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A planetary boundary for green water

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Abstract | Green water — terrestrial precipitation, evaporation and soil moisture — is fundamental to Earth system dynamics and is now extensively perturbed by human pressures at continental to planetary scales. However, green water lacks explicit consideration in the existing planetary boundaries framework that demarcates a global safe operating space for humanity. In this Perspective, we propose a green water planetary boundary and estimate its current status. The green water planetary boundary can be represented by the percentage of ice-free land area on which root-zone soil moisture deviates from Holocene variability for any month of the year. Provisional estimates of departures from Holocene-like conditions, alongside evidence of widespread deterioration in Earth system functioning, indicate that the green water planetary boundary is already transgressed. Moving forward, research needs to address and account for the role of root-zone soil moisture for Earth system resilience in view of ecohydrological, hydroclimatic and sociohydrological interactions.

The planetary boundaries framework demarcates a global safe operating space for humanity based on Earth system dynamics[1,2] (FIG. 1a). The framework defines boundaries to human pressures on nine biophysical systems and processes that regulate the state and resilience of the Earth system, using the comparatively stable interglacial Holocene (initiated 11,700 years ago) as the baseline. Conceptually, each boundary is associated with a control variable that allows tracking of risks for Earth system impacts. Notably, persistent and substantial boundary transgression of either of the two core boundaries — those for 'Biosphere integrity' and 'Climate change' — can push the Earth system towards an irreversible state shift[3]. Transgression of other boundaries, including that of freshwater use, imply deterioration in Earth system functioning that can increase the risk of regional regime shifts and predispose transgressions of core boundaries. Based on the precautionary principle, the boundary is placed conservatively at the lower level of scientific uncertainty.

Global-scale and basin-scale definitions of the 'Freshwater use' planetary boundary (PB) are solely defined by blue water (rivers, lakes, reservoirs and renewable groundwater stores) as a provisional proxy for overall water flux changes in a river basin. At the global scale, the boundary is currently set to an annual maximum of 4,000 km^3 consumptive blue water use. At the basin scale, boundary positions are set based on minimum levels of monthly environmental water flow required to maintain adequate aquatic ecosystem states[4]. According to an estimated current global water withdrawal rate of 2,600 km^3 $year^{-1}$, the 'Freshwater use' PB is deemed to be within the planetary-scale boundary, despite widespread basin-scale transgressions[2,4].

Yet, human pressures on green water (terrestrial precipitation, evaporation and soil moisture) Earth system functions were intended to be implicitly represented by the 'Freshwater use' PB[1,2], which focuses solely on blue water. The lack of an explicit representation of green water in the planetary boundaries framework can, therefore, conceal and misrepresent extensive human modifications of green water functions[5–7]. For example, according to the current definition, deforestation that deteriorates green water functioning in favour of increased blue water availability would not contribute towards boundary transgression[8]. Given the fundamental importance of green water for Earth system resilience, there is an urgent need to better understand the level of terrestrial wetness that maintains a Holocene-like state of the Earth system. Indeed, green water is critical for supporting and regulating most terrestrial biosphere processes, including energy, carbon, water and biogeochemical cycles[5], with human perturbation generating non-linear changes, collapse and irreversible regime shifts in terrestrial ecosystems and hydroclimatic regimes[5,9–12].

In this Perspective, we propose a green water PB for quantifying green-water-related changes that reflect the capacity of the Earth system to cope with human perturbations (FIG. 1b). We identify a set of processes that comprehensively captures the hydroecological and hydroclimatic functions of green water in the Earth system, and, based on scientific evidence, propose a definition of a green water PB control variable. Subsequently, the green water PB's boundary position and current status are set, and the use and interpretation of the PB discussed to guide sustainability governance. Finally, we discuss research priorities to better understand the biophysical and societal Earth-system-scale risks of substantial and persistent green water modifications. In doing so, we argue that the 'Freshwater use' PB should be renamed to the 'Freshwater change' PB composed of green and blue water components (FIG. 1a).

Green water as control variable

In order to establish and define a green water PB, an appropriate control variable needs to be selected. Candidate variables must represent important green-water control (FIG. 1b), rather than green-water responses, to ecological and climatic change. For this reason, green water indicators of anthropogenic appropriation (for example, green water footprint[13]) cannot be considered. Instead, major non-blue freshwater flows and stocks — precipitation, evaporation and soil moisture — form viable

