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A macroeconomics-inspired interpretation of the terrestrial water cycle

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Abstract

This article develops an approach that applies macroeconomic concepts to the interpretation of complex, water related natural processes. By translating and re-interpreting these processes into a language that is more accessible to a broader audience otherwise unaccustomed to its terms will likely help sharpen our understanding of the terrestrial water cycle. For economists, we describe climate-forming natural processes in a manner consistent with the fundamentals of the mainstream approach. For noneconomists, parallels from economically determined, relatively short-term observations can be applied conceptually to identify dynamics which occur over much longer and therefore more elusive natural occurrences, in particular considering the role of forests and how persistent land conversion over a millennium has shaped the earth's surface and impacted climate stability. The set of "supporting ecosystem services" highlighted in the Millennium Ecosystem Assessment (MEA) coincides with the ground phase of the terrestrial water cycle, taking the concept beyond the ecosystem service perspective and identifying it as a planetary service. Ecosystem and planetary services differ in the same way that microeconomic and macroeconomic perspectives do. The water cycle intensity of a geographical area may well be related to a rainfall multiplier that measures the ability of continental ecosystems to increase the amount of water moving across terrestrial surfaces and descending as rainfall through transpiration and deposition, and re-transpiration and re-deposition of the water content in the air that originally arrives from the oceans. Building upon the MEA's association of human wellbeing with ecosystem features, the rainfall multiplier serves as a physical indicator and measure of the natural basis of wellbeing creation.

This article is categorized under:

Human Water > Water as Imagined and Represented
Water and Life > Conservation, Management, and Awareness
Human Water > Value of Water

KEYWORDS

ecosystem services, macroeconomics, water cycle

1 | INTRODUCTION

From an economic and accounting point of view, CO_2 in the atmosphere and nature can be easily conceptualized as a stock variable (Stern, 2008). Although the underlying interrelations are complex, this easily accountable stock-like feature provides relative clarity on the connection between global outcomes (the CO_2 content in the atmosphere) and the role of local inputs to the system (emission and sequestration). The clarity of this concept has aided in the development of cross-disciplinary and cross-sectoral cooperation initiatives throughout society in a way that is essentially in line with standard economic approaches (Tietenberg & Lewis, 2009). For the time being there is no globally-recognized instrument for explicitly regulating the CO2 content of the atmosphere. This failure is due, however, to gaps on the implementation side (politics), and is not, for the most part, the result of conceptual disagreements regarding the science behind global warming and climate change.

Water, on the other hand, still lacks a similar, widely accepted working concept that could serve as the foundation for a cross-disciplinary platform that is not too complex for social comprehension while simultaneously being compatible with general economic principles. The reason for this asymmetry is presumably that water plays a far more complex role in nature and society than CO_2, and the connection between its global and local processes is significantly more intricate and impenetrable (Kravčík, Pokorny, Kohutiar, Kováč, & Tóth, 2008). Perhaps because of this, both the role and importance of water continue to be debated (Bennett & Barton, 2018; Ellison, 2018; Ellison, Futter, & Bishop, 2012; Filoso, Bezerra, Weiss, & Palmer, 2017; Jackson et al., 2005).

This article intends to sketch such a working concept for a coherent understanding of water's many roles. It exploits analogies provided by the conceptual similarities of natural and economic systems, analogies, which, for the most part, continue to be overlooked because experts tend to have deep knowledge in only one of these two fields. The article thus provides an economically inspired vision and interpretation of complex, multilevel system processes in nature at both the local and global scales.

Water is an essential element of microscale processes on land. At the same time, terrestrial water cycling is a crucial, aggregating planetary phenomenon and the outcome of these microscale processes (Ellison et al., 2012; Ellison et al., 2017; Keys, Wang-Erlandsson, & Gordon, 2016; van der Ent, Savenije, Schaefli, & Steele-Dunne, 2010). A focus on the connection between these two levels can play an illuminating role in the development of a working concept. It is thus the intention of this article to expound upon the phenomenon of terrestrial water cycling in order to arrive at an improved understanding of its importance for ecosystem service potential.

The article starts with the presentation of the most important elements from both the economic and the natural perspectives upon which the analogies are built, highlighting analogous relationships. Based on this side-by-side elucidation, the second part of the article applies this approach to the ecosystem service paradigm of the Millennium Ecosystem Assessment (MEA, 2005) and illustrates one possible way of thinking about the results of forest and water science-driven knowledge development (Creed & van Noordwijk, 2018) with respect to the sources and fate of water vapor processes over land. We conclude with the proposal of a useful, cross-disciplinary indicator for water, similar in stature to the concept of atmospheric CO_2 content.

2 | DEVELOPING THE PERSPECTIVE

The parallel juxtaposition of economies and ecosystems offers several useful and potentially revealing analogies. In both systems, "competition over scarce resources" represents a defining trait and basic driver. In this sense, the motivation for businesses to create additional value in the economy is similar to growth as the outcome of the will to reproduce in nature, representing mutually reinforcing analogous structures. The theoretical architecture of national economies can provide well-documented information that fosters the understanding of complex, system level (macro) processes that we are only just beginning to understand in the context of nature. Similarities are not always easy to recognize due to the vastly different timespan, speed and scale over which we observe these two systems. Complex economic processes occur much faster, are better documented and parallel processes across different countries provide a basis for comparison and improved understanding of the cumulative effects of action and missed opportunities due to inaction. This state of affairs is rarely present in nature. Understanding the similarities across these two systems, however, can help us grasp an important characteristic: the cumulative cost of lost opportunities for an area or region when the level of succession in the environment has been curtailed in order to obtain human benefits. Examples for this may include forest destruction or the exploitation of land for agricultural production.

