How Forests Attract Rain: An Examination of a New Hypothesis

DOUGLAS SHEIL AND DANIEL MURDIYARSO

A new hypothesis suggests that forest cover plays a much greater role in determining rainfall than previously recognized. It explains how forested regions generate large-scale flows in atmospheric water vapor. Under this hypothesis, high rainfall occurs in continental interiors such as the Amazon and Congo river basins only because of near-continuous forest cover from interior to coast. The underlying mechanism emphasizes the role of evaporation and condensation in generating atmospheric pressure differences, and accounts for several phenomena neglected by existing models. It suggests that even localized forest loss can sometimes flip a wet continent to arid conditions. If it survives scrutiny, this hypothesis will transform how we view forest loss, climate change, hydrology, and environmental services. It offers new lines of investigation in macroecology and landscape ecology, hydrology, forest restoration, and paleoclimates. It also provides a compelling new motivation for forest conservation.

Keywords: climate change, environmental services, macroecology, transpiration, paleoclimate

Downloaded from http://bioscience.oxfordjournals.org/ by guest on September 26, 2014

Life depends on Earth's hydrological cycle, especially the processes that carry moisture from oceans to land. The role of vegetation remains controversial. Local people in many partially forested regions believe that forests "attract" rain, whereas most modern climate experts would disagree. But a new hypothesis suggests that local people may be correct.

The world's hydrological systems are changing rapidly. Food security in many regions is heavily threatened by changing rainfall patterns (Lobell et al. 2008). Meanwhile, deforestation has already reduced vapor flows derived from forests by almost five percent (an estimated 3000 cubic kilometers [km^3] per year of a global terrestrial derived total of 67,000 km^3), with little sign of slowing (Gordon et al. 2005). The need for understanding how vegetation cover influences climate has never been more urgent.

Makarieva and Gorshkov have developed a hypothesis to explain how forests attract moist air and how continental regions such as the Amazon basin remain wet (Makarieva et al. 2006, Makarieva and Gorshkov 2007, and associated online discussions; hereafter, collectively "Makarieva and Gorshkov"). The implications are substantial. Conventional models typically predict a "moderate" 20 to 30 percent decline in rainfall after continental-scale deforestation (Bonan 2008). In contrast, Makarieva and Gorshkov suggest that even relatively localized clearing might ultimately switch entire continental climates from wet to arid, with rainfall declining by more than 95 percent in the interior.

Whereas Makarieva and Gorshkov's publications are technical, detailing the physics behind their hypothesis, we explain the basic ideas and their significance for a wider audience. We begin by noting why the ideas are credible and merit notice. We then summarize the conventional understanding of forest-climate interactions and Makarieva and Gorshkov's proposals. We focus on tropical forests. After examining what makes these forests special, we consider various implications and research opportunities related to Makarieva and Gorshkov's hypothesis. Finally, we underline the importance of these ideas for forest conservation.

Credible

Despite considerable research, the mechanisms determining global climate remain poorly understood. Any consensus summary on climate physics must spend more words on detailing uncertainties than on facts (e.g., IPCC 2007). Despite recognized advances in recent decades, not all key insights are immediately noted among the thousands of published articles. Makarieva and Gorshkov's work, which focuses on the equations of atmospheric behavior, appears to have been unjustly ignored. Our own assessment, as well as that of expert colleagues with whom we have consulted, is that

BioScience 59: 341–347. ISSN 0006-3568, electronic ISSN 1525-3244. © 2009 by American Institute of Biological Sciences. All rights reserved. Request permission to photocopy or reproduce article content at the University of California Press's Rights and Permissions Web site at *www.ucpressjournals.com/reprintinfo.asp.* doi:10.1525/bio.2009.59.4.12

Makarieva and Gorshkov's hypothesis is interesting and important. It must now be scrutinized and evaluated.

Conventional understanding

Deforestation has been implicated as contributing to declining rainfall in various regions (including the Sahel, West Africa, Cameroon, Central Amazonia, and India), as well as to weakening monsoons (Fu et al. 2002, Gianni et al. 2003, Malhi and Wright 2005). But the links remain uncertain.

Observations suggest that extensive deforestation often reduces cloud formation and rainfall, and accentuates seasonality (Bonan 2008). Forest clearings can cause a distinct, convection-driven "vegetation breeze" in which moist air is drawn out of the forest (Laurance 2005). Atmospheric turbulence resulting from canopy roughness and temperature-driven convection are thought to explain the localized increase in rainfall sometimes associated with fragmented forest cover (Bonan 2008).

