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TROPICAL MONTANE CLOUD FORESTS

Key points

- Tropical montane cloud forests (TMCFs) are among the most valuable terrestrial ecosystems for their role in the hydrologic cycle because they influence the amount of available water and regulate surface and groundwater flows in watersheds while maintaining high water quality.
- The high water yield of TMCFs arises from their location in areas with high rainfall, additional inputs of cloud-water capture by canopies, and low evaporative losses.
- TMCFs are rare; area estimates range from 1 percent to 14 percent of tropical forests globally. Approximately 55 percent of the original area of TMCFs has been lost.
- The conservation of remnant mature TMCF forests needs strengthening and their conversion to agricultural land uses avoided.
- Low-intensity selective logging in secondary TMCFs conforming with low-impact logging guidelines is strongly recommended to mitigate the deleterious effects of logging on soils, water yields and biomass.
- In restoring TMCFs, efforts should be made to plant mixtures of native water-use-efficient species.
- Payment schemes for the water services of TMCFs could help compensate landowners, maintain forest cover and counteract deforestation and water scarcity.
- Research is needed to better understand the hydrologic impacts of climate change on TMCFs.

The generally high water yields in tropical montane cloud forests (TMCFs) (Box 5.8) arise because of their location in areas with high rainfall, additional inputs of cloud-water capture by canopies ("fog stripping"), and low evaporative losses (Hamilton, Juvik and Scatena, 1995; Bruijnzeel, 2001). Catchment water yields typically increase from lower to upper montane forests, reflecting concurrent increases in incident precipitation and decreases in evaporative losses at higher elevations (Bruijnzeel, 2005). The presence of clouds not only increases water inputs from fog capture but also reduces losses via evaporation because of the lower radiation and higher atmospheric humidity they generate (Bruijnzeel, Mulligan and Scatena, 2011).

Cloud interception is highly seasonal in many regions and becomes a more crucial component of total water budgets during dry seasons and therefore in sustaining flows in those dry periods. In comparison with montane forests unaffected by fog or low clouds, waterflows from TMCFs tend to be more stable during extended periods of low rainfall (Bruijnzeel, 2001).

BOX 5.8

What are tropical montane cloud forests?

Tropical montane cloud forests receive frequent moisture inputs from fog and mist. There are multiple classifications of such forests, but the broadly adopted definition is "forests that are frequently covered in cloud or mist" (Hamilton, Juvik and Scatena, 1995), highlighting the importance of clouds for these ecosystems. Tropical montane cloud forests are among the most valuable terrestrial ecosystems for their role in the hydrologic cycle because they influence the amount of water available and regulate surface and groundwater flows in watersheds while maintaining high water quality.

TMCFs are important in the protection of soils because they are often found on steep slopes, which tend to be highly susceptible to erosion and mass movement if forests are removed (Bruijnzeel, 2004). TMCFs are also a priority hotspot for biodiversity conservation because of their high species richness and endemism (Hamilton, Juvik and Scatena, 1995; Beck *et al*., 2008; Bendix *et al*., 2013), especially for epiphytes (Gentry and Dodson, 1987) and insects (Brehm *et al*., 2005).

Threats to tropical montane cloud forest–water relationships

Because TMCFs develop in particular climatic and topographic conditions, their spatial distribution is naturally fragmented and restricted in extent. They are relatively rare: estimates of the area of TMCFs range from 1 percent to 14 percent of the total area of tropical forests worldwide (Bruijnzeel, Mulligan and Scatena, 2011; Mulligan, 2011). Of all mapped TMCFs, 43 percent are in Asia, 41 percent are in the Americas and 16 percent are in Africa. (Mulligan, 2011; Hamilton, Juvik and Scatena, 1995).

There is a lack of up-to-date data on change in the area of TMCFs; it has been estimated that 55 percent of original cover had been lost by 2000 (Mulligan, 2011). An annual deforestation rate of 1.55 percent has been estimated for tropical montane forests (including TMCFs) in Latin America (Armenteras *et al*., 2017). Conversion to agriculture and cattle grazing are the main drivers of deforestation in TMCFs (Scatena *et al*., 2011; Aide, Ruiz-Jaen and Grau, 2010; Armenteras *et al*., 2017). Large areas of pasture created on land formerly occupied by TMCFs have been abandoned worldwide, however, giving rise to secondary forests (Scatena *et al*., 2011; Mulligan 2011). Overharvesting and invasive grasses and ferns such as bracken are also significant threats (Aide, Ruiz-Jaen and Grau, 2010). Unplanned selective logging usually involves the exploitation of high-value timber species (e.g. in the families Juglandaceae, Lauraceae and Podocarpaceae), causing forest degradation and thereby increasing the probability of conversion to agricultural land uses.

