Ecological rainfall infrastructure: investment in trees for sustainable development

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Partnership for the Tropical Forest Margins

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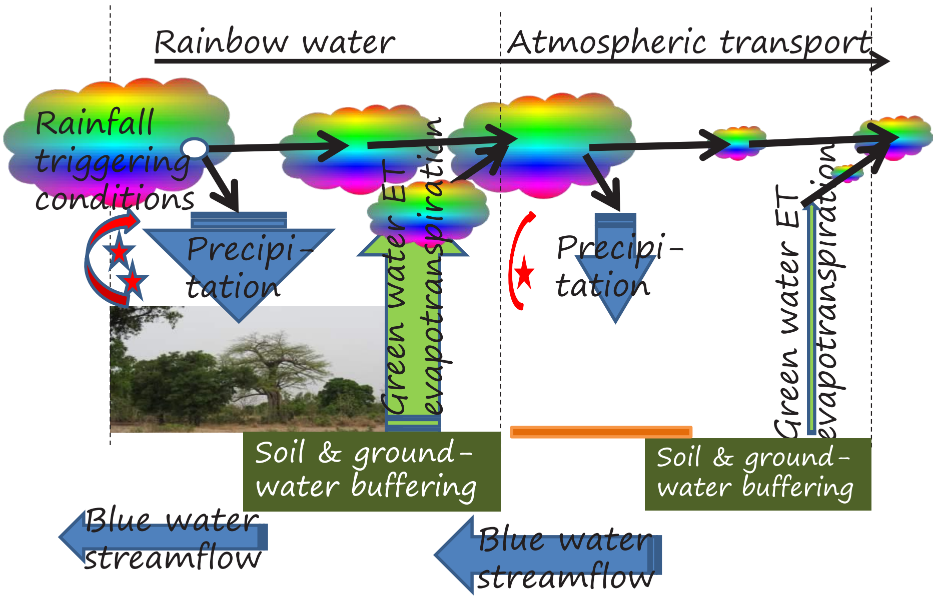

In many parts of the world local people are convinced that forests, trees and rainfall are related in more than one way: forests and trees not only depend on rainfall but help to generate it. Scientists confronted with this perspective have always denied such effects, or at best been 'agnostic', as it seemed impossible in their data to find evidence. New evidence on credible mechanisms for forest and tree effects on rainfall is, however, emerging. It can revolutionize current climate negotiations that all focus on greenhouse gas emissions.

Key findings

1. Atmospheric moisture transport ('precipitable water') in relation to prevailing winds define precipitationsheds (source area of rainfall in a target area, typically including ocean + land areas)
2. Forests and trees can trigger rainfall by releasing ice nucleating bacteria and volatile organic carbon compounds, but systematic comparison between vegetation types and species has yet to be made
3. A century after 'Biological Nitrogen Fixation' was clarified, the outlines are becoming clear of a 'Biological Rainfall Generation' mechanism, influencing atmospheric moisture transport and triggering rainfall events
4. The predicted shortages of freshwater in many areas of the world may not be unavoidable
5. The geopolitics of anthropogenic impacts on rainfall as key climate variable will call for new types of collective action at (sub)continental scale, different from current UNFCCC debate

Implications for climate negotiations

- Spatially explicit dependencies of rainfall are emerging in Africa and Asia that are similar to the better known relationships between Amazon forest and rainfall in W. Amazon and NW Argentina
- Incorporation of new findings on rainfall triggering effects from vegetation may help improve the notoriously challenged vegetation-atmosphere-climate models
- 'Biological Rainfall Generation' (BRG) may equal or surpass 'Biological Nitrogen Fixation' (BNF) in importance for reconciling the ambitions of sustainable development with the realities of planetary boundaries
- Current accounting schemes take rainfall as external (exogenous) variable; it may, however, respond to changes in tree cover in response to policy.
- Policymakers have enough ground to act: With a primacy for continental scale relationships in dealing with quantified rainfall teleconnections, regions don't have to wait for global agreements or full scientific backing to start meaningful negotiations on a 'no regrets' basis. But relations with global climate agreements need to be clarified