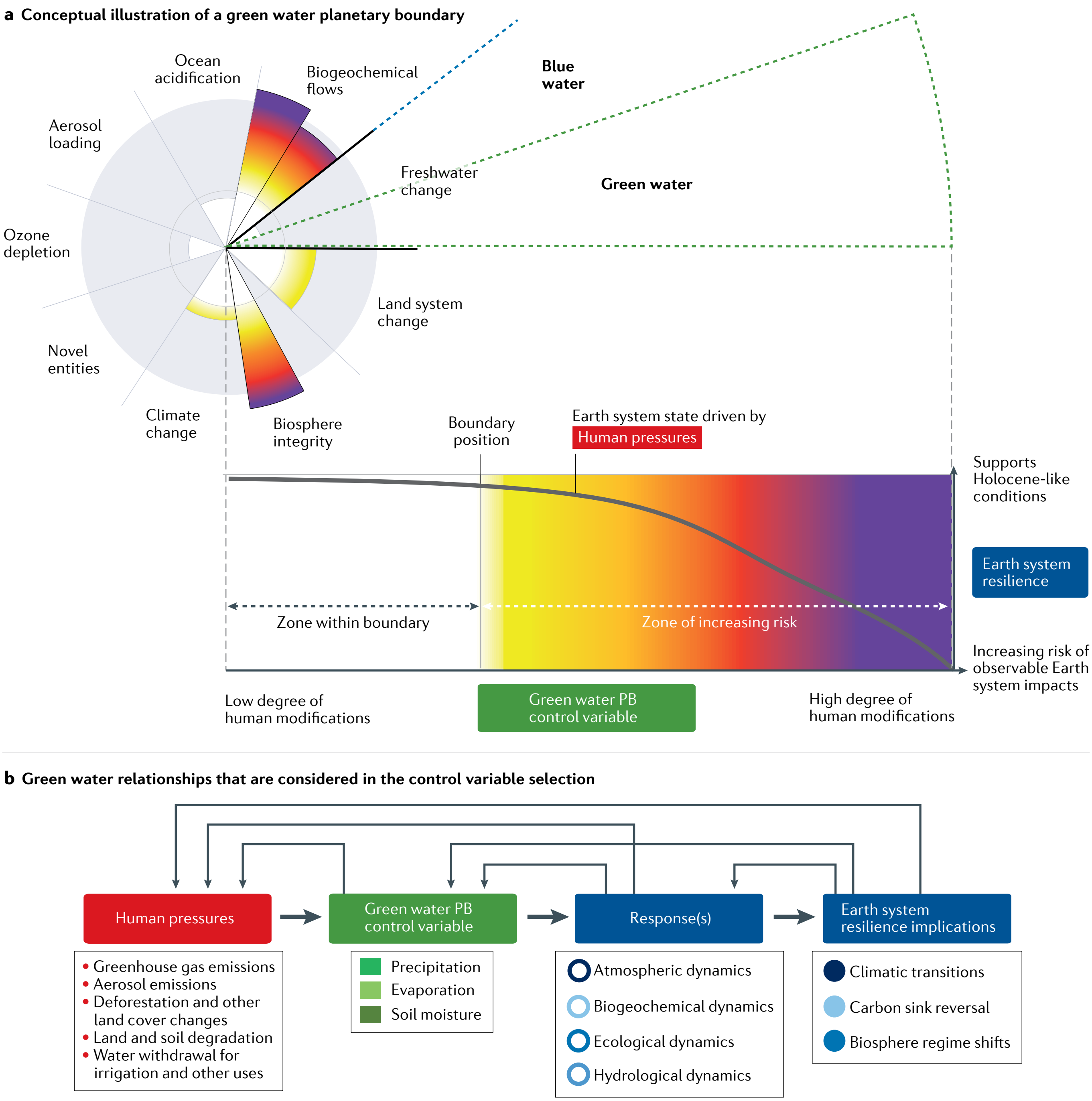

Fig. 1 | **The conceptual framework of a green water planetary boundary.** **a** | The planetary boundaries framework with its nine boundaries, including the proposed renaming of 'Freshwater use' as 'Freshwater change', subdivided into a blue and a green water sub-boundary. The lower panel illustrates the relationship between the degree of human modification of the green water planetary boundary (PB) control variable and Earth system resilience implications. **b** | The key relationships (thick grey arrows) considered in selecting a suitable green water PB control variable. Adding a new green water component to the planetary boundaries framework requires defining a quantifiable control variable that can signal rising Earth system risks caused by anthropogenic green water modifications. Top left illustration in panel **a** is adapted, with permission, from REF.[2], AAAS.

candidates, each with critical importance in hydroecological and hydroclimatic functions. In considering these variables, the definition of green water is broader than most others. Indeed, other definitions sometimes only comprise terrestrial evaporation[14] that directly contributes towards biomass production (transpiration), thereby, excluding the direct and indirect role of precipitation and unproductive evaporation in regulating ecological and climatic processes[5,9,15–17]. The basis of precipitation, evaporation and soil moisture as potential control variables in a green water PB are now discussed, focusing on their control–response relationships that modify Earth system functioning.

Precipitation control. Precipitation, the largest flux in the terrestrial water cycle (FIG. 2a) and a strong predictor of soil moisture[18] and vegetation productivity[19], exhibits strong green-water control on

Earth system functioning. Indeed, human activities influence precipitation patterns at various spatio-temporal scales, motivating the use as a green water PB control variable. For example, land-use change (such as deforestation, irrigation and urbanization[20]) alters precipitation by modifying local land–atmosphere coupling, atmospheric water balance and large-scale circulation patterns, including monsoon dynamics[21–25]. Greenhouse gas and aerosol emissions also alter atmospheric water holding capacity, cloud formation, circulation and, subsequently, the magnitude and spatio-temporal variability of precipitation[13,26–28]. Notably, precipitation anomalies are projected to increase under anthropogenic warming at a range of timescales[29–31], with potential non-linear impacts on hydroecological and hydroclimatic functioning (FIG. 2b, Supplementary Tables 1 and 2).

From a planetary boundaries perspective, the resilience of the Amazon and Congo rainforests is critical, as these forests are considered tipping elements of the Earth system[3,10,32]. Radical changes in mean annual precipitation result in non-linear responses in tropical tree cover[10,33,34] (FIG. 2b), drought deciduousness in tropical forests[35], changes in tropical tidal-wetland vegetation cover[36], reduction in evolutionary diversity[37] (FIG. 2b) and interannual variability of net ecosystem carbon exchange[38] (FIG. 2b). Moreover, below a critical threshold of ~2,000 mm year^{-1}, tropical rainforests cannot maintain year-round photosynthesis[39].

Widespread deterioration of ecological, climatic and hydrological Earth system functioning is further associated with changes in the temporal variability of precipitation. Indeed, precipitation seasonality in tropical rainforests[34], dry forests[40] and drylands[41–43] is a critical, persistent and non-linear driver of tree cover extent and fire[34], functional traits diversity[44], vegetation productivity[45], soil moisture and carbon sequestration[41], and the overall strength of the tropical carbon sink[46]. Severe meteorological droughts in semi-arid regions reduce tree growth that wet anomalies cannot compensate for[47] and decrease overall ecosystem production[48]. Increasing extreme precipitation under anthropogenic warming can also cause soil erosion[49], decrease infiltration, decrease soil moisture and increase surface runoff[49], although the implications for flooding risk are not straightforward[29,50,51].

Precipitation constitutes an important candidate to a green water PB control variable, based on the strong control it

