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FORESIGHT Brief
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025
Early Warning, Emerging Issues and Futures

Working with plants, soils and water to cool the climate and rehydrate Earth's landscapes

Background

The Foresight Briefs are published by the United Nations Environment Programme to highlight a hotspot of environmental change, feature an emerging science topic, or discuss a contemporary environmental issue. The public is provided with the opportunity to find out what is happening to their changing environment and the consequences of everyday choices, and to think about future directions for policy. The 25th edition enhances our understanding of the interwoven relationships and the subsequent fluxes of energy between plants, soils and water on the ground, as well as in and with the atmosphere. It explains how these can help mitigate climate change, while at the same time creating a resilient ecosystem.

Abstract

The continued destruction of forests, the deterioration of soils, the subsequent loss of terrestrial soil water storage and the reduction of water retention in the landscape are disrupting the movement of water in and through the atmosphere. This disruption causes major shifts in precipitation that could lead to less rainfall and more droughts in many areas of the world, increases in regional temperatures and an exacerbation of climate change. These changes affect regional climate, but can also impact regions far away. Understanding the interwoven relationships and the subsequent fluxes of energy between plants, soils and water on the ground, as well as in the atmosphere, can help mitigate climate change and create more resilient ecosystems.

Introduction

Vegetation plays an important – and often neglected – role in regulating the climate. Think of the difference between standing on a hot summer afternoon on a ploughed and barren field or in a dense forest. Clearly, the conversion of, for example, forests to cropland or urban areas brings major changes that can influence the climate.

From the solar radiation reaching a densely vegetated field surface only 1% is used for photosynthesis and 5-10% heats the air ("sensible heat"[i]). Over 70% of the radiation is used for transpiration by the plants, by which liquid water is transformed to water vapor, a very energy-demanding process ("latent heat"[i]) (**Figure 1**). Counting non-vegetated and water surfaces, around 50% of the solar energy reaching the ground is used for evaporation and transpiration of water ("evapotranspiration"[ii]).[1–4]

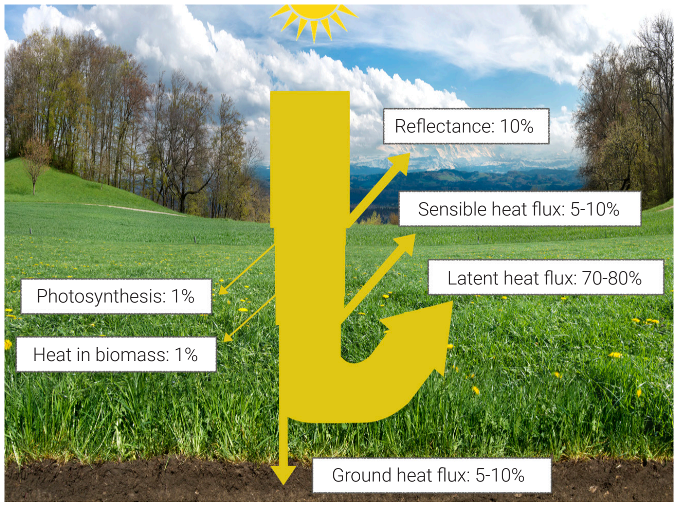

Figure 1: *Distribution of the solar energy incident on vegetation.*[1]

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As these masses of air rise into the atmosphere, the water vapor will eventually condensate and release the same amount of energy as consumed on the ground, some of it dissipating into space. The newly created clouds will reflect incoming solar radiation and are the source of new precipitation.

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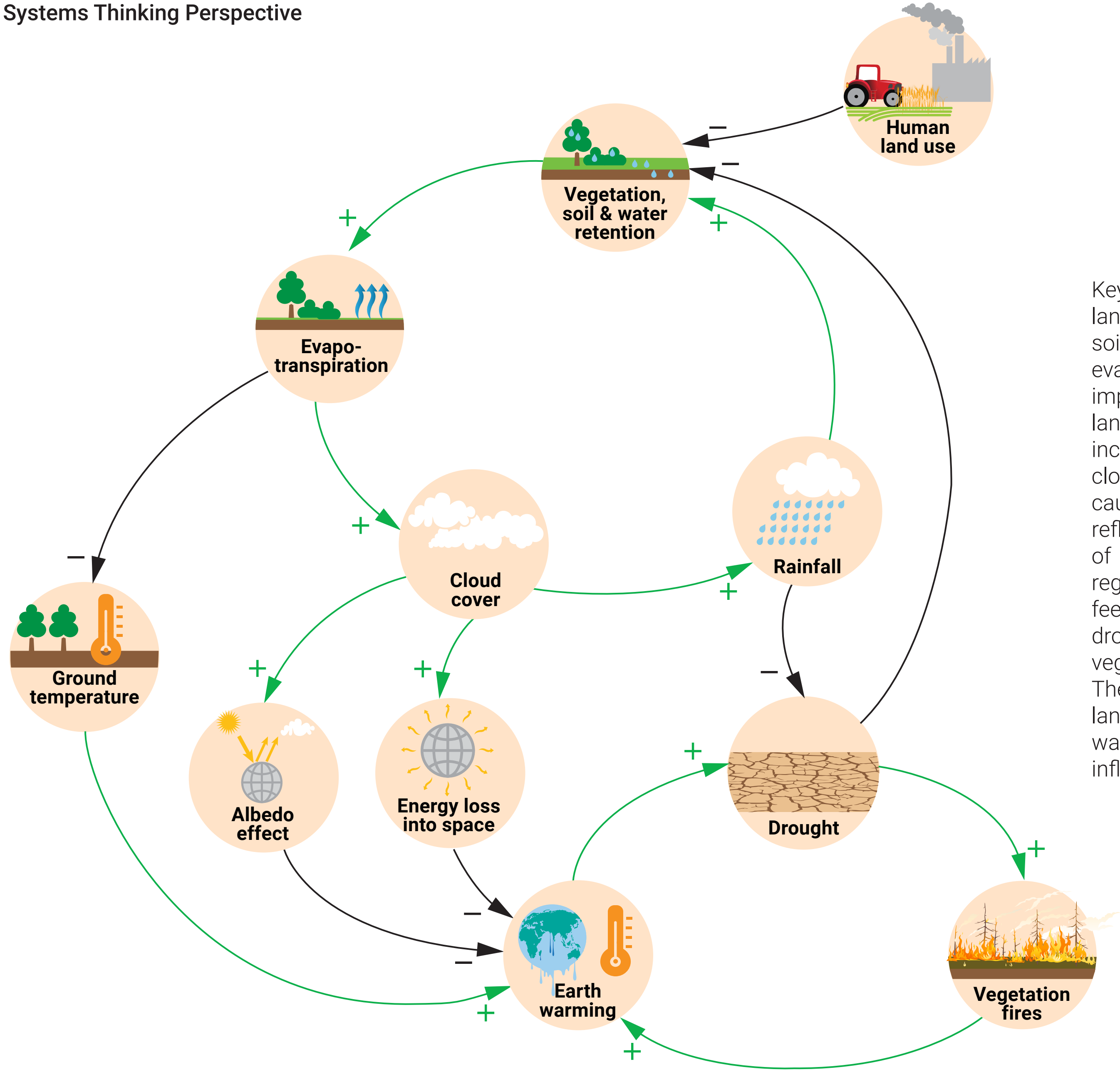
i Latent and sensible heat are types of energy released or absorbed in the atmosphere. Latent heat is related to changes in phase between liquids, gases, and solids. Sensible heat is related to changes in temperature of a gas or object with no change in phase. (https://climate.ncsu.edu/edu/Heat)