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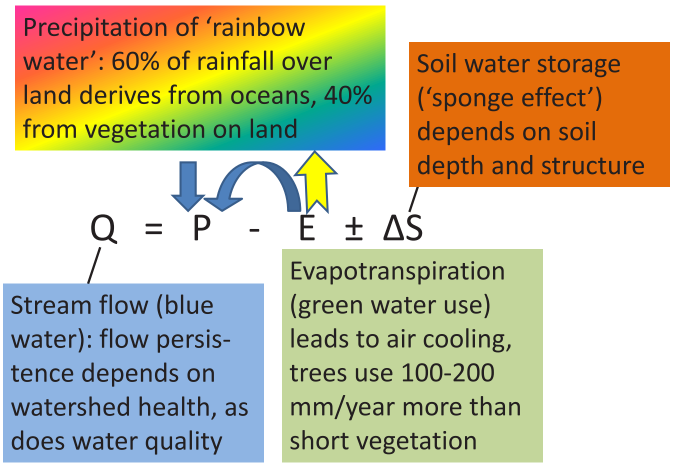
Local and scientific knowledge regarding rainfall effects of forest change do not match. When scientists measure rainfall and hydrological response in paired catchment they usually don't see effects, but they may be at the wrong scale. In real-world data, claimed decreases in rainfall after deforestation or increases after reforestation do not often exceed the normal and unexplained parts of variation.

Spatial patterns in rainfall vary with latitude, distance to the ocean, terrain and 'rain shadows' of mountain slopes preceding it in the direction of prevailing winds. Temporal patterns vary with seasons (prevailing winds, monsoons) and ocean temperature (El Nino, Indian Ocean Dipole, for example).

The forest-climate debate has in the past decade been dominated by carbon and greenhouse gasses. Evidence is accumulating, however, that water may form a more prominent part of the rationale for protecting forests of various types and tree cover outside forest.

Forest and water – big picture on 'cool' forests



In ASB-PB 8 the view was expressed that "There is evidence that large-scale (> 1,000 – 10,000 km^2) removal or addition of old-growth forest in humid parts of the world affects rainfall during the transition between rainy and dry season. Effects on annual rainfall are modest (5-10%) but do manifest themselves mostly during this critical time of year. Any increments in rainfall after widespread forestation will often be less than increments in local water interception and use. The effects of partial tree cover are still largely undescribed." **Bruijnzeel and van Noordwijk (2008)**

Figure 1. The basic equation of water balance studies relates water flowing in rivers (Q) to evapotranspiration (E) and precipitation (rainfall+) (P)

What do we know about rainfall?

"Most hydrological studies have assumed that rainfall is an 'exogenous' variable which responds to ocean temperatures and global circulation patterns, but not in a predictable way to land cover. Local ecological knowledge offers frequent suggestions that changes in rainfall have occurred in conjunction with changes in tree cover. But such effects have not been observed in paired catchment studies. However, several research lines within the past decade have altered this perspective, suggesting that serious re-evaluation of current thinking is needed where the relations between vegetation and climate are almost exclusively discussed in terms of carbon storage and impacts on global climate, without the regional specificity that such rainfall effects have." (Ong et al 2015).

Fire – rainfall relations

Smoke	Cloud
Fire	Rainfall

Where there's smoke there must be fire. Rainfall and clouds are related like fire and smoke but in reverse order (clouds precede rainfall). The effects of smoke on cloud formation are less clear than the effects of rainfall on fire.