Based on economic experience, reciprocal feedback effects are at work between micro- and macro-level processes. Efficiency gains boosted by technological development represent firm level effects, but these accumulate in the form of increased growth at the macroeconomic level. Improved (macro)economic stability is self-reinforcing in the sense that it eases the individual burden of doing business and creates income and livelihoods that free up surplus individual resources for further economic activities. These released resources can again contribute to solidifying favorable macro level circumstances. Of course, this interaction can play out in the opposite direction, that is, when forgone opportunities on the ground (microlevel) are the basis for perpetual instability at the macro-level. This paper aims to highlight the analogous disparities that emerge in comparisons between natural processes/systems and economic systems. This perspective aims to connect the core decline of ecosystem production efficiency (microlevel) in nature with emergent macro-level instability observed as disturbances in climate patterns (e.g., intense rainfall and extreme flood events, excess surface heat accumulation, drought, etc.). Because there is an impact in both directions, appropriate ground level actions can potentially start to re-generate stabilizing forces on regional and global climate.

3 | ANALOG STRUCTURES IN ECONOMIC- AND ECO-SYSTEMS

For a start assume that money and water play a similar intermediary role in their respective systems, the economy and nature. Both are used in interactions as a medium of exchange in order to create value or to enable primary production, and then re-emerge unchanged. For economic actors on the ground, liquidity is crucial and money is a scarce resource, though the economy-at-large is typically not deficient in money. Rather, money is in constant flow through economic transactions and scarcity is primarily perceived through the lens of its temporary distribution (Keynes, 1936). It is the same in the case of water. The overall global quantity is constant and immense, but its temporal and spatial distribution can vary greatly from abundance to scarcity and shortage. In both cases, the quality of the internal organizational structure of the system - the institutions within an economy (Williamson, 2000) and the structure of the ecosystem (Nováky & Szesztay, 2002)- is responsible for how effectively these systems can maintain the stability of internal processes across changing external circumstances. This parallel focuses on water quantity, not questioning the importance of quality issues. With respect to the following discussion, water quality is considered as a function of the ecosystem service provision capacity that falls back on primary production and the volume of water.

3.1 | Defining the resource efficiency frontier for economics

In an economy, the creation of value is both the principal motivation for business organizations, as well as, simultaneously, the instrument of survival. The creation of value occurs if labor, capital, and an idea (a business plan) can be successfully matched. Economists know that this alignment, the successful matching of resources, is neither given nor free (Coase, 1937; Williamson, 1994).An important objective of the economic system as a whole is to enhance its internal organizational structure in ways that underpin more efficient interactions. The more mature an economy, the more complex the role of the institutions that lubricate its smooth operation. The seamless circulation of money as a medium of exchange and an intermediary for interaction between resources, the buttressing of factors that ensure capital accumulation, represent system level aspects of stability in economic processes in the context of ever-changing external circumstances.

For the purposes of this article, we coin the term “Resource Efficiency Frontier” (REF), which indicates the maximum production potential based on the optimal combination of the available economic resources such as labor, capital, and technology. This frontier is strongly connected to the institutional set up (the organizational structure). The REF should be viewed as a composite overall indicator of a society's functioning and relative wellbeing, based on how successful it is at combining resources for the purposes of value creation.

From a macroeconomic perspective, money circulation and the volume of economic transactions they catalyze are important. In an economy that operates close to its REF, money circulates at a higher frequency, driving transactions across economic agents and consumers and creating above average value from a given set of resources. An economy that is able to sustain such interactions will have a higher output than another economy with similar resource endowments but with less mature institutions.

3.2 | Applying the resource efficiency frontier concept to ecosystems

In nature, the basis of all terrestrial life is plant life that stems from primary (biomass) production. This encounter happens on the soil where and when water meets solar energy in a plant's kitchen to produce biomass and transpiration. The vegetation period is the time window during the year when there is enough (or more than enough) solar energy to induce primary production, assuming adequate amount of water is available (Thornthwaite & Hare, 1955). This approach was further formalized and improved as the Thronthwaite-Mather water balance calculation method (Thornthwaite & Mather, 1957). Thornthwaite's principal contribution to the topic of this article is the combined representation of water (moisture) and energy in the same basic relationship. This is represented in Figure 1 (from Thornthwaite & Hare, 1955). This approach helps to bring together and frame water, energy and land as interlinked parts of the same allocation dilemma, within which the role and impact of limited resources and varying resource efficiency can be highlighted.

Figure 1 illustrates this allocation issue for a specific geographic location based on monthly average values for available energy, water and the production of evapotranspiration. Solar energy radiation is represented through the amount of water (in centimeters height) that it can evaporate and transpire from the same land area on which monthly precipitation was measured. The water surplus, the blue area in the figure, is the runoff. This blue area represents the amount of water that the existing ecosystem is unable to retain or use. The unused, superfluous solar energy volume is defined as water deficiency, represented by the red area, which quantifies the mismatch, that is, the failure of the constituent resources to align.

As Figure 1 illustrates, the annual evapotranspiration (evaporation or biomass production of the vegetation) is lower than what the annual volume of solar energy and water could potentially produce under circumstances that better align. Specific features of the vegetation and the soil influence the efficiency of matching these two resources (water and energy) for primary production through trans-seasonal water reallocaion. In other words, the actual status and structure of the vegetation and soil define the actual Resource Efficiency Frontier of biomass production at a specific location. If the features of the vegetation and soil that drive the trans-seasonal water allocation ability are improving, more biomass production will take place from the same annual set of resources – in essence, REF is moving outward, the potential is increasing. This is a crucial dynamics: the allocation challenge of the annual, on average finite amount of water, solar energy and the significance of the intra year water reallocation efficiency to maximize primary production and transpiration that Figure 1 reveals.