ii The combined processes of evaporation and transpiration of the water from the earth's surface into the atmosphere.

A Systems Thinking Perspective



Key causal influences in this system - increased human land use has resulted in reduced vegetation cover, degraded soil and diminished water retention, which directly reduces evapotranspiration, increasing ground temperatures, in turn impacting global temperature rise. Increasing vegetation on land will increase soil fertility and ground water recharge, increasing evapotranspiration, in turn leading to increased cloud cover and increased rainfall. Increased cloud cover causes an increase in atmospheric cooling through additional reflectance of incoming solar radiation as well as an increase of energy transfer back into space, which together have regulatory effects on earths' warming. When this balancing feedback is weakened, a hotter earth will result in more droughts, further worsened by reduced rainfall, and more vegetation fires which in turn warms the earth even further. These cycles can be reversed through policies that promotes land use that increases vegetation cover and improves soil water retention. (+) Influence is in the Same direction, (-) influence is in the Opposite direction.

Why is this issue important?

Of the approximately 120,000 km³ of water that falls on terrestrial surfaces as precipitation each year, around 60% comes from the ocean while 40% derive from land (see **Figure 2**).[5,6] 60-80% of this land-derived atmospheric moisture comes from transpiration by plants[2,7,8,] demonstrating the important role vegetation plays in feeding the precipitation cycle, as well as in transferring energy from the ground into the upper atmosphere.

Until recently, human impact on water vapour in the atmosphere was assumed to be negligible, compared to evaporation from oceans. However, the impact humans have on atmospheric water vapour stems from major human-induced land cover changes, not only from industrial emissions, as previously argued. These land cover changes indeed have a major influence on the atmospheric water vapour cycles.[9–11]

Almost half of the world's forests have been lost since the beginning of agriculture (with most of the deforestation happening since 1950)[12,13] and converted into much less vegetated fields. What impacts do these vast human-induced land cover changes have on the earth's water and energy fluxes?

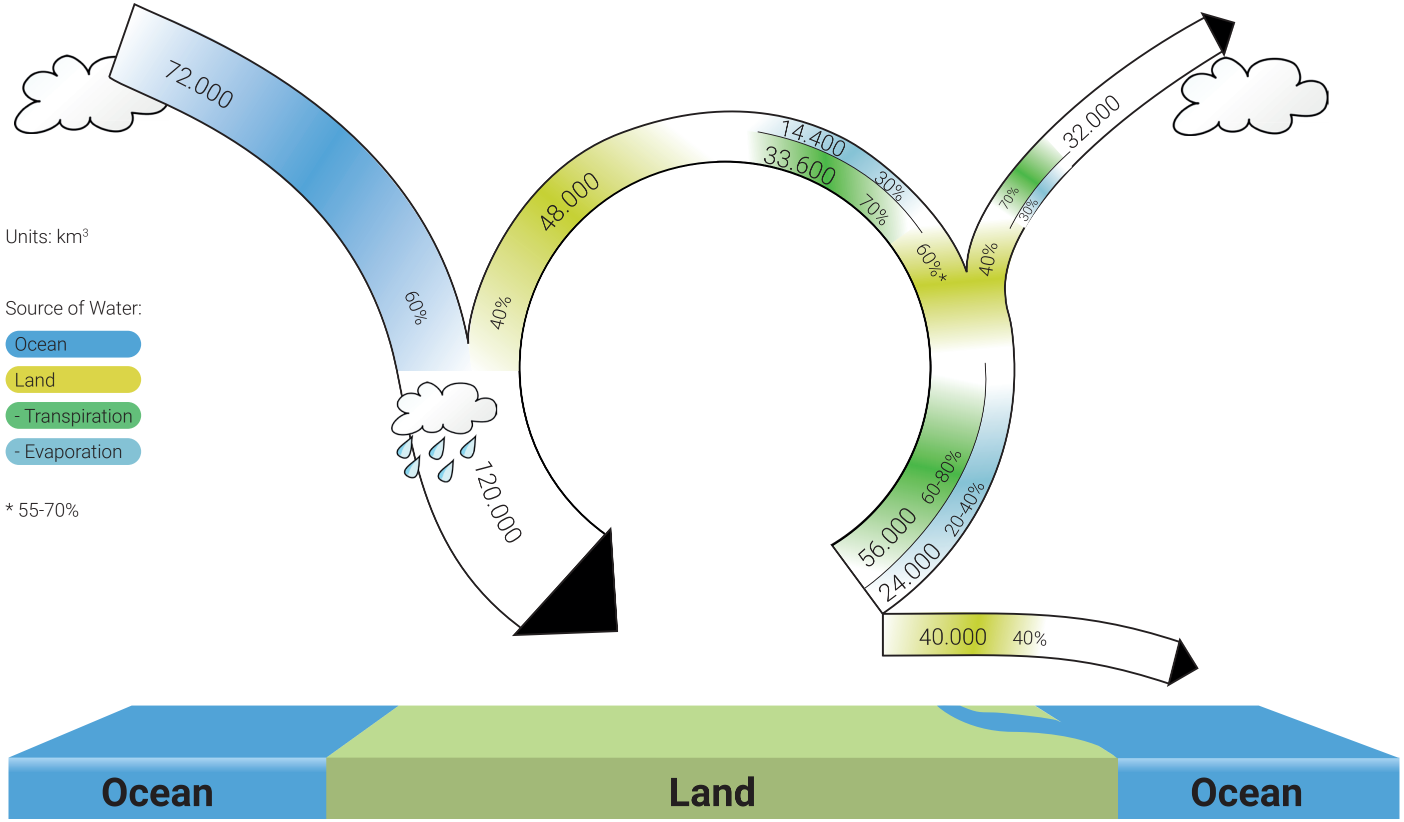


Figure 2: *Global water flows. Out of the 120,000 km³ of rain, which falls onto the continents, 72,000 km³ originates from the ocean, and 48,000 km³ stem from the land. Out of this, 60-80% comes from transpiration of plants and 20-40% from water bodies and soils. 32,000 km³ of land-based evapotranspiration goes back to the ocean via humidity in the air; 40,000 km³ are drained via rivers to the oceans.*[11]

