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Who or what makes rainfall? Relational and instrumental paradigms for human impacts on atmospheric water cycling

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Human impacts on water cycles (HIWC) can include modification of rainfall. Spatial and temporal variation in rainfall, with implications for 'water security', has been attributed to multiple causal pathways, with different options for human agency. Ten historical paradigms of the cause of rainfall imply shifts from 'nature controlling humans' to 'human control over nature' and 'human control over other humans'. Paradigm shifts have consequences for human efforts, interacting with social–ecological systems, to appease spirits, please rainmakers, expose 'rainfakers', protect forest, plant trees, reduce greenhouse gas emissions, apply cloud seeding, or declare rainfall modification an illegitimate tool in warfare. The 'instrumental' and 'relational' values of atmospheric water cycling depend on cognitive paradigms of rainfall causation as represented in local, public/policy, or science-based ecological knowledge. The paradigms suggest a wide range of human decision points that require reinterpretation of rationality for any paradigm shift, as happened with the forest–rainfall linkages.

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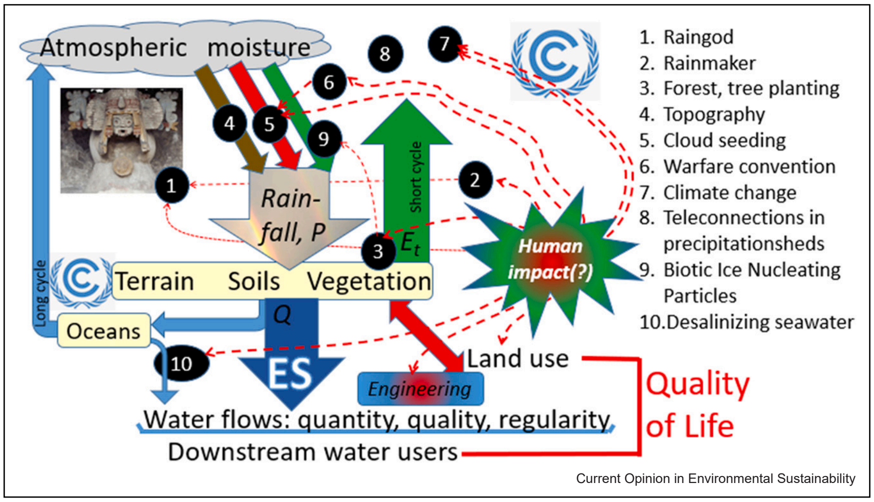
Introduction

Without rainfall, life on earth would be restricted to oceans, where 97% of the world's water currently resides. Evaporation of seawater started the water cycle over land, with 69% of the world's freshwater currently stored in ice caps, 30% in groundwater, and a mere 1% in soils, lakes, and vegetation [1]; only 0.03% of the world's water is at any point in time atmospheric — feeding rainfall, while evapotranspiration over both land ('short cycle') and oceans ('long cycle') replenishes the atmospheric pool. Human well-being depends on rain that greens the lands, allows crops to grow, and quells human thirst. Historically, the onset of the rainy season has been a period of stress, with a strong incentive for humans to control the process, with rainmakers addressing the social tension and 'buying time' until rains start. Beyond broad spatial and seasonal patterns, rainfall still has low temporal and spatial predictability, especially where modern weather forecasts and radar-based monitoring of rain-fronts is lacking. While other aspects of human impacts on water cycles (HIWC) are widely discussed, metrics such as 'footprints' consider rainfall to be 'exogenous', rather than as a direct target for human action [2].

Figure 1



Ten paradigms of provision of water through rainfall or alternate means, with different pathways for and degrees of (presumed) human impact; ES = ecosystem services, P = precipitation, Q = river discharge, Et = evapotranspiration, interrupted red arrows = human impacts.

