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Climate Change in Remote Mountain Regions: A Throughfall-Exclusion Experiment to Simulate Monsoon Failure in the Himalayas

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*The Himalayas are predicted to experience more than 3 times the mean global rise in temperature, as well as erratic rainfall patterns and an increased likelihood of total monsoon failures. While many ecosystem manipulation experiments aiming at understanding the effects of altered precipitation, temperature, and carbon dioxide are conducted globally, such experiments are rare in Asia, particularly in the Himalayas. To fill this gap, we simulated late onset of monsoon precipitation, as well as total monsoon failure, in a multiyear drought stress experiment in Bhutan. Two treatments, 100% throughfall exclusion and ambient control plots, were applied to 725 m² plots (25 m × 29 m), each with 2 replicates in a hemlock-dominated (*Tsuga dumosa*) and oak-dominated (*Quercus lanata *and* Quercus griffithii*) ecosystem at 3260 and 2460 m elevations, respectively. Roof application reduced the volumetric soil water content in the upper (0–20 cm) soil layer by ∼ 20% in coniferous and ∼ 31% in broadleaved forest; the deeper soil layers were less affected. We demonstrate that large-scale throughfall-exclusion experiments can be successfully conducted even in a remote Bhutan Himalayan setting. The experiences gathered could be utilized for future long-term ecological monitoring studies in the Himalayan region.*

Keywords: *Throughfall exclusion; roof; drought; soil moisture; monsoon failure; eastern Himalayas; Bhutan; Sustainable Development Goals; Agenda 2030.*

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Introduction

Drought tolerance is a major determinant of global plant species distribution (Maherali et al 2004; Bréda et al 2006; Engelbrecht et al 2007; Choat et al 2012) and of tree mortality as a result of climate change (McDowell et al 2008; Adams et al 2009; Allen et al 2010). By reducing plant resistance to biotic disturbances, droughts interact with insect herbivores and pathogens to create large-scale forest dieback (McDowell et al 2008). Droughts may also alter fire regimes, with stark consequences for ecosystem dynamics (Pausas and Fernández-Muñoz 2012; Brando et al 2014; Alencar et al 2015). Drought-driven disturbances that cause mortality, both directly and indirectly, have increased (Allen et al 2010; Hartmann et al 2015). Recognized hotspots of drought since the 1970s are North American piñon pine–juniper woodlands (McDowell et al 2008; McDowell 2011), Mediterranean woodlands and savannas (Allen et al 2010), and tropical rain forests in Asia and South America, where droughts have a particularly high potential to alter global carbon dynamics (Phillips et al 2009), as drought hotspots usually occur more frequently in drier climates. Responding to the occurrence of disturbances caused by climatic extremes and the difficulty of predicting drought responses at community and individual tree levels, scholars have recently called for more experiments on such extremes, and for experiments simulating more extreme conditions rather than just evaluating climate change impacts beyond currently experienced thresholds (Bahn et al 2013; Reichstein et al 2013; Cavaleri et al 2015; Kayler et al 2015).

Hartmann et al (2015) suggested focusing on current drought hotspots. While this has strong merits in its

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potential for combining field assessments with experiments and modeling approaches, as showcased by McDowell et al (2013), we argue for the need to also study megadroughts in areas where knowledge on the effects of such events is limited, and the events have a large potential to cause severe reductions of ecosystem services, with concomitant effects on human populations. This would not only address United Nations (UN) Sustainable Development Goal (SDG) 13, in which all 193 signing states committed themselves to take urgent action to combat climate change and its impacts, but it also strongly connects to achieving SDGs 1 (end poverty in all its forms everywhere) and 2 (end hunger, achieve food security and improved nutrition, and promote sustainable agriculture), as well as 15 (protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss).

These criteria are met by the Himalayas, which are located in a region that is part of one of the tipping elements (Lenton et al 2008) in Earth's climate system. Although mountainous, the Himalayan range hosts a large population of around 210 million people (Bolch et al 2012), and, together with the Hindu Kush, it is the source of freshwater for an estimated 800 million people living downstream. The Himalayas have shown a consistent warming trend for the last century (Yao et al 2006; IPCC 2013), and a stronger warming than lowlands (Liu et al 2009), with a 3 times greater increase in temperature than the global average (Xu et al 2009). With increasing climatic change, the Asian summer monsoon patterns are also expected to vary. The Indian summer monsoon is crucial for the livelihoods and socioeconomic wellbeing of around 15% of the global population. It has shown decreasing precipitation trends in the last half century (Turner and Annamalai 2012; Singh et al 2014).

Simulation studies have unequivocally agreed on a future increase in extreme events, both for increases and decreases of precipitation. Schewe and Levermann (2012) and Menon et al (2013) predicted a strong increase in the probability of total monsoon failures by end of the 21st century. Total failures of the South Asian monsoon precipitation have caused megadroughts in the last 500 years, according to a recent dendro-climatological study. That analysis, which led to the construction of the South Asian Monsoon Atlas (Cook et al 2010), revealed the occurrence of multiyear monsoon failures and linked them to reported famines with millions of deaths in the region.

We therefore argue that there is a need to study ecosystem response to droughts in this region, which, to our knowledge, has not been attempted so far. Given the described high sensitivity of this region and its climate, closing these gaps in knowledge is crucial for deriving adaptation strategies. The Himalayas reflect a global pattern; a meta-analysis of experiments altering temperature, precipitation, or both revealed severe data gaps in certain geographical regions and biomes (Wu et al 2011). In China, several manipulation experiments have been carried out recently (Fu et al 2015), but economically disadvantaged regions in Asia, Africa, and South America are rarely covered by such cost-intensive experiments.

Considering recent advances in the understanding of plant and ecosystem responses to drought-induced mortality, as reflected by many plant physiological studies (Körner 2003; McDowell et al 2008; Anderegg et al 2012; Palacio et al 2014; Rowland et al 2015), there is a dire need for more studies in yet another area—especially one with difficult terrain and challenging research infrastructure. For countries like Bhutan, with a forest cover of 70% and an ambitious goal of staying carbon neutral (RGoB 2009), knowledge on future risks to the forests and whole landscapes is especially important. The high forest cover and the low anthropogenic impact in most of the forests of Bhutan lend themselves to experiments for "pushing the envelope" (Kayler et al 2015) in terms of ecosystem and species responses to climate extremes in largely unaltered environments.

Especially in terms of assessing drought mortality risks, important knowledge gaps remain, like "why some trees survive and others die in a given drought" (Hartmann et al 2015: 965). Particularly where trees of different phylogenies and strategies (gymnosperm and angiosperm, evergreen and deciduous, overstory and understory) coexist, individual, community, and ecosystem responses to drought cannot yet be predicted. This is particularly true for extreme events such as monsoon failures.

The study reported here is part of a replicated throughfall-exclusion experiment in old-growth mountain forests in Bhutan that was set up to test hypotheses on ecosystem responses to drought. The overall duration of the study was 5 years, starting from 2014. In this publication, we tested the functionality and potential artifacts of the roofing method and explored the challenges and benefits of carrying out such experiments in remote mountain regions of developing countries. We specifically tested whether the roofs used in the study (1) successfully excluded throughfall, as reflected in soil moisture differences between roofed and nonroofed plots, and (2) altered the temperature of the air and soil below them. To answer these research questions, we used climatic data from 2014.