Graphic: Stefan Schwarzer, UN Environment/GRID-Geneva

Main findings

Trees as water vapour generators

Every tree in the forest is a water fountain, sucking water out of the ground by its roots, pumping it through the trunk, branches and leaves, releasing the water as water vapour through pores in its foliage into the atmosphere. On a normal sunny day, a single tree can transpire several hundred litres of water, cooling its environment with a 70 kWh of power output per 100 litres, which represents a cooling effect equivalent of two domestic air conditioners running for 24 hours[14,15]. In their billions, the trees create giant rivers of water in the air ("flying rivers") – rivers that form clouds and create rainfall hundreds or even thousands of kilometres away (**Figure 3**).[16,17]

Evapotranspiration as source of precipitation

Globally, 40-60% of the rain falling over land comes from moisture generated through upwind, land evapotranspiration, mostly by transpiring trees.[11,14,18–20] In some regions of the world, the share amounts to 70% of the rainfall.[11] This recycling becomes more dominant further inland (**Figure 4**).

Tropical evergreen broadleaf forests only occupy about 10% of the Earth's land surface, but contribute 22% of global evapotranspiration[22], highlighting their importance for the supra-regional water cycle. The typical distances that moisture evaporated from land travels in the atmosphere before it falls back to the land are on the order of 500–5000 km; the typical time scale ranges from 8-10 days.[23,24] For example, moisture evaporating from the Eurasian continent is responsible for 80% of China's water resources.[11] The main source of rainfall in the Congo Basin is moisture evaporated over East Africa, while in its turn, it is a major source of moisture for rainfall in the Sahel.[11] The state of the West African rainforest is particularly important

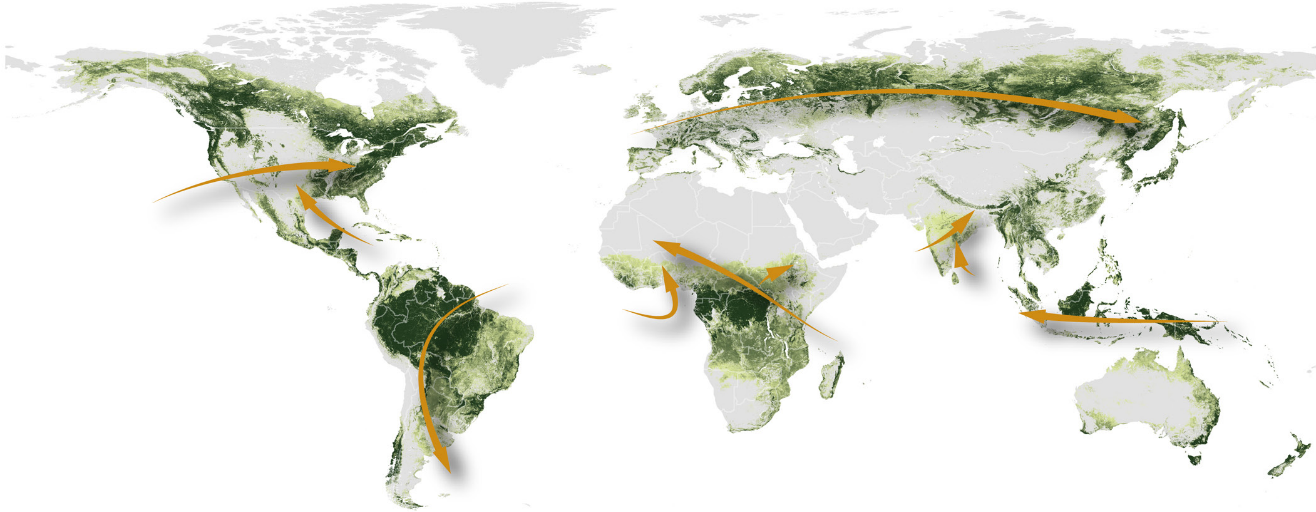


Figure 3: *Flying rivers transport water vapor over long distances covered by forests, which play an essential role in the creation of this vapor, acting as a massive water pump by absorbing and releasing billions of liters of water in the form of humidity.*
Graphic: Stefan Schwarzer, UN Environment/GRID-Geneva

for the flow of the Nile.[25] This explains why even in major river basins, including the Amazon, Congo and Yangtze, precipitation is more strongly influenced by land-use change occurring outside than inside the basin. Even in several river basins that do not span multiple countries, flows were considerably affected by land use in other countries.[26]

Land-use change and altered heat fluxes

Models show that local changes from forests or grasslands to croplands reduce their annual terrestrial evapotranspiration by 30-40%.[27] On a global scale, land-cover change between 1950-2000 reduced annual terrestrial evapotranspiration by 4-5% or 3,000-3,500 km^3, and increased surface water runoff by 6.8%.[27,28] Scientists found, on the other hand, that increased vegetation has a cooling effect that comes from an increased efficiency in the vertical movement of heat and water vapor between the land surface and atmosphere.[29]

Changes in atmospheric patterns due to deforestation

Satellite observations suggest that forests have a major influence on cloud formation, not only in the tropics, but also in temperate zones: disappearing forests can lead to significant decreases in local cloud cover and thus rainfall.[30] Modelling has shown that the extensive global deforestation between the 1700s and 1850s resulted in a decrease in monsoon rainfall over the Indian subcontinent and southeastern China and an associated weakening of the Asian summer monsoon circulation.[31] In the tropics, deep cumulus convection has been considerably altered as a result of landscape changes (mostly the conversion of forest to crop land). This not only affects local precipitation, but also has an impact over long distances through processes known as "teleconnections". These teleconnections can have impacts at higher latitudes, which significantly alters the weather in those regions.[10,25,32,33] Even relatively small land-cover perturbations in the tropics can lead to impacts at higher latitudes[34,35], as for example connections between the Amazon and northwest United States.[36] Vanishing forests can also lead to less rainfall and longer dry seasons locally as reported for example from Rondônia in Brazil[37] or Borneo, where it was found that the watersheds with the greatest forest loss have seen a 15% reduction in rainfall.[38] In India, patterns of declining rainfall during the Indian monsoon matched changing forest cover in India, due to reduced evapotranspiration and subsequent decreases in the recycled component of precipitation.[39] This demonstrates the large patterns of water vapour and precipitation flows.