Although precipitation is one of the most relevant aspects of climate, the UN Framework Convention on Climate Change (UNFCCC) has focused on warming as the primary impact of greenhouse gas emissions, and on land-cover change as the emission factor, rather than as direct modifier of climate. Current global circulation (or 'Climate') models have limited skill to predict changes in rainfall patterns, although improvements of the representation of vegetation feedback are a frontier in this science [3]. Rainfall as a process is not included in the The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) conceptual scheme of Nature's Contributions to People and its 18 categories [4], nor is it listed as a nature-based solution [5]. However, a growing body of literature considers it an 'Ecosystem Service' [2,6,7]. People's worldview about who or what causes rain informs their actions. With progress in empirical and science-based understanding, concepts that were part of traditional ecological knowledge (such as 'rainmakers') can be replaced. Sometimes, however, such concepts re-emerge with a new mechanistic interpretation, as happened with 'forests' in relation to rainfall. Rainfall is subject to widely differing explanatory models or paradigms (spiritual, geographical, biological, technical, warfare, etc.). Based on a recent review [8], at least 10 different paradigms have, across time and space, been used as explanatory causes of rain (Figure 1).

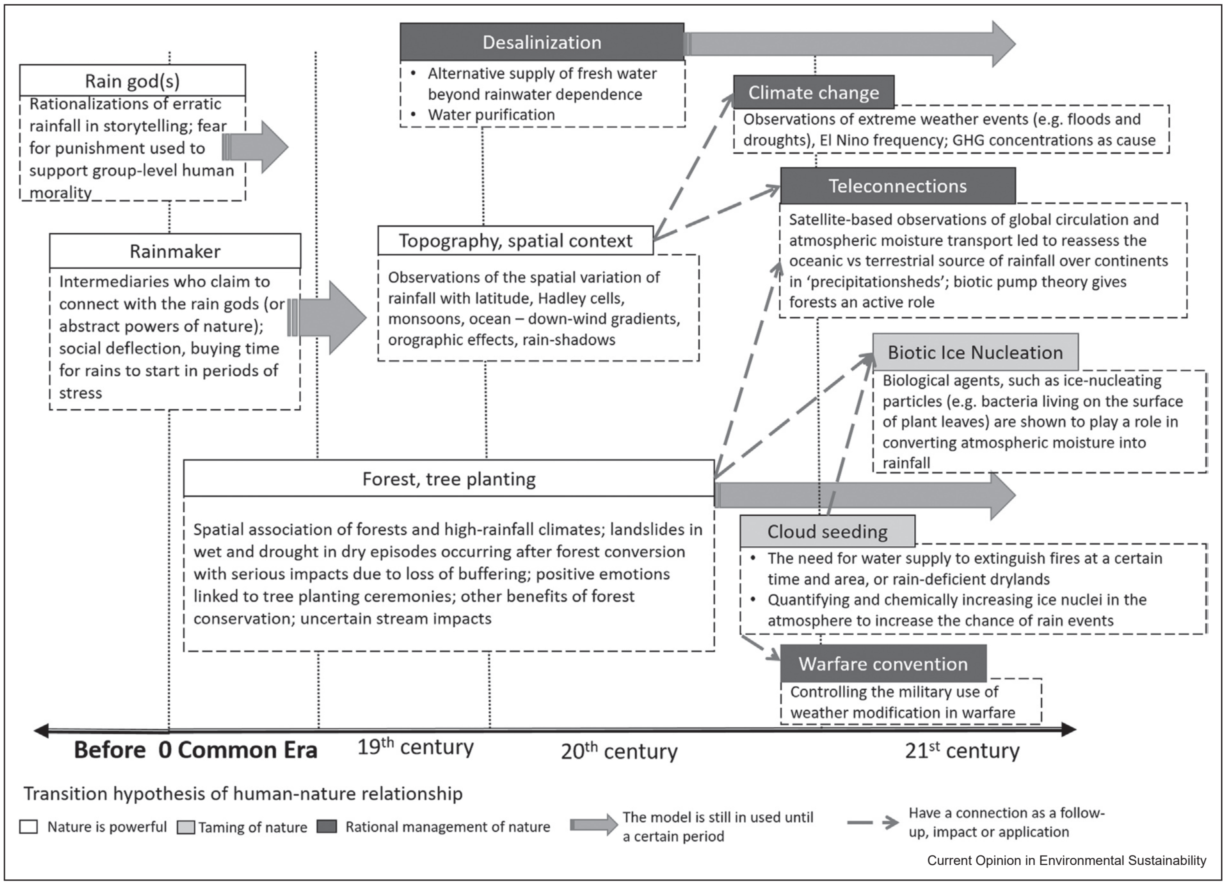
We briefly review these 10 different rainfall paradigms that currently coexist providing an overview of how humans have connected with rain throughout the history of social–ecological systems. We grouped the human–nature relations into four phases, according to a recent transition hypothesis [9*]: I. Nature is powerful, II. Taming of nature, III. Rational management of nature, and IV. Reconnecting with nature. These paradigms suggest very different actions and operational metrics to be used as indicators [10] (Figure 2). After reviewing the paradigms, we discuss 'how has the balance of instrumental and relational values in the human–nature relationship on rainfall changed over time and how manageable is future rainfall?'.