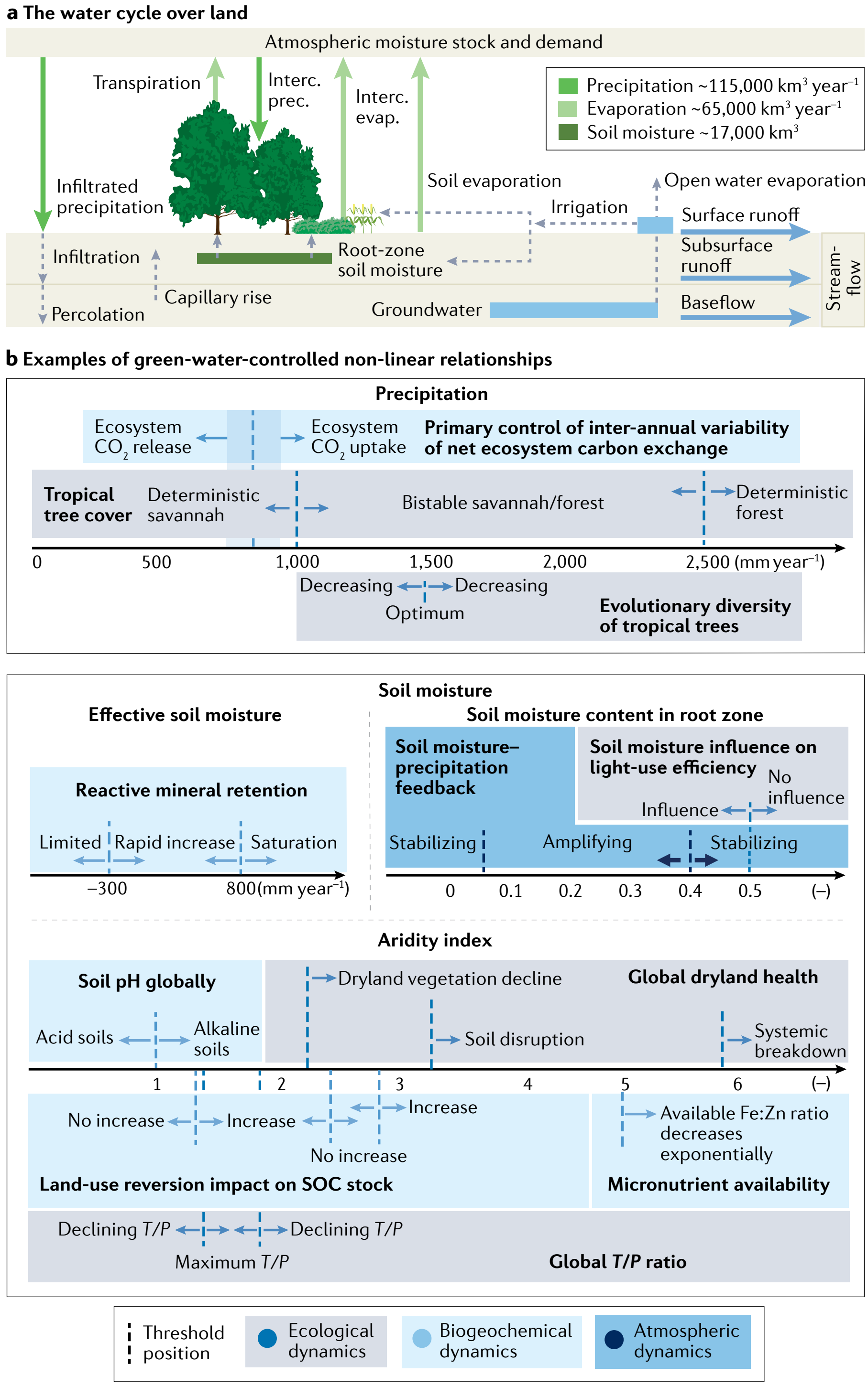

Fig. 2 | **Green water and associated non-linear relationships. a** | Overview of the water cycle over land, including estimates[9] of global land precipitation[119], evaporation[198] and soil moisture[199]. Green arrows and boxes indicate green-water flows and stocks, respectively. Blue arrows indicate the flows accounted for in the current blue-water-based 'Freshwater use' planetary boundary. Dashed grey arrows indicate other considerable hydrological flows that indirectly affect the green and blue water flows and stocks. **b** | Non-exhaustive overview of precipitation (*P*, top) and soil-moisture (bottom)-controlled non-linear relationships: effective soil moisture is defined as precipitation minus potential evaporation (E_{pot}) and the aridity index as E_{pot}/P. The *x* axes indicate the value of a specific green water planetary boundary control variable, with vertical dashed lines representing thresholds for ecological, biogeochemical or atmospheric responses (different blue shading); the threshold is broadly used to refer to a point or small range of values, on either side of which the relationship between the control and response variable considerably differs in character. Green water changes across a wide range of wetness can generate non-linear ecological, biogeochemical and atmospheric change. Interc., interception; SOC, soil organic carbon; *T*, transpiration.

exerts on Earth system dynamics. However, while human activities clearly influence the magnitude and temporal distribution of precipitation, the impact pathways are partly indirect and occur via changes to terrestrial evaporation and soil moisture.

Evaporation control. Terrestrial evaporation — the sum of transpiration, soil evaporation and interception evaporation[14] — offers a further option as the green water PB control variable, constituting the second largest flow in the global water cycle over land (FIG. 2a). Like precipitation, human activities also impact evaporation, with marked spatial and temporal variability. For instance, agriculture and pasture expansions covering nearly half of the Earth's ice-free land surfaces are associated with both 2,000–3,000 km^3 $year^{-1}$ decreases and 800–2,600 km^3 $year^{-1}$ increases in evaporation[22,52–54]. Moreover, anthropogenic forcing is associated with higher average terrestrial evaporation rates and a higher risk for drought-induced decreases in evaporation[55]. Increased atmospheric CO_2 concentration can further increase, decrease or have a minimal effect[56] on transpiration, owing to changes in vegetation productivity[57] and higher water-use efficiency[58].

Such changes in evaporation mediate the energy and water balance of the atmosphere and affect regional climate and temperature. For example, irrigation can delay monsoon onset[17], increase downwind precipitation[22,23,59] and, on the hottest days of the year, have a cooling effect[60,61]. However, irrigation-induced evaporation can also create humid heatwaves beyond human physiological survivability limits[62,63]. In addition, forest-loss-induced decreases in dry season evaporation can self-amplify forest loss through weakened moisture recycling cascades[64,65] and increase the occurrence of drought by shifting precipitation patterns[66,67].

Terrestrial evaporation is a strong candidate to a green water PB control variable based on its direct response to human pressures and control on hydroclimatic Earth system functions. Nevertheless, evaporation primarily responds to human impacts on ecological dynamics and only indirectly controls hydroecological Earth system functions.

Soil moisture control. The green water PB control variable could also be based on soil moisture, a critical interface between all major flows in the water cycle (FIG. 2a). Soil moisture retention and availability[68–70] are impacted by human activities both directly through agricultural intensification, agricultural expansion and urbanization[71,72], and indirectly via precipitation and evaporation changes[73] induced by anthropogenic climate change[74], land system change and water use (FIG. 2a).

Soil moisture can be commonly defined as surface soil moisture, total soil moisture column and root-zone soil moisture, particularly in large-scale modelling and analyses. Mechanistically, it is root-zone soil moisture that is most directly linked to transpiration, biomass production and soil moisture drought, and, thus, the soil moisture definition that could best serve as a candidate for a green water PB control variable. However, owing to the absence of reliable, detailed and widespread estimates of root-zone soil moisture, proxy indicators are often used to assess impacts on hydroecological and hydroclimatic functioning. These proxy indicators include various combinations of precipitation, evaporation, surface soil moisture, potential evaporation, temperature or radiation, such as the aridity index[75] (the ratio between mean annual potential evaporation and precipitation) and a range of seasonal water deficit indices[44–46,76–78].

Soil moisture change is linked to a variety of non-linear responses in ecological, biogeochemical, atmospheric and hydrological dynamics. For example, root-zone soil moisture deficit is a key driver of persistent and non-linear ecological states. During periods of limited or no precipitation, vegetation maintains photosynthesis and transpiration by accessing moisture from the soil. Below a critical threshold of plant-available water, vegetation mortality increases, particularly in vegetation types without alternative drought coping strategies (such as dormancy, deciduousness and plant water storage), including tropical trees[79,80]. In drylands, transgressing aridity index thresholds might be associated with vegetation decline, soil disruption and systemic breakdown[11] (FIG. 2b). However, the use of hydroclimatic proxy variables (such as the aridity index) to examine ecological impact is debated, notably owing to plant physiological changes being unaccounted for. Furthermore, while some research suggests that CO_2 fertilization has limited to no effect in counteracting the vegetation decline[81], others outline that greening associated with CO_2 fertilization is critical in the model simulation of future carbon sink[82] and dryland extents[83].