The other easily accessible implication that Figure 1 nicely illustrates through water deficiency is the basic reason behind the unused, superfluous energy volume that is generally responsible for warming up both the soil surface and the lower atmosphere. This water deficiency is again related to the area's constrained ability to reallocate water trans-seasonally. (This approach focuses on regions with a water-limited climate. In countries at the outer latitudes, energy, not water, is the scarce resource of ecosystem production.) Superfluous warming as an undesirable consequence of the recent shift in climate proceedings provides further context for the evaluation of the vegetation's trans-seasonal water allocation efficiency.

Micro-level or ground-based effects ultimately cause a feedback that modifies the vegetation's own (macro)environment. This is the same type of reinforcing effect that takes place when the increasing productive efficiency of a firm drives growing profitability and thereby creates demand for new, innovative and specialized niche services from other firms, engendering a shift in the greater business environment. Taking all other aspects as fixed, efficiency gains and the new services favored by

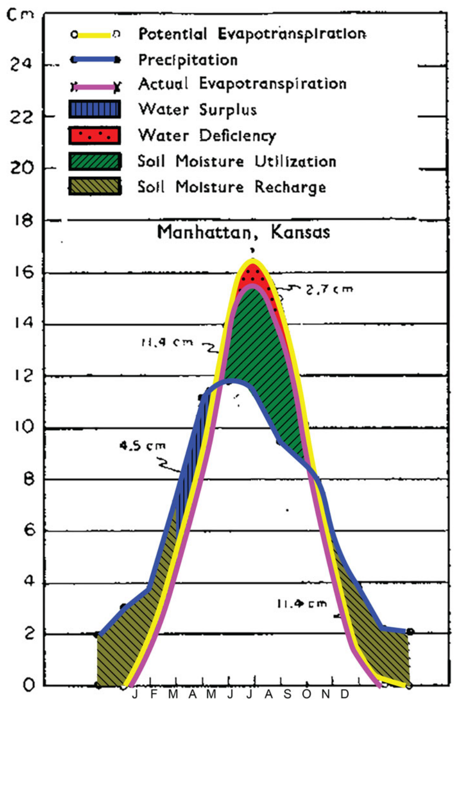

FIGURE 1 Trans-seasonal water allocation and the mitigation of warming. *Source*: Thornthwaite, Hare (Unasylva, 1955). Horizontal axis is the months. *Note*: The white area below both the "Precipitation" and the "Actual Evapotranspiration" curves is explained as the transpiration from the readily available precipitation for a given period of the year

these changes could provide the same total amount of business tax revenue at a reduced tax rate that extends these beneficial circumstances to others as a result of the improved business environment.

Such feedback across system levels is present in nature as well. While primary production is the vegetation's basic instrument at the micro level for pursuing the "goal" of reproduction, there are system-reinforcing feedback mechanisms or "side effects" that gather pace with increasing primary production: transpiration and vegetation cover accumulate to create a cooling effect that prevents both the surface and the lower layers of the atmosphere from warming. This energy allocation feature was also quantitatively described by Thornthwaite and Hare (1955). Maximizing transpiration is not simply growth for reproduction. It is consequently also the instrument of energy management for decreasing the risk of harm that the ecologically unused concentrated summer radiation through local heat shocks could cause to the same vegetation community (Pokorný, Brom, Cermák, & Hesslerová, 2010). The higher an ecosystems' primary productivity, the higher this reinforcing effect against extreme circumstances. Moisture condensation (be it precipitation or dew) is the reverse process of transpiration and is triggered by declining temperature, decreasing latitude, or by the shift to night time. It is another reinforcing feedback mechanism, the natural redirection of already used water back to the ecosystem. Because these reverse processes happen later in time, they add a further layer to the way in which ecosystems improve their operative circumstances and resilience (Agócs, 2018).

Agócs (2018) uses the expression "whirl-system" to illustrate how terrestrial ecosystems drive material and energy flows into multiple circulation systems. The higher the intensity of the vegetation's whirling system, the greater the volume of solar energy mitigation that the movement of water (vapor) above land can support. The more efficiently this whirl system functions, the more favorable the circumstances for all members of the vegetation community are against the extremes of oscillating solar radiation over the continents, where water supply for solar radiation mitigation is not as abundant as over the seas. It is a sub-system of the global water cycle that is robustly driven by atmospheric interactions with the ocean surface (Szesztay, 2004).

Succession and climate-maximum

Figure 1 provides a snapshot of the long-term dynamics of vegetation change in the landscape. Ecological succession is the process that describes the regime shift and adds time-dynamics of changing resource allocation efficiency and which thereby, in the long term, alters the respective water and energy flows (Kravčík et al., 2008; Nováky & Szesztay, 2002). In nature's succession process to a higher level, the process of soil formation (the accumulation phase) improves the conditions among changes in vegetation are better able to make use of the essential ingredients (water, nutrients) available during the period when solar energy offers a window of opportunity to maximize biomass/primary production (Agócs, 2018). In the long run, this structural accumulation enhances diversity, spawned by the efficiency gains in the area's material flow management (Ripl, 2010).

As a combination of views, the current ecological succession level is interpreted as the de-facto resource efficiency frontier of an ecosystem for primary production and soil formation. A shift outward (a step in the level of succession) represents gains in production efficiency, while an inward shift means losses in production efficiency (a curtailment of the succession level).

Using the concept of succession levels may raise the question of how this view handles the theoretical end point of the succession process, the climate maximum (climax) community status or equilibrium (Levin, 1989). In our understanding the climax community level of the succession process is a theoretical reference point, an optimal adaptation to the circumstances that existing resources provide. It may never be reached in full. But the concept helps to reveal the obstacles thwarting the advance of this essential process. This is analogous to how economists view a mature market with perfect competition. In reality, it never occurs in its pure form. But comparing an actual market to its perfect competition reference point helps us to understand the underlying forces shaping the actual structure of the market.