Methods

Study site

The study focused on 2 dominant forest types along an elevational gradient in the eastern Himalayas of Bhutan, where forest zonation is determined by temperature and soil moisture, controlled by elevation and precipitation, and locally modified by topography (Wangda and Ohsawa 2006; Table 1).

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TABLE 1 Description of the study sites. (Table continued on next page.)

Parameter	Coniferous forest	Broadleaved forest
Elevation (m)	3260	2460
Latitude	27°28′00″N	28°28′51″N
Longitude	89°44′31″E	89°51′28″E
Annual precipitation (mm)	1175	1027
Mean annual temperature (°C)	8	12
Topography	Concave, convex/concave	Concave
Slope position	Midslope	Midslope, shoulder
Aspect	S-SSE	E-ESE
Slope	25–30°	15–25°
Soil characteristics		
Soil type[a)]	Endoskeletic Cambisols	Endostagnic Luvisols
Soil depth (cm)	70–> 100	> 130
Geology	Greater Himalayan Zone, Orthogneiss Unit	Greater Himalayan Zone, Lower Metasedimentary Unit
Bedrock	Mica schist, gneiss	Mica schist, gneiss quartzite
pH (0–10 cm)[b)]	5.2 ± 0.2	5.0 ± 0.2
Electrical conductivity (mS cm^{-1})[b)]	62.75 ± 6.43	93.75 ± 12.07
CEC (cmol kg^{-1})[b)]	90.56 ± 14.6	35.65 ± 4.13
Organic carbon (%)[b)]	9.30 ± 0.60	9.16 ± 0.87
Total nitrogen (%)[b)]	0.48 ± 0.02	0.41 ± 0.05
Carbon/nitrogen[b)]	19.21 ± 0.48	22.38 ± 0.81
Organic matter (%)[b)]	16.02 ± 1.02	15.78 ± 1.49
Bulk density at 0–30 cm (g cm^{-3})[b)]	0.75 ± 0.06	0.72 ± 0.02
Textural class	Clay loam	Silty clay
% sand[b)]	34.52 ± 1.39	9.41 ± 2.14
% silt[b)]	28.18 ± 3.41	46.26 ± 5.68
% clay[b)]	37.30 ± 4.77	44.33 ± 7.66
Soil organic carbon stock 0–30 cm (t ha^{-1})[b)]	142.0 ± 25.4	96.07 ± 28
Nitrogen stock 0–30 cm (t ha^{-1})[b)]	7.39 ± 1.07	4.31 ± 0.87
Stand characteristics		
Dominant overstory species	*Tsuga dumosa*	*Quercus griffithii*
	Quercus semecarpifolia	*Quercus lanata*
Dominant understory species	*Rhododendron arboreum*	*Rhododendron arboreum*
Tree density (number per ha)[b)]	401 ± 83	667 ± 145
Tree height (m)[b)]	20.3 ± 11.6	13.7 ± 8.4

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TABLE 1 Continued. (First part of Table 1 on previous page.)

Parameter	Coniferous forest	Broadleaved forest
Tree diameter at breast height (cm)[b)]	41.1 ± 33.5	25.9 ± 16.4
Leaf area index (m^2 m^{-2})	2.8	3.1
Tree basal area (m^2 ha^{-1})[b)]	77.8 ± 14.2	47.3 ± 12.4
Standing volume (m^3 ha^{-1})[b)]	1140.6 ± 226.6	501.9 ± 82.7
Total aboveground biomass (t ha^{-1})[b)]	811.5 ± 154.9	241.6 ± 72.3
Fine root biomass, dry weight, 0–30 cm (t ha^{-1})[b)]	4.04 ± 0.85	6.27 ± 0.87

[a)] World Reference Base for Soil Resources categories (WRB 2014).
[b)] Mean ± standard deviation.

Here, the warm temperate climatic zone ranges between 2000 and 2500 m and is dominated by evergreen broadleaved species of Fagaceae and Lauraceae, with the notable exception of the deciduous *Quercus griffithii* (Ohsawa 1987). The upper limit of the warm-temperate zone coincides with the upper limit of the distribution of *Q. griffithii* and *Quercus lanata*. This elevation range houses a large part of Bhutan's population and contains important cultural and economic centers, along with important areas for agriculture, mainly paddy farming. *Q. griffithii* forests are particularly heavily utilized and thus highly disturbed in many parts of the country. Based on species composition and structural properties as well as the age of trees (estimated at more than 200 years), the stands of the study area closely resemble old-growth conditions, but there are signs of historical utilization as farmland (such as remains of terraces, indications of plough layers, and buried soil horizons).

Above 2500 m, the cool-temperate climatic zone is dominated by conifers, including *Tsuga dumosa* and *Picea spinulosa*, as well as evergreen broadleaved *Quercus semecarpifolia*. At 3000 to 3200 m, the cool-temperate zone gives way to the cold-temperate zone, and this coincides with the upper limit of the distribution of the dominant species *T. dumosa*, as well as the upper limit for evergreen broadleaved trees, including *Q. semecarpifolia*. Economic utilization of cool-temperate forests is disproportionately high, and the respective climate zone houses the main urban and political centers of Bhutan.

The boundary between the 2 forest types coincides with the boundary between the Paleotropical and Holarctic floristic regions. *Q. griffithii*, *Q. lanata,* and *Q. semecarpifolia* are xeric species, while *T. dumosa* is a mesic species with higher moisture requirements.

We chose sites at the upper limits of the distribution of these 2 forest types for our study, expecting that drought stress would have particularly marked effects at these ecotones. Our study sites were located along an elevational gradient on the flank of a dry inner valley, dissecting the southern slopes of the Himalayas and leading to distinctly dry azonal xeric climate in the valley (Schweinfurth 1956). Therefore, our lower-elevation ecotone belongs to a moderately dry variant of warm-temperate broadleaf forests (28°28′51.06″N; 89°51′27.73″E), while the upper elevation ecotone close to the ridge is in mesic cool-temperate conifer forests (27°28′00″N; 89°44′30.79″E).

The total precipitation, measured on site from July 2014 to June 2015, was 1027 mm at the broadleaf forest site (BF) and 1175 mm at the coniferous forest site (CF). Both sites experienced a marked monsoon climate, with ~ 75% of the precipitation occurring between June and September. The mean summer temperatures from June to August 2014 at the BF and CF sites were 17.4°C and 13.7°C, respectively, and the mean winter temperatures, from December 2014 to February 2015, were 6.3°C and 2.5°C, respectively (Figure 1). Both sites are located in the Greater Himalayan geological zone. Whereas the CF is in the Orthogneiss Unit and has a bedrock dominated by mica schists and gneisses, the BF is part of the Lower Metasedimentary Unit, and the bedrock additionally contains quartzite (Long et al 2011). The soil parent materials originated from Tethyan metamorphic sediments with considerable colluvial drifts (Jangpangi 1978; Baillie et al 2004).