Rainfall paradigms

Rain god(s)

Our ancestors who lived as hunters and gatherers, but also the subsequent pastoralists and their herds who followed the rains and fresh grass it generates, were not constrained by fences and borders. Place-bound crop growers of the last 10 000 years had to pray for rain to arrive at the desired time to plant their seeds, for the rivers to bring water and soil fertility to flood plains, for springs to continue to flow, and for pastoralists to go elsewhere. Associated with these lifestyles, spiritual and religious concepts diverged among people of different habitats [11]. Deities associated with water or bodies of water were important in many mythologies from the Middle East, Greeks, Romans, and American first nations [12*]. Various beliefs and rituals were performed to please the rain gods/goddesses as shown by rock art in Mexico [13,14], and to attack water-dwelling companion spirits of bad-acting local rulers and settlers in Huitzilan, Mexico [15]. Using a worldwide, largely nonindustrial sample of 46 societies with high gods, a recent study [16] found that belief in a high god being directly involved in rainfall was more common in drier climates. The ancient Greeks often considered a king to be a magician at the

Figure 2



Ten paradigms of the cause of the rain according to time period and transition hypothesis of human-nature relationship.

service of the (water) gods. This indicates a gradual transition to paradigm 2, the rainmaker.

The rainmaker

Rainmaking is surrounded by mystery and dark magic [17], seen as exploiting clients by 'rainfaking', but also described as part of indigenous knowledge that needs to be studied since it affects decision-making and actions at local level [17–19]. A real contest in faith of rainmaking occurred when Sechele, the Bakwena chief in current Botswana, had, as part of accepting the new religion brought by missionaries in the 19th century, renounced his traditional ritual functions of rainmaker [20] during a continuous drought affecting his area. After conversions from African traditional religions to Christianity, the churches' willingness to 'pray for rain' has been described as a slippery slope [21] reconciling the relational need for communion with the instrumental requirement of providing explanation, prediction, and control of everyday events. Interestingly, in the humid tropics of South-East Asia, where heavy rainfall can disturb events such as weddings or motor races, the 'pawang hujan' who, after suitable ceremonies, can avoid rainfall at a specified time and place is still popular; some operate on a 'no cure, no pay' accountability clause that protects them from blame. In recognition of relational values that communities place on the rainmakers, some countries have integrated indigenous knowledge with scientific knowledge as an important component of making rain. These include the use of the Nganyi rainmakers in Kenya [17,22]. Whether rainmakers make it rain or not, this cultural phenomenon made humans view themselves as a part of nature, thus nurturing nature instead of utilizing it for own benefits [23,24]. The rainmakers also provide a cause for endurance around drought and floods with anticipation that he/she will provide spiritual solutions to rainfall [25].