Rainfall needs water in the air and a reason to fall. The two primary requirements for rainfall are the presence of precipitable water in the atmosphere, mostly by advection (prevailing winds), and its phase shift from water vapour to solid (ice) or fluid (water) form. The phase shifts in an air mass depend on temperature (as vapour saturation depends strongly on temperature), but also on the presence of condensation nuclei and aerosols. Ice nucleation in supercooled water clouds with temperatures between 0 and –35 °C can be initiated in four different ways (Kulmala et al 2011): deposition nucleation, immersion freezing, condensation freezing and contact freezing; their relative importance varies between types of clouds and their roles on local rainfall. Condensation can start around dust particles, volatile organic compounds, hydrophilic molecules (e.g. salt sprays) or cell wall surfaces of a biological origin. From a review of older literature Andreae and Rosenfeld (2008) concluded that "CCN (cloud condensation nuclei) concentrations over the pristine continents were similar to those now prevailing over the remote oceans, suggesting that human activities have modified cloud microphysics more than what is reflected in conventional wisdom." Primary biological aerosol particles (PBAP) are bacteria and archaea, fungal spores and fragments, pollen, viruses, algae and cyanobacteria, biological crusts and lichens and others like plant or animal fragments and detritus (Després et al 2012).

The balance between the two requirements of rainfall–atmospheric moisture transport in prevailing winds, and condensation (plus ice nucleation)–depends strongly on position on the globe. Observers in W. Europe will know that the weather forecast is dominated by depressions, high pressure areas and their impact on dry or wet, warm or cold atmospheric flows. Rainfall prediction is based on rainfall fronts travelling over continents, especially in winter, and much less spatially predictable cloudbursts in summer linked to lightning and thunderstorms. Elsewhere in the world typhoons may be major sources of episodic rainfall (and associated floods and landslides), or the more predictable seasonal movements of the intertropical convergence zone (ITCZ) relative to the

Methods for cloud triggering effects

Many relevant methods do exist. Others require further exploration. Després et al (2012) gave an overview of sampling methods and physical, chemical and biological techniques for analysis in relation to their ability to act as ice nuclei or cloud condensation nuclei. These authors suggested a concerted effort to define standardized protocols for studies of seasonal variation at regional and global scales (atmospheric biogeography) and use this, in combination with lab experiments to constrain numerical models of atmospheric transport, transformation and climate effects of primary biological aerosol particles. Kulmala et al (2011) gave an overview of the European Integrated project on Aerosol Cloud Climate and Air Quality interactions (EUCAARI). The project developed a comprehensive database on the physical, chemical and optical properties of aerosol particles over Europe, China, India, Brazil, and South Africa. It started modeling tools to connect aerosol processes from nano to global scale and their effects on climate and air quality.

earth. Overgeneralization on mechanisms and bias due to place of origin are a challenge to all of us. The two-way relationship between forests and rainfall (rainfall exceeding thresholds as pre-requirements for various types of forest growth, forests influencing rainfall) have been a challenge to any traveller, who comes with implicit interpretation patterns shaped at home.

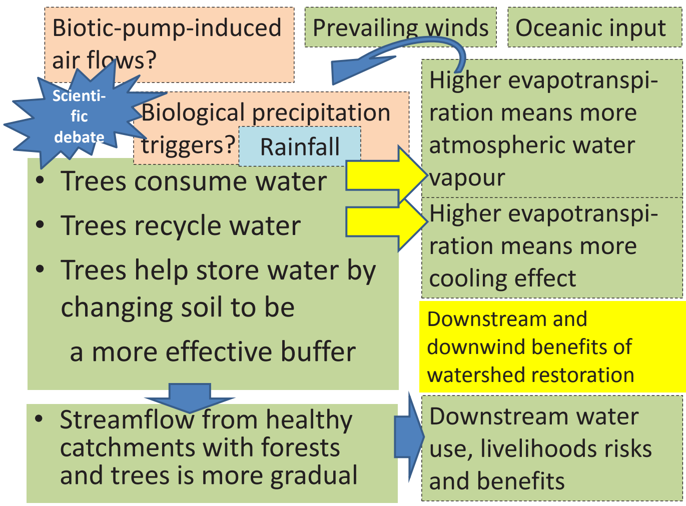


Figure 2. Taking stock of the various relationships between trees and the full hydrological cycle

Where, when and how do tree cover (and other vegetation aspects) influence rainfall?