Soil types differ between the 2 ecotones (Figure 2). In concave slope positions, CF soils have developed from colluvial debris, and in convex positions, mica schist forms the bedrock material. Soils are classified as endoskeletic Cambisols (WRB 2014); the humus form is moder (Zanella et al 2011). The mesorelief is inhomogeneous, and soil depth and rock content vary depending on slope position. Soils are loamy, and plant-available water storage capacity varies from 100 mm in convex slope positions to 195 mm in concave positions (down to bedrock). BF soils are deeply weathered, exhibit luvic properties, and partly show signs of waterlogging. The humus form is mull, and soils are classified as endostagnic Luvisols. Though soil depth exceeds 130 cm, roots are confined to approximately 1 m. Soil texture varies from silty clay in the topsoil to clay in the subsoil. Plant-available water storage capacity is approximately 280 mm down to 130

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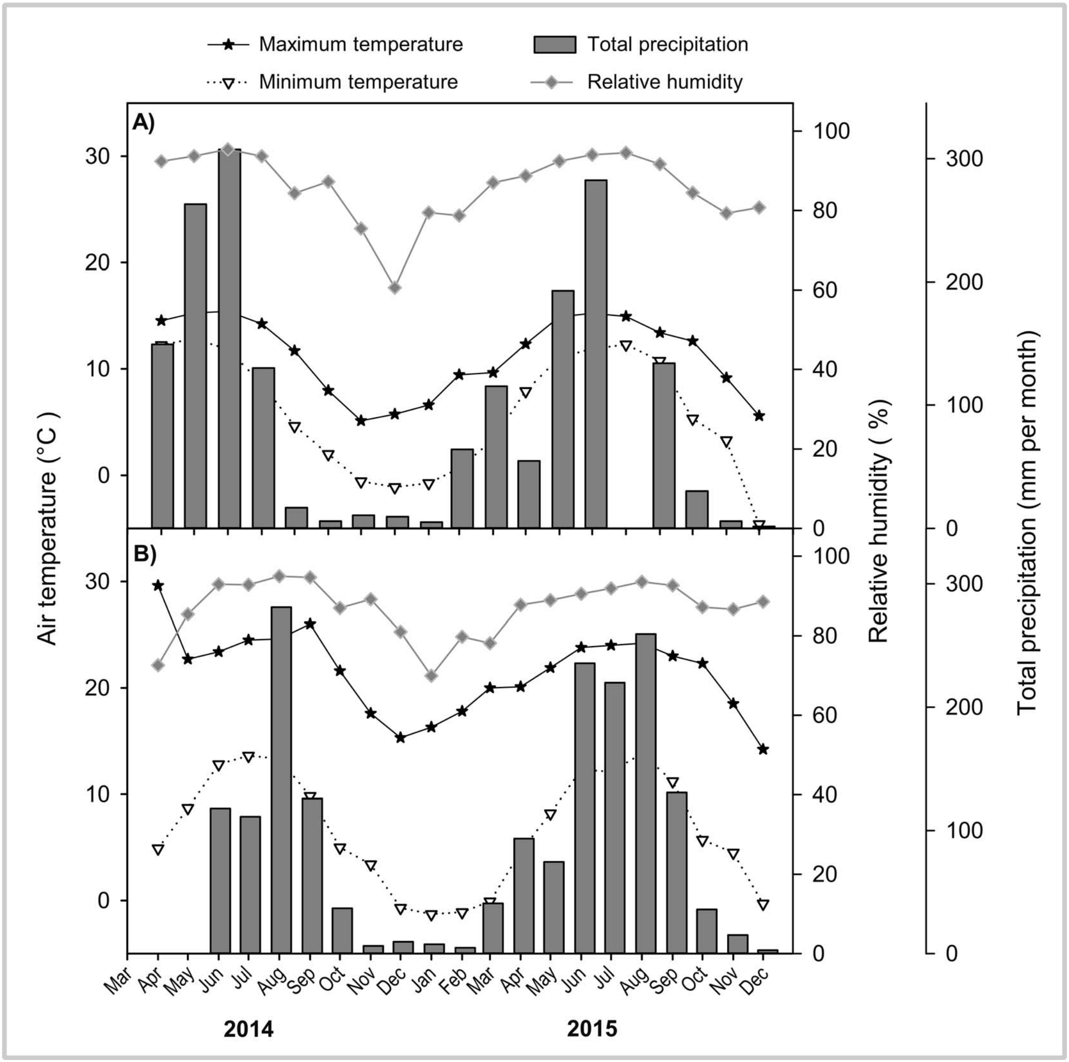
FIGURE 1 Mean monthly maximum and minimum air temperature, relative humidity, and precipitation at 2 study sites in Bhutan, eastern Himalayas. (A) Cool-temperate coniferous forest; (B) warm-temperate broadleaved forest.



cm, or 210 mm within the rooting depth of ~ 100 cm, as observed when excavating the soil pits (Figure 2).

Dominant tree species at the CF included *T. dumosa* and *Q. semecarpifolia*, while the BF was dominated by *Q. lanata* and *Q. griffithii*. *Rhododendron arboreum*, a species with a wide ecological amplitude, was the most important understory tree species at both sites. These 5 tree species were targeted for intensive investigation of plant physiological responses at the individual level.

Experimental design

Paleoclimatic records suggest that the monsoon system has a bistable nature with rapid switches from active to suppressed states and back (Berkelhammer et al 2013). This is corroborated by dendro-climatological analysis, which has led to the identification of historic monsoon failures in the last millennium across Asia (Cook et al 2010). The bistability of the Asian summer monsoon somewhat eases the development of a precipitation reduction scenario mimicking the described extreme climate events (Smith 2011), against which the experimental setup can be assessed. To avoid exceeding the (unknown) ecosystem responses at the beginning of the experiment, a stepwise increase in reduction of precipitation was chosen. This was also intended to reveal nonlinearities in the responses and enable us to approach drought thresholds in the system as suggested by Kayler et al (2015). We thus chose the following precipitation reduction scenarios: 70%, 75%, and 85% reduction of the annual precipitation in years 1, 2, and 3, respectively, and 85% in years 4 and 5. This could be achieved by excluding 100% of throughfall from the beginning of May to the end of August in the first year, the beginning of May to the end

FIGURE 2 Typical soil profiles in the 2 study sites.

Site	Soil profile	Depth (cm)	Texture and structure	Coarse soil fraction (>2mm) (%)	Munsell Color	Rooting
Coniferous forest 	M	0–1				
	F	2.5–3.5	Layered, sticky, many fungal hyphae	0		Many
	H	2–3	Loose	0		Many
	Ahbiog	0–10	Clay loam, fine to medium blocky, granular (worm casts), half-open to open	0	7.5YR3/4	Common
	ABw	10–30	Clay loam, fine to medium blocky, subangular, half-open	10	7.5YR4/4	Many
	Bw1	30–60	Clay loam, fine to medium blocky, subpolyhedral, half-open to closed	20	7.5YR6/8	Few
	BwCw	60–80	Sandy clay loam, single grain to slightly coherent	50	10YR6/8	None
	Cw	80–100+	Sandy clay loam	100	10YR5/6	None
Broadleaved forest 	L/F	0–1.5	Loose			None
	Ahbiog1	0–2.5	Silty clay, loose, crumbly	0	10YR2/2	Many
	Ahbiog2	2.5–23	Loam, fine crumb to fine blocky, open	0	10YR3/6	Common
	Bw/E	23–53	Silty clay, fine to medium blocky, half open	0	10YR5/8	Common
	Bw/Bt	53–70	Clayey loam, medium blocky, closed	0	7.5YR4/3	Few
	Bth	70–100	Clay, blocky polyhedral, closed	0	10YR2/2	Very few
	Btgc	100–130+	Clay, coarse blocky -polyhedral, closed	0		None

of September in the second year, and the beginning of May to the end of October for the following 3 years.