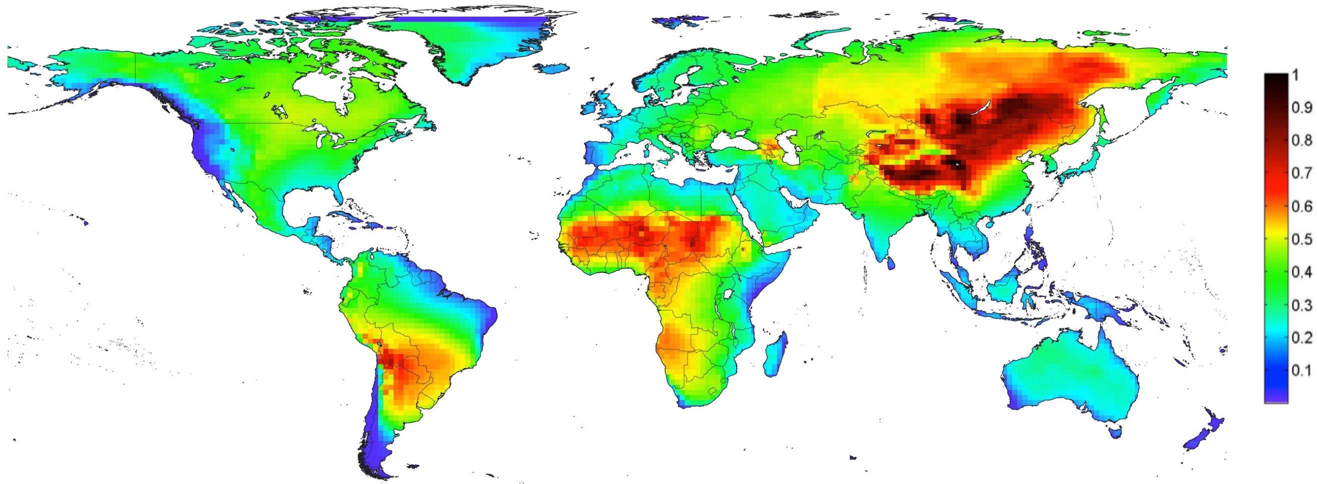


Figure 4: *Average continental precipitation recycling ratio (1999-2008). The higher the number, the more the precipitation stems from land evapotranspiration.*[11,21]

Re-radiation of bare soil

Normally, more than 50% of the sun's solar radiation reaching the earth's surface will be converted by evapotranspiration into latent heat, which in turn gets transferred into the atmosphere, feeding the precipitation cycle, and partially radiating back into space.

On bare surfaces, for example fallow fields, dry meadows (in the summer season and after hay harvest), and on concrete or asphalt surfaces, the soil will absorb more incident solar radiation, heat up, create sensible heat and emit, proportional to the fourth power of its absolute temperature (Stefan-Boltzman Law), heat power into the atmosphere (**Figure 5, Figure 6**).

Surface temperature differences between these bare surfaces and forested areas can, based on a central European example, be as much as 20°C on summer afternoons (**Figure 7**).[40] In the Indonesian island of Sumatra, temperature differences between forest and clear-cut land of up to 10°C were found, explained, again, by an evaporative cooling effect of forests, which outweighs the albedo warming effect generated by the darker forested surfaces.[41]