Because opportunities for experimental investigations are limited, climate researchers rely heavily on simulation models to advance their understanding. Most modern models imply a local decline in rainfall after deforestation, along with regional and even intercontinental climate impacts (Bonan 2008). For climate modelers, key changes associated with deforestation are reduced leaf-area index, rooting depth, canopy roughness and roughness length (measures that influence air flow), and higher albedo (reflectivity). But these changes, their interactions and influences, and their dependence on contexts and scales are understood only in broad terms. Many uncertainties remain, especially about the influence of evaporation, convection, cloud development, and aerosols and land cover, and about how changes in cloud cover translate into changes in rainfall (IPCC 2007).

Recycling

Atmospheric moisture originates from oceanic and terrestrial evaporation. Rain derived from terrestrial sources and contributing to local rainfall is termed "recycled." Conventional explanations of wet continental interiors emphasize such recycling—but do the numbers add up?

The proportion of recycled rain, a measure dependent on the extent of the area considered, shows little consistent difference between wet and dry regions: an estimated 25 to 60 percent in the Amazon (e.g., Marengo 2005), 28 percent in the Nile region (Mohamed et al. 2005), more than 50 percent for summer rain in the midwestern United States (Bosilovich and Schubert 2002), and more than 90 percent for the Sahel (Savenije 1995). What is puzzling about wet regions is not the proportion of recycling, but the question of what drives the inward flows of atmospheric moisture required to replace what flows out through rivers (Savenije 1996).

Conventional theory offers no clear explanation for how flat lowlands in continental interiors maintain wet climates. Makarieva and Gorshkov show that if only "conventional mechanisms" (including recycling) apply, then precipitation should decrease exponentially with distance from the oceans. Researchers have previously puzzled over a missing mechanism to account for observed precipitation patterns (Eltahir 1998). Makarieva and Gorshkov's hypothesis offers an elegant solution: they call it a "pump."

An atmospheric moisture pump

Pressure gradients driven by temperature and convection are considered to be the principle drivers of air flows in conventional meteorological science. Makarieva and Gorshkov argue that the importance of evaporation and condensation has been overlooked.

Makarieva and Gorshkov draw attention to the fact that under typical atmospheric conditions, the partial pressure of water vapor near the earth's surface greatly exceeds the weight of the water held in the atmosphere above it. They argue that this imbalance can generate powerful airflows. Force results from the way temperature and pressure both decline with altitude in the troposphere (lower atmosphere). When the vertical temperature decline (the "lapse rate") is less than the critical value of 1.2 degrees Celsius (°C) per km, atmospheric water can remain static and in a gaseous state. But the global average lapse rate is more than 6°C per km. At these higher rates, water vapor rises and condenses. The reduction in atmospheric volume that takes place during this gas-to-liquid phase change causes a reduction in air pressure. This drop in pressure has routinely been overlooked.

Air currents near Earth's surface flow to where pressure is lowest. According to Makarieva and Gorshkov, these are the areas that possess the highest evaporation rates. In equatorial climates, forests maintain higher evaporation rates than other cover types, including open water. Thus, forests draw in moist air from elsewhere; the larger the forest area, the greater the volumes of moist air drawn in (see figure 1). This additional moisture rises and condenses in turn, generating a positive feedback in which a large proportion of the water condensing as clouds over wet areas is drawn in from elsewhere. The drivers (solar radiation) and basic thermodynamic concepts and relationships are the same as in conventional models, thus most behaviors are identical—the difference lies in how condensation is incorporated.

Makarieva and Gorshkov's estimates, incorporating volume changes from condensation, imply that when forest cover is sufficient, enough moist air is drawn in to maintain high rainfall inside continents. The numbers now add up: thus, condensation offers a mechanism to explain why continental precipitation does not invariably decline with distance from the ocean.

Evaporation and forests

We distinguish two types of evaporation. Transpiration is the evaporation flux from within plants; plants determine this flow by controlling their stomata (pores on leaves and other surfaces). Evaporation from wet surfaces, soils, and open water is also important. Which pathway contributes most to overall evaporation depends on conditions (Calder 2005, Savenije 2004).

Downloaded from http://bioscience.oxfordjournals.org/ by guest on September 26, 2014

Forests evaporate more moisture than other vegetation, typically exceeding flux from herbaceous cover by a factor of 10 (Calder 2005). Closed tropical forests typically evaporate more than a meter of water per year (Gordon et al. 2005). Some evaporate more than two meters (Loescher et al. 2005).