Root-zone soil moisture anomalies are also key drivers of the land carbon cycle via controls on ecosystem productivity. Indeed, modifications in soil moisture under a high emission scenario risk turning the land from a net carbon sink to a carbon source by the middle of the century[84]; with increased temperatures, dry soils suppress carbon uptake[85]. Soil moisture content below 50% can also trigger abrupt light-use efficiency changes, impacting ecosystem productivity and carbon uptake[86] (FIG. 2b). In fact, ample evidence supports the critical role of soil moisture for the carbon cycle[87] across various ecosystem types, including temperate grasslands[88], semi-arid areas[89,90], peatlands[91,92] and permafrost areas[93,94]. In many such cases, carbon cycle dynamics are linked to aridity through soil biogeochemical processes (FIG. 2b), including pH (REF. 95), micronutrient availability[96], microbial abundance and diversity[97], land management impact on soil organic carbon storage[98] and reactive mineral retention[99].

Soil moisture deficits can further directly affect atmospheric dynamics through land–atmosphere interactions and resultant energy balance perturbations[100]. Surface soil moisture anomalies have non-linear relationships with evaporation variability[16], temperature extremes[101–103], local precipitation[104] (FIG. 2b) and water availability[105]. Amplifying feedbacks between soil moisture deficit, intensified surface warming, anticyclonic circulation anomalies and heatwaves[106] that further exacerbate soil drying might lead to abrupt shifts in regional climate[107]. The influence of antecedent soil moisture on the probability of subsequent precipitation appears to depend on aridity, particularly in semi-arid and semi-humid regions[108].

Moreover, soil moisture is linked to non-linear transitions in hydrological states. Locally, small changes in soil moisture near thresholds, such as wilting point or field capacity, can modify evaporation rates and deep percolation[109]. Globally, the aridity index is associated with non-linear changes in the sensitivity of plant transpiration to hydroclimatic change[110] (FIG. 2b). Soil moisture–precipitation feedback also opens up the possibility of two distinct preferential states of seasonal soil moisture[111]. Initial spring or early summer soil moisture conditions might enable the switch between inherently resilient soil moisture states, locking the system into those conditions over a season[111]. Stochastic, amplifying feedbacks might, thus, cause bimodality of soil moisture and transitions between different soil moisture states[112]. Temporary soil moisture deficit can also lock watersheds into long-term low-flow conditions, potentially owing to adaptive increases of root-zone storage capacity that do not easily return to pre-drought levels[113]. The ability of soil moisture deficits to induce alternative stable states in soil hydraulics is also demonstrated experimentally[70].

Root-zone soil moisture fulfils two of the most important considerations in the selection of a green water PB control variable: it is directly influenced by human pressures and it directly impacts a range of large-scale ecological, climatic, biogeochemical and hydrological dynamics.

Control variable selection

Precipitation, evaporation and root-zone soil moisture are all viable green water PB control variables based on their biophysical control–response relationships. Nevertheless, control variables in the planetary boundaries framework further need to usefully represent scientific knowledge and serve in management contexts. To systematically account for all these aspects, eight evaluation questions (adapted from REFS[6,114]) were used to assess and compare the suitability of precipitation, evaporation and soil moisture for defining the green water PB (TABLE 1; Supplementary Methods).

Table 1 | **Qualitative evaluation[a] of the suitability of green water flows and stocks as a planetary boundary control variable**

Question	Precipitation	Evaporation	Root-zone soil moisture
Scientific evidence and biophysical representation[b]			
Human perturbation: is the green water variable a robust and comprehensive indicator of anthropogenic perturbation on green water processes?	+	+++	+++
Earth system functioning: can changes in the green water variable contribute towards a non-linear change in the functioning of the Earth system within an 'ethical time horizon'?	+++	++	+++
Holocene-like conditions: can the Holocene-like conditions of the green water variable be defined and estimated?	++	++	++
Boundary position: can a boundary position be robustly defined for the green water variable based on knowledge of the system dynamics?	++	++	++
Universality: is the green water variable able to directly or indirectly represent all relevant components and dynamics of green water?	+	++	+++
State representation: does the green water variable represent a state of the Earth system?	+	++	+++
Usefulness for management			
Measurability: can the status of the green water control variable be measured, tracked in time and monitored?	+++	++	++
Parsimony: does the green water variable minimize overlaps and redundancy with other planetary boundaries?	++	++	++
Overall evaluation results and total scores[c]	15	17	20

[a]Consensus-based assessment performed by the authors (Supplementary Methods). [b]Responses to each question answered as: +, 'yes, to a limited extent'; ++, 'yes, to a large extent'; +++, 'yes, to a satisfactory extent'. [c]Total score determined as the total number of '+'.

Root-zone soil moisture is inherently better at representing overall green water dynamics (universality) compared with precipitation and evaporation (TABLE 1). Indeed, root-zone soil moisture is directly affected by changes in precipitation and evaporation, and is critical in mediating the relationship between the two. It further controls transpiration and indirectly affects interception storage capacity[115,116]. Although saturated root-zone soil moisture will not change in response to precipitation increase or evaporation decreases, it is more prone to translating precipitation increase into runoff increase. In contrast, evaporation does not respond to precipitation when the atmospheric demand is low, and the precipitation response to land and water is indirect and contingent on land–atmosphere feedback strength. As a result, precipitation also scored lower in its representation of human perturbation (TABLE 1).

By definition, root-zone soil moisture also outperforms the flow-based variables in reflecting the state of the Earth system (state representation in TABLE 1), contributing to consistency across the planetary boundaries framework. The control variables for most of the other quantified boundaries are state variables: atmospheric CO_2 concentration ('Climate change'), biodiversity intactness index ('Functional diversity'), stratospheric O_3 concentration ('Stratospheric ozone depletion'), carbonate ion concentration ('Ocean acidification'), area of forested land ('Land system change') and aerosol optical depth ('Atmospheric aerosol loading'). Flow variables have only been employed in the planetary boundaries framework where state variables have been deemed inappropriate: extinction rate ('Genetic diversity'), phosphorus flow and nitrogen fixation ('Biogeochemical flows') and consumptive blue water use ('Freshwater use')[2].

Moreover, root-zone soil moisture (and precipitation) outperform evaporation when representing green water drivers of non-linear hydroecological and hydroclimatic impacts (Earth system functioning in TABLE 1). In terms of hydroecological control, evaporation-related variables more commonly represent responses to — and not control of — ecological change. For example, transpiration is a by-product of photosynthesis, and both interception and soil evaporation are influenced by vegetation growth[117]. In the instances where evaporative flows can be considered to control ecological processes, it is largely through their consumptive influence on plant-available moisture in the soil[16]. In contrast, water availability in the soil directly restricts and asserts control on vegetation biomass production and carbon dynamics[84,118]. The distinction is not as evident in terms of hydroclimatic control. On the one hand, it can be argued that soil moisture asserts control of atmospheric processes only via evaporation, in which case, evaporation constitutes the primary control variable. On the other hand, it can be argued that evaporation, as latent heat flux, is itself a hydroclimatic functioning controlled by soil moisture[16].

For the three other evaluation aspects — Holocene conditions, boundary position and parsimony — precipitation, evaporation and root-zone soil moisture can be considered equally suitable. For measurability, precipitation is considered most suitable, given the accuracy and coverage of various gauge-based, radar-based and satellite-based precipitation measurements[119]. Based on the consideration of all evaluation criteria, root-zone soil moisture outperforms precipitation and evaporation, and is, thus, the most suitable control variable of a green water PB (TABLE 1).