4 | THE LONG-TERM DECLINE IN EFFICIENCY ACCUMULATES DEFICIT

This section focuses on the analogy of economic instability resulting from deficit accumulation that occurs due to the deterioration of resource efficiency. Based on an economic example, a context is set for the curtailment in the level of succession of an ecosystem: the resulting losses in efficiency are represented by an inward shift in the resource efficiency frontier. Over time, such a change opens up the possibility of a continuous degradation through lost opportunities in primary production, whereby the unmatched flow of resources accumulates into a form of hidden deficit.

4.1 | An economic example

Societal losses from foregone efficiency gains were evaluated recently by the World Bank Human Capital Index (WB, 2018): "The Human Capital Index quantifies the contribution of health and education to the productivity of the next generation of workers. Countries can use it to assess how much income they are foregoing because of human capital gaps, and how much faster they can turn these losses into gains if they act now." A country with fewer foregone opportunities becomes more prosperous (and more stable) than countries that fall short and waste opportunities.

Returning to the notion of matching resources for value creation, lost opportunities can result if incumbent market actors can prohibit others from starting new ventures, or if excessive taxes on labor discourage employers from hiring and unemployment rises. All such patterns and examples of stalled market entries and labor market rigidities will eventually result in suboptimal gross domestic product production below the potential that existing social resources should make possible, leading to lower tax revenues and lower public spending on education, healthcare, the military and security, etc. Such circumstances thus result in general welfare losses and a shrinking of the resource efficiency frontier.

If we undertake a comparison between two otherwise similar countries after a few decades of development under these two different market regulation strategies (resource matching policies), the contrast in each country's capacity to maintain inner stability against future external shocks (e.g., a global economic crisis with or without major political instability or accelerated indebtedness) will become steadily more self-evident. The initially not so obvious loss of micro-level opportunities will add up to a real, accumulated macroeconomic deficit.

This macroeconomic overview of the cumulative effect of foregone opportunities for growth on overall stability lends a perspective for defining how deficits resulting from curtailed succession might begin to arise. In nature, it is generally far more complicated to effectively compare and thereby demonstrate the consequences of different succession levels from the same location or region. Nonetheless, as higher vegetation levels across succession processes equate to higher levels of ecosystem production efficiency, the effect of suboptimal land use practices that negatively affect the matching potential of natural resources is analogous to deficit accumulation.

4.2 | An example in nature

The advance of anthropogenic processes (e.g., land reclamation, drainage of wetlands, deforestation, land degradation, and soil sealing) constantly shifts the resource efficiency frontier of the impacted area's ecosystem inward. When land has been converted and water is diverted for social goals, the succession level of that land's ecosystem is curtailed, meaning its ability to retain water, evapotranspire and thereby live up to its primary production potential, declines. Under such circumstances, the water cycling capacity of the landscape is reduced.

In this regard, human land use has advanced at the expense of the accumulation of superfluous and unabsorbed energy that is heating up both the land surface and the lower atmosphere. The contribution of a landscape's current land use pattern to macro-level processes must be weighed against the potential developmental pathway of a more mature ecosystem in that same area, producing more biomass and evapotranspiring more water from the same annually available water and solar energy resources. Figure 2 (left panel) provides an example that essentially translates differences in inter-seasonal water storage capacity into temperature differences which result from abundant solar inflow on a summer day for different land use types. The higher the temperature, the lower the volume of evapotranspiration and the higher the volume of foregone primary biomass production. The sheer temperature differences (20°C between the forest and the asphalt on Figure 2) underscore the importance of the foregone natural cooling effect, which otherwise mitigates the formation of extreme heat and serves to secure a more vegetation-friendly environment. The water retention capacity of the landscape, again favored by extensive vegetation cover, drives cumulative resilience against such extremes for a given area.

The Millennium Ecosystem Assessment (MEA, 2005) provides a revealing figure highlighting the scale of curtailed succession levels on Earth's land surface (Figure 2; right panel). By extrapolation, the data in this Figure highlights foregone opportunities for water circulation and therefore for cooling. The persistently accumulating loss driven by land conversion and the subsequent decline of the water regulation capacity of the land surface is driven by the sum total of human intervention across time.

The effect of foregone cooling is represented as the impact of anthropogenic activities on the global climate and is strongly linked to the persistent accumulation of CO_2 concentrations in the atmosphere (Pielke et al., 2009). On a continental level, water, as well as CO_2, shows symptoms of an essential ingredient that has been crowded out from the maximum, potential vegetation-driven, resource flow.

Higher atmospheric CO_2 concentrations represent, at least in part, an underutilized natural resource

While the accelerated build-up of CO_2 concentrations in the atmosphere drives excessive warming, at its core, CO_2 is one of the essential ingredients in ecosystem primary production. In this sense, the atmospheric build-up of CO2 suggests primary production is well below its potential volume (i.e., its potential CO_2 uptake). And these increasing concentrations can, in part, be explained by the fact that human land use practices have radically curtailed the ecosystem resource efficiency frontier (Alkama & Cescatti, 2016; Pielke et al., 2009). The persistent intrusion of this human curtailment of the natural ecosystem resource efficiency frontier has directly contributed to an over-supply of CO_2 in nature and the atmosphere (fossil fuel combustion provides an additional shock of oversupply).

Current global processes resemble an economy whose resource mismanagement is brewing instability at higher-level dimensions of society. The excess supply of CO_2 from burning fossil fuels fosters instability in the same way that surplus labor can destabilize society (consider, e.g., the impact of too rapid population growth on youth employment prospects). The effect of land conversion on ecosystem primary production parallels the decline of business opportunities (lost added value creation) due, for example, to the impact of rising interest rates on economic activity. In both cases, the outcome is the diminishing capacity of the public budget to maintain a smoothly functioning social system which further shrinks the resource efficiency frontier. Resource mismanagement results in the necessity of coping with an increasing public burden from shrinking public resources and the growing risk of social instability.