Forest evaporation benefits from canopy height and roughness, which leads to turbulent airflows. This has been termed the "clothesline effect," as it is the same reason laundry dries more quickly on a line than when laid flat on the ground (Calder 2005). If moisture is sufficient, forest evaporation is constrained principally by solar radiation and weather (Calder et al. 1986, Savenije 2004). Large tropical trees can transpire several hundred liters of water each day (Goldstein et al. 1998).

Water reserves are important. Plants with high stem volumes allow transpiration to outstrip root uptake, as stem water reserves are depleted by day and replenished at night (Goldstein et al. 1998, Sheil 2003). Trees (and forest lianas) typically have deeper roots than other vegetation and can thus access subterranean moisture during droughts (Calder et al. 1986, Nepstad et al. 1994). Many forest soils possess good water infiltration and storage—properties often lost with deforestation (Bruijnzeel 2004). Vertical translocation of soil water through the forest soil profile by roots at night may also be important (Lee et al. 2005). In some sites—notably, cloud forests and forests subjected to coastal fogs—abundant bryophytes and dense foliage contribute to efficient mist and dew interception (Dietz et al. 2007).

Makarieva and Gorshkov suggest that forests can influence *when* rain falls. Precipitation occurs once condensed moisture has accumulated and the buoyancy generated by rising humid air is low enough. They note that evaporation declines when plants close their stomata, as often occurs in the latter half of the day to alleviate moisture stress (Pons and Welschen 2004). This decline may help explain why most tropical rain falls after midday in many terrestrial (but not in marine) settings (Nesbitt and Zipser 2003). This prediction requires investigation.

Rainfall transects

Makarieva and Gorshkov's hypothesis predicts two types of coast to continental interior rainfall trends (following a transect path perpendicular to the regional isohyets [contours of long-term rainfall averages]; Savenije 1995). They propose and demonstrate that, regardless of location and seasonality, forest-free transects show a near-exponential reduction in annual rainfall with increasing distance from the coast, while well-forested transects show none (figure 2).

Global climate models may fit these rainfall patterns, but they do not predict them. This is an important distinction. As Makarieva and Gorshkov note, "it is widely admitted that the modern representation of atmospheric convection in GCMs [global circulation models] is a parameterization, not a theory."

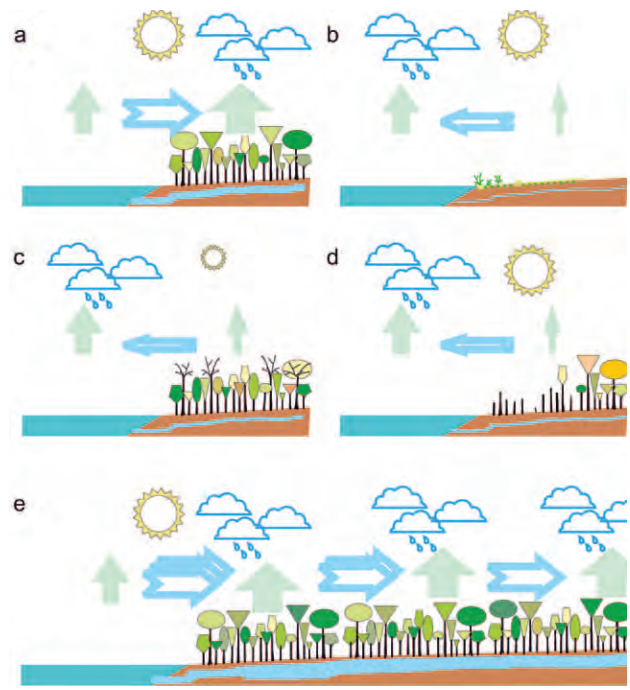

Figure 1. Makarieva and Gorshkov's "biotic pump." Atmospheric volume reduces at a higher rate over areas with more intensive evaporation (solid vertical arrows, widths denotes relative flux). The resulting low pressure draws in additional moist air (open horizontal arrows) from areas with weaker evaporation. This leads to a net transfer of atmospheric moisture to the areas with the highest evaporation. (a) Under full sunshine, forests maintain higher evaporation than oceans and thus draw in moist ocean air. (b) In deserts, evaporation is low and air is drawn toward the oceans. (c) In seasonal climates, solar energy may be insufficient to maintain forest evaporation at rates higher than those over the oceans during a winter dry season, and the oceans draw air from the land. However, in summer, high forest evaporation rates are reestablished (as in panel a). (d) With forest loss, the net evaporation over the land declines and may be insufficient to counterbalance that from the ocean: air will flow seaward and the land becomes arid and unable to sustain forests. (e) In wet continents, continuous forest cover maintaining high evaporation allows large amounts of moist air to be drawn in from the coast. Not shown in diagrams: dry air returns at higher altitudes, from wetter to drier regions, to complete the cycle, and internal recycling of rain contributes significantly to continental-scale rainfall patterns. Source: Adapted from ideas presented in Makarieva and Gorshkov (2007).