Green water planetary boundary

While a green water PB control variable based on root-zone soil moisture can be proposed according to the published literature and variable evaluation, a more precise definition is required to determine the boundary position and its current status, as are now discussed.

Control variable formulation. We propose the following formulation of a green water PB control variable: the percentage of ice-free land area on which root-zone soil moisture anomalies exit the local bounds of baseline variability in any month of the year. This specific definition offers many advantages. First, this direct measure of the root-zone soil moisture state better represents ecological responses, such as stomatal conductance and vegetation growth response to rising CO_2 concentrations[120,121], compared with popular proxies, such as the aridity index. Second, a land-area-based measure is preferred over a water-volume-based measure, which can mask the spatial heterogeneity of water cycle dynamics by disproportionately discounting hydrological changes in arid regions[5,6]. Such a land-area-based metric has also been proposed to replace the current water-flow-based blue water PB (REF.[6]). Third, a monthly scale overcomes issues associated with sub-monthly scales (which are below the scale of agricultural and ecological droughts[122,123]) and annual scales (which can potentially average out and, thereby, conceal ecological impacts from dry and wet extremes at seasonal scales[124]). Last, a percentile-based formulation removes outliers, and the use of upper and lower bounds accounts for both wet and dry departures from baseline. In this case, these local bounds are defined as the 5th and 95th percentiles of root-zone soil moisture for a given month for all years within the baseline period (Supplementary Methods).

Baseline departure. Within the planetary boundaries framework, boundary positions and transgressions of control variables are quantitatively assessed in relation to a baseline period, preferably the Holocene. However, given that there are no publicly available data on root-zone soil moisture covering the whole 11,700-year Holocene, mid-Holocene (500 years beginning ~6,000 years ago) and pre-industrial (1850–1899) periods can provisionally be considered the baseline. Since the global baseline departure is based on the percentage of land area that exits local bounds of root-zone soil moisture variations, deviations are considered at both the local and the global scales. Exit from local bounds occurs when root-zone soil moisture variations are beyond the 5th and 95th percentiles for a given month during the baseline; local bounds are based on an area of the considered grid cell (0.5°) and its neighbours. Departures from the global baseline occur where percentage variations in land area that exit wet or dry local bounds are beyond the 95th percentile lowest variations for a given month during the baseline. A fraction of ice-free land area exiting local bounds can be expected within these baseline periods, since the local bounds are defined by percentiles rather than the maximum and minimum monthly root-zone soil moisture.

Using these definitions and baselines, the extent of baseline departure of the green water PB is assessed. Root-zone soil moisture data are obtained from MPI-ESM1.2-LR (REFS[125,126]) and simulated using the dynamic vegetation model LPJmL5.1 forced with data from CMIP6 (Supplementary Data, Supplementary Table 3). Pre-industrial baseline departures are analysed over 1900–2014 and mid-Holocene baseline departures over 1850–2014.

These preliminary analyses indicate that the green water PB control variable has departed from the variability envelope of the pre-industrial baseline (FIG. 3). Permanent departures, where the time series of the percentage of land area exiting local bounds do not fall within the variability envelope by the end of the time series by 2014, occurred across all model outputs. Indeed, both wet and dry departures from the pre-industrial baseline have steadily increased between 1900 and 2014, with permanent wet departures occurring from the 1980s and permanent dry departures from the 1920s (LPJmL5.1) or 1980s (MPI-ESM1.2-LR). There is also a possibility of departures from the mid-Holocene baseline (FIG. 3). Specifically, a permanent wet departure is simulated from the 1920s. In contrast, dry departures from the mid-Holocene are substantial and permanent, but relatively stable over 1850–2014.

These findings should be cautiously interpreted. For instance, neither the pre-industrial nor the mid-Holocene baselines can be claimed to be representative of the entire Holocene period. The pre-industrial period is extremely short in a palaeoclimatic perspective and already considerably impacted by human land system change[127,128]. The mid-Holocene was also wetter than most other periods during the Holocene, with land precipitation over a large area, particularly in the tropics, appearing to have declined since[129]. Moreover, many important control–response relationships are not represented by the models. For example, rooting depth was fixed in both land surface model simulations and LPJmL5.1 simulations were not dynamically coupled to represent land–atmosphere feedback. Mid-Holocene model outputs were also only available for a single simulation from a single Earth system model (MPI-ESM1.2-LR) and should, thus, be considered highly uncertain (Supplementary Data).

Earth system resilience. Boundary positions in the planetary boundaries framework are determined based on the assessed self-regulatory biophysical capacity of the Earth system to remain in Holocene-like conditions (Earth system resilience)[2,114]. Thus, while the degree of baseline departure provides a reference point (FIG. 3), the boundary position of the green water PB can only be set by taking into account the overall Earth system resilience. High Earth system resilience suggests that the boundary can be positioned beyond the baseline departure level, assuming that the Earth system can recover from a temporary pressure on green water. Conversely, low Earth system resilience suggests that the boundary needs to be set below the baseline departure level. In this instance, Earth system resilience is considered high if no other planetary boundaries are transgressed and/or stabilizing feedbacks dominate over amplifying feedbacks, or low if other planetary boundaries are transgressed and/or amplifying feedbacks dominate.

On this basis, the self-regulatory capacity of the Earth system to absorb human-induced green-water perturbations might be considered compromised. Specifically, at least five of the nine planetary boundaries are presently considered transgressed: the core boundaries 'Climate change' and 'Biosphere integrity', as well as 'Land system change', 'Biogeochemical flows'[2] and 'Novel entities'[130]. The 'Freshwater use' PB is also potentially transgressed[4,131,132]. Furthermore, interactions and interdependencies among planetary boundaries amplify human impact and shrink the planetary safe operating space[133].