Another significant threat to TMCFs is climate change: because of their restrictive climatic requirements and fragmented distribution, TMCFs are highly vulnerable to increased temperatures and alterations in patterns of precipitation and cloud distribution (Feeley *et al*., 2013; Lutz, Powell and Silman, 2013). Alterations in the altitude at which cloud condensation occurs and increased evapotranspiration – both possible due to global warming – would reduce the area of montane land directly exposed to clouds (Still, Foster and Schneider, 1999; Bruijnzeel, 2004). Recent projections indicate that cloud immersion could shrink or dry out 57–80 percent of neotropical TMCFs (Helmer *et al*., 2019). This would make TMCFs more susceptible to fire, disease and invasive species, reducing ecosystem resilience. The impacts of such alterations on TMCF water cycles are likely to be considerable, causing reductions in water availability in lower parts of watersheds; these impacts are little studied, however.

The conversion of TMCFs to annual crops and pasture causes an increase in the volume of surface runoff because soil compaction reduces infiltration capacity (Bruijnzeel, 2004). Although forest transpiration is significantly reduced, causing an overall increase in the streamflow (Bruijnzeel, 2005), such extra soil water does not compensate for the loss of soil infiltration capacity; runoff peaks increase during wet seasons and streamflows decline in dry seasons (Bruijnzeel, 1989; 2004). Forest clearing also reduces tree and epiphyte interception of rain and fog water (Bruijnzeel, 2004). The replacement of mature TMCFs with pastures has decreased water input in the Venezuelan Andes and eastern central Mexico (Ataroff and Rada, 2000; Holwerda *et al*., 2010; Muñoz-Villers and López-Blanco, 2008).

The abandonment of agriculture and livestock grazing in former TMCFs enables the development of secondary TMCFs, but these younger forests capture less water from rainfall and fog than mature forests (8 percent versus 17 percent in Mexico; Holwerda *et al*., 2010). Nevertheless, water yields are higher in secondary TMCFs, likely due to the higher canopy storage capacity of mature TMCFs. This, in turn, is because leaf area per unit ground surface area and epiphyte biomass are higher in mature TMCFs, contributing to the capture and storage of water (Holwerda *et al*., 2010; Köhler *et al*., 2011). Epiphytes are abundant in the canopies of TMCFs, possess a high capacity for water storage, and can release stored water slowly (Veneklaas *et al*., 1990). Despite their considerable water-storage capacity, however, the contribution of non-vascular epiphytes to overall rainfall interception is relatively low (6 percent; Hölscher *et al*., 2004). Leaf and epiphyte surface area reductions in secondary TMCFs decrease canopy water retention and evaporation, thereby increasing throughfall and stemflow inputs to soil (Nadkarni *et al*., 2004; Ponette-González, Weathers and Curran, 2010). Overall, however, Muñoz-Villers *et al.* (2012) found very similar hydrologic behaviour between a 20-year-old secondary TMCF and a mature TMCF in Mexico, showing the value of natural regeneration in the recovery of hydrologic functioning in TMCFs.

Soil erosion is a potentially significant impact of any type of forest operation in the humid tropics (Bruijnzeel, 1992). The resultant input of sediments into rivers reduces water quality and channel capacity, the latter of which can increase the risk of flooding (Chappell *et al*., 2005).

Management of cloud forests for water services

Given their essential role in the hydrologic cycle and as reservoirs of biodiversity, the management of TMCFs should aim to integrate multiple ecosystem services, including those related to water, soil and biodiversity. Management objectives may vary widely, from conservation to timber production, depending on the socio-economic and biogeographic context.

Ideally, all old-growth TMCFs would be protected because of their valuable ecosystem functions. This is only likely to occur, however, when pressure from other land uses is low or the enforcement of conservation measures is high, which is not the case in many areas. Unplanned selective logging is common among communities in or near TMCFs (Hölscher *et al*., 2010; Toledo-Aceves *et al*., 2011), but the impacts of this exploitation on water services have not been evaluated systematically. The use of TMCFs for commercial timber production is rare, no doubt because of the low commercial timber volumes and grow rates; moreover, the steep slopes of most TMCFs make timber extraction complicated and costly.