Successful economic crisis management cannot solely rely on austerity measures (budget cuts in public services) because this further suppresses the potential to restore value generation at the micro level of the economy (Posner & Sommerfeld, 2013). Without such restoration, positive effects will not accumulate at the macro-economic level. This explains the logic behind the counter-cyclical economic policies governments pursue across the economic cycles of downturns and growth periods (OECD, 2009). In order to re-kindle growth, the availability (supply) of the most constrained element must be expanded. The monetary expansion policy of national banks, which provides the missing liquidity/money supply for the markets/banks, is an example of this type of policy (OECD, 2009). On the other hand, from the perspective of overly abundant resource's (surplus labor) it is also clear that an expansion of participation in economic activities provides a preferable solution (compared to emigration).

With respect to nature, water availability for high volume evapotranspiration (and thus cooling) is the constrained resource on most of the continental surface. This is why even plans for a CO_2 neutral society must be coupled with meaningful strategies for achieving integrated water and land management, and thus for boosting the intensity of water circulation above continents. This is presumably the optimal way to overcome the accumulated deficit of previously unrealized primary production and tackle the superfluous solar energy side of the drivers of climate instability.

There is a seeming contradiction here. The IPCC climate change report (IPCC, 2018) predicts that rainfall events will become more intense, that is, there will be more rain when it rains, with a higher probability of floods. This is based on the logic that higher temperatures result in higher atmospheric vapor content which implies a bigger potential for more intense rainfall events and droughts subsequently. This shift is sometimes interpreted as an "acceleration of the water cycle," or as an acceleration of global water circulation. The occurrence of more intensive, short-term, rainfall and other extreme events (flooding and water shortages), in our view, should be seen as a consequence of the direct outcome of the weakening of the larger scale terrestrial water circulation intensity. These interpretations are in line with each other. Vegetation-mitigated material and energy flows are losing out and being crowded out by processes that lead to the accumulated curtailment of natural ecosystem functions. It is this crowding out that generates excess CO_2 accumulation, warming, and extreme rainfall events. The curtailment of the REF for ecosystems means that more energy accumulates in the system (e.g., the atmosphere) that then has to find an outlet, giving rise to more extreme events.

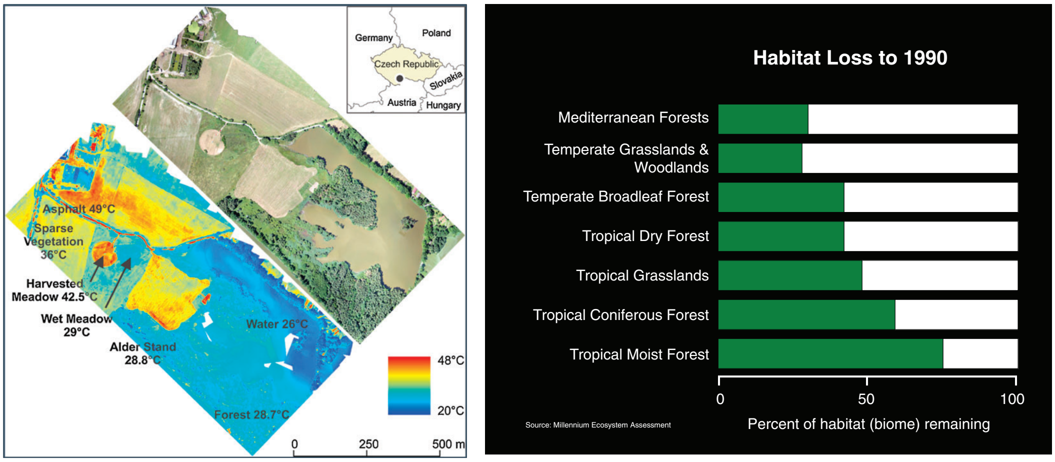

FIGURE 2 Land use's effect on surface temperature and habitat loss. *Sources*: Left panel; Ellison et al. (2017); Right panel; MEA (2005)

What we experience on a global scale, due to the long-term inward shift of the land ecosystems' resource efficiency frontier, is the oversupply of CO_2, coupled with the deficit resulting from foregone opportunities for evapotranspiration and cooling. If the ecosystem balance between carbon, water and solar energy is to be restored, the minimum requirement for moving toward stability is the relative improvement in the existing set of land use practices and their ability to impact/expand ecosystem resource efficiency frontiers.

5 | TERRESTRIAL WATER CYCLE INTENSITY AND THE MILLENNIUM ECOSYSTEM ASSESSMENT

5.1 | Interpreting the supporting ecosystem service group

One of the most important outcomes of the Millennium Ecosystem Assessment (MEA, 2005) is that it has shed light on the various components of the ecosystem service pillars of human well-being. As part of this paradigm, the MEA conceptualizes the set of "supporting ecosystem services" (SES). The current article's explanation prefers the ecosystem service categorization provided in the Millennium Ecosystem Assessment (the right-hand panel in Figure 3—"Focus: Consequences of Ecosystem Change for Human Well-being"). Subsequent categorizations, such as that provided for example in the Mapping and Assessment of Ecosystems and their Services (MAES), dissolve the Supporting Ecosystem Service Group (MAES, 2016). The original MEA conceptualization better highlights integrating elements, such as those provided by terrestrial water circulation, in the overall description of complex ecosystem processes and services.