Forests

Since ancient times, humans have observed the spatial association of forests and rainfall, but debated the causality involved: forest dependence on rainfall and/or forests as rainmaker. The notion that 'forests make rain' was reinforced in the colonial era with tree planting as logical rainmaking consequence [8]. Increasing evidence in the last quarter of the 20th century that planting fastgrowing trees, such as *Eucalyptus* species, can actually dry up, instead of return, streams casted doubt on the causal pathways involved, or at least on the relevance of spatial context and functional traits of tree species chosen. While hydrologists clarified the water balance of forests and trees, given rainfall, the focus was on evaporation, transpiration, enhancing soil infiltration, and stream flow persistence. Meanwhile, statistical evidence that links long-term rainfall data sets to regional deforestation (or reforestation) has generally been inconclusive, although a recent study for Africa found significant patterns [26*]. A considerable science-policy gap arose when the general belief that there is 'no water without forests' and that tree planting is a solve-all intervention, was replaced by the blue-green water competition concept that more trees means less water in the streams [8]. When the assumption of 'no effects on rainfall' was revisited, however, it became clear that forests and trees can also affect several factors required for rainfall, such as the presence of atmospheric moisture through evapotranspiration and convection processes and the local capture of atmospheric moisture at higher altitudes (cloud forests) [27]. Current science, however, does not support a generic 'all forests cause rainfall' theory, but accepts that the role land cover plays in precipitation depends on location on the globe, and interacts with other factors [28,29] that are discussed below. Reconciliation of local, public-policy, and science-based knowledge is needed to guide tree planting efforts [30].

Topography

Travelers, since the ancient Greeks at least, noticing dry and brown, or wet and green places started to speculate about spatial variation in rainfall and its consequences, preferentially settling where springs or rivers provided water in pleasant, not-too-humid, disease-ridden climates. Seafarers noticed winds and ocean streams, and their seasonal and latitudinal patterns. On land, travelers noticed orographic rainfall and rain shadows [8]. Terrain features, as studied in topography, play an important role in determining the planet's atmospheric circulation [25], hence they are an important paradigm of rainfall causation. Topography can explain the differences in spatial–temporal rainfall distribution starting from local, regional, to global levels. Land surface features produce a gradient of atmospheric and earth surface energy budget that influences precipitation in space and time [31]. At the local level, rainfall distribution differs as the gradient changes from highly elevated areas, for example, mountains (characterized by high rainfall, low temperatures) to an area with lower elevation, for example, lakes, oceans, and arid environments. Three different types of rainfall emerge, including orographic rainfall [32], convectional rainfall [29], and frontal rainfall. At the regional level, monsoon circulations occur due to atmospheric energy differences between oceans and lands, hence seasonal rainfall variations (i.e. summer, winter, spring, and autumn seasons) [33–35]. Global-scale atmospheric convection produces Hadley cells, the salient features that control precipitation in both the northern and southern hemispheres of the globe [36,37*]. This type of understanding does not suggest human interventions, other than informed choices of where to settle, start water-dependent agricultural practices, or engineer water flows.

Cloud seeding

Naturally, water molecules need to coalesce before water droplets are formed. This process is highly dependent on the presence of particles as nuclei, without which rain fails to materialize although air is saturated with water vapor. A cloud seeding experiment in 1946 demonstrated the potential for inducing precipitation [38]. However, changes in cloud structure at the microlevel during the cloud seeding process were found to affect the success rate. A range of hygroscopic materials such as salt, urea, dry ice, silver iodide, and potassium iodide was tested [39]. Detailed statistical evaluation of current practice in water-scarce and arid areas in the Middle East suggests a 23% increase in annual surface rainfall over the seeded target area [40]. Today, cloud seeding is not only used to increase rain, but also to regulate the weather such as to reduce cloud cover, to clean air from pollutants, to extinguish wildfire [40], and to store water as ice in the mountainous area during the snowy season [41]. Contested applications aim to shift heavy rainfall away from flood-sensitive metropoles, leading to complex 'loss and damage' claims to the areas receiving unwelcome rain. The drawbacks to cloud seeding remain the costs, atmospheric pollution, low predictability of impacts, and risks of unintended damage elsewhere.

