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Pricing rainbow, green, blue and grey water: tree cover and geopolitics of climatic teleconnections

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Atmospheric moisture (''rainbow water'') is the source of all green, blue and grey water flows. Current water-related legislation and policies have moved beyond blue (water allocation) and grey (waste water treatment) water concerns to incorporate the green water concept of additional water use by fast-growing trees; it may require further change to incorporate rainbow water relations as evident in recent literature on short-cycle rainfall derived from evapotranspiration over land. Specific teleconnections relate rainfall dynamics at any specific site to land use and sea conditions elsewhere. Government-mandated water use charges for payments for ecosystem services (PES) exist in some African countries but their use in enhancing actual water related ecosystem services covering the full hydrological cycle is still evolving as rainbow water science is new.

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Introduction

Rainfall patterns across Africa interact with land cover, with important teleconnections, relationships between conditions in one part of the globe and the climate of a non-neighbouring location elsewhere. Water shortage and excess linked to variable rainfall may well be the most immediate consequence of global climate change affecting human livelihoods while we get dangerously close to planetary boundaries in the Anthropocene [1,2]. Nearly all public discourse on the influence of changes in tree cover on climate, however, has become focused on the carbon emissions and their contribution to greenhouse gas effects rather than on relations with rainfall [3]. There is reason, as we discuss here, to return to a hydro-climatic perspective on tree effects, just when the expectations of carbo-climatic forest finance through REDD+ are starting to look grim [4].

Environmental sustainability requires a convergence of the knowledge base of (1) public opinion and the policies it supports, (2) the local ecological knowledge derived by people with a long-term track record of survival, and (3) the way patterns and processes are understood in science and its models [5]. In reality these three knowledge systems can be widely divergent, and evidence-based policies can be hard to achieve [6,7]. Theories of dynamic knowledge systems, however, suggest that there cannot be lasting differences between theory and practice, although in practice there are [8,9]. We will discuss recent scientific evidence that matches more closely with local ecological knowledge of tree cover effects than what has been the consensus of hydrologists for some time [10,11].

Human land use and actual land cover interact with the hydrological cycle and climate at local (micro), landscape and regional (meso) and global (macro) scale. The two-way relationship between forests and climate has a long history of scientific discourse [12]. While the dominant effect of rainfall regime and temperature on natural vegetation type was clear to any traveller who could make comparisons between different parts of the world, the reverse influence of forest on local climatic conditions was apparent during the rapid conversion of natural forests to agriculture. Increases in ambient air temperature were noted in response to landscape-wide changes in tree cover, while associated changes in rainfall pattern were acknowledged in local ecological knowledge. Formal measurement of climate, however, had a major challenge in quantifying such effects, as the background variability at multiple temporal scales was large. Related claims on relations between deforestation and flooding risk are very hard to prove beyond micro catchment scale [13].

In reviewing the literature we use the palette of colours of water as guidance: while most of the early water policies relate to (blue) water in streams and rivers and its alternate uses, an additional interest arose in the high water use and depletion of groundwater reserves by

Table 1

Environmental components and aspects involved in policies regarding tree use, based on impacts on stakeholders beyond local land users

Aspect	Policy concern	Stakeholders beyond local land users	Policy instruments
Microclimate	Minimize vulnerability to climate extremes and global climate change	Local interest in wind speed, temperature, humidity	Facilitate voluntary tree planting
Blue water	Allocate scarce resource to highest-value use; reduce conflict	Downstream within watershed	(Tradable) water use rights; water infrastructure (engineering)
Blue water buffering and quality	Temporary storage of water in vegetated soil with sufficiently high infiltration rates; reduction of sedimentation of eroded soil particles by vegetation and litter layers	Direct users of blue water and managers of reservoirs	Regulatory land use zonation and/or use of economic incentives to reduce sediment loads
+ grey	Reduce water pollution; maximize re-use	Downstream within watershed	Waste water treatment obligations; water use charges
+, + green	Increase blue water availability by reducing green water use (esp. fast-growing trees)	Downstream within watershed	Rules and taxation of fast-growing trees
+, +, + rainbow	Minimize disturbance of pre-human vegetation-climate systems	Downstream + downwind (precipitationshed [34••])	Recognition of and negotiations with downwind beneficiaries of green water use
Carbon storage	Maximize terrestrial carbon storage to reduce global climate change	Global (carbonshed)	Economic incentives for REDD+, A/R-CDM; voluntary offset markets

fast-growing trees, labelled as green water issues and related policies. Recent research on the role of terrestrial evapotranspiration as source of atmospheric moisture and subsequent rainfall ('rainbow water') points to the relevance of a further refinement of the policy instruments of regulation and economic incentives that are aimed to bring the micro-economic decisions of land users in harmony with the interests of others who are part of the same hydrological cycle. Our discussion follows the rows of Table 1 that relate ecosystem services (the benefits that humans derive from ecosystem function) across scales to water policies and payment or taxation schemes.