This article takes one step further in this direction with an interpretation of the set of supporting ecosystem services as embodied in terrestrial water circulation. This link is revealed in Figure 3. Ecosystem services that belong to the set of "supporting" ecosystem services were described as those that constitute the foundation for the services in the other three sets (provisioning, regulating, and cultural). What is missing in latter categorizations was the MEA implication that the elements categorized as supporting ecosystem services: "Nutrient cycling, Biomass production, Soil formation," overlap with the land phase of the terrestrial water cycle. This should be thought of as one continuous flow: as precipitation or water first infiltrates, transports and dynamically stores nutrients on its way into the soil, and plants use these ingredients (both water and nutrients) to produce biomass by absorbing solar energy and transpiring water back into the atmosphere. These elements together provide the foundation for the directly harnessed ecosystem services of society. In this way, the Supporting Ecosystem Services framework further supports an asset-based, natural capital perspective (TEEB, 2010) with respect to the terrestrial water cycle.

The crucial contextual step our article advocates is that the well-being described by the Millennium Ecosystem Assessment can potentially be integrated with the terrestrial water cycle and the biotic pump concept (Sheil & Murdiyarso, 2009). This is the basic relationship described in the series of arrows in Figure 3, and which indicates vegetation's role in inducing additional precipitation over land. This representation emphasizes that the terrestrial water cycle is best understood as a sequence or series of cycles based on the current state of land-use management and the subsequent functioning of existing vegetation as the principal distributor of water toward downwind continental interiors via the mechanism of precipitation recycling (the return of water to the atmosphere for reuse as rainfall in downwind locations).

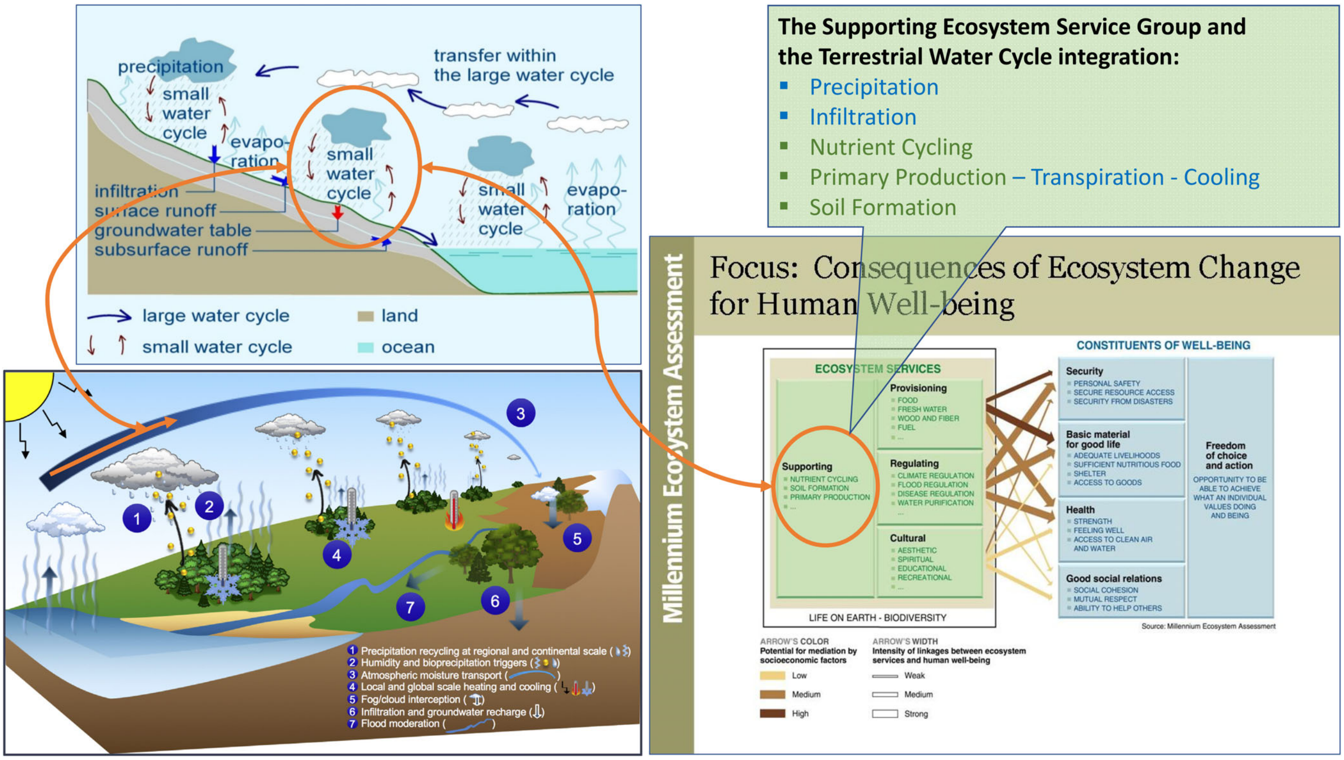

FIGURE 3 The connection between the weakening intensity of the terrestrial water cycle and the notion of human well-being as a declining asset. *Sources*: On the right: MEA (2005), top left: Kravčík et al. (2008), down left: Ellison et al. (2017)). *Note*: Small water cycle means the terrestrial water cycle in this article's context

The set of Supporting Ecosystem Services and the terrestrial water cycle also provide a coherent frame for explaining and better understanding the consequences of past change in human land use activities on the potential to harness benefits from ecosystem services in the present. Land use conversion is a process that typically shifts the ecosystem service potential of an area into the set of Provisioning Ecosystem Services. This shift may enhance direct and private benefits. However, this shift further results in a reallocation of ecosystem resources from the set of Regulating and Cultural Ecosystem Services (usually these are indirect and common public benefits) (TEEB, 2010), as well as causing the decline of the set of Supporting Services, which was the asset base and thus foundation of all Ecosystem Services. Consequently, this shift has to have an effect on precipitation recycling capacity. The significant decline of Regulating and Cultural Ecosystem Services reflects the combined impact of these reallocation and asset changes. Maintaining a constant flow of direct benefits from the set of provisioning ecosystem services requires an ever-larger share from a shrinking pie, with a smaller volume of nature-regenerated rainfall over the land.