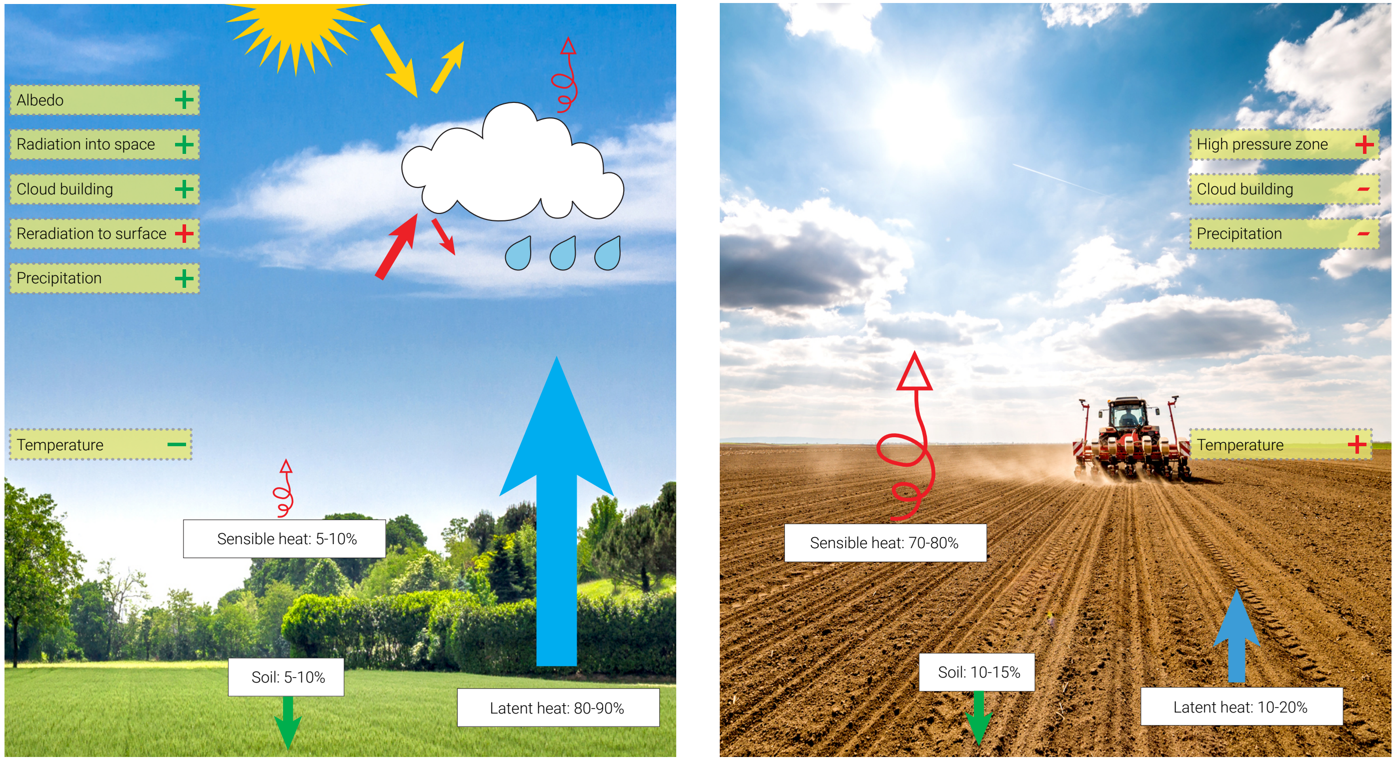


Figure 5: *Evapotranspiration decreases ground temperature and increases cloud albedo, radiation into space during condensation process, cloud building and thus precipitation. Removing vegetation increases temperature at ground level, emit with increasing ground temperature exponentially increasing heat energy, creates high pressure zones which hinder the passing of low pressure (and thus moist) air masses, lessen cloud building potential and thus reduce precipitation*
Graphic: Stefan Schwarzer, UN Environment/GRID-Geneva

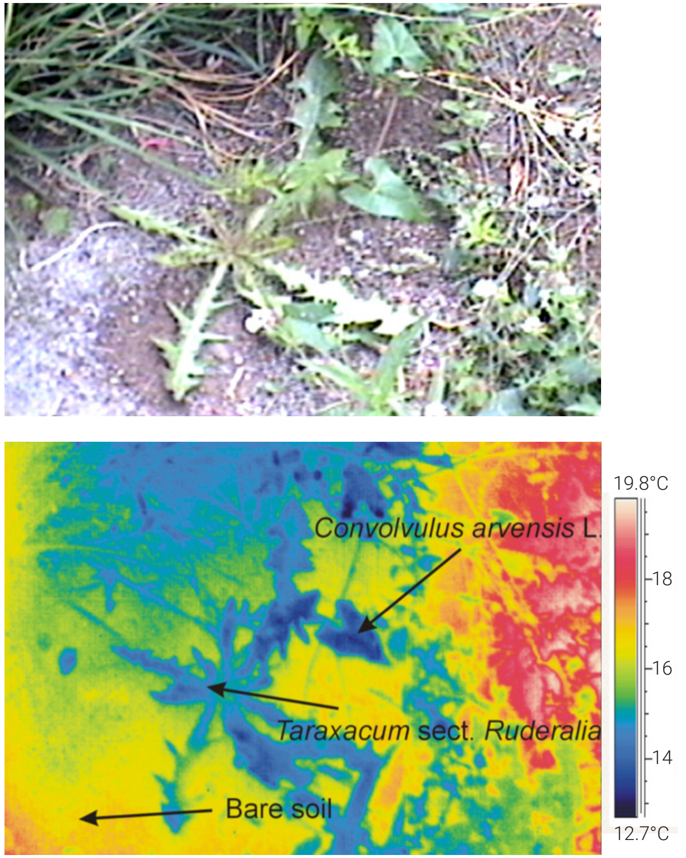


Figure 6: *The same patch of sparse vegetation photographed in the infrared spectrum and in the visible spectrum. The bare surface of the ground is visibly warmer than the surface of the leaves cooled by transpiration.*[9]

This highlights the fact that local biophysical processes triggered by forest losses can effectively increase summer temperatures in all world regions.[42]

Historical deforestation has indeed reduced the latent heat flux on land and increased sensible heat on the ground.[43–47] Deforestation has caused significant warming in the decade from 2003-2013, of up to 0.28°C on average temperature trends in tropical

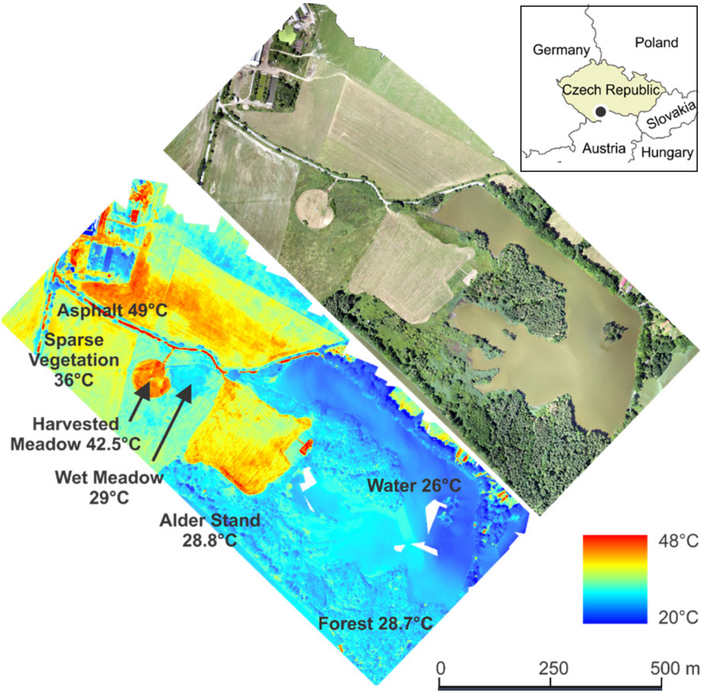


Figure 7: *Surface temperature distribution in a mixed landscape.*[14,40]

regions, and a strong warming of up to 0.32°C in the southern temperate regions.[48] At the current rate of deforestation, tropical forest loss could add 1.5°C to global temperatures by 2100, not accounting for other human-induced temperature increases.[49]

Between 1950 and 2000, surface temperature increased globally by 0.3°C due to land cover changes.[27] Perturbations in the surface energy balance generated by vegetation change from 2000 to 2015 have led to an average increase of 0.23°C in local surface temperature where those vegetation changes occurred.[50] Mean warming due to land cover change may explain 18-40% of current global warming trends through the reduction of evapotranspiration and in spite of the increase in surface albedo.[42,51,52]