Trees influence microclimate

People associate trees with microclimate and may inadvertently extrapolate to macroclimatic effects of forests [14•]. In recognition of the obvious microclimatic effects of vegetation, weather stations were, worldwide, standardized on open grassland conditions typical of airports. In subsequent discourse, however, it became forgotten that these are grassland-climate data rather than data representing all other possible local land cover types [15,16].

The direct modification of microclimate by trees does not generally become a policy issue with external stakeholders involved, except at local scales where trees might cast undesirable shade in (peri)urban settings. Generally, policies encourage tree planting in areas where tree cover is low (Table 1).

When climate science started to focus on global climate change, the 'urban heat island' effects [17,18] where urban sprawl had engulfed former grassland-weather stations were noted, and led to removal of some stations from the data sets, but the further influence of local effects, and cooling effects of other vegetation was discounted or at least ignored, despite criticism [19•]. In the discussions of forest and climate the net effects of changes in surface albedo and evaporative cooling imply that deforestation has a warming effect in the tropics, but can have a cooling effect at mid and high latitudes [20,21].

From blue to green water paradigms of the hydrological cycle

Hydrology started as the study of the regularity and volume of water flow in rivers, with an interest in how the energy of water flow could be harnessed for various forms of hydropower, how rivers could be used for transport and as source of water for irrigation, industrial or domestic use, and how negative effects of floods and droughts could be reduced or avoided. When water balance models were made, it appeared that this "blue" water was only about one-third of rainfall, depending on season and location. The term "effective rainfall" was coined to be able to discard all steps between rainfall and blue water flows.

Engineers aimed at using all blue water flows for a direct economic purpose saw as their target the "closed basin" where all blue water is used and none flows back to the oceans. With the increase in water use for irrigation keeping pace with the increased blue water availability due to deforestation, (both being around 3.000 km^3/yr) [22,23], it was realized that the current model of agricultural intensification based on irrigation cannot be sustained: there simply will not be sufficient blue water to support much expansion beyond current patterns. There is some opportunity to better use the "grey water" return flows from industrial and urban use for local solutions, but at a continental scale this does not add up to what is needed.

This brought attention to the two-thirds of rainfall used by vegetation as ''green water'' [24]. Forests and landscapes with high tree cover utilize incoming rainfall differently from landscapes without trees. While the resulting river flow (blue water) is likely to be more buffered due to improved infiltration and soil water holding capacity [25,26], a larger amount of green water (200-300 mm/year for an average patch) is returned to the atmosphere [27••]. If rainfall can be considered to be largely independent of land cover, as most of the early climate models assumed, any reduction in green water use increases blue water availability [28].

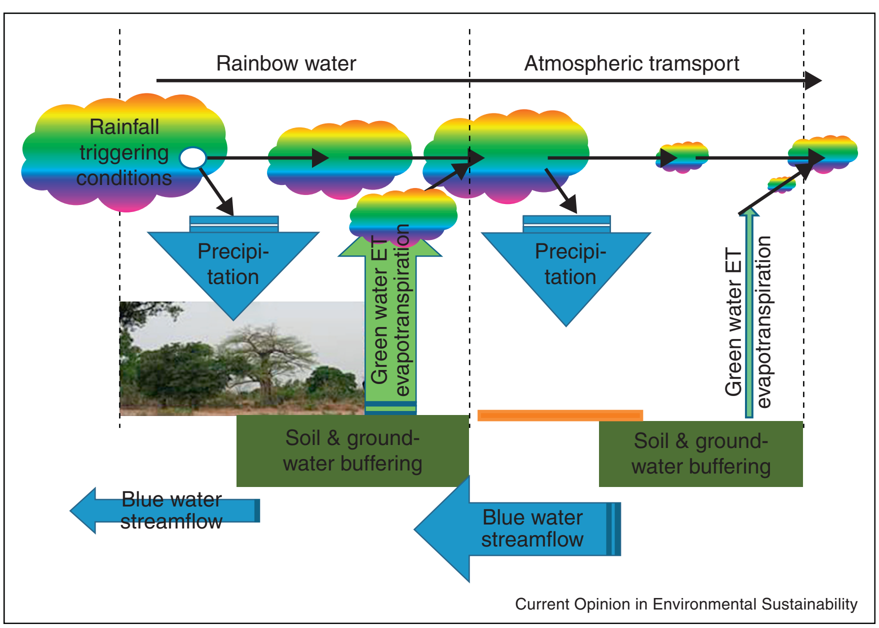
Economic incentives for tree planting have been used to reduce sediment loads and improve quality of blue water [29]. The impact of fast-growing trees on blue water has led to ample public debate and to proactive policy formulation in Africa. For example, in South Africa, the Conservation of Agricultural Resources Act, 1983 (Act No 43 of 1983) (CARA) legislates against weeds and invasive plants including woody species that are believed to be a threat to water security because they use more water than the plant communities they replace. In the South African Water Policy, forest plantations are categorized as stream-flow reduction activities and investors in them must acquire licenses and pay water charges [30•]. The debate about *Eucalyptus* in Kenya during the 1990s and 2000s concluded it consumed too much water; the Kenya Forestry Services stated these species should not be planted near marshlands, rivers or large water bodies or in areas receiving less rainfall than 1200 mm/year. Such legislation has led to restrictions and loss of the many economic values of plants classified as invasive yet studies of their water use have mostly been conducted on small scales [31,32] and have not been conclusive about wider hydrological impacts.