Seasonal rainfall

How does Makarieva and Gorshkov's hypothesis apply in the seasonal tropics? These monsoonal climates switch between two states: wet and dry. This switch is driven by the annual rhythm of solar energy outside the equatorial regions and its different impact on land and seas. Rather than a

Downloaded from http://bioscience.oxfordjournals.org/ by guest on September 26, 2014

classical temperature-based explanation, in Makarieva and Gorshkov's view, switching is dependent on relative evaporation fluxes. During seasons of reduced solar energy, land evaporates less moisture than does open water (oceanic evaporation remains substantial even in winter) and the seas draw air from the land, leading to a dry season (see figure 1c). When stronger sunshine returns, solar energy is again sufficient for the land to evaporate more moisture than neighboring seas, causing the swing in air currents that marks the classic monsoons. The switching depends on the positive feedbacks involved in the evaporation-rainfall system.

Not all seasonal shifts in tropical rainfall are similar, however. Much of tropical South America experiences a prolonged dry season—but without a clear switching of air currents flowing to and from the coast (Zhou and Lau 1998). Notably, vast areas of these forests remain green through the dry season by accessing deep soil moisture reserves that are replenished each wet season (Juarez et al. 2007, Myneni et al. 2007). The resulting dry-season evaporation does not wholly overcome the influence of lower air pressure at sea, but according to Makarieva and Gorshkov, it can keep the difference small and increase the likelihood of terrestrial rain.

In Makarieva and Gorshkov's hypothesis, wet seasons can start sooner if they are preceded by high land-based evaporation, and can begin later (or not at all) if evaporation is low. This prediction is consistent with observations in southern Amazonia, where severe drought reduces the ability of vegetation to transpire and delays the onset of the wet season (Fu and Li 2004). Forest loss and diminished evaporation can thus reduce the penetration of monsoon rains and reduce the duration of the wet season.

Spatial contexts and switching states

Makarieva and Gorshkov's ideas agree with, but go well beyond, conventional climate models that imply that land-locked climatic systems, being less buffered by oceans, are more vulnerable to land-cover change than are coastal areas (Zhang et al. 1996), while forest loss in coastal regions typically has a wider climatic impact (van der Molen et al. 2006). According to Makarieva and Gorshkov, if the near-continuous forest needed to convey moist air from coasts to continental interiors is severed, the flow of atmospheric moisture stops. Thus, clearing a band of forest near the coast may suffice to dry out a wet continental interior. Further, clearing enough forest within the larger forest zone may switch net moisture transport from ocean-to-land to land-to-ocean, leaving any forests remnants to be desiccated. Clearly, such risks need to be assessed and understood.

As an illustration, Makarieva and Gorshkov propose that a forested Australia was "switched" to desert by prehistoric settlers. Aboriginal burning reduced coastal forests, leading to continental desiccation. Is this credible? The jury remains out. Humans arrived in Australia during the last glacial period, when much of the world was drier than it is now. Certainly Australia has been well forested in the past, but, then again, dry episodes have occurred before human arrival (Morley 2000).