Biogenic aerosols for cloud formation

In addition to the importance of forests for the energy fluxes and the generation of precipitation, large forests appear to be biogeochemical reactors, in which the biosphere and atmospheric photochemistry produce nuclei for cloud and precipitation formation, thereby sustaining the hydrological cycle.[53] Trees produce volatile organic compounds and "release" microorganisms – bacteria and fungal spores, pollen and other biological debris – that live on the leaves and become airborne during and after rain in forest ecosystems.[54–57] In the atmosphere, they form an important part of cloud condensation and ice nuclei, in turn impacting cloud formation and precipitation.[53,54,57–59] The biogenic aerosols can further help to raise the freezing temperature by creating ice nuclei. Without this phenomena, freezing would not occur until clouds reach -15°C or cooler; with the aid of these ice nuclei, the process can be achieved at temperatures near 0°C, enabling efficient cloud formation and generating rain more easily and locally.[59–62]

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Oceans, a buffer in two directions

A third of anthropogenic CO_2 emissions and more than 90% of the additional anthropogenic heat emitted into the atmosphere have been absorbed and buffered by the oceans. When talking about global temperature rise, we should be aware that we see only ~10% of the total effect.[63,64]

The buffering of CO_2 by the oceans runs in the opposite direction too: When we retrieve CO_2 from the atmosphere in order to decrease atmospheric CO_2 concentrations, the oceans will re-emit CO_2 due to the newly created gas pressure difference, trying to regain a CO_2 concentration equilibrium between the atmosphere and the ocean. Thus, over shorter time periods, a rapid decrease of CO_2 in the atmosphere will hardly happen, even if we succeeded in a) stopping CO_2 emissions and b) developing natural or technical CO_2 fixation solutions.

What are the implications for policies?

Vegetation, fertile soils and water retention must be recognized as prime regulators of the water, energy and carbon cycles. Some of the policy implications are listed below:

- Be aware of **positive feedback loops**: As explained above, when forests are cut down, land surfaces and the climate become dryer and warmer. This leads to conditions which exacerbate the risk of forest and vegetation fires which further emit CO_2 and cause additional deforestation, thus creating a vicious circle.[68,69] Climate change, deforestation, drought and forest fires form a triple-loop of reinforcing feedbacks (**Figure 8**).
- Given the teleconnections of large forest ecosystems, they should be considered as providing **global goods**. The REDD+ mechanism developed under UNFCCC could, for example, provide a model for recognizing and funding the international water and energy services provided by these forests.
- Especially important and **sensitive forest regions** should be protected and managed accordingly.
- It is of the utmost importance to **stop deforestation** and to increase **reforestation** efforts around the world.
- Agricultural practices should focus on **soil building**, year-round **soil cover** with plants and the use of **agroforestry** methods[iii].

Photo credit: Shutterstock.com

iii Agroforestry is the integration of trees or shrubs into agricultural fields and pastures.

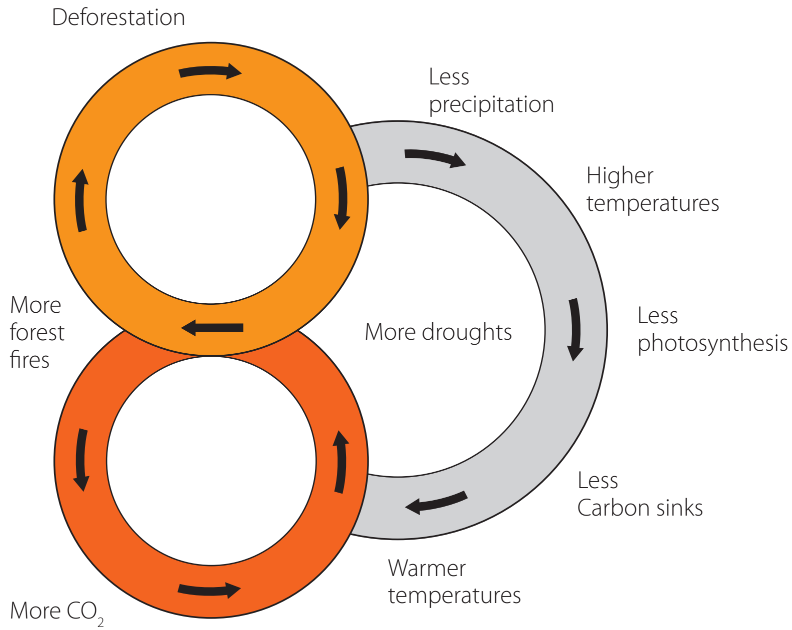

Figure 8: *Due to the interrelated nature of forest fires, deforestation, drought and climate change, isolating one of the processes fails to describe the complexity of the interconnected whole.*[65–67]

Conclusion

It is important to understand that the carbon, water and energy cycles are intimately coupled over land. Re-establishing atmospheric and terrestrial moisture cycles in vegetation, soils and the atmosphere is of the utmost importance for cooling the planet and securing precipitation patterns around the world. The drying out of the terrestrial landscape is the price of failure.

Stopping deforestation, increasing reforestation and implementing agroforestry practices are mandatory if we are to successfully avoid a climate catastrophe. A systems thinking approach is required to understand and use the underlying patterns of rain formation. Bringing back the rain to areas such as the Sahel will require more than just planting trees in the region; it will demand (re) building forests from the coast to draw the humid air from the ocean into the land.[70]

At the same time, increasing soil fertility, water retention and soil protection through the practices of the regenerative organic movement (see UNEP Foresight Briefs 010 and 013), like year-round vegetation cover through cover crops and undersow or the implementation of agroforestry, represents another important approach to feeding the water and energy cycles. Finding ways to build additional soil organic matter is one of the keys to success for large areas of the world currently under cultivation.

In general terms, we need a paradigm shift, valuing the hydrological and climate-cooling effects of vegetation in general and forest in particular, alongside their carbon sequestration potential. The effects of vegetation – and especially tree – cover on climate at local, regional and continental scales offer benefits that demand wider recognition.[14,32,71]

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Authors

Stefan Schwarzer, UN Environment/GRID-Geneva and University of Geneva

Reviewers

External

David Ellison, University of Bern
Prof. Douglas Sheil, Wageningen University
Lera Miles, UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC)
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UNEP Foresight Briefs Team

Alexandre Caldas, Sandor Frigyik, Audrey Ringler, Esther Katu, Erick Litswa, Pascil Muchesia