The process of setting up and maintaining a precipitation manipulation experiment in remote forests is far from trivial. Several manipulation experiments have been carried out in grasslands and other ecosystems with smaller plants (Wu et al 2011), in young forests and forest plantations, and in mature forests. However, ecosystem manipulations are experiments and cannot predict future environmental conditions with any certainty. Thus, these experiments have certain limitations, both conceptually and technically (Gundersen et al 1998; Beier et al 2012), to their ability to simulate natural ecosystems.

We made use of natural forests with coexisting conifer and broadleaf (deciduous and evergreen) species, located along a strong environmental gradient, to conduct a replicated 5 year throughfall-exclusion experiment. We studied drought response at the individual tree level (plant water potential, sap flux, nonstructural carbohydrates) and ecosystem level (root dynamics, tree growth and mortality, soil carbon dynamics [Wangdi et al 2017], and pathogen interactions) (Figure 3), with an anticipated ultimate treatment response (Smith 2011) of tree mortality at the individual level and a concomitant loss of ecosystem services (carbon sink strength, hydrological functions, and biodiversity) at the ecosystem level.

Roof construction and testing: In order to test the feasibility of establishing throughfall exclosure roofs under the local circumstances, a test roof of 15 × 13 m was established in 2013 at the CF site on a midslope. This allowed for an estimate of the required resources and a fine-tuning of the applied methods. Based on the experience with the test roof, we selected 4 plots each at the CF and BF sites, with homogeneous topography, canopy cover, and species composition and free of visible signs of anthropogenic disturbance. Plots were rectangular, 25 × 29 m, with the shorter side along the contour and the longer side along the slope. Plot size was chosen to accommodate the rooting zone of at least 3 mature trees per focal species in the center area of the plots. Around the plots, a buffer was

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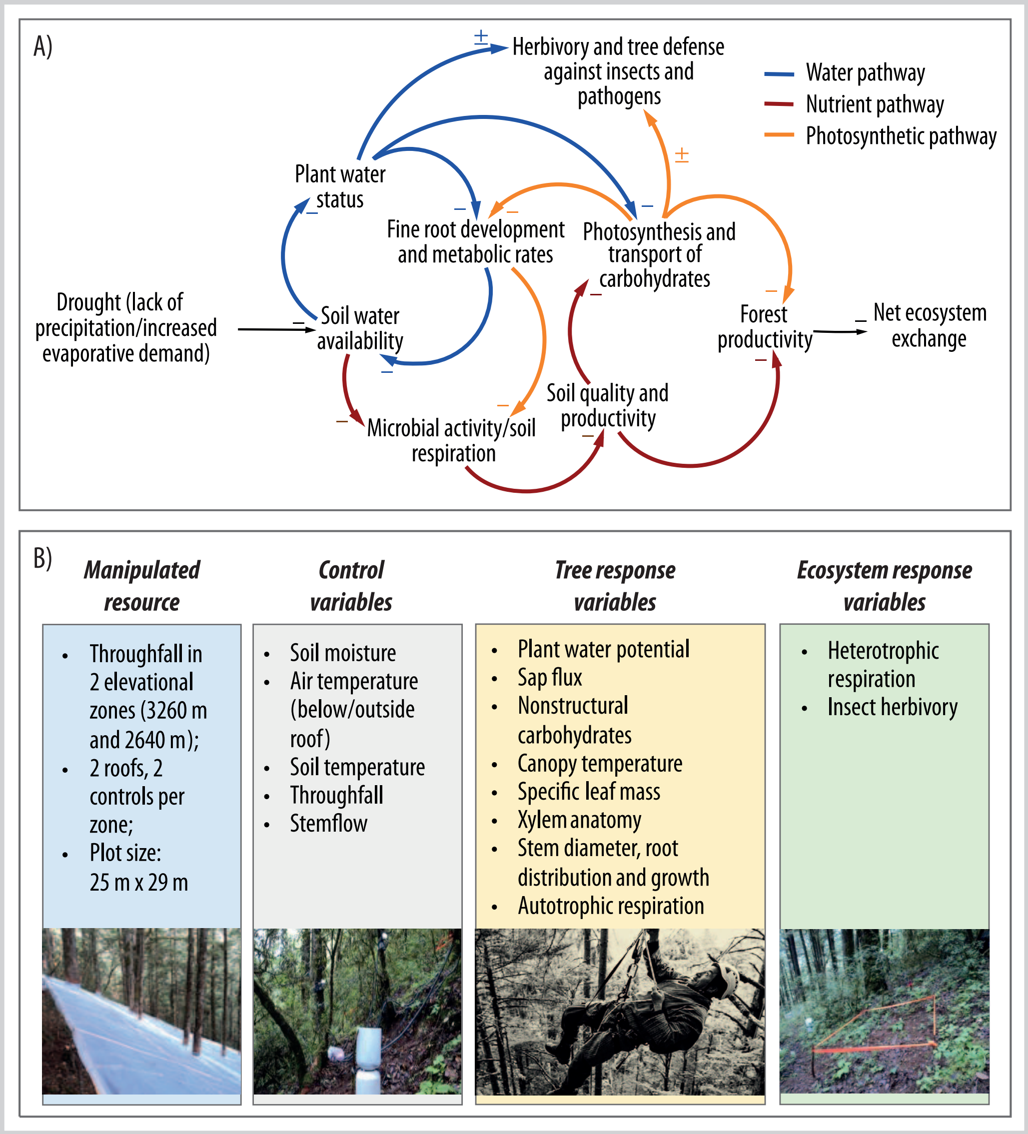
FIGURE 3 Conceptual framework for the study. (A) Causal loop diagram of the effect of drought on water, nutrients, photosynthetic pathways, and ecosystem productivity; (B) resources and variables monitored in the experiment.



maintained of 3 m from the top and 1 m at the bottom and 2.5 m from each side. We took care not to place the plots in locations prone to lateral soil water influx, like depressions or valleys. Within the plots, soil moisture measurements maintained a buffer of 7 m from the top and 1.5 m from the sides. Within these buffers, a regular 5 m grid, with a total of 25 grid points, was established as orientation for subsequent soil moisture measurements (Figure 4).