Rainbow water as emerging concept

The return flow of green water to the atmosphere is now seen as recycling rather than as loss [33•,34••], or even as a biotic pump attracting moist air influx and further rainfall [35,36]. The fraction of rainfall that derives from rainfall and evapotranspiration on land ('short cycle' rain) is larger than was commonly believed. New datasets of atmospheric moisture transport are the basis for the recent insights [32,33•,37] reviewed here (see Figures 1 and 2).

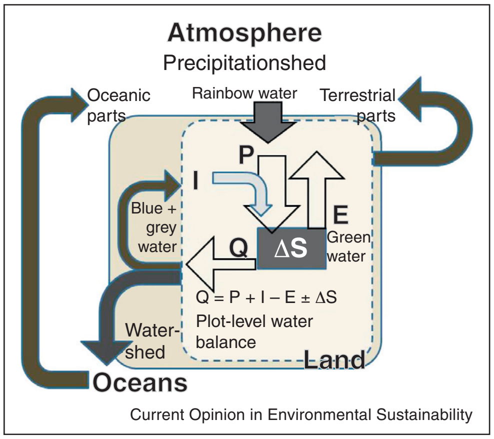
White water is the part of rainfall that feeds back to the atmosphere through evaporation from interception and bare soil; it differs from green water which directly supports plant functioning through transpiration [38]. Water droplets in the lower atmosphere can act as lenses that break up sunlight into the full spectrum of colours that we

Figure 1



Visualization of a model where atmospheric moisture moves land-inwards over a series of land compartments, losing water by precipitation in each compartment, but gaining by evapotranspiration; the difference between rainfall and evapotranspiration in each compartment equals contribution to stream-flow in the watershed plus a change in soil and groundwater buffer stocks; the left, (agro)forested, compartment returns most of rainfall as green water, the right, de-vegetated, one generates more blue water.

Figure 2



Paradigm shift from plot-level considerations of a water balance where evapotranspitation E represents a loss of water in its pathway from precipitation P plus irrigation I to river flow Q, towards a hydrological cycle perspective at regional or continental scale where E generates new P in a short hydrological cycle, and Q not used for I forms or E returns to oceans in the long hydrological cycle; the watershed is the area contributing blue water to a river, the associated precipitationshed is the ocean and land areas contributing rainbow water to the atmosphere, that will become precipitation over the watershed.

can, under the right angle, see as a rainbow. Similarly, ''rainbow water'' as here defined on the basis of all water present in the atmosphere, whether derived from oceanic or terrestrial evapotranspiration, can be the starting point for all other colours of water in their next passage through the hydrological cycle.

A recent study [39•] of the pathway of air movements that preceded rainfall in Africa, showed that passage in the preceding ten days over vegetation with at least a leaf area index of 1 increased rainfall. This interpretation is challenged by other researchers who see creation of low pressure systems over forests as the primary mechanism at play in the forest-rainfall interaction [40].Their 'biotic pump' concept implies that forest cover drives the ocean-to-land atmospheric moisture transport on a continental scale. Where measured atmospheric moisture transport is dominated by the latitude, effects of vegetation on air pressure systems can modify patterns, but it is not clear which properties of ''forest'' are important beyond leaf area and associated evapotranspiration.