Inspired by a talk by Walter Jehne

Contact

unep-foresight@un.org

Bibliography

1. Pokorny, J. et al. Solar energy dissipation and temperature control by water and plants. International Journal of Water 5, 311 (2010).
2. Jasechko, S. *et al.* Terrestrial water fluxes dominated by transpiration. *Nature* **496**, 347–350 (2013).
3. Trenberth, K. E., Fasullo, J. T. & Kiehl, J. Earth's Global Energy Budget. *Bulletin of the American Meteorological Society* **90**, 311–324 (2009).
4. Wang, K. & Dickinson, R. E. A review of global terrestrial evapotranspiration: Observation, modeling, climatology, and climatic variability: GLOBAL TERRESTRIAL EVAPOTRANSPIRATION. *Reviews of Geophysics* **50**, (2012).
5. Ellison, D., Wang-Erlandsson, L., van der Ent, R. & van Noordwijk, M. Upwind forests: managing moisture recycling for nature-based resilience. *Unasylva* **70**, 13 (2019).
6. Schneider, U. *et al.* Evaluating the Hydrological Cycle over Land Using the Newly-Corrected Precipitation Climatology from the Global Precipitation Climatology Centre (GPCC). *Atmosphere* **8**, 52 (2017).
7. Schlesinger, W. H. & Jasechko, S. Transpiration in the global water cycle. *Agricultural and Forest Meteorology* **189–190**, 115–117 (2014).
8. Wei, Z. *et al.* Revisiting the contribution of transpiration to global terrestrial evapotranspiration: Revisiting Global ET Partitioning. *Geophysical Research Letters* **44**, 2792–2801 (2017).
9. Kravčík, M., Pokorný, J., Kohutiar, J., Kováč, M. & Tóth, E. Water for the Recovery of the Climate - A New Water Paradigm. 94 (2007).
10. Mahmood, R. *et al.* Land cover changes and their biogeophysical effects on climate: LAND COVER CHANGES AND THEIR BIOGEOPHYSICAL EFFECTS ON CLIMATE. *International Journal of Climatology* **34**, 929–953 (2014).
11. van der Ent, R. J., Savenije, H. H. G., Schaefli, B. & Steele-Dunne, S. C. Origin and fate of atmospheric moisture over continents. *Water Resources Research* **46**, (2010).
12. Crowther, T. W. *et al.* Mapping tree density at a global scale. *Nature* **525**, 201–205 (2015).
13. FAO. *State of the world's forests 2012*. (Food and Agriculture Organization of the United Nations, 2012).
14. Ellison, D. *et al.* Trees, forests and water: Cool insights for a hot world. *Global Environmental Change* **43**, 51–61 (2017).
15. Pokorny, J. What can a tree do? (2012).
16. Weng, W., Luedeke, M. K. B., Zemp, D. C., Lakes, T. & Kropp, J. P. Aerial and surface rivers: downwind impacts on water availability from land use changes in Amazonia. *Hydrol. Earth Syst. Sci.* **22**, 911–927 (2018).
17. Nobre, A. D. The Future Climate of Amazonia. 42 (2014).
18. Eltahir, E. A. B. & Bras, R. L. Precipitation recycling in the Amazon basin. *Quarterly Journal of the Royal Meteorological Society* **120**, 861–880 (1994).
19. Keys, P. W., Wang-Erlandsson, L. & Gordon, L. J. Revealing Invisible Water: Moisture Recycling as an Ecosystem Service. *PLOS ONE* **11**, e0151993 (2016).
20. Staal, A. *et al.* Forest-rainfall cascades buffer against drought across the Amazon. *Nature Climate Change* **8**, 539–543 (2018).
21. van der Ent, R. J. A new view on the hydrological cycle over continents. (2014).
22. Wang-Erlandsson, L., van der Ent, R. J., Gordon, L. J. & Savenije, H. H. G. Contrasting roles of interception and transpiration in the hydrological cycle – Part 1: Temporal characteristics over land. *Earth System Dynamics* **5**, 441–469 (2014).
23. van der Ent, R. J. & Savenije, H. H. G. Length and time scales of atmospheric moisture recycling. *Atmospheric Chemistry and Physics* **11**, 1853–1863 (2011).
24. van der Ent, R. J. & Tuinenburg, O. A. The residence time of water in the atmosphere revisited. *Hydrol. Earth Syst. Sci.* **21**, 779–790 (2017).
25. Gebrehiwot, S. G. *et al.* The Nile Basin waters and the West African rainforest: Rethinking the boundaries. *Wiley Interdisciplinary Reviews: Water* **6**, e1317 (2019).
26. Wang-Erlandsson, L. *et al.* Remote land use impacts on river flows through atmospheric teleconnections. *Hydrology and Earth System Sciences* **22**, 4311–4328 (2018).
27. Sterling, S. M., Ducharne, A. & Polcher, J. The impact of global land-cover change on the terrestrial water cycle. *Nature Climate Change* **3**, 385–390 (2013).
28. Gordon, L. J. *et al.* Human modification of global water vapor flows from the land surface. *Proceedings of the National Academy of Sciences* **102**, 7612–7617 (2005).
29. Chen, C. *et al.* Biophysical impacts of Earth greening largely controlled by aerodynamic resistance. *Sci. Adv.* **6**, eabb1981 (2020).
30. Teuling, A. J. *et al.* Observational evidence for cloud cover enhancement over western European forests. *Nature Communications* **8**, (2017).
31. Takata, K., Saito, K. & Yasunari, T. Changes in the Asian monsoon climate during 1700-1850 induced by preindustrial cultivation. *Proceedings of the National Academy of Sciences* **106**, 9586–9589 (2009).
32. Pielke, R. A. Influence of the spatial distribution of vegetation and soils on the prediction of cumulus Convective rainfall. *Reviews of Geophysics* **39**, 151–177 (2001).
33. Sheil, D. & Murdiyarso, D. How Forests Attract Rain: An Examination of a New Hypothesis. *BioScience* **59**, 341–347 (2009).
34. Chase, T. N., Pielke Sr., R. A., Kittel, T. G. F., Nemani, R. R. & Running, S. W. Simulated impacts of historical land cover changes on global climate in northern winter. *Climate Dynamics* **16**, 93–105 (2000).
35. Chase, T. N., Pielke, R. A., Kittel, T. G. F., Nemani, R. & Running, S. W. Sensitivity of a general circulation model to global changes in leaf area index. *Journal of Geophysical Research: Atmospheres* **101**, 7393–7408 (1996).
36. Medvigy, D., Walko, R. L., Otte, M. J. & Avissar, R. Simulated Changes in Northwest U.S. Climate in Response to Amazon Deforestation*. *Journal of Climate* **26**, 9115–9136 (2013).
37. Coe, M. T. *et al.* The Forests of the Amazon and Cerrado Moderate Regional Climate and Are the Key to the Future. *Tropical Conservation Science* **10**, 194008291772067 (2017).