Warfare convention

During the Cold War era starting in the late 1940s, opportunities for wet warfare by inducing heavy storms at will, were explored by both sides of the military–technological arms race [42]. The political, military, and ethical implications of geotechnical climate engineering to 'control' the climate led to a public outcry in the aftermath of the Vietnam War. The United States used cloud seeding to flood northern Vietnam, to aid photoreconnaissance, as a way to reduce enemy troop morale or damage harvests. Elsewhere, it triggered snow to expose camouflage and reveal signs of enemy activity on supply routes [43]. As a result of the debate this sparked, an international treaty was negotiated in the United Nations and ratified on 5 October 1978 that prohibits the military or other hostile use of such environmental modification techniques [44]. The public phaseout of military cloud seeding was discussed as an example of the social and political aspects of technologies that are rejected for adverse social or environmental effects, opening the door to new, peaceful applications [45]. The relevance of regulating the domestic use of cloud seeding, that likely will have both winners and losers in any application, is still unresolved [46,47*].

Global climate change

The increasing concentrations of greenhouse gases (GHG) in the atmosphere modify the global atmospheric circulation affecting the intensity and frequency of precipitation [30,48,49]. Human climate impact was summarized by The Intergovernmental Panel on Climate Change (IPCC) in 2021 [3] as already reaching a 1.5°C global warming in the 2010–2019 period relative to 1850–1900, but counteracted by a 0.4°C aerosol-induced cooling — based on clouds that reflect incoming radiation but do not bring rain. Global warming leads to greater atmospheric energy on the earth's surface, hence high surface evaporation on oceans and surface drying on land, affecting the intensity and duration of droughts. In line with increasing oceanic and terrestrial evaporation, globally averaged precipitation over land has likely increased since 1950, with a faster rate of increase since the 1980s. At the global scale, extreme daily precipitation events are projected to intensify by about 7% for each 1°C of global warming [3]. A recent study identified two human fingerprints on the global climate in multiple ensembles of earth system model simulations [50*]. The first is characterized by global warming, intensified wet–dry patterns, and progressive large-scale continental aridification. This is largely driven by multidecadal increases in GHG emissions. The second captures a pronounced interhemispheric temperature contrast, associated meridional shifts in the intertropical convergence zone, and correlated anomalies in precipitation and aridity.

Precipitation-shed teleconnections

Terrestrial evapotranspiration, moisture recycling, and transportation are now understood to be a major source of rainfall over continents [51,52]. Teleconnections link precipitation to upwind areas that contribute atmospheric moisture [53] and explain how droughts can spread from upwind to downwind areas, as has happened during the 2012 Midwest drought in the United States [54]. Teleconnections also explain why precipitations within large basins (e.g. Amazon and Yangtze) are strongly influenced by land-use changes occurring outside the basins [50*]. They have important implications for (international) water management and governance, particularly when land-use change in a given region (e.g. deforestation, which diminishes evapotranspiration) disrupts rainfall patterns elsewhere [55]. For example, West African rainfall depends on East African evapotranspiration [49]; deforestation in West African rainforest threatens food security in the Nile Basin [56]. While watersheds, rather than precipitation sheds, are still the focus of water governance [57], understanding tele-coupled patterns of land-use change and moisture recycling can support transregional water management and governance [49,54,55]. So far, legal and institutional implications ('moisture recycling governance') remain to be explored [55]. One study of atmospheric recirculation [58] suggests that increased groundwater use for irrigation in India contributes to increased rainfall in Pakistan, relevant for ongoing 'Loss and Damage' debates in the UNFCCC. As Pakistan, due to its topography, appears to have a high recycling ratio [59] for its own use of groundwater (replenished in a multiyear balance), the cause–effect relations will be hard to disentangle; blaming global climate change for recent floods may be oversimplified.