Morris et al (2014) reviewed what we currently understand of bioprecipitation as a feedback cycle linking Earth history, ecosystem dynamics and land use through biological ice nucleators in the atmosphere. Després et al (2012) reviewed primary biological aerosol particles in the atmosphere and concluded that "Atmospheric aerosol particles of biological origin are a very diverse group of biological materials and structures, including microorganisms, dispersal units, fragments and excretions of biological organisms. In recent years, the impact of biological aerosol particles on atmospheric processes has been studied with increasing intensity, and a wealth of new information and insights has been gained."

In a study of rainforest aerosols as biogenic nuclei of clouds and precipitation in the Amazon, Pöschl et al (2010) concluded that "The Amazon is one of the few continental regions where atmospheric aerosol particles and their effects on climate are not dominated by anthropogenic sources. During the wet season, the ambient conditions approach those of the pristine pre-industrial era. We show that the fine submicrometer particles accounting for most cloud condensation nuclei are predominantly composed of secondary organic material formed by oxidation of gaseous biogenic precursors. Supermicrometer particles, which are relevant as ice nuclei, consist mostly of primary biological material directly released from rainforest biota. The Amazon Basin appears to be a biogeochemical reactor, in which the biosphere and atmospheric photochemistry produce nuclei for clouds and precipitation sustaining the hydrological cycle. The prevailing regime of aerosol-cloud interactions in this natural environment is distinctly different from polluted regions."

Evidence that tree cover not only responds to, but also influences rainfall has accumulated, as reviewed by Ong et al (2015):

1. Availability of satellite observations of wind at multiple levels in the atmospheric column and humidity (a measure of precipitable water) have allowed calculation of the net moisture transport vectors over the earth surface. In combination with satellite-derived rainfall grids, this showed that terrestrial recycling, and hence the type of land cover, has a significant role in securing there is sufficient atmospheric moisture to account for the rainfall received (Bosilovich and Schubert, 2002; van der Ent et al 2010, 2014).
2. The concept of a 'precipitationshed' (Keys et al 2012), as the area of ocean and/or land that contributes moist air to the rainfall recorded at specific locations or to watersheds and the algorithms to derive this from data. The inclusion of land in a 'precipitationshed' implies dependency on current levels and patterns of evapotranspiration.
3. Backtracking the geographic pathway of airflows that brought rainfall has revealed a correlation with the leaf area index beneath the air movement trajectory, implying a role for terrestrial evapotranspiration in causing rainfall elsewhere (Spracklen et al 2012).
4. Ellison et al (2012) helped shift the forest cover – water yield debate from demand to supply-side thinking.
5. Specific hypotheses about mechanisms by which forests may influence wind and attract moist air, as proposed by Makarieva and Gorshkov (2007), explained by Sheil and Murdiyarso (2009), and reviewed by Makarieva et al (2013). Further supported by Poveda et al (2014).