38. McAlpine, C. A. *et al.* Forest loss and Borneo's climate. *Environmental Research Letters* **13**, 044009 (2018).
39. Paul, S. *et al.* Weakening of Indian Summer Monsoon Rainfall due to Changes in Land Use Land Cover. *Scientific Reports* **6**, (2016).
40. Hesslerová, P., Pokorný, J., Brom, J. & Rejšková – Procházková, A. Daily dynamics of radiation surface temperature of different land cover types in a temperate cultural landscape: Consequences for the local climate. *Ecological Engineering* **54**, 145–154 (2013).
41. Sabajo, C. R. *et al.* Expansion of oil palm and other cash crops causes an increase of the land surface temperature in the Jambi province in Indonesia. *Biogeosciences* **14**, 4619–4635 (2017).
42. Alkama, R. & Cescatti, A. Biophysical climate impacts of recent changes in global forest cover. *Science* **351**, 600–604 (2016).
43. Bounoua, L., Defries, R., Collatz, G. J., Sellers, P. & Khan, H. Effects of Land Cover Conversion on Surface Climate. 36 (2002).
44. Brovkin, V. *et al.* Biogeophysical effects of historical land cover changes simulated by six Earth system models of intermediate complexity. *Climate Dynamics* **26**, 587–600 (2006).
45. Pitman, A. J. *et al.* Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. *Geophysical Research Letters* **36**, (2009).
46. Pongratz, J., Reick, C. H., Raddatz, T. & Claussen, M. Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change: CLIMATE EFFECTS OF HISTORICAL LAND COVER CHANGE. *Geophysical Research Letters* **37**, (2010).
47. Zhao, M., Pitman, A. J. & Chase, T. The impact of land cover change on the atmospheric circulation: *Climate Dynamics* **17**, 467–477 (2001).
48. Li, Y. *et al.* Potential and Actual impacts of deforestation and afforestation on land surface temperature: IMPACTS OF FOREST CHANGE ON TEMPERATURE. *Journal of Geophysical Research: Atmospheres* **121**, 14,372-14,386 (2016).
49. Mahowald, N. M., Ward, D. S., Doney, S. C., Hess, P. G. & Randerson, J. T. Are the impacts of land use on warming underestimated in climate policy? *Environmental Research Letters* **12**, 094016 (2017).
50. Duveiller, G., Hooker, J. & Cescatti, A. The mark of vegetation change on Earth's surface energy balance. *Nature Communications* **9**, (2018).
51. Ban-Weiss, G. A., Bala, G., Cao, L., Pongratz, J. & Caldeira, K. Climate forcing and response to idealized changes in surface latent and sensible heat. *Environmental Research Letters* **6**, (2011).
52. Wolosin, M. & Harris, N. Tropical Forests and Climate Change: The Latest Science. *World Resources Institute* 14 (2018).
53. Poschl, U. *et al.* Rainforest Aerosols as Biogenic Nuclei of Clouds and Precipitation in the Amazon. *Science* **329**, 1513–1516 (2010).
54. Bigg, E. K., Soubeyrand, S. & Morris, C. E. Persistent after-effects of heavy rain on concentrations of ice nuclei and rainfall suggest a biological cause. *Atmospheric Chemistry and Physics* **15**, 2313–2326 (2015).
55. Bowers, R. M. *et al.* Characterization of Airborne Microbial Communities at a High-Elevation Site and Their Potential To Act as Atmospheric Ice Nuclei. *Applied and Environmental Microbiology* **75**, 5121–5130 (2009).
56. Conen, F., Eckhardt, S., Gundersen, H., Stohl, A. & Yttri, K. E. Rainfall drives atmospheric ice-nucleating particles in the coastal climate of southern Norway. *Atmospheric Chemistry and Physics* **17**, 11065–11073 (2017).
57. Joung, Y. S., Ge, Z. & Buie, C. R. Bioaerosol generation by raindrops on soil. *Nature Communications* **8**, (2017).
58. Després, VivianeR. *et al.* Primary biological aerosol particles in the atmosphere: a review. *Tellus B: Chemical and Physical Meteorology* **64**, 15598 (2012).
59. Morris, C. E. *et al.* Bioprecipitation: a feedback cycle linking Earth history, ecosystem dynamics and land use through biological ice nucleators in the atmosphere. *Global Change Biology* **20**, 341–351 (2014).
60. Christner, B. C., Morris, C. E., Foreman, C. M., Cai, R. & Sands, D. C. Ubiquity of Biological Ice Nucleators in Snowfall. *Science* **319**, 1214–1214 (2008).
61. Lazaridis, M. Bacteria as Cloud Condensation Nuclei (CCN) in the Atmosphere. *Atmosphere* **10**, 786 (2019).
62. Morris, C. E., Soubeyrand, S., Bigg, E. K., Creamean, J. M. & Sands, D. C. Mapping Rainfall Feedback to Reveal the Potential Sensitivity of Precipitation to Biological Aerosols. *Bulletin of the American Meteorological Society* **98**, 1109–1118 (2017).
63. Cheng, L. *et al.* Record-Setting Ocean Warmth Continued in 2019. *Advances in Atmospheric Sciences* **37**, 137–142 (2020).
64. Pörtner, H.-O. *et al.* IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Summary for Policymakers. (2019).
65. Hasler, N., Werth, D. & Avissar, R. Effects of Tropical Deforestation on Global Hydroclimate: A Multimodel Ensemble Analysis. *Journal of Climate* **22**, 1124–1141 (2009).
66. van der Werf, G. R., Randerson, J. T., Giglio, L., Gobron, N. & Dolman, A. J. Climate controls on the variability of fires in the tropics and subtropics: CLIMATE CONTROLS ON FIRES. *Global Biogeochem. Cycles* **22**, n/a-n/a (2008).
67. Zhao, M. & Running, S. W. Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009. *Science* **329**, 940–943 (2010).
68. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2012). doi:10.1017/CBO9781139177245.
69. International Union of Forest Research Organizations. Global Fire Challenges in a Warming World. (2018).
70. Ellison, D. & Speranza, C. I. From blue to green water and back again: Promoting tree, shrub and forest-based landscape resilience in the Sahel. *Science of The Total Environment* **739**, 140002 (2020).
71. Lemordant, L., Gentine, P., Swann, A. S., Cook, B. I. & Scheff, J. Critical impact of vegetation physiology on the continental hydrologic cycle in response to increasing CO_2. *Proceedings of the National Academy of Sciences* **115**, 4093–4098 (2018).