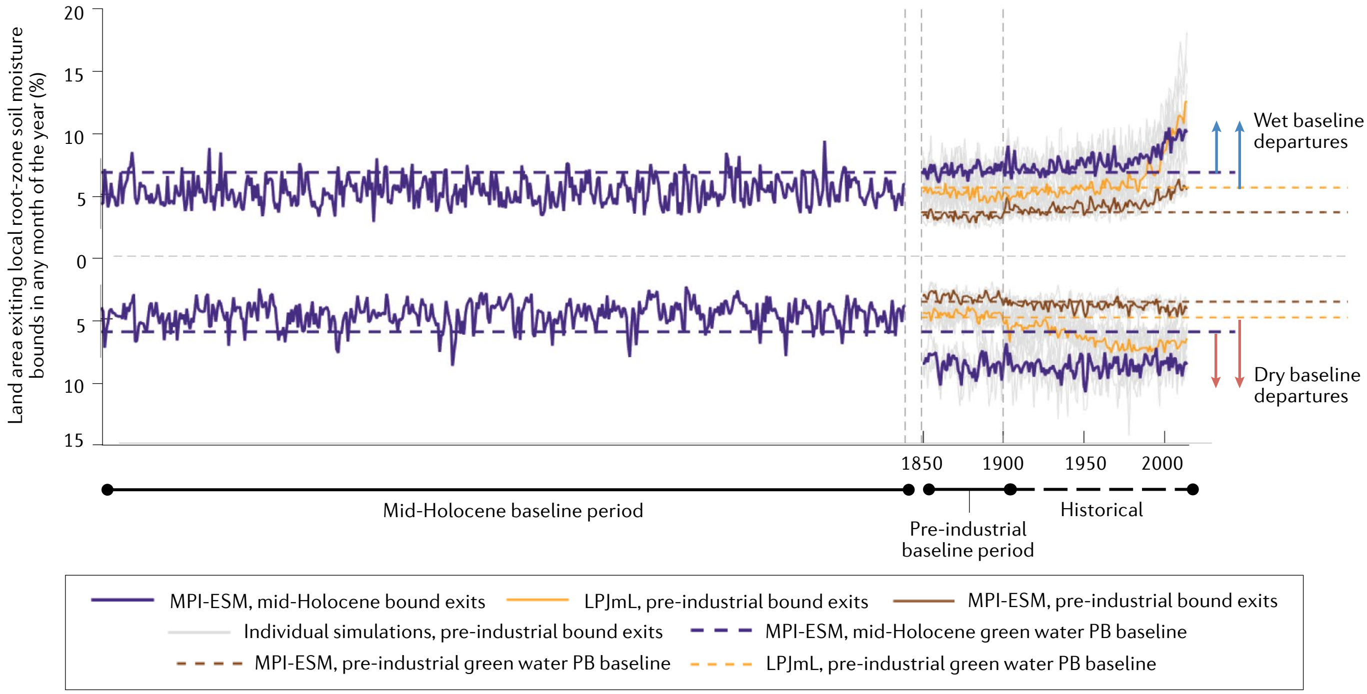

Fig. 3 | **Departure from the envelope of baseline variability.** Percentage of land area with monthly root-zone soil moisture deviations beyond local lower (dry departure) and upper (wet departure) bounds. Dry and wet bounds are defined as the 5th and 95th percentiles of root-zone soil moisture over the mid-Holocene (500 years from ~6,000 years ago) and pre-industrial (1850–1899) baseline periods, respectively (Supplementary Methods), using data from the Earth system model MPI-ESM1.2-LR (REFS[125,126]) (purple and brown lines) and the global vegetation and water balance model LPJmL (REF.[200]) (yellow lines; Supplementary Data). Pre-industrial baseline departures were considered for the historical period (1900–2014) and mid-Holocene baseline departures for the entire historical period (1850–2014), as transient root-zone soil moisture data are unavailable over the entire Holocene. Simulations of the proposed green water planetary boundary (PB) control variable have, thus, already departed from the variability envelope (5th and 95th percentiles) of both the pre-industrial and the mid-Holocene baseline.

The other criteria for low Earth system resilience, the dominance of amplifying feedbacks, also points towards a compromised green water PB (FIG. 4). For instance, there are suggestions that the stabilizing CO_2 fertilization feedback is weakening[134], potentially because of limitations in nutrient and soil moisture availability[87,134,135]; however, these findings are debated[136–139]. Observation-based analyses further suggest that carbon uptake peaked in the Amazon rainforest in the 1990s, and more recently in the African tropical forests[46]. In the boreal forests, the carbon sink appears to be still increasing[140,141], although observed increases in water-use efficiency might not translate to stem growth and increase in carbon sequestration[142]. In drylands, amplifying feedbacks are increasing: climate change and degradation trigger vicious cycles[4,143] of infiltration capacity loss[69], decrease in soil moisture and moisture recycling[144,145], and loss in biodiversity[146], although soil moisture–atmosphere feedbacks might help mitigate some of the declining water availability in drylands[105,147]. In permafrost regions, carbon feedbacks are amplifying, with the hydrological cycle having a complex role[148]. Soil moisture saturation risks accelerating thawing, creating anaerobic conditions and methane emissions[93], although further progress in permafrost thawing might decrease or, ultimately, even offset and counter any intensification in the Arctic hydrologic cycle[149]. In peatlands, drying can be associated with shrubification and CO_2 emissions, which are more long-lived than methane release from waterlogged conditions[91,92]. Owing to highly complex ecohydrological dynamics and multifactor interactions, substantial uncertainty persists concerning the overall land carbon cycle feedback under global warming[150–152].

Boundary transgression. Conceptually, boundary transgression can be determined under three scenarios of Earth system resilience (FIG. 5). In a first scenario, Earth system resilience is not considered and/or neutral (amplifying and stabilizing feedbacks are in balance), and a baseline departure can, thereby, be interpreted as a boundary transgression. This scenario is aligned with the original method for proposing individual boundary positions[114], which assumes that no other boundaries are transgressed. This interpretation would imply a transgressed green water PB (top bar in FIG. 5), since the current status (~18% of land area exiting wet and dry local bounds) of the green water PB control variable is slightly beyond the mid-Holocene baseline departure level (~13% of land area exiting local bounds) (FIG. 3).

In a second scenario, the Earth system is assumed to have a high resilience (other planetary boundaries are not transgressed and stabilizing feedbacks dominate) and the capacity to absorb temporary perturbations, thereby, allowing a boundary position to be placed above the baseline departure level (middle bar in FIG. 5). With a sufficiently high Earth system resilience, the current status of the green water PB control variable could be considered safe.

In our present situation, however, Earth system resilience is compromised (other planetary boundaries are transgressed and amplifying feedbacks dominate) and a safe distance to baseline departures needs to be kept based on the precautionary principle (bottom bar in FIG. 5). Thus, the boundary position is set below the baseline departure level. The boundary position of the green water PB can be provisionally considered