A recent study [60**] found four distinct terrestrial moisture recycling hubs in the tropics: the Amazon Basin, the Congo Rainforest, South Asia, and the Indonesian Archipelago, with contrasting network patterns. The Amazon strongly relies on directed (upwind–downwind) connections for moisture redistribution, the other hubs have less-directional reciprocal moisture connections. Current debate looks at how such results relate to the 'biotic pump hypothesis' [25] that condensation of water vapor over forests creates horizontal pressure differences in the lower atmosphere that propel local atmospheric dynamics [61,62]. Rather than generic 'forest' theories, the teleconnections suggest specific topologies shape specific effects of land-use changes on precipitation.

Biotic ice-nucleating particles

The transition of atmospheric moisture to droplets and rainfall depends on the presence of ice-nucleating particles (INPs), including abiotic dust and hygroscopic salts, and biotic volatile organics or biological cell wall material. Particularly, microbial communities living on the surface of plant leaves play an important role in water cycling [63]. Bacteria such as *Pseudomonas syringae* use ice-nucleating proteins to induce ice formation at temperatures just below the ice melting point, to frost-damage the plants they attack [64]. When these bacteria join the atmospheric microbiome as aerosols, they can catalyze ice crystal formation and cloud formation, generating precipitation [65,66]. Precipitation, in turn, is beneficial for the growth of plants and associated microorganisms, forming a positive bioprecipitation feedback cycle [66] that may complement the biotic pump.

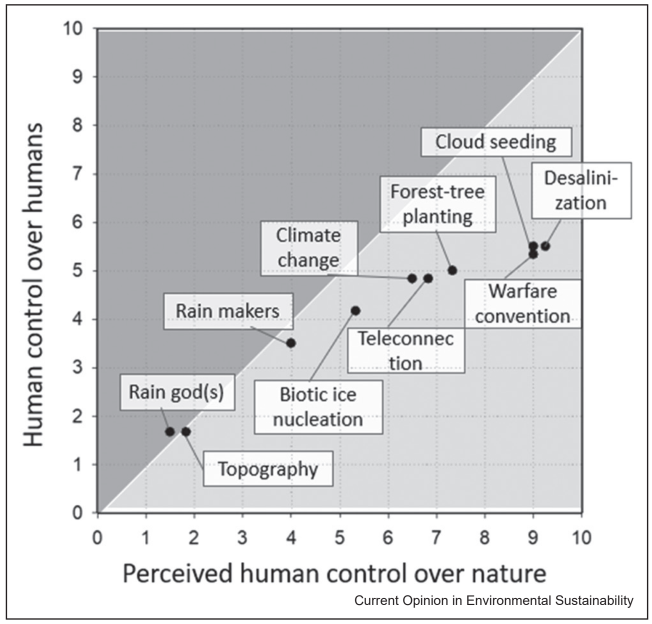
Desalinizing seawater

Large-scale desalination of seawater drives the main hydrological cycle, through evaporation of seawater, condensation in the atmosphere, and rainfall over land [67]. In the past, sailors used small-scale versions of this process to provide freshwater for long-distance travel; soldiers also used this desalination technique to supply water during war [68]. In the modern era, the increasing population, changing climate, human interventions, and subsequent demand for freshwater has pushed humans to look for options to address scarcity of freshwater [69–71]. Since installation of the first desalination unit in 1885 in Scotland, the technology has been refined [72,73] and spread to over 177 countries across the world [74] with 44% of global production of desalinated water occurring in the Persian Gulf. The negative effects on local marine environments of commonly used technologies include discharges of waste water that increase salinity, temperature, and nutrient concentrations affecting marine ecosystems such as seagrass meadows, coral reefs, and soft-sediment ecosystems [75,76].

