driven by land-use change for commodity production (42) and is a major cause of biodiversity loss (43, 44). The relatively fast agricultural expansion in rainforests in the Amazon and in Southeast Asia is to be understood in the context of the global scarcity of still unused lands with sufficient rain. While green water flows are intensively used in most places around the world, the rainforests are among the few places with vast unused green water flows. Primary causes for deforestation across Central and South America are cattle ranching and large-scale agriculture, often for animal feed and bioenergy crops (45). Hotspots are the Atlantic Forest/Gran Chaco in Bolivia (46), Argentina (47–49), and Paraguay (50) [clearing for pasture and overgrazing (51); and agricultural expansion for soy], the Amazon (52, 53) and Cerrado (54) in Brazil (cattle ranching; soy plantations for food, animal feed, and biofuels), and the Chocó-Darién (45, 55) in Colombia and Ecuador (coca production; cattle ranching). In South Asia forest degradation is linked to crop production and wood logging (45). In the Greater Mekong in Cambodia, Thailand, Laos, and Myanmar (56) deforestation pressures include plantations of sugar, rice, rubber (57), and timber production, with logging in protected areas being prevalent across the region (58). On Sumatra and Borneo, wood logging severely degrades forest and leaves them vulnerable for land conversion, particularly for palm oil plantations (44, 59).

The tensions between green water for humans versus nature are intensifying as the green water demand for biomass in the economy grows. This growth is not only driven by population growth, but also by increasing green water demands per capita due to changes in the food and energy mix. Increasing affluence and urbanization are driving a global dietary transition with a higher consumption of animal products (60), which have much larger $\mathrm{WF_g}$ than nutritionally equivalent plant-based products (61). Current policies aiming for a higher share of bioenergy in the energy mix will increase the $\mathrm{WF_g}$ of the energy sector (16, 62, 63). Averting increased pressure on limited green water resources requires policies to slow down the growth of the human $\mathrm{WF_g}$—targeting the consumption of livestock products and increased use of biofuels in particular.

We can hardly "grab" more green water flows for human society at the cost of nature (*Trade-Offs Between Allocating Green Water to Humans Versus Nature*), and although there is the potential to locally increase the green water availability to some extent by improved soil management (to retain more water in the soil that can then be taken up and transpired by crops), this will reduce beneficial blue water flows. Green- and blue water are communicating vessels and their sum is limited by the available precipitation, which is essentially the resource that is being allocated to competitive uses. For this reason, we deliberately assessed the human appropriation of the green water flow under current land use, for which blue water scarcity has been assessed as well by others (e.g., ref. 13).

Green water productivity can be increased by using the green water flow more effectively through a vapor shift (64), i.e., turning nonbeneficial evaporation from the soil into transpiration that contributes to biomass growth. This can be achieved by soil and crop residue management to maintain the infiltration and water-holding capacity of the soil, particularly by no-till and reduced tillage systems which conserve soil organic matter (65, 66). The transpiration efficiency (the ratio of plant transpiration to total ET from the crop field) will also be higher if the crop has a dense foliage and a well-developed root system (64), which requires proper supply of nutrients and effective control of weeds, pests, and diseases (67). Also, the application of mulches on the field is an effective way to enhance green water productivity by limiting evaporation from the bare soil (68). Closing the yield gap (69) by other means than a vapor shift, e.g., by using well-suited stress-resistant crop cultivars (67), also increases crop water productivity. Adding some blue water (deficit or supplemental irrigation) to bridge short dry spells can also help to achieve higher yields and hence boost green water productivity (64, 70). In some places which we have identified as highly green water scarce, increased use of blue water might offer a solution to increase production in this way (e.g., Northwestern Europe), yet in other places (e.g., the Middle East, Central America, Southern Europe, and India) blue water is severely scarce as well (13).

Assessing the differences and similarities between green- and blue water in terms of appropriation and scarcity, and related conflicts and solutions, remains an interesting avenue of further research. A major difference between the two types of water resources is that green water is landbound and indirectly allocated through land-use decisions (2, 14), while blue water can be diverted and supplied to other locations. Blue water scarcity (the competition over limited runoff) generally translates to reduced river flows and declining levels in groundwater, rivers, and lakes, which affect ecosystems and people depending on these flows and levels (11). The effects of increasing $WS_g$ (viz. increased competition over limited ET) are not as visible as the effects of increasing blue water scarcity. The reason is that green water use does not change catchment hydrology as blue water use does; green water use just means that a green water flow that was available to natural vegetation before use has now been reallocated to produce biomass for the human economy.