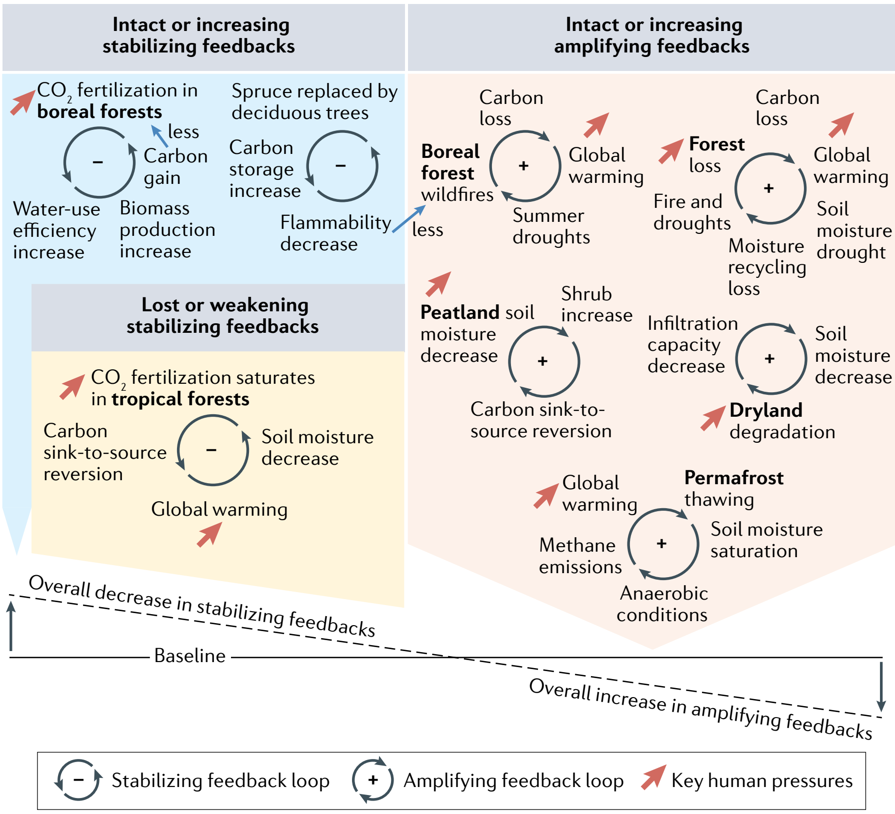

Fig. 4 | **Balance between green-water-driven stabilizing and amplifying feedbacks.** Overview of green-water-related feedbacks in the Earth system, including those that are stabilizing (minus sign) or amplifying (plus sign). Stabilizing feedbacks are either intact or increasing (blue background) or lost or weakening (yellow background). Amplifying green-water-mediated feedbacks (peach background) are increasing more than stabilizing feedbacks, suggesting that green-water changes in the Earth system are self-amplifying rather than self-stabilizing.

at ~10% of the land area in which root-zone soil moisture is wetter or drier than the local variability bounds. In the absence of data over the entire Holocene period (the preferred baseline period in the planetary boundaries framework), this proposed boundary position corresponds to the median of mid-Holocene local bound exits. Since ~18% of land area currently exits local bounds, the green water PB is considered to be considerably transgressed. This assessment is further motivated by the overall increasing trend of human influence on green water[153] and the fact that green water modifications are likely to progress further before any trend reversals can be observed due to inertia in the Earth system[154].

Taken together, a quantifiable and transgressed green water PB emerges: model outputs of unprecedented areas with root-zone soil moisture anomalies already indicate a departure from baseline, and worrying signs of a low Earth system resilience could further motivate a precautionary placement of the boundary position well below the baseline departure level. Green water modifications are now causing rising Earth system risks at a scale that modern civilizations might not have ever faced.

Interpretation and application

The current extent of green-water perturbations is inadequately addressed in global governance[155]. Mitigating green water PB transgressions thus requires globally coordinated policy attention. The green water PB can meet this requirement, acting as an integral part of the planetary boundaries framework that contributes to Earth system governance through regulatory (formal regulations, laws and treaties), procedural (such as forums for negotiations), generative (such as reframing the discourse narrative) and programmatic (such as programmes to meet international targets) functions in governance, business and civil society settings[156,157]. Moreover, a green water PB can highlight the need to address threats to green water and the soil[158] in a range of international sustainability policies and treaties, including the Sustainable Development Goals, the Convention on Biological Diversity and the Paris Agreement.

A green water PB complements other planetary boundaries by shedding light on underlying Earth system resilience. For example, complementary to the 'Land system change' PB, decreasing green water availability can indicate loss in forest resilience prior to abrupt forest–savannah shifts[10]. In addition, a green water PB complements a blue-water-based PB by reflecting the negative impacts of deforestation on the water cycle, even where such changes result in increases in river flows[8,22]. A green water PB can further account for functional restoration in human-dominated landscapes, achieved through, for example, rainwater harvesting[159], soil erosion prevention[160], peatland water management[161] and other sustainable land management practices.

As with the rest of the planetary boundaries framework, the green water PB is not designed to be spatially disaggregated[2] and directly operationalized. Operationalization requires articulating concrete policy targets and management approaches at a sectoral, national, city or business level (downscaling through fair share or local safe operating space approaches)[162–166]. A direct application to the local scale is complicated by a boundary-setting rationale based on continental-to-planetary system resilience considerations, and because the drivers of green water change involve interactions with a variety of human pressures. Downscaling approaches must harmonize cross-scale conflicts and leverage cross-scale synergies sensibly and intelligently for the highly spatially heterogeneous green water PB. In areas with strong moisture recycling, disproportionate impact of soil moisture change on downwind water cycle can be accounted for using data of evaporation recycling[141,167] (defined as the fraction of terrestrial evaporation that returns as terrestrial precipitation)[168]. Using the green water PB to motivate practices and interventions that would otherwise be considered unsustainable and harmful to people and nature is not advised.

A green water PB also complements other green water management metrics[169] by proposing a ceiling to human green water modifications and accounting for green water's role in supporting the Earth system to remain in Holocene-like conditions. Existing green water concepts and metrics[169] are typically concerned with human nature allocation (such as green water footprint and virtual water) or direct crop yield impacts at local spatial scales and short timescales (such as drought indices). In contrast, the green water PB can help inform governance actors on green water's role for large-scale and long-term resilience. For example, the Earth system perspective can highlight the role of the time delay in peak carbon emissions due to hysteresis effects[10] and the role of various climate mitigation measures for green-water-mediated Earth system impacts (such as afforestation and biomass plantations[170]). Beyond serving as a diagnostic metric, the green water PB points at the need for integrative research on how land, water and climate governance policies affect overall Earth system functioning.

A transgressed green water PB implies increased Earth system risks, but green water impacts on societies will also depend on factors that are beyond the scope of the planetary boundaries framework. An optimistic view might be that technological advances enable modern societies to address unprecedented water variability and environmental challenges[171]. This argument would suggest that the boundary position proposed here is too conservative concerning societal impacts, although changing the boundary position would violate the precautionary principle. Conversely, historical research of social collapse illustrate that environmental challenges, such as hydroclimatic shifts towards drier conditions, could trigger societies to grow more complex, with the outcome depending on a society's position along a trajectory of increasing complexity and diminishing returns on further investments in complexity[172]. This line of argument would suggest that water variability in the Holocene that sustained former societies might not sustain modern, complex and interdependent societies. An application of this view could suggest that societies set more stringent limits to green water modification than proposed here.

Summary and future perspectives

Within the planetary boundaries framework, freshwater — the bloodstream of the biosphere[173] — has only been implicitly considered through the 'Freshwater use' PB. However, an explicit articulation of green water is required to better represent the full extent and diversity of human pressures on the water cycle. The 'Freshwater use' PB should, thus, be renamed as 'Freshwater change', divided into a blue and a green water sub-boundary. The green water sub-boundary can be represented by a control variable based on root-zone soil moisture, specifically, the percentage of ice-free land area on which root-zone soil moisture anomalies exit the local bounds of Holocene variability in any month of the year. Given the current extent of root-zone soil moisture departures from mid-Holocene and pre-industrial baselines, as well as widespread deteriorations in Earth system resilience, there are indications that a green water PB might already be transgressed; human interference with green water has now reached an extent that increases the risk of large-scale non-linear change and compromises the capacity of the Earth system to remain in Holocene-like conditions. The current global trends and trajectories of increasing water use, deforestation, land degradation, soil erosion, atmospheric pollution and climate change need to be promptly halted and reversed to increase the chances of remaining in the safe operating space.