Low-impact logging should be applied in any harvesting operations in TMCFs, adapting its key elements of pre-logging planning; the maintenance of vegetated stream buffer zones; the timing of operations to avoid very wet periods and minimize soil compaction; and post-harvesting measures such as soil bunding and the installation of cross-drains on skid trails (Cassells and Bruijnzeel, 2005). Directional felling is also an important measure to minimize the risk to workers and damage to harvested and potential crop trees.

The minimization of disturbances in forests on very steep slopes is crucial. Means for reducing the impact of log extraction in TMCFs by reducing the need for skid trails (which can have substantial impacts on hydrology and increase erosion) include using horses for skidding; mobile sawmills or chainsaw frames to mill logs on site; and cable yarding (Günter *et al*., 2008).

Given the protective functions of TMCFs for soils and their role in the hydrologic cycle, permanent forest cover and forest structure should be maintained wherever possible (Aus der Beek and Sáenz, 1992). Polycyclic selection systems will best enable this, and clearfelling should be avoided in TMCFs. Ensuring the financial competitiveness of selective timber harvesting compared with other land uses may require a PWS scheme (Günter, 2011; Knoke *et al*., 2014).

PWS schemes have been popular in TMCFs as a means to compensate landowners and thereby reduce deforestation and water scarcity. For PWS to be effective, however, the financial benefits must be comparable with the opportunity costs associated with not converting to pasture or other land-use activities; Box 5.9 presents a case study in Mexico, and there have also been promising experiences in Bolivia (Plurinational State of), China, Colombia, Costa Rica, Ecuador, the Dominican Republic and Viet Nam; there are few in Africa, however (Asquith, Vargas and Wunder, 2008; Bösch, Elsasser and Wunder, 2019).

BOX 5.9

A payment scheme for ecosystem services provided by cloud forests in Mexico

Programmes making payments for water services in Mexico began in central Veracruz, where a combination of high deforestation rates, associated losses of water services such as the regulation of water quality and flood–drought cycles, and climate change made the sustainable management of water and forest resources a top priority for decision-makers. Table 5.1 summarizes the region's two main programmes, one in the Gavilanes watershed (providing 90 percent of the water supply for the city of Coatepec) and the other in the Pixquiax watershed (providing 40 percent of the water supply for the city of Xalapa), both co-financed by the National Forest Commission, local water operators and municipal governments.

TABLE 5.1

The strengths and weaknesses of two payment schemes for water services in Veracruz, Mexico

<table>
<tr><th></th><th>Fidecoagua (Coatepec)</th><th>Acuerdos por Nuestra Agua (Xalapa)</th></tr>
<tr><td rowspan="2">Strengths</td><td>First payment scheme for ecosystem services in Mexico (2002)
Stable financing, with a fee of MXN 2 included in water bills
Novel "Adopt a Hectare" programme to conserve shade-coffee farms
The target watershed is entirely within one municipality</td><td>Started by Sendas, a non-governmental organization, in 2005
Novel combination of cash payments and technical assistance to promote sustainable alternatives (Nava-López *et al.*, 2018)
Science-based approach used to concentrate payments in hydrologic priority areas
Long-term monitoring using citizen science
Significantly stronger alliances and social network with greater impacts on landowner well-being (Torres-Pérez, 2018)</td></tr>
<tr><td colspan="2">Both programmes monitor deforestation, which has declined significantly in areas where the schemes operate (by 5.5 percent compared with areas where they don't operate), with no detectable leakage (von Thaden *et al.*, 2019)</td></tr>
<tr><td rowspan="2">Weaknesses</td><td>Government-run, with limited growth and creativity
Few efforts to partner with other sectors</td><td>Lack of legal framework, making local-government funding and support unstable
Operation across multiple municipalities is politically difficult</td></tr>
<tr><td colspan="2">Both programmes focus more on water providers than on downstream users, whereas the latter could help ensure long-term political support
Both programmes have poor additionality, with only 38.5 percent of payments made in areas of high deforestation risk (von Thaden *et al.*, 2019)</td></tr>
</table>

Source: Compiled by Robert H. Manson.