**Trade-Offs Between Allocating Green Water to Humans Versus Nature.** The current allocation of green water is the result of past land-use decisions, which entailed (implicit) considerations of the trade-off between green water for mankind versus nature, as referred to by Rockström et al. (20). Mostly, these decisions have favored mankind. When natural vegetation was converted to agricultural land, the green water flow was reallocated from supporting biodiversity to supporting human food supply. This has been accompanied by tremendous impacts on habitats and biodiversity (69) with trillions of dollars in losses of ecosystem service values (30). Since the green water flow is a limited resource in space and time, increased human appropriation of the green water flow is at the cost of natural ecosystems. This trade-off is always present, even when $WF_g$ remains below the estimated $WF_{g,m}$.

We have estimated $WF_{g,m}$ considering agroecological suitability and accessibility of land, biophysical constraints to intensifying land use, and biodiversity conservation needs (based on ABT 11; *Materials and Methods*). However, despite this solid basis, limits to $WF_g$ are debatable to some extent, especially at the local level. ABT 11 is a global target that calls for effective conservation of at least 17% of the terrestrial world, especially focusing on areas of particular importance for biodiversity and ecosystem services, but without regional specification of this target. We used the map by Montesino Pouzols et al. (26), who mapped those areas of highest conservation value, thus representing an effective spatial configuration to achieve ABT 11. However, different configurations are possible.

Despite uncertainties, we believe that our estimate of the $WF_{g,m}$ of humanity is rather an under- than an overestimation, considering that some have argued for far more ambitious targets to preserve vital ecosystems services (71), or even leave half of the Earth to nature (72). Nevertheless, we recommend future work that aims to improve upon our estimate of $WS_g$ to focus on better estimates of the $WF_{g,m}$, in particular regarding the green water flow that should be reserved for nature.

## Conclusions

We have mapped the $WF_g$ of the global economy and compared it to maximum sustainable levels, considering green water requirements to support biodiversity. We find that the total $WF_g$ of humanity currently appropriates 56% of the world's sustainably available green water flow. About 18% of humanity's $WF_g$ overshoots local sustainable levels, by being located in biodiversity conservation areas needed to achieve ABT 11. By expressing $WS_g$ per country as the ratio of the national aggregate $WF_g$ to the national aggregate $WF_{g,m}$ we showed that countries facing high $WS_g$—thus having no or very limited potential remaining to increase rainfed biomass production—are mainly found in Europe, Central America, the Middle East, and South Asia.

The world's limited green water flow is shared by human society and nature. By ignoring limits to human's growing $WF_g$—driven by an increased demand for food, feed, fiber, timber, and bioenergy—we risk further loss of ecosystem service values. Green water is a critical and limited resource that should explicitly be part of any assessment of water scarcity, food security, or bioenergy potential.

## Materials and Methods

We estimated the human appropriation of the green water flow as the sum of the $WF_g$ of crop production, wood production, livestock grazing, and urban areas at a 5 × 5 arc-minute grid cell spatial resolution, using estimates of $WF_g$ of crop and wood production from Mekonnen and Hoekstra (73) and Schyns et al. (34), and our own estimates on $WF_g$ of livestock grazing and urban areas (details in *SI Appendix*).

Limits to the $WF_g$ are expressed by $WF_{g,m}$, which we estimate at 5 × 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 (details in *SI Appendix*), which is similar to the practice of accounting for environmental flow requirements to support natural aquatic ecosystems (74). We set aside lands ($WF_{g,m} = 0$) that have a protected status (75) or have priority to receive that status to achieve the ABT 11. 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. (26) using the map for present land-use conditions. Furthermore, we estimate $WF_{g,m}$ based on agroecological suitability and accessibility of land, and biophysical constraints to intensifying land use. Therein, we distinguish between lands that are currently utilized to some extent for agriculture, forestry, or urban areas, and those lands that are nonutilized at the moment but do have the potential to be used considering a range of constraints (details in *SI Appendix*).

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