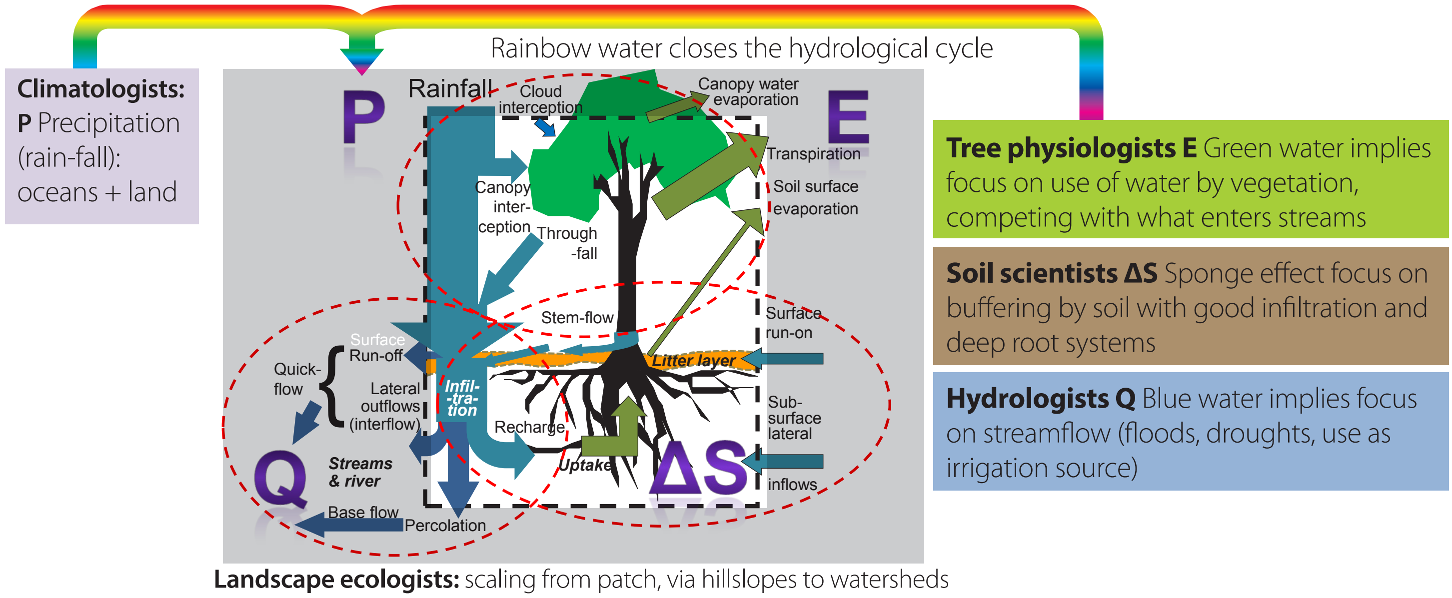


Figure 3. The 'colours of water' in relation to the parts of the hydrological cycle of concern

6. Isotope studies of rainfall, surface and groundwater, current uptake of water and growth rings allows reconstruction of past rainfall patterns and its potential relationship with land cover in the precipitationshed (Gebrekirstos et al 2014).
7. Better understanding of the role vegetation can play in triggering rainfall where sufficient atmospheric moisture is present through Volatile Organic Compounds (VOCs), icenucleating bacteria derived from the phyllosphere (Morris et al 2014), pollen and atmospheric turbulence (forest edge effects (Pielke 2013)). Bio-aerosols are themselves responding to rainfall (Huffman et al 2013), and the typical smell after rain may contain soil particles plus compounds of biological origin (Bigg et al 2015). At this point in the emerging field of science it is not clear what types of distinctions between vegetation with various degrees of tree cover (incl. various types of forest) and human management interventions (incl. forms of agroforestry are involved, and it is best if the net is cast widely to include all types of vegetation of local importance and known variation in tree cover (Zomer et al 2014).
8. The realization that the traditional focus of hydrology on 'blue water', or water in streams and rivers that can be allocated for irrigation, industrial and domestic users addresses only some 40% of the total rainfall, while the 'green water' used for evapotranspiration so far remains unaccounted for. As contributor of 'rainbow water' it can now be recognized in explorations of the full hydrological cycle (van Noordwijk et al 2014).
9. Careful case studies, such as that of the Rungwe mountain water tower in Tanzania (Williamson et al 2014) where forest conversion ('aridification') on the lower slopes may imply that more water reaches streams in this part of the landscape, but less water falls on the higher slopes and therefore fewer crosses between watersheds, affecting water levels in Lake Masoko.
10. More comprehensive perspectives on water-focused landscape management (van Noordwijk et al 2015).