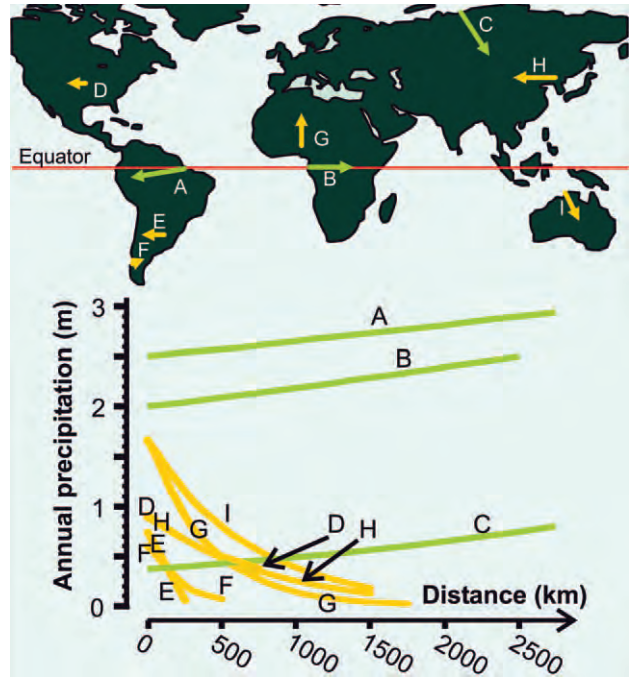

Figure 2. How rainfall (precipitation in meters) varies with increasing distance (in kilometers) inland in three forested (A, B, C) and six nonforested (D, E, F, G, H, I) regions. The map shows approximate locations, while the graph shows the best-fit trend lines ($P = P_0 e^{b \times dist}$, *where* P *is precipitation,* e *is the base of natural logarithms,* dist *is distance,* P_0 *is precipitation at* dist = 0, *and* b *is a constant that expresses rate of decline). These fall into two groups: (1) the near-linear (gently rising) forested transects (green), and (2) the near-exponentially declining nonforested transects (orange). Source: Data derived and replotted from Makarieva and Gorshkov (2007).*

The search for further evidence

Where else, aside from the transect data and the timing of monsoons, might we seek evidence for or against Makarieva and Gorshkov's hypothesis? Presumably, in deep continental interiors surrounded by disappearing forest the pattern would be ideal. Unfortunately, where good long-term data on rain and forest are available, they are from coastal regions, where marine climates prevail, and in mountainous regions, where rainfall is governed by terrain. The widely quoted observation that a century of rainfall records in the now heavily deforested foothills of Karnataka, southern India, is associated with only a minor decline in annual rain days is thus not very illuminating (Meher-Homji 1980).

Data on climatic variability may be more revealing: Makarieva and Gorshkov's hypothesis suggests that forest loss will be associated with a loss of stabilizing feedbacks and increased climatic instability. In Brazil's Atlantic Forest just such a correlation has been detected between reduced tree

Downloaded from http://bioscience.oxfordjournals.org/ by guest on September 26, 2014

cover and increased local interannual variation in rainfall (Webb et al. 2005).

New investigations

Makarieva and Gorshkov's hypothesis has implications for many different fields. We briefly consider some.

Water yields. Makarieva and Gorshkov's prediction and demonstration of distinct rainfall patterns over forests and nonforested transects are persuasive. But these are generalizations: they ignore variations in landform and cover types within each transect, and the influence of air circulation patterns (the ideal transect direction varies through the year). They do not predict the behavior of moist air over mixed forest/nonforest transects—the regions where forest cover is often disappearing fastest. Satellite observations (e.g.,Wang et al. 2009) and various existing data, such as those from the International Geosphere Biosphere Programme transects, may shed more light on these patterns (see *www.igbp.kva.se*). Along with more field data, local and regional simulators are required in which mechanisms, scenarios, and consequences can be explored.

Hydrological trade-offs in modified landscapes are scale dependent. In the standard view, well verified by field data, a marked reduction of forest canopy results in less water lost to evaporation and increased local runoff (Calder 2005). In contrast, Makarieva and Gorshkov's hypothesis suggests that water evaporated by forests is typically returned with interest, so we would expect a decline in rainfall, leading to lower runoff over a wider region, if forests are depleted.

Fire. The role of fire damage in forest degradation is an established positive feedback: once a forest has already burned or been otherwise disturbed and damaged, it becomes more flammable and thus more likely to burn again (Laurance 2005). Makarieva and Gorshkov's hypothesis adds drought to this cycle. Fire damages the properties that keep forests moist and nonflammable—the same properties that drive Makarieva and Gorshkov's pump. Fire reduces leaf area and the root densities responsible for hydraulic lift, and thus weakens the ability of the vegetation to maintain understory humidity. Reduced evaporation in turn reduces rainfall, leading to increased droughts, greater flammability, and increased fire risk—thus adding an additional and unwelcome positive feedback in the degradation cycle.

Vegetation feedbacks. Makarieva and Gorshkov's hypothesis raises questions regarding the role of feedbacks in landscape ecology. For example, the most competitive leaf phenological behavior is dependent on the climate. Among trees, evergreen foliage is favored by high seasonal unpredictability and also by low seasonal variation in moisture availability, while deciduous foliage is favored by intense and extended droughts as well as by seasonal predictability (Givnish 2002). In addition, some deciduous trees flush (i.e., produce new leaves) well before—and some only after—the rains come, with the former favored in more predictable seasonal contexts and the latter in more irregular conditions. Makarieva and Gorshkov's hypothesis implies that these behaviors, by affecting the rates of evaporation, will influence climate. In monsoon regions, evergreen and early-flushing deciduous vegetation encourage the dry season to end sooner and more regularly, whereas late-flushing deciduous forests experience longer dry seasons. Applying Makarieva and Gorshkov's hypothesis, we expect that these phenological behaviors favor the climatic conditions to which they are best adapted.