Two plots at each site were randomly assigned to throughfall-exclusion and control treatments. Roofs were erected by applying an improved version of the test roof (Figure 5). The roof frame was constructed of wooden posts and bamboo culms along a horizontal plane at 1.5 to 2 m above the ground to ensure accessibility. A durable ultraviolet (UV)-stabilized, cross-laminated polyethylene sheet of 129 μm thickness and 80–86% transparency to photosynthetically active radiation (Supreme Industries, Mumbai, India) was stretched across the roof plane and fixed on the edges with rubber bands sliced out of truck tubes. When it encountered trees, the sheet was carefully tailored around them, applying horizontal cuts from the closer edge running along the slope. The sheet was waterproofed around the trees by applying rubber bands, and the horizontal cuts were sealed with waterproof tape, placing the uphill sheet on top of the downhill sheet with an overlap of a few centimeters in order to achieve 100% throughfall exclusion when the roof was up. A 1.3 m deep

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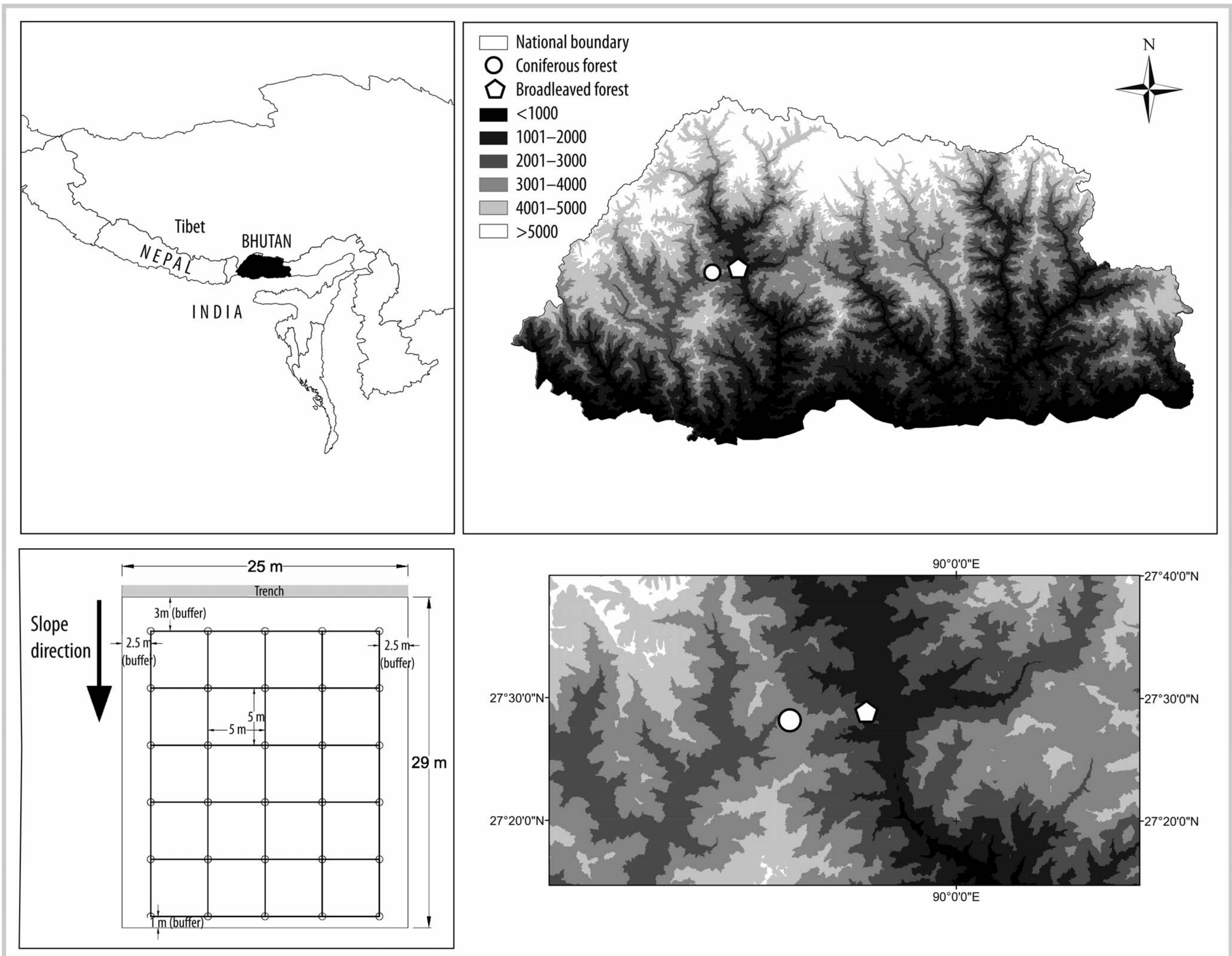
FIGURE 4 Location of the study sites and experimental plot layout. (Map by Norbu Wangdi, 2017)



trench was dug upslope of the roof and sealed at the bottom with a plastic sheet and a half pipe to divert water well away from the plot in one direction (Figure 5).

Two to 3 tree individuals of each target species, up to a total of 8 individuals per plot, were selected for intensive physiological measurements.

Climatic parameters: Meteorological stations were established approximately 1 km distance from each study site in both the CF and BF sites at comparable elevations and aspects. Precipitation was assessed with an ECRN-100 rain gauge; net radiation was assessed with a PYR solar radiation sensor; wind speed and direction were assessed with a DS-2 Sonic anemometer; air temperature and relative humidity were assessed with a VP-3 vapor pressure, temperature, and relative humidity sensor; and climate data were stored on a Decagon-Em50 data logger (Decagon Devices, Pullman, WA).

We used the recordings of the internal temperature sensors of the RailBox V16 data logger (Jiří Kučera-Environmental Measuring System Turistická, Brno, Czech Republic) as proxies for air temperature at throughfall-exclusion plots (below roofs) and control plots, as the covers were not exposed to direct radiation.

Loggers/sensors were installed at approximately 1 m height, under shaded conditions, in the center of each throughfall-exclusion and control plot.

Soil moisture and temperature: Soil moisture was monitored at 1 m distance uphill, downhill, and in both horizontal contour directions from each individual grid point of the regular 5 m × 5 m soil moisture grid at each plot every 3 weeks during April–November 2014, using a handheld time domain reflectometer (FieldScout 100, Spectrum Technologies, Aurora, IL) with 20 cm rod length, calibrated for soils at both sites. At the same time, soil temperature was measured using a handheld

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FIGURE 5 Experimental manipulation of precipitation using temporary plastic roofs (top) resting on 1–1.5 m bamboo poles (middle). Upslope of the roofed plot, a trench (bottom) was dug to prevent interflow of water.

thermometer probe (Hana Instruments, Vöhringen, Germany). Additionally, at the center of each control and throughfall-exclusion plot, a Decagon Em50 data logger stored soil moisture and temperature readings at 15 minute intervals, recorded at periodic depths between 5 and 120 cm, depending on soil depth using five 5TM soil moisture sensors (Decagon Devices Inc, Pullman, WA, USA). Additionally, at the CF site, one GS3 sensor

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(Decagon Devices, Pullman, WA) was used in each plot to record soil moisture in the well-developed humus layer at 2 cm depth. Sensors were calibrated individually for representative soil layers (Cobos and Chambers 2010).

Soil sampling: Soil samples were collected from soil pits dug either down to solid bedrock or to 30 cm below rooting depth at each plot in both sites, once, in May 2014. Soils were described according to Jahn et al (2006) and classified according to the World Reference Base for Soil Resources (WRB 2014). Undisturbed soil cores (250 cm^3) for the determination of soil physical parameters (hydrological properties, bulk density, and soil texture) were collected at fixed depths (0–5, 20, 50, 70, 90, and 120 cm). Similarly, soil samples for determining soil chemical parameters were taken.