Future research now needs to increase the robustness of the green water PB control variable quantification, and understand the risks for and the dynamics through which green-water perturbations can disrupt Earth system resilience.

How can reliable quantifications of past and present root-zone soil moisture be achieved? Despite the fundamental importance of root-zone soil moisture for terrestrial ecosystems and hydroclimatic processes, its state and dynamics have hitherto been relatively sparsely modelled, measured and considered. The Global Observing Systems Information Center recognizes soil moisture as one of fifty Essential Climate Variables since 2010 (REF.[174]). However, in contrast to surface soil moisture, limited attention has been directed towards root-zone soil moisture[175], as reflected in the variable seldom being provided as a model output[176]. Such uncertainties in model representation of plant water limitations across Earth system models translate into large uncertainties in terrestrial carbon cycle simulations, comparable with global primary production[177]. Fortunately, there are promising signs that better understanding of root-zone soil moisture can be reached. Reconstructions can potentially be improved based on progress in global-scale palaeoclimatic research[178,179] and within the Paleoclimate Modelling Intercomparison Project[180]. Opportunities for improved estimates of present-day root-zone soil moisture are also increasing, owing to a rise in available data that can be used for inference, including field measurements[181,182] and satellite-based observations of surface soil moisture, precipitation, total water storage, other hydrologically relevant variables and

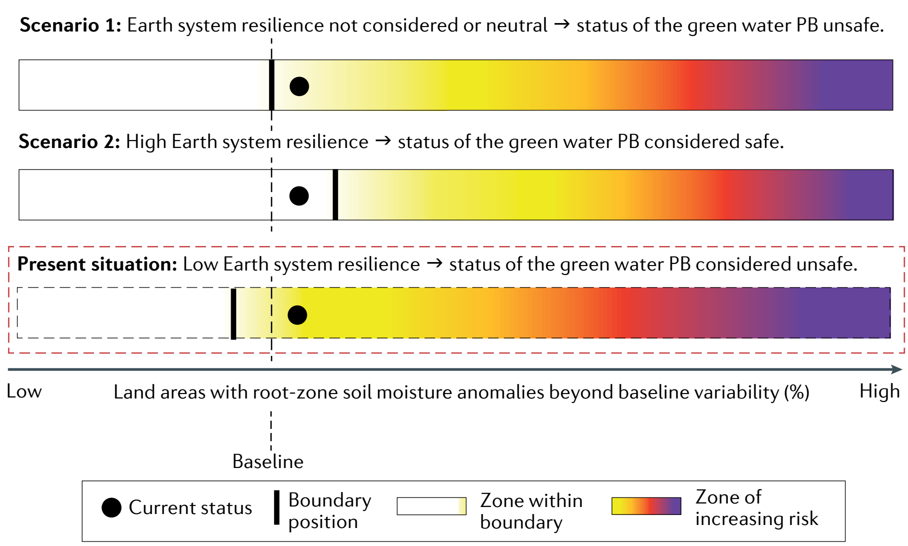

Fig. 5 | **Current status and boundary position of the green water planetary boundary.** An assessment of the green water planetary boundary (PB) under three scenarios: the status of other planetary boundaries are not considered, and stabilizing and amplifying related feedbacks are in balance (top bar); the other planetary boundaries are not transgressed, and/or stabilizing feedbacks dominate over amplifying feedbacks (middle bar); there are at least five other PB transgressions[2,130], and amplifying feedbacks dominate over stabilizing feedbacks, as in the current situation (bottom bar). The stabilizing and amplifying feedbacks refer to major green-water-mediated feedbacks considered to have considerable ecological, biogeochemical and climatic implications at the Earth system scale. The positions of the baseline (dashed black vertical line) and the current status (solid black circles) are fixed based on available data, while the boundary position is based on consideration of Earth system resilience. The green water PB is transgressed.

various vegetation characteristics[175,183–188]. Nevertheless, direct measurements of plant water access are still severely lacking, especially in areas with high importance for green water Earth system functioning, including tropical rainforests and drylands. Moreover, root-zone soil moisture's critical role in regulating ecological, hydrological, biogeochemical and climatic dynamics strongly motivates its inclusion among standard outputs in continuation of existing Model Intercomparison Projects.

What are the risks for human-driven green water modifications to contribute to crossing irreversible, near-future continental-to-planetary-scale tipping points? Understanding regime shift risks requires a good understanding of green-water-related interactions and feedbacks. Nevertheless, research on regime shifts and biome resilience frequently rely on proxy variables to represent plant water stress limitations, thereby, ignoring dynamic responses and evolutionary changes in water-use efficiency[56,142], light-use efficiency[86], plant groundwater access[187], plant bedrock water access[189], infiltration[190] and rooting depth[186,191,192]. The availability and simplicity of the aridity index and other proxy variables explain their popularity. However, their limitations should be overcome by improved, open data sharing principles[193] in order to facilitate collaboration across the Earth system sciences. Collaborative research on Earth system resilience, such as the Tipping Element Model Intercomparison Project, also has the potential to provide important insights in tipping risks and pathways associated with green water modifications.

Finally, research is needed for understanding how management and governance can account for the multiple roles of green water, both as an ecosystem service provider and a highly complex and dynamic Earth system function. The planetary boundaries framework has already triggered extensive discussions that challenged global paradigms on economic growth, legal national sovereignty and anthropocentrism[194]. As such, setting a global boundary to green water interference can be considered an act of governance in itself[158], and its political, economic, social and ethical implications will require further consideration[194–197].

Data availability

The LPJmL model outputs and data in FIG. 3 can be accessed at https://doi.org/10.5281/zenodo.6339619. The MPI-ESM1.2-LR data can be downloaded at https://esgf-node.llnl.gov/projects/cmip6/.

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Author contributions
L.W.-E. led the writing of the article, produced the visualizations and performed the baseline deviation analyses. A.T. produced Fig. 2a and conducted the LPJmL model runs underlying Fig. 3. L.W.-E., A.T., R.J.v.d.E., I.F., S.t.W., M.P., A.S., F.J., H.D. and J.R. contributed to the writing of the manuscript. L.W.-E., A.T., R.J.v.d.E., I.F., S.t.W., M.P., A.S., F.J., H.D., C.S. and P.W.K. performed the literature review. L.W.-E., A.T., R.J.v.d.E., I.F., M.P., A.S., F.J., H.D., C.S., P.G., D.G. and P.W.K. evaluated the green water variables. L.W.-E., A.T., R.J.v.d.E., I.F., S.t.W., M.P., A.S., F.J., H.D., C.S., P.G., D.G., P.W.K., J.R. and X.B. contributed to the editing and/or reviewing of the manuscript. All authors contributed substantially to the discussion of content. Overall author contributions of A.T., R.J.v.d.E., I.F., S.t.W., M.P., A.S. and F.J. can be considered equal.

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