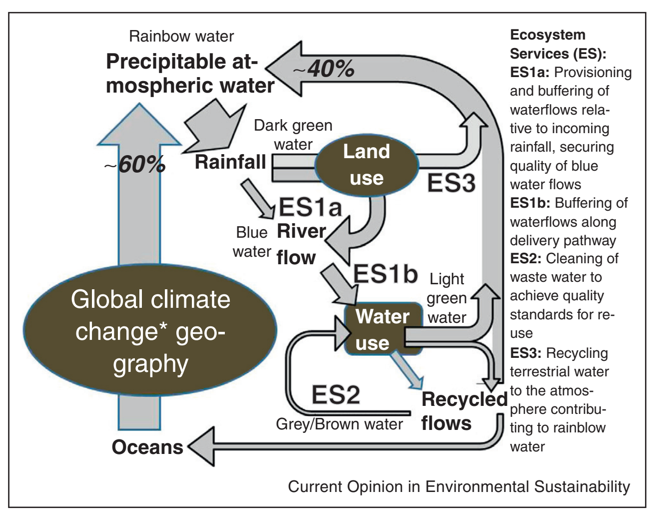
Existing climate assessments have not yet adequately factored in whether, where and how landscape changes alter large-scale atmospheric circulation patterns far from where the land use and land cover changes occur. Failure to factor in this type of forcing risks a misalignment of investment in climate mitigation and adaptation [41]. State of the art modelling reveals that the likely response of precipitation to land cover change depends strongly on the location, not only the type of land cover change within the La Plata basin, with early indications of specific teleconnection effects [42].

Specific to the African continent, moist air influx from the Indian Ocean and its terrestrial recycling in the African Easterly Jet interact with moisture advection from the Atlantic Ocean, with seasonal shifts in spatial gradient of precipitation recycling [43]. A recent modelling study of the interactions between land cover change in Central Africa and the Africa monsoon investigated a Congo Basin deforestation scenario and found that decreased evaporation over the deforested area locally would reduce precipitation [44•]. Much will depend on the type of vegetation that will replace forest in such scenario studies and how much its access to deeper groundwater resources will allow continuation of evapotranspiration into the dry season (see Figure 3).

Implications for policy and salient research

Recognition of tree cover effects on regional climates will keep forests on the global climate change agenda when the carbon-based institutional mechanisms prove to be less tractable than expected. Current climate policies are built on the dominance of global anthropogenic climatic forcing through greenhouse gas emissions. While this is uncontested when total emissions are considered (with

Figure 3



Hydrological cycle, combining the long cycle involving oceans and short cycle based on terrestrial recycling of rainfall, and components of ecosystem services from a water user perspective: ES1 delivery of a regular flow of good quality blue water, based on regulation along delivery pathways (ES1b) and partitioning of incoming rainfall to river flow (ES1a) and atmospheric recycling of green to rainbow water (ES3); ES2 operating at the grey water level of allowing re-use of water not evaporated in its primary use.

fossil-fuel and cement-based emissions now at 9.5 Pg/yr, more than 91% of total anthropogenic emissions) [45], there is new evidence that land cover effects on important regional and continental scale climate patterns operate via the hydrological rather than the carbon cycle. The ''mitigation'' approach to reducing anthropogenic climatic effects, rather than adapting to their consequences, needs to be broadened to include land cover effects on rainfall patterns and the regional hydrological cycle, since atmospheric water vapour recharge from tree vegetation has high relevance as precursor of rainfall further downwind. Water vapour itself is a very effective, although little known, greenhouse gas and clouds have since long been recognized to have immediate influence on local weather conditions [46]. With increasing sophistication and complexity of global climate models, the dynamic feedbacks from land cover can now be evaluated [47,48].

While rainfall in the Amazonian climate system is well studied [49], further attention is needed on a case of equal significance: the Nile basin as part of the precipitation shed of West Africa, linking E & W African climate, where the Sahel precipitation shed is now understood to include East Africa, and the White-Nile watershed contributing to the Sudd in South Sudan. The impacts of climatic teleconnections through precipitation shed land use may involve tens of percents of total rainfall for areas in W Africa where rainfall variability is directly linked to human wellbeing. Changes in vegetation cover along the border between the Sahara desert and West Africa (desertification) may have a minor impact on the simulated monsoon circulation and rainfall, but coastal deforestation may cause the collapse of the monsoon circulation and have a dramatic impact on the regional rainfall [50].

There are exciting new research opportunities to reconstruct a century of climate-vegetation history when dendrochronological analysis of inter-annual and intra-annual variation in tree ring width, $^{12}C/^{13}C$ ratios and $^{16}O/^{18}O$ isotope ratios can be used to reconstruct past rainfall patterns [51–53].

The pricing of rainbow water at any geographic location, if such a concept can indeed play a role in making environmental policies more evidence-based and adaptive, will have to be negotiated between downstream users of blue water and downwind beneficiaries from additional rainbow water. Human landuse at continental scale may change timing and location rather than total size of terrestrial rainbow-water generation, and a more integrative assessment is urgently needed of how the teleconnections can be influenced by landuse change on the ground. This requires fundamental reorientation and restructuring of national, regional and international institutions towards more effective Earth system governance and planetary stewardship [54].

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