In addition, soil samples were collected from the top soil layers (0–10 cm) of all 8 plots (4 replicates each) by soil corer in May 2014. Samples were air dried (at 22°C for 48 hours), ground, and passed through a 2 mm sieve.

Soil physical and chemical properties

The pH and bulk density: Soil pH and electrical conductivity were determined in a 1:2.5 suspension of distilled water and $CaCl_2$. The bulk density of the soil was determined using a stainless-steel core (5.5 cm diameter). Bulk density was corrected for the volume and mass of stones.

Nutrients and total organic carbon: Phosphorus was determined by inductively coupled plasma-optical emission spectroscopy (ICP-OES) (Perkin Elmer Optima 8300 Spectrometer, Waltham, MA, USA) in a Bray and Kurtz P-1 extract (Bray and Kurtz 1945). Total potassium, calcium, magnesium, manganese, aluminum, iron, sodium, and sulfur contents were analyzed after wet digestion (microwave, $HNO_3/HClO_4$ for organic layers, aqua regia for mineral layers) with an ICP-OES (Perkin-Elmer Optima 3000 XL; Austrian Standard L1085).

Exchangeable cations were determined in a 0.1 M $BaCl_2$ extract (Austrian Standard L1086) with ICP-OES. Effective cation exchange capacity was calculated as the sum of exchangeable ion equivalents. Total carbon was derived according to Austrian Standard L1080 with a LECO TruSpec CN elemental analyzer (Leco Corp., Saint Joseph, MI, USA).

Data analysis

The data from the first year of the roofing experiment (2014) were used for all statistical analyses. We used PROC MIXED (SAS 9.4, SAS Institute, Cary, NC, USA) to perform a linear mixed-effects analysis of the development of volumetric soil water content (SWCv) between treatments over time. As fixed effects, we entered treatment, month, and their interaction into the model. We included random intercepts for grid location nested within replicate and treatment, as well as an effect to account for the repeated-measures nature of the monthly measurements at each grid location and replicate for each treatment. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. P values were obtained by likelihood ratio tests of the full model with the effect in question against the model without the effect in question.

We tested whether the roofing had significant effects on air temperature at 1 m height and soil temperature at 20 cm soil depth at both study sites using 1-way analysis of variance (ANOVA). The significance level was set at 0.05.

Results

Effectiveness of treatments

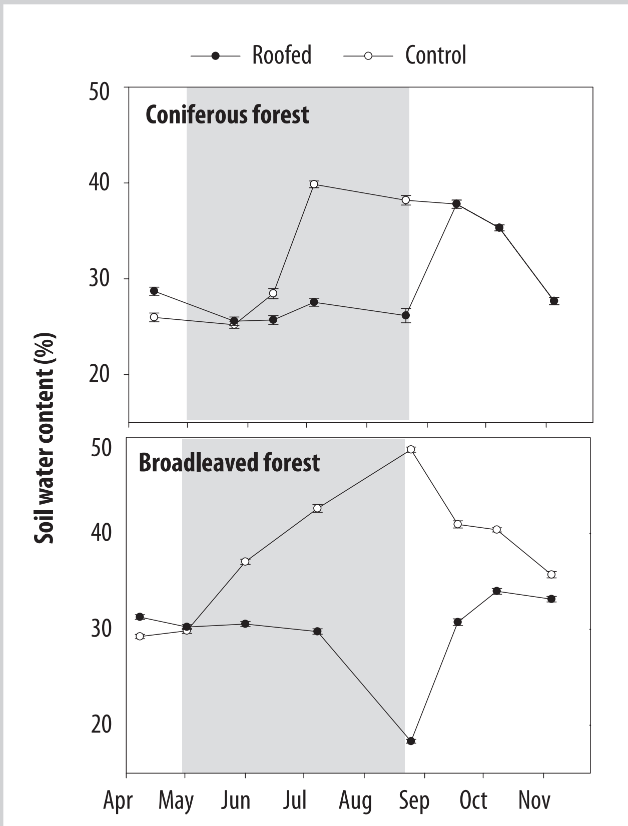
Roof effect on precipitation: The CF site received a total of 1152 mm of rainfall, whereas the BF site received about 895 mm of rainfall in 2014. On all plots, the rainfall-exclusion period lasted from 1 May–28 August 2014. At the CF, 863 mm (75%) of rainfall was excluded from the roofed plots, and at the BF, 608 mm (68%) of rainfall was excluded (Figure 1).

Roof effect on soil moisture: At the onset of the study period, SWCv was not significantly different between the control and throughfall-exclusion plots at both sites (Figure 6; *Supplemental material*, Table S3: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00097.S1; $P > 0.05$). However, from the onset of the rainy season onward (June 2014), SWCv began to differ between the treatments at both sites. Soils in the roofed plot were significantly drier than those in the control plots; as time progressed, the effect of reduced throughfall on SWCv became more distinct (Table 2). We observed a significant decrease in SWCv values during the roofing period (May–August 2014). Results from the linear mixed-model analysis also showed that the effect of roofing was significant at both sites ($P < 0.05$) (*Supplemental material*, Table S1: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00097.S1).

At the CF site, 1 month after opening the roofs, the SWCv did not differ between control and previously covered plots, whereas at the BF site, the SWCv values were different, even 3 months after opening the roofs (Table 2; Figure 7). In the deeper (50–120 cm) soil layer, the mean SWCv value in roofed plots was significantly lower ($P < 0.05$) at the BF site, but there was no significant roofing effect at the CF site (Figure 7).

Roof effect on air and soil temperature: Mean air temperatures in the roofed and control plots were not significantly different (*Supplemental material*, Figure S1: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00097.S1). Similarly, mean soil temperatures showed no significant difference between the control and the roofed plots at any soil depth at either site (Figure 8; *Supplemental material*, Table S2: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00097.S1).

FIGURE 6 Daily mean volumetric soil water content ± standard error in control and roofed plots, 2014. Gray shading indicates the roofing period ($n = 200$ days).



General soil properties

Sand content was higher at the CF than at the BF site, and hence soil textural class differed. Bulk density was comparatively low at both sites at < 0.60 g cm^{-1}. Soils at both sites were noncalcareous and slightly acidic, with pH aqueous slurry of 5.2 ± 0.2 and 5.0 ± 0.2 at the CF and BF sites, respectively. The mineral soils at the CF site had significantly higher cation exchange capacity (CEC) than the BF soils. Soil from both sites had similar organic carbon and total nitrogen contents, while the carbon/nitrogen ratio was slightly higher at the BF site (Table 1).

Soil nutrient status

The chemical composition of organic layers was more-or-less similar at both sites. The only variation was observed in calcium content, which was significantly higher at the CF site. Soils at the CF site showed significantly higher exchangeable calcium and magnesium than at the BF site, while iron and aluminum were higher at the BF site. Phosphorus, potassium, and magnesium concentrations were significantly higher at the CF site. Available and total macronutrients were higher in CF soil at higher elevations, but micronutrients, such as aluminum, iron, and manganese, were higher in the BF soil (*Supplemental material*, Table S3: http://dx.doi.org/10.1659/MRD-JOURNAL-D-16-00097.S1).