But not all feedbacks are necessarily positive. For example, evergreen lianas make up a significant proportion of the canopy in many seasonal tropical forests, where their dominance appears favored by the long dry season (Schnitzer 2005). Any resulting increases in rainfall should favor the trees over the lianas.

Evolution and emergent stability. Have forests evolved to generate rain? This idea touches on the much-debated possibilities of emergent self-stabilizing behavior (or "Gaia"; e.g., Lenton and van Oijen 2002). Trees and forests have evolved numerous times in Earth's history, suggesting a repeated trend to generate rich, self-watering terrestrial habitats. As the previous discussions illustrate, there is scope for self-stabilizing interactions to arise (see also Makarieva and Gorshkov 2007). But, as the properties required for an effective forest pump also benefit the individual trees, it appears that any pump emerges as an evolutionary consequence of individual-level competition—it increases forest extent, but this is not *why* it evolved.

Paleoclimates. Makarieva and Gorshkov's hypothesis, with its climate switch, provides new twists to old controversies. Human arrival in previously uninhabited regions over the last 50,000 years is invariably associated with extinctions, especially among larger fauna (as in the Australia example mentioned above). The concurrent role of climate change, viewed as a natural phenomenon, continues to be debated (Koch and Barnosky 2006). If severe climate impacts could plausibly result from ancient, human-induced habitat changes, then the sequence of events will need to be reassessed in this framework.

Makarieva and Gorshkov's hypothesis does not tell us how forests can become reestablished after the catastrophic events that punctuate Earth's history (Morley 2000). This question will require us to unravel the feedback processes and thresholds that operate spatially at different scales, and the influences that act upon them. Certainly the hypothesis does not argue that such greenings cannot occur. Presumably, a forest can establish even in a wet coastal site where rainfall declines exponentially with distance from the coast, and it can advance progressively inland, drawing moist air with it. Makarieva and Gorshkov's hypothesis may clarify how South America, but not Africa, managed to maintain large-scale, wet interior climates through past glacials. Perhaps in Africa the presence of large herbivores, and ancestral humans with fire, influenced

Downloaded from http://bioscience.oxfordjournals.org/ by guest on September 26, 2014

the balance between forest and nonforest vegetation reducing stability and allowing the climate to switch.

Managed vegetation. In contrast to Makarieva and Gorshkov, who propose that only natural and intact forests can maintain a working atmospheric pump, we suspect that secondary forest and plantations can have desirable evaporation properties (see, e.g., Olchev et al. 2008). While the higher flammability of such vegetation suggests a less-wet environment, which in turn implies a less-effective pump, such properties are not inevitable and can be influenced by management. These properties need to be investigated.

Greening deserts. Could we one day afforest the world's deserts? Makarieva and Gorshkov's hypothesis suggests we might. Contrary to most conventional models, Makarieva and Gorshkov's calculations imply that once forests are established in these regions, the biotic pump would be powerful enough to water them. Despite the scales, and the inevitable technical and ethical challenges, such projects may become easier to fund and to implement as carbon dioxide concentrations rise (Brovkin 2002).

Outlook

If Makarieva and Gorshkov's hypothesis proves valid, important questions will remain concerning how the biotic-pump mechanism interacts with other processes to provide a fuller account of local, regional, and global climate. If the hypothesis proves flawed, a mechanism to explain wet continental interiors will still be needed.

Acceptance of the biotic pump would add to the values that society places on forest cover. By raising regional concerns about water, acceptance of Makarieva and Gorshkov's biotic pump demands attention from diverse local actors, including many who may otherwise care little for maintaining forest cover.

Acknowledgments

We thank Anastassia Makarieva, Victor Gorshkov, Antonio Nobre, Ian Calder, Meine van Noordwijk, Wolfgang Cramer, and three anonymous reviewers for valuable comments. We also thank Claire Miller and Miriam van Heist for editorial suggestions, and the CIFOR Library and Wageningen Library for locating references. D. S. was supported by an European Commission grant to the Center for International Forestry Research, and by Wildlife Conservation Society support to the Institute of Tropical Forest Conservation.