BRG in payments for watershed services

Based on the effects of land use on different parts of the hydrological cycle and couple to human benefits in multiple ways, Leimona et al (2015), described ten prototypes for payments for watershed services. Economic incentives for, or coinvestment in, rainbow water will need further evidence and metrics to become 'performance-based', but may be a relevant part of future collective action to secure a climate for sustainable development.

Biological Nitrogen Fixation (BNF) as analogy

The discovery of biological nitrogen fixation was a gradual process, with Roman authors two thousand year ago discussing the merits of leguminous plants, just as Greek authors already discussed the relationship between forest and rainfall. Three steps in recognition of BNF were:

William Marsden (1754-1836), an English orientalist and linguist, documented local knowledge and history in Indonesia, including a remark on a commonly used leguminous live stake for pepper (and shade tree for coffee) (*Erythrina orientalis*): "not to insist on the opinion of a celebrated writer, that trees act as siphons, derive from the air and transmit to the earth as much of the principle of vegetation as is expended in their nourishment"

Hermann Hellriegel (1831 - 1895) German agricultural chemist who provided quantitative evidence that leguminous plants assimilate the free nitrogen of the atmosphere with tubercles on the roots as the agency through which this takes place (Hellriegel and Wilfarth, 1888).

Martinus Willem Beijerinck (1851-1931) Dutch microbiologist who is recognized for the discovery of plant viruses and the microbiological agency in biological nitrogen fixation (Beyerinck, 1901), using his previous specialization in plant galls to recognize the dual life forms involved in nodulated plant roots.

Despite the fact that more than three-quarters of the atmosphere consists of nitrogen, there is a limited

Table 1. Comparing biological rain generation (BRG) and biological nitrogen fixation (BNF) in their consequences for agriculture and other lands uses

BNF = Biological nitrogen fixation	BRG = Biological rain generation
A world without BNF	**A world without BRG**
Despite the fact that more than ¾ of the atmosphere consists of nitrogen, there is a limited amount of nitrogen circulating between plants, soil and aquatic systems; occasionally lighting strikes add to the pool, but denitrifier bacteria return it to the atmosphere. Ultimately we'll have to learn to make the best use of what little N we have – and maximize all the ocean-derived guano we can lay our hands on.	Despite all the water in the oceans, rainfall over land is uneven, uncertain and limited in amount. All current hydrology is 'given rainfall': we can understand what happens to water finding its way to rivers and the sea (blue water) and water that is evaporated back to the atmosphere, mostly by plants (green water). We can prevent river water flowing to the sea by using it for irrigating crops, and can reduce forests and tree cover (users of large amounts of green water), but that's it.
A world with BNF	**A world with BRG**
Some plants (10 families) have symbiotic N_2 fixation, adding almost-free resources, as long as they are around. Smart agriculture is centered around the use of *Leguminosae* trees, forbs and annuals (and a few other N_2 fixers).	Plants influence rainfall by a combination of mechanisms: providing (*recycling*) atmospheric moisture, influencing air flows, releasing ice-nucleating agents (volatile organics, phyllosphere bacteria). Once we know which plants and bacteria do what, we can use them and protect/restore the vegetation that will secure rainfall.
A world with BNF + Haber-Bosch industrial nitrogen	**A world with BRG + geo-engineering of rainfall**
As long as we have enough energy we can make as much N fertilizer as we want, it's only a matter of cost, and avoiding eutrophication and N_2O emissions.	Anthropogenic disturbance of rainfall cycles by deforestation, change of albedo, and haze, can be balanced by tactic use of ice-nucleating agents. But the geopolitics of this is daunting.

amount of nitrogen circulating between soil and plants and efficient agriculture requires buffers to avoid excess and access problems (van Noordwijk and Cadisch, 2002). Despite the fact that the oceans are full of water, the way this is transferred to the continents as rainfall is uneven in space, poorly predictable in time and requires large buffers to protect from both excess and access problems of human use of the planet. Table 1 suggests that indeed there are relevant parallels between biological nitrogen fixation and biological rain generation in the way they shift thinking about 'carrying capacity' and 'planetary boundaries' of agricultural use of the planet.