Discussion

Effectiveness of throughfall exclusion

The target set for reduction of throughfall was exceeded at the CF site (75% versus 70%) and almost reached (68% versus 70%) at the BF site. SWCv in both treatments at both sites exhibited similar strong seasonal variations (Figure 6). As anticipated, the roofs had a strong effect on the SWCv values. In our study, we observed a 20% and 31% reduction in SWCv at the CF and BF sites, respectively, in the upper 20 cm during May–August. Pangle et al (2012) reported a 45% reduction in the upper SWCv in their throughfall-exclusion plots, compared to

TABLE 2 Mean soil water content (%) ± standard error at the study sites, 2014.

Month	Coniferous forest[a]			Broadleaved forest[a]		
	Control plot	Roofed plot	*P* value	Control plot	Roofed plot	*P* value
April	26.0 ± 0.45 A	28.7 ± 0.42 B	< 0.001	29.2 ± 0.22 A	31.3 ± 0.24 B	< 0.001
May	25.2 ± 0.37 A	25.6 ± 0.43 A	0.97	29.8 ± 0.26 A	30.2 ± 0.25 A	0.14
June	28.5 ± 0.52 A	25.7 ± 0.46 B	< 0.001	37.0 ± 0.27 A	30.5 ± 0.27 B	< 0.001
July	39.9 ± 0.34 A	27.6 ± 0.41 B	< 0.001	42.6 ± 0.40 A	29.8 ± 0.27 B	< 0.001
August	38.2 ± 0.51A	26.2 ± 0.74 B	< 0.001	48.8 ± 0.27 A	18.3 ± 0.20 B	< 0.001
September	37.8 ± 0.43 A	37.8 ± 0.43 A	1	40.9 ± 0.37 A	30.7 ± 0.35 B	< 0.001
October	35.3 ± 0.31 A	35.3 ± 0.31 A	1	40.4 ± 0.21 A	33.9 ± 0.30 B	< 0.001
November	27.7 ± 0.38 A	27.7 ± 0.38 A	1	35.7 ± 0.2 A	33.1 ± 0.28 B	< 0.001

[a] Values within a row followed by the same letter are not statistically different at the 0.05 significance level, based on a Tukey's honest significant difference (HSD) test.

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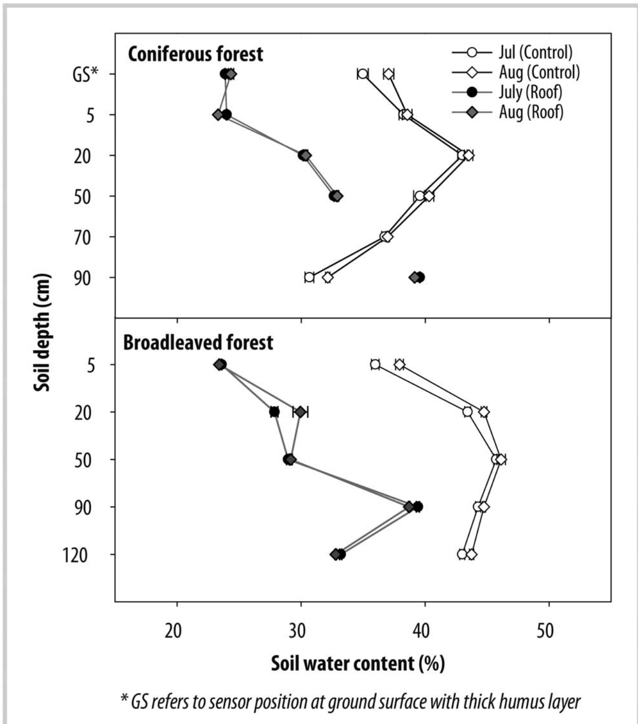
FIGURE 7 Mean volumetric soil water content ± standard error at different soil depths in the control and roofed plots during the roofing period (July and August 2014) ($n = 50$).



the mean values of the controls with ambient precipitation. Gimbel et al (2015) also reported a reduction in soil moisture and soil water potential at all depths under their plots receiving the precipitation reduction treatment. In our experiment, deeper soil horizons were only significantly affected by roofing at the BF site (Figure 7). The low response of SWCv to roofing in deep soil horizons could be caused by interflow from above the plot or laterally, or by slow drying out of soil horizons with high clay and/or carbon content at the CF site. Given that deep trenches down to the bedrock were dug above the plots, later water influx is rather unlikely. Therefore, slow soil drying is the more likely cause of the higher SWCv values in deep soil horizons at the CF site.

With the exception of Brando et al (2008), none of the roofing experiments we are aware of has presented data on SWCv at deeper soil horizons. Although most of the fine root biomass of trees is in the upper 50 cm, deeper taproots would reach the soil horizons with higher SWCv. This may lead to a weaker drought response by the trees, and it may also cause hydraulic lift into shallower soil horizons. Compared to natural droughts, trees in experiments generally respond fairly slowly to throughfall exclusion (Nepstad et al 2007; Brando et al 2008; Allen et al 2010; da Costa et al 2010; Martin-StPaul et al 2013; Meir et al 2015). Slow drying of deep soil horizons could add to the differences between experimental and natural drought responses (in addition to the fact that precipitation-reduction experiments can only manipulate SWCv but not alter atmospheric drivers of plant water content like vapor pressure deficits). This calls for a better assessment of SWCv in deeper soil horizons.

Effect of roofs on temperature

Roofs can alter the air temperature and humidity due to the greenhouse effect. As air temperature and humidity significantly affect growth processes, microbial activity, and soil evaporation, any unintended effects on air and soil temperature can confound the effects of the throughfall-exclusion treatment (Gimbel et al 2015).

Roofing structures have been found to raise the mean air temperature by 1.2–4°C in some experiments (Pangle et al 2012; Selsted et al 2012; Glaser et al 2013). However, like Gimbel et al (2015), we did not observe significant roofing effects on air and soil temperature. Roofing also had no effects on soil temperature in other experiments (Schindlbacher et al 2012; Zhang et al 2015), although roofs in these experiments were smaller. Our roof structures did not induce any greenhouse effect, and we were successful in separating the effect of prolonged drought from the effect of changes in air temperature.

Logistics and acceptance by local communities

Logistical feasibility is a crucial requirement for large-scale manipulative experiments. Accessibility; security; availability of facilities, electricity, and materials; and local communities' willingness to collaborate are some of the key features that should be considered while selecting sites for such experiments (Cavaleri et al 2015). Bhutan is still listed as a least developed country (UNCTAD 2014), and limitations in infrastructure (roads and electricity) posed challenges to the study.

Local acceptance of the research was actively sought by (1) locating the study areas close (half an hour walking distance) to monasteries; (2) involving monks and heads of the monasteries in guarding the plots, and paying them for their work, thus initiating and maintaining ownership in the research activity; and (3) following local traditions, including by conducting opening ceremonies and observing suitable dates for starting the work. So far, this has resulted in a strong commitment by the local population to maintaining the research sites. Damage by transmigrating cattle has been avoided, and there has only been 1 theft of instruments from the plots.