References cited

Bonan GB. 2008. Forests and climate change: Forcing feedbacks and the climate benefits of forests. Science 320: 1444–1449.

Bosilovich MG, Schubert SD. 2002. Water vapor tracers as diagnostics of the regional hydrologic cycle. Journal of Hydrometeorology 3: 149–165.

Brovkin V. 2002. Climate-vegetation interaction. Journal de Physique IV 12: 57–72.

Bruijnzeel LA. 2004. Hydrological functions of tropical forests: Not seeing the soil for the trees? Agriculture Ecosystems and Environment 104: 185–228.

Calder IR. 2005. The Blue Revolution: Land Use and Integrated Water Resources Management. 2nd ed. London: Earthscan.

Calder IR, Wright IR, Murdiyarso D. 1986. A study of evaporation from tropical rain forest—West Java. Journal of Hydrology 89: 13–31.

Dietz J, Leuschner C, Holscher D, Kreilein H. 2007. Vertical patterns and duration of surface wetness in an old-growth tropical montane forest, Indonesia. Flora 202: 111–117.

Eltahir EAB. 1998. A soil moisture–rainfall feedback mechanism, 1: Theory and observations. Water Resources Research 34: 765–776.

Fu C, Harasawa H, Kasyanov V, Kim J-W, Ojima D, Wan Z, Zhao S. 2002. Regional-global interaction in East Asia. Pages 109–149 in Tyson P, Fun C, Fuchs R, Lebel L, Mitra AP, Odada E, Perry J, Steffen W, Virji H, eds. Global-Regional Linkages in the Earth System. Berlin: Springer.

Fu R, Li W. 2004. The influence of the land surface on the transition from dry to wet season in Amazonia. Theoretical and Applied Climatology 78: 97–110.

Gianni A, Saravanan R, Chang P. 2003. Oceanic forcing of Sahel rainfall in interannual to interdecedal timescales. Science 302: 1027–1030.

Givnish TJ. 2002. Adaptive significance of evergreen vs. deciduous leaves: Solving the triple paradox. Silva Fennica 36: 703–743.

Goldstein G, Andrade JL, Meinzer FC, Holbrook NM, Cavelier J, Jackson P, Celis A. 1998. Stem water storage and diurnal patterns of water use in tropical forest canopy trees. Plant, Cell and Environment 21: 397–406.

Gordon LJ, Steffen W, Jonsson BF, Folke C, Falkenmark M, Johannessen A. 2005. Human modification of global water vapor flows from the land surface. Proceedings of the National Academy of Sciences 102: 7612–7617.

[IPCC] Intergovernmental Panel on Climate Change. 2007. Climate Change 2007: The Physical Science Basis. Cambridge (United Kingdom): Cambridge University Press. (18 February 2009; *www.ipcc.ch/ipccreports/ar4-wg1.htm*)

Juarez RIN, Hodnett MG, Fu R, Goulden ML, von Randow C. 2007. Control of dry season evapotranspiration over the Amazonian forest as inferred from observations at a southern Amazon forest site. Journal of Climate 20: 2827–2839.

Koch PL, Barnosky AD. 2006. Late quaternary extinctions: State of the debate. Annual Review of Ecology Evolution and Systematics 37: 215–250.

Laurance WF. 2005. Forest-climate interaction in fragmented tropical landscapes. Pages 31–38 in Malhi Y, Phillips O, eds. Tropical Forests and Global Atmospheric Change. Oxford (United Kingdom): Oxford University Press.

Lee J E, Oliveira RS, Dawson TE, Fung I. 2005. Root functioning modifies seasonal climate. Proceedings of the National Academy of Sciences 102: 17576–17581.

Lenton TM, van Oijen M. 2002. Gaia as a complex adaptive system. Philosophical Transactions of the Royal Society of London B 357: 683–695.

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL. 2008. Prioritizing climate change adaptation needs for food security in 2030. Science 319: 607–610.

Loescher HW, Gholz HL, Jacobs JM, Oberbauer SF. 2005. Energy dynamics and modeled evapotranspiration from a wet tropical forest in Costa Rica. Journal of Hydrology 315: 274–294.

Makarieva AM, Gorshkov VG. 2007. Biotic pump of atmospheric moisture as driver of the hydrological cycle on land. Hydrology and Earth System Sciences 11: 1013–1033.

Makarieva AM, Gorshkov VG, Li BL. 2006. Conservation of water cycle on land via restoration of natural closed-canopy forests: Implications for regional landscape planning. Ecological Research 21: 897–906.