In degraded TMCFs, efforts may be needed to restore structure and function. Passive restoration – that is, restoration involving no active intervention (although it requires the diminution or exclusion of the factors that caused the degradation, such as cattle grazing) – natural processes will determine forest structure and function. This type of restoration requires less investment than active restoration, but its effectiveness depends on the intensity and type of the previous land use and the quality of the surrounding landscape. For example, the natural regeneration of tropical montane forest on abandoned pastures can be limited by low seed arrivals and the absence of seed dispersers (Aide, Ruiz-Jaen and Grau, 2010); competition with pioneer species (e.g. grasses and ferns; Aide, Ruiz-Jaen and Grau, 2010); and unfavourable microhabitats (e.g. due to high solar radiation, soil compaction, erosion and infertility; Holl, 1999). Moreover, whereas relatively high tree diversity might be achieved through passive restoration in TMCF landscapes (Muñiz-Castro, Williams-Linera and Benayas, 2006; Trujillo-Miranda *et al*., 2018), varying rates of recovery of other important taxa have been observed for epiphytes and insects (Köhler *et al*., 2011; Adams and Fiedler, 2015). Additionally, the slow recovery of provisioning services achieved through passive restoration increases the risk of conversion to agricultural land. Lower rates of vegetation recovery have been reported with increasing distance from mature TMCFs (Muñiz-Castro, Williams-Linera and Benayas, 2006; Trujillo-Miranda *et al*., 2018). Active restoration should be encouraged, therefore, in landscapes with few, small or degraded remnants of TMCFs or with high forest-conversion pressure.

Various active restoration strategies can be pursued depending on management goals and the economic, social and environmental context. The most common approach is to establish plantations in deforested areas, which, by increasing forest cover, may improve infiltration and runoff and help reduce erosion, sedimentation and downstream flooding. Efforts should be made to establish mixes of native species to restore some of the original tree diversity and thereby increase forest resilience and to encourage the growth of native plant species in plantation understoreys (Aide, Ruiz-Jaen and Grau, 2010; Liu *et al*., 2018; Trujillo-Miranda *et al*., 2018). In landscapes with few or distant patches of existing TMCFs, practices such as the installation of bird perches, direct seed-sowing and soil translocation may help in establishing nuclei of native vegetation (Boanoares and de Azevedo, 2014).

The design of TMCF restoration should take into account the potential for altered biophysical conditions associated with climate change and, where necessary, accommodate the potential future redistribution of tree species to higher altitudes and latitudes. Shifts in the distribution of TMCF tree species towards higher elevations – and increased mortality at lower elevations – in response to increased temperatures have been observed in Colombia, Costa Rica and Peru (Feeley *et al*., 2011; 2013; Duque, Stevenson and Feeley, 2015). The assisted migration of plant species via enrichment plantings using shade-tolerant TMCF tree species at sites above the reported limit of their present distribution has shown early promise as a climate-change mitigation strategy (García-Hernández *et al*., 2019).

Cloud forest research needs and knowledge gaps

Given the large diversity of TMCF types and the lack of data in most countries, it is essential to monitor changes in TMCF cover and to analyse drivers to improve understanding of the causes of TMCF loss and ways to reduce this.

Assessments are needed of the relationships between change in TMCF cover and water services under various climatic regimes at the watershed scale. A priority should be the identification of causes of decreases in dry-season flows and the development of approaches for restoring hydrologic function. More investigation is also needed on the effects of changes in TMCF water cycles on erosion and landslides. Increased knowledge on this aspect would support the development of integrated water resource management plans at the watershed scale.

There is a lack of knowledge on the relationship between biodiversity and water cycles in TMCFs. Managing for water services should not mean trade-offs with biodiversity conservation. Indeed, high biodiversity in TMCFs could increase ecosystem resilience in the face of altered patterns of precipitation and cloud formation. TMCF tree species differ in their tolerance and responses to environmental change; although some species might be more vulnerable, others could be more successful as conditions change (Feeley *et al*., 2011, 2013; Toledo-Aceves *et al.*, 2019). Studies of long-term catchment-scale hydrologic changes associated with selective logging in TMCFs under various felling intensities, forest ages and structures would generate valuable information for regional water resource planning and TMCF conservation.

Additional research is needed to better understand the hydrologic impacts of climate change on TMCFs: areas for further study include quantifying associated changes in fog-stripping, forest water use and, ultimately, streamflow. More knowledge is also needed on how changes in the composition of tree communities as a result of increasing temperatures might affect water yield. Such knowledge is essential for the design of effective climate-change mitigation measures. Adaptive management requires flexibility, with the knowledge generated from monitoring and evaluation used to modify management practices to ensure the ongoing optimal provision of water services.

Cloud forest in Veracruz, Mexico