Challenges

The general challenges of large experiments can be exacerbated by infrastructure-related problems, particularly in poor countries. The size of individual plots and their number are mainly restricted by economic and practical constraints. To reduce the costs, small plot sizes are often preferred; however, small plots have increased edge effects (Beier et al 2004) and do not contain enough trees, particularly if the forests are old growth. We adjusted

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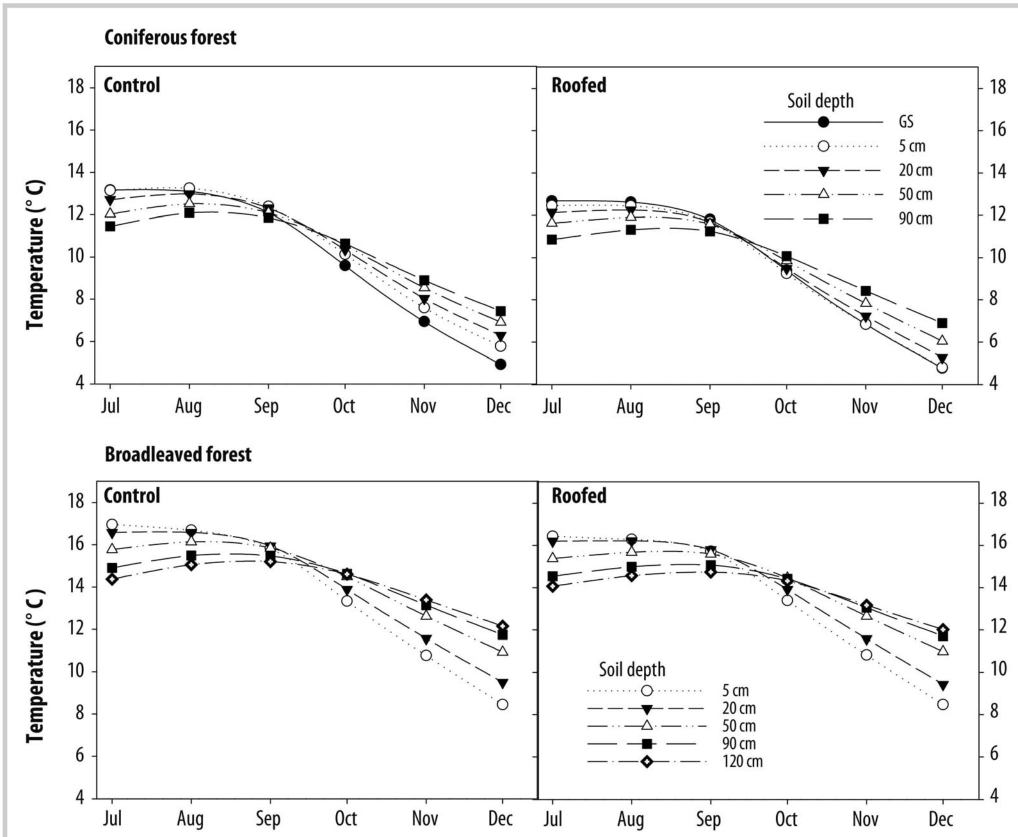
FIGURE 8 Monthly mean soil temperature ± standard error measured continuously in the control and roofed plots in 2014.



our plot size to the forest stem density, so that we had representation of coexisting species from the different phylogenies and strategies (gymnosperm and angiosperm, evergreen and deciduous, overstory and understory) in our plots. We replicated each treatment in order to meet the statistical requirement of sufficient replications for statistical tests of effects, resulting in a total of 8 plots. Another important challenge is selecting the precipitation scenario that best encompasses variability and extremity and ensures a realistic treatment with minimum undesired side effects and artifacts (Beier et al 2012; Pangle et al 2012). This challenge is heightened by the uncertainty and complexity of future precipitation scenarios, particularly for the Himalayas (Beier et al 2012; Cavaleri et al 2015).

The effects of extremes in precipitation regimes cannot be clarified in short-term experiments (Leuzinger et al 2011). Therefore, experiments with a duration of > 5 years are recommended (Beier et al 2012; Smith et al 2014; Cavaleri et al 2015; Fu et al 2015). Due to logistical and financial constraints, our experiments will run for 5 years and then enter a multiyear lower-level monitoring period without roofing.

The construction of the roofs using locally available materials proved difficult, but suitable technical solutions using a combination of wooden poles and bamboo were finally found. In running the experiment, the energy supply was and still is a challenge, as well as occasional damage of data loggers by monkeys and bears. We initially tried to keep the data loggers operating with batteries, but in the end, power lines were installed from the monasteries at both sites. Power was required mainly for the sap flow measurements; solar panels were not feasible at the sites because there was no open space. Accessibility of the research sites was also a challenge, especially during the summer, due to frequent landslides and slippery, muddy roads.

The greatest challenge, however, in such activities, is to synergize the academic pursuit with long-term national goals and action plans and to garner support from national institutions and the political will and support of the government. For this study, both these conditions were met—facilitated through a collaborative project funded by the UN Framework Convention on Climate Change's "fast start" finance scheme (UNFCCC 2015).

The results of this study show that such a large-scale experiment is feasible even in a remote Bhutan Himalayan setting. Experiences in running the experiment are expected to prove useful for future long-term ecological monitoring studies. Although the study was started before the SDGs were signed, it may contribute to achieving several of the goals and targets: It directly addresses target 13.1 and contributes to 13.2 and 13.3 by including work at the science–policy and science–society interfaces (with the development of a detailed communication action plan and the production of policy briefs of major findings) and through human capacity building components (grants for 8 master students studying mountain forestry and 3 doctoral students were funded by the project; in addition, the project offered on-the-job training during the study presented here) as part of the project activities. The human capacity training components directly contributed to SDG 4, target 4.7. The decision to conduct the study in a poor mountain area with a paucity of knowledge on climate change effects and a resulting lower adaptive capacity created positive interactions with the poverty and hunger-related SDGs 1 and 2.

Conclusion

The roofs used in our throughfall-exclusion experiment effectively reduced precipitation at the defined reduction targets. Soil moisture was reduced in the upper soil horizons in a similar range to that of other throughfall-exclusion experiments. Deeper soil horizons (50–120 cm) showed a reduction of soil moisture at only 1 of the 2 study sites. We attribute this to slow drying out of soil horizons with high clay and/or carbon content at that site. This reduced the effectiveness of the treatment by water uptake of trees from deeper soil layers and by hydraulic lift. A longer roofing period may reduce the recharge of soils and may lead to a stronger drying out of these horizons. While we did impose drought conditions in the treated ecosystem, the treatment effect, at least in the first year, may have been far from equivalent to a true monsoon failure. This is also reflected in the generally slow response of trees to experimental droughts observed in other studies around the world, and it points to the need for better assessment of soil moisture in deeper soils.

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Supplemental Material

TABLE S1 Results of the linear mixed model for soil water content as a function of site and treatment over time and the interaction between months for 2014. Significant probabilities ($P < 0.05$) are shown in bold.
TABLE S2 Mean soil temperature (°C) ± standard error during the treatment periods, 2014. Similar superscript

letters indicate that no significant differences were found during the repeated ANOVA test ($P = 0.05$).

TABLE S3 Macro- and micronutrient concentrations in mineral soils (0–10 cm) and organic layers at the study sites.

FIGURE S1 Monthly mean air temperature ± standard error in control and roofed plots, 2014. Gray shading indicates the roofing period.

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