Landscape context of BRG as step towards active management?

Relationships between vegetation (or 'forest') and rainfall cannot be treated as a 'co-benefit' of carbon-based climate policy as, in many locations, it will probably be the other way around, with carbon stock changes being a co-benefit of tree cover policies aimed at improving the hydrologic cycle. If the dominant paradigm of payments for environmental services shifts from a 'carbon market' towards a co-investment scheme (Namirembe et al 2014), a better balancing of local and external co-benefits and shared risk may well emerge.

"Elucidation of bioprecipitation feedbacks involving landscapes and their microflora could contribute to appraising the impact that modified landscapes have on regional weather and biodiversity, and to avoiding inadvertent, negative consequences of landscape management." Morris et al (2014)

Reforestation is widely believed to increase streamflow, especially during low flow conditions when it is most valued. But empirical tests of this expectation (Ghimire et al 2014) have often failed to find evidence, or found opposite effects. It may well be that the scale at which paired catchment studies can be done prevents the rainfall effects to be expressed.

Science progresses by shifting paradigms

The terminology of 'paradigm shift' has been used in many contexts of less importance for human wellbeing. From a perspective that rainfall is an exogenous factor, or 'act of god', with limited opportunities for people to change the mood, or only under the influence of specialized 'rainmakers', we are now at the verge of understanding how specific vegetation change increases or decreases the chances of rainfall at specific places elsewhere. The 'leverage' may be only ten-to-fifteen percent – but a change of ten-to-fifteen percent in rainfall can make a noticeable difference. We have good reasons to revise the public perception that climate change and forest is all about carbon – and return to the basic understanding that it is mostly about water and temperature, as most people always expected it to be.

Way forward

After reviewing the literature we propose that five complementary efforts are needed to further the science on the interface with action:

1. Atmospheric moisture transport ('precipitable water') in relation to prevailing winds and possible local 'biotic pump' mechanisms, defining precipitationsheds at seasonal scale and allowing study of their interannual variability under various evapotranspitration scenarios,
2. Historic variation in source of water used by trees as studied in dendrochronology, as basis for assessment of the effects of changes in downwind tree cover at (sub)continental scales in various parts of the world,
3. Quantify the agency of vegetation of different types, and the plant species that they contain, in releasing ice nucleating bacteria and volatile organic carbon compounds, along with the seasonal pattern of these releases,
4. Incorporation of new findings in synthetic vegetation-atmosphere-climate models that can account for

interactions between known processes and used for scenario studies,

5. Exploration of the geopolitics involved and possible pathways to support the type of cross-border collective action that will be needed to reduce conflict over the use of biologically generated rainfall, and/or associated geo-engineering methods.

To make progress on this requires a concerted effort of scientists with a range of disciplinary expertise, and a policy environment in which 'no regrets' responses emerge: biological rainfall generation will not be a stand-alone effect, but will synergize with other reasons to manage global tree cover to secure a global-to-local climate conducive for sustainable development.

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The ASB Partnership for the Tropical Forest Margins is working to raise productivity and incomes of rural households in the humid tropics without increasing deforestation or undermining essential environmental services.

ASB is a consortium of over 90 international and national partners with an eco-regional focus on the forest–agriculture margins in the humid tropics, with benchmark sites in the western Amazon Basin of Brazil and Peru, the Congo Basin forest in Cameroon and DRC Congo, southern Philippines, northern Thailand, and the island of Sumatra in Indonesia.

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