Malhi Y, Wright J. 2005. Late twentieth-century patterns and trends in the climate of tropical forest regions. Pages 3–16 in Malhi Y, Phillips O, eds. Tropical Forests and Global Atmospheric Change. Oxford (United Kingdom): Oxford University Press.

Marengo JA. 2005. Characteristics and spatio-temporal variability of the Amazon River Basin Water Budget. Climate Dynamics 24: 11–22.

Meher-Homji VM. 1980. Repercussions of deforestation on precipitation in western Karnataka, India. Archiv für Meterologie, Geophysik und Bioklimatologie 28B: 385–400.

Downloaded from http://bioscience.oxfordjournals.org/ by guest on September 26, 2014

Mohamed YA, van den Hurk B, Savenije HHG, Bastiaanssen WGM. 2005. Hydroclimatology of the Nile: Results from a regional climate model. Hydrology and Earth System Sciences 9: 263–278.

Morley RJ. 2000. Origin and Evolution of Tropical Rain Forests. Chichester (United Kingdom): Wiley.

Myneni RB, et al. 2007. Large seasonal swings in leaf area of Amazon rainforests. Proceedings of the National Academy of Sciences 104: 4820–4823.

Nepstad DC, de Carvalho CR, Davidson EA, Jipp PH, Lefebvre PA, Negreiros GH, da Silva ED, Stone TA, Trumbore SE, Vieira S. 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. Nature 372: 666–669.

Nesbitt SW, Zipser EJ. 2003. The diurnal cycle of rainfall and convective intensity according to three years of TRMM measurements. Journal of Climate 16: 1456–1475.

Olchev A, Ibrom A, Priess J, Erasmim S, Leemhuis C, Twele A, Radler K, Kreilein H, Panferov O, Gravenhorst G. 2008. Effects of land-use changes on evapotranspiration of tropical rain forest margin area in Central Sulawesi (Indonesia): Modelling study with a regional SVAT mode. Ecological Modelling 212: 131–137.

Pons TL, Welschen RAM. 2004. Midday depression of net photosynthesis in the tropical rainforest tree *Eperua grandiflora*: Contributions of stomatal and internal conductances, respiration and Rubisco functioning. Tree Physiology 23: 937–947.

Savenije HHG. 1995. New definitions for moisture recycling and the relationship with land-use changes in the Sahel. Journal of Hydrology 167: 57–78.

———. 1996. The runoff coefficient as the key to moisture recycling. Journal of Hydrology 176: 219–225.

———. 2004. The importance of interception and why we should delete the term evapotranspiration from our vocabulary. Hydrological Processes 18: 1507–1511.

Schnitzer SA. 2005. A mechanistic explanation for global patterns of liana abundance and distribution. American Naturalist 166: 262–276.

Sheil D. 2003. Growth assessment in tropical trees: Large daily diameter fluctuations and their concealment by dendrometer bands. Canadian Journal of Forest Research 33: 2027–2035.

van der Molen MK, Dolman AJ, Waterloo MJ, Bruijnzeel LA. 2006. Climate is affected more by maritime than by continental land use change: A multiple scale analysis. Global and Planetary Change 54: 128–149.

Wang J, Chagnon FJF, Williams ER, Betts AK, Renno NO, Machado LTT, Bisht G, Knox R, Bras RL. 2009. Impact of deforestation in the Amazon basin on cloud climatology. Proceedings of the National Academy of Sciences: Online Early (published online before print 23 February 2009). doi:10.1073/pnas.0810156106

Webb TJ, Woodward FI, Hannah L, Gaston KJ. 2005. Forest cover-rainfall relationships in a biodiversity hotspot: The Atlantic Forest of Brazil. Ecological Applications 15: 1968–1983.

Zhang H, Henderson-Sellers A, McGuffie K. 1996. Impacts of tropical deforestation, I: Process analysis of local climatic change. Journal of Climate 9: 1497–1517.

Zhou JY, Lau KM. 1998. Does a monsoon climate exist over South America? Journal of Climate 11: 1020–1040.

Douglas Sheil (e-mail: DouglasSheil@itfc.org or D.Sheil@cgiar.org) is with the Institute of Tropical Forest Conservation, Mbarara University of Science and Technology, in Kabale, Uganda. He and Daniel Murdiyarso are with the Center for International Forestry Research in Jakarta, Indonesia.

Downloaded from http://bioscience.oxfordjournals.org/ by guest on September 26, 2014