Expressed in this way, reduction in the resource efficiency frontier of precipitation recycling over land is not just a physical phenomenon, it also describes a progressive limitation of social potential and thus human welfare as well. The resource efficiency frontier of the terrestrial ecosystem's primary production and soil formation is the upper bound constraint of the (a) extent of precipitation recycling, and hence (b) the availability of precipitation further inland and (c) the foundation of potential well-being.

Two conclusions can be derived from this connection:

1. Terrestrial water circulation represents the constrained capacity that the set of supporting ecosystem services capitalize on. It can be interpreted as a quantifiable indicator of the ecosystem service base (and its changes) from what a society is able to buttress and support human well-being, while the ultimate level of human well-being will depend on how this asset is used (or misused).
2. The set of supporting ecosystem services is not just a compound element, or the outcome of the other sets of Ecosystem Services. The supporting services represent the foundational link between the landscape and other global, planetary service levels, based on the share of vegetation-driven, material and energy flows over the continents. The role of landscape and global levels is analogous to how quite distinct macroeconomic and microeconomic approaches work; together these two levels help communicate the status and health of the economy/ecosystem.

5.2 | Introducing the rainfall multiplier for social interpretation

In the economic context, the long-term growth potential (long-term growth rate) is a macro level indicator that describes the multiplication (value adding) potential of an economy in quantitative terms (and produced from the given set of resources). This value accumulates the interconnected effects from several sub-parts of the society (from education, quality of institutions, to health, trust, innovation, management culture and quality of regulation in the economy etc). Long-term, comprehensive internal development (a succession process) can result in sustainable outward shifts of the resource efficiency frontier that will "materialize" in an increased level of the long-term economic growth rate. The effect of bad policies and the dismantling of institutional and other capacities that buttress long-term growth potential can be calculated and represented as future lost production (as illustrated, e.g., with the Human Capital Index).

The rainfall multiplier (exact definition later in the text) is the appropriate higher-level system indicator that can be used to assess the overall ecosystem service performance of an area in the same way that the long-term growth rate represents an instrumental summary indicator for evaluating the national level performance of an economy.

The evolution of the scientific debate and thinking on forests' role in promoting water availability for social purposes has revealed the importance of understanding the role of massive evapotranspiration mechanisms (the supply-side role forests play) on precipitation patterns and the distribution of water resources across terrestrial surfaces (Ellison, 2018; Ellison et al., 2012; Ellison et al., 2017; Keys et al., 2016; Sheil, 2014; Sheil & Murdiyarso, 2009; Wang-Erlandsson et al., 2018). This strategy for thinking about forest-water interactions has shifted the focus to quantifying the contribution of ecosystem functioning (evapotranspiration) to the total volume of precipitation over land and thus the degree to which it can supplement the volume that the oceanic circulation originally provides (Creed & van Noordwijk, 2018).

Despite the diversity of potential calculation methods (Bosilovich, Sud, Schubert, & Walker, 2002; Keys et al., 2016; van der Ent et al., 2010), all agree that the re-transpired water plays a fundamental role in total precipitation volumes. From this article's perspective, it is not so much the calculation method that is important, as it is the phenomenon of multiplication itself. This is the specific piece of information that describes the potential success of ecosystem-based material and resource flow management across the sum of landscapes (van Noordwijk & Ellison, 2019).

For a brief understanding of the concept (from precipitation recycling to multiplication) the work of van der Ent et al. (2010) is used. Calculations of the rate of continental precipitation recycling and the contribution of terrestrial evapotranspiration to rainfall over land are still somewhat in its infancy. Figure 4 illustrates the share of rainfall explained by upwind terrestrial evapotranspiration. Following along the principal direction of the prevailing winds above the continents, the gradual rise in the share of recycled precipitation (precipitation sourced from terrestrial evapotranspiration) over precipitation with an oceanic origin is clearly visible. For example, a 0–10% share of terrestrial precipitation recycling in rain's origin on the Atlantic shore of Europe shifts to a 70–80% share of recycled precipitation of rain's origin in Central Asia. This shift from oceanic to terrestrial vapor dominance as precipitation's principal water vapor resource goes hand in hand with the downwind decline in precipitation volume. This decline reflects the actual efficiency of ecosystems in retaining water and recycling it as precipitation to ever more distant locations. This actual efficiency of managing water on land is a key driver of how much water remains in circulation over the continent (as opposed to flowing in rivers back to the seas), and how far into continental interiors it is able to reach. In this sense, Figure 4 essentially quantifies the information in the lower left-hand panel of Figure 3 related to the transport of atmospheric moisture toward continental interiors.