Human–nature relationship

The balance of instrumental and relational values in the human–nature relationship changed over time, as across the 10 paradigms. With an increasing sense (perception) that human actions influence rainfall, either positively or negatively (e.g. by disturbing the cosmic balance, displeasing gods, deforesting, emitting greenhouse gasses, and cloud seeding), specific groups of people become status-worthy (e.g. rainmakers, tree planters, forest protectors, and cloudseeders), but their power may be contested, as both evidence of effectiveness and desirability of impacts are contested. Increasing perceived control of humans over nature and biophysical processes thus shifts attention to political and social challenges of control over human actions that are understood to modify where and when rainfall occurs (Figure 3).

Figure 3



Increasing inter-human power questions when perceived human control over rainfall increases; perceived human control represents the authors' interpretation of the human perceptions, in any of the 10 paradigms, of the degree to which rainfall responds (positively or negatively) to human actions (0 = no control, 10 = strong control), summarizing a small survey involving all the co-authors of this paper.

According to the four stages in a transition hypothesis of human–nature relationships [9*], the 10 rainfall paradigms cover the first three (Figure 2, nature is powerful, taming of nature, and rational management), as humans take control over natural processes. The fourth stage, a rediscovery of spiritual values of forests, may represent a synthesis that sees rain as part of ecosystem services that need to be respected, protected, and managed. The technical cloud seeding experience helped in the emergence of biotic INP theories, a newly understood role of forest and other high-water-use vegetation, beyond the presence of atmospheric moisture and its movement to places where condensation can occur. Current global circulation models are still deficient in their representation of land-cover feedbacks [3], a major constraint to current rainfall forecasts and restoration efforts.

Future rainfall is not manageable in the same way as other parts of the water cycle are [2], however, it is not independent of human actions either. The Harm-Care pillar of human morality in Refs. [77,78] is directly linked to instrumental values, ecosystem services, and nature-based solutions. Human capacity in engineering to 'work with nature' is possible and can make effective use of science-based understanding, as long as it aligns with the morality pillars of social relations: Fairness–Cheating (reciprocity), Loyalty–Betrayal (within a group), Authority–Subversion, and Sanctity–Degradation (purity), that include relational values of nature to people. Attribution of flood-causing rains in Pakistan to global climate change or to land-use change in a neighboring country has huge political ramifications. The Sanctity–Degradation (purity) axis tends to be invoked in a social and political context to blame others for misbehaving ('against nature') and causing nature to be affected with disastrous consequences for all, whether disturbance of rainfall patterns or a COVID-19 pandemic. The distinction between instrumental and relational values is a gradual one, as language is full of crossover metaphors [79*]. The analysis of social–ecological systems needs to reconcile a relational understanding of the social–political and human–nature subsystems with a mechanistic or instrumental understanding of the nonhuman world [80]. The various water-related issues, from droughts to floods, are physically related through the water balance, but may socially connect in different ways, interacting with the way the nature–people relationship is perceived [81]. How people understand the answers to who or what causes rainfall shapes ways to rationalize and communicate relational preferences for aspects of nature. Despite the complexity, rainfall deserves a more prominent place in efforts to better align human activity with planetary resources and boundaries and reduce negative HIWC [82,83]. In the recent call to collective action by the Global Commission on the Economics of Water [84], understanding of human impact on the water cycle goes beyond the allocations of a fixed water budget, as rainfall can be influenced, if not controlled.

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Given his/her role as Guest Editor, Meine van Noordwijk had no involvement in the peer review of the article and has no access to information regarding its peer-review. Full responsibility for the editorial process of this article was delegated to Erika Speelman.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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- •• of outstanding interest

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