The concept of the rainfall multiplier goes one step further. It accumulates the spatially diverse precipitation recycling ratios (effects) of larger areas and compares the area's precipitation volume to the volume that could be derived from oceanic

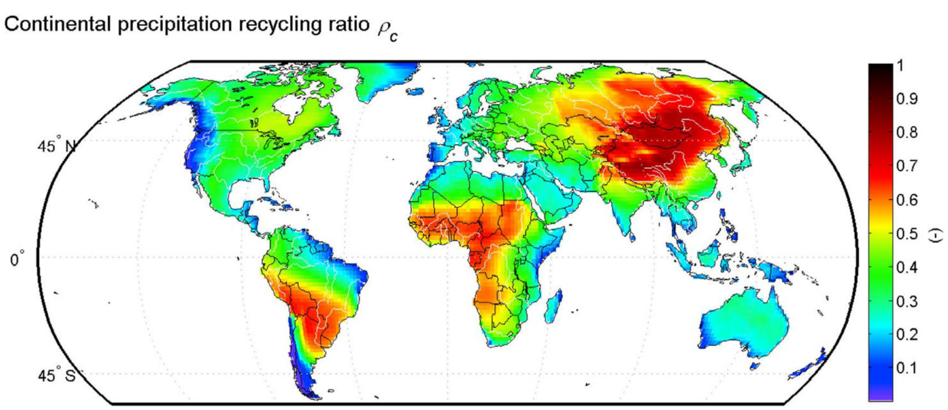

FIGURE 4 The share of Total precipitation deriving from terrestrial evapotranspiration. *Source*: The precipitation recycling ratio is the share of terrestrial evapotranspiration in precipitation (van der Ent et al., 2010)

vapor supply alone. van der Ent et al. (2010) measure the amplification of precipitation by continental evapotranspiration over the volume that arrives from an oceanic origin: "Globally, recycled moisture multiplies our freshwater resources by a factor 1.67". (Continents vary between 1.45 and 1.95), "but locally there are bigger differences that amount to factor three, or even factor ten." The rainfall multiplier demonstrates the same type of aggregated information about the successfulness of the co-functioning of sub-systems as the growth rate describing an economy.

Ellison's (Ellison et al., 2012) calculations on major river basins suggest that shifting the scale to smaller territorial units may indicate a possible way forward for obtaining distinctive results in areas with diverging land use policy. As the ecological succession status drives ecosystem production efficiency, the rainfall multiplier, as an indicator, supplies the connection between the effects of small-scale land use change activities on the ground and the global climatic processes. Raising the rainfall multiplier is thus, presumably, a desirable, although a long term, goal.

Because the rainfall multiplier is a relative, not an absolute measure, it helps to compare the cumulative contribution of different regions'/watersheds' land use to the terrestrial water cycle intensity, identifying which territories contribute more to sustaining the actual multiplication level of the terrestrial water cycle and the connected potential of beneficial ecosystem service effects. Or from a different perspective, it can pinpoint the territories where cultivation has resulted in a stronger curtailment of natural succession resulting in a lower level of contribution of the multiplication effect than the average of other territories, and in this way overexploiting a common and presumably "public" resource.

6 | CONCLUSION

Applying macroeconomic language to ecosystem processes helps to put a greater emphasis on the frequently overlooked aggregation effect produced by terrestrial ecosystems. Biomass production is the basic life function of vegetation, an unrelenting process in a plant. On the global scale, however, it also performs the water and solar radiation management function embodied by terrestrial plant-based water circulation. This is the planetary level mitigation feedback service that helps ecosystems buffer against the over-accumulation of extreme (cold, heat, and aridity) conditions which otherwise threaten their existence. Enhancing this regulating feedback service is a global challenge of the same magnitude as, and goes hand-in-hand with, the management of CO2 concentrations in the atmosphere.

The related flow management capacity—the Resource Efficiency Frontier—has been gradually depleted through the long history of human land conversions. Global scale curtailment of the natural succession process on the land surface has resulted in lost opportunities for primary (biomass) production that have left large volumes of CO_2 and radiation influx diverted away from the water cycle and unassimilated by vegetation. The weakening of terrestrial water circulation resulting from lost opportunities in the ecosystem's primary production and soil accumulation function has given way to the surplus buildup of these unused resources, resulting in a cumulative system deficit that continues to amplify climate instabilities. Moreover, this trend has been significantly exacerbated by the increase of unassimilated CO_2 concentrations in the atmosphere from fossil fuel burning. This progressive accumulation of a system-level deficit is analogous to the accumulation of macroeconomic instability in a country due to the persistent decline of economic productivity. Increased environmental resilience can only originate from the enhancement of ecosystem-based terrestrial water circulation, similar in important respects to the role of economic stimuli driving investment, employment and growth during the worst periods of an economic crisis. Moreover, the mutual interconnection between the microeconomic level of businesses and markets and the macroeconomic operation of a national economy is a useful portrayal that lends itself to the interpretation of similar relationships between land use and regional climatic forces.

The set of Supporting Ecosystem Services highlighted by the Millennium Ecosystem Assessment is the framework that substantiates the view that terrestrial water cycle intensity is the finite natural capacity on which human well-being creation and development is based among water limited climate conditions. It could be approximated by the rainfall multiplier, a comparatively simple numerical system index that describes an area's contribution to terrestrial water circulation. Moreover, in doing this, it connects the effects of small-scale land use change on the ground to global climate processes.

Suggestions for further research based on the connections established in the article:

1. The rainfall multiplier can play a role as a point of comparison for area and river basin contributions to global climate stability in the same way that the atmospheric CO_2 content is an indicator and a reference measure for country-level contributions or depletion of the common struggle for a more friendly climate.
2. Mature forests are the most efficient driving force of the terrestrial water cycle's energy and water regulation. Improvement of an areas' resource efficiency frontier (e.g., by afforestation) and its potential impact on water availability downstream and downwind should be handled through institutional arrangements that create a framework for the joint investment of

stakeholders from the proper water basin and beyond in a dispute resolution context, for example, filling up flow-through reservoirs. Initial investigations in this direction have been undertaken by several authors (Creed & van Noordwijk, 2018; Ellison et al., 2017; Gebrehiwot et al., 2019; Keys, Wang-Erlandsson, Gordon, Galaz, & Ebbesson, 2017).

3. In regions where floods are a regular and common, natural occurrence, their window of abundance should be considered as an additional source of water for reaching additional land surfaces in an orderly way to enhance vegetation, terrestrial water circulation and thereby preventing drought and stabilizing regional climate.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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