Part I
General perspectives

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1 Setting the stage

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BACKGROUND

The cloudy, wet, and generally difficult terrain of the world's Tropical Montane Cloud Forests (TMCF) has not only made them hydrologically and ecologically unique, but has historically given them some *de facto* protection compared to other tropical forests. In the late 1970s and early 1980s it became apparent that this *de facto* protection was diminishing and that TMCF in many parts of the world were rapidly becoming converted or fragmented and in need of protection (LaBastille and Pool, 1978; White, 1983; Stadtmüller, 1987). Indeed, by the early 1990s it was clear that TMCF were high on the list of the world's most threatened terrestrial ecosystems. Moreover, during the period 1981–1990, montane forests were being lost at a rate considerably greater than that estimated for lowland tropical forests (1.1% year^{-1} vs. 0.8% year^{-1}, respectively; Doumenge *et al.*, 1995). It was also being recognized that the scientific information needed to manage and protect these unique but vulnerable ecosystems was generally lacking (Stadtmüller, 1987).

In response to this information need, an international Symposium on TMCF was held in San Juan, Puerto Rico between 31 May and 5 June 1993. The meeting resulted in a 27-chapter book on the world's TMCFs (Hamilton *et al.*, 1995), which included overview chapters on the hydrology and nutrient dynamics of TMCF (Bruijnzeel and Proctor, 1995) and the importance of TMCF for endemic and threatened birds (Long, 1995), as well as the first in-depth description of guidelines for managing and valuing an especially vulnerable type of TMCF – elfin cloud forest (Scatena, 1995) – and useful summary descriptions of the biogeography of TMCF in widely different settings, including a host of Pacific islands, Sri Lanka, NE Borneo, Mexico, SE Brazil, NW Argentina, and Perú.

Since the San Juan Symposium there have been many new local studies as well as several international initiatives aimed at increasing the understanding, appreciation, and protection of TMCF. The latter include the 1995 "Campaign for Cloud Forests" by the World Conservation Union (IUCN) (Hamilton, 1995) and the 1999 "Tropical Montane Cloud Forest Initiative" of UNEP–WCMC, WWF, IUCN, and UNESCO-IHP (Aldrich *et al.*, 2000) which has since evolved into a "Cloud Forest Agenda" designed to encourage new TMCF conservation actions (Bubb *et al.*, 2004). In addition, there have been various regional symposia as well as compilations of (mostly biological) information on montane forests (e.g. Churchill *et al.*, 1996; Nadkarni and Wheelwright, 2000; Kappelle and Brown, 2001; Kappelle *et al.*, 2001; Kappelle, 2004; Beck *et al.*, 2007; Gradstein *et al.*, 2008). TMCF hydrometeorological aspects have also been discussed at a series of Conferences on Fog and Fog Collection that have been held every three years since 1998 (Schemenauer and Bridgman, 1998; Schemenauer and Puxbaum, 2001; Rautenbach and Oliver, 2004; Biggs and Cereceda, 2007) whereas a recent overview of Andean studies has been provided by Tobón (2009). Whilst all of these activities have improved our knowledge of TMCF, most of the post-1993 efforts have had a Neotropical focus. Knowledge on the Asian and African TMCF has not only lagged behind considerably but has also remained limited to a few iconic mountains, like Mt. Kinabalu in Borneo (Kitayama, 1995; Kitayama *et al.*, 2000; Kitayama and Aiba, 2002; Kitayama and Nais, 2002) and Mt. Kilimanjaro in Tanzania (Røhr, 2003; Hemp, 2005, Hemp, this volume #12 and references therein).

Major threats to TMCF have been identified in several venues (Hamilton *et al.*, 1995; Aldrich *et al.*, 1997; Bruijnzeel and Hamilton, 2000; Kappelle and Brown, 2001; Bubb *et al.*, 2004; Beck *et al.*, 2007; Gradstein, 2008; cf. Mulligan, this volume). Conversion to agricultural and grazing lands, over-harvesting,

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alien invasions, roads, and various types of development are threats in all regions. Mining, fire, forest clearing for drug cultivation, and other activities can be locally important. The various symposia and venues cited above have also identified the following major information gaps in our understanding of TMCF:

- Inadequate information on the spatial distribution, biological richness, and ecological variation of TMCF at the continental, regional, mountain, and local scales.
- Inadequate information on the hydrometeorology and plant physiology of TMCF.
- Inadequate information on the nutrient and carbon dynamics of TMCF, especially in relationship to their productivity, resilience, and potential for restoration.
- Inadequate information on the hydrological and ecological consequences of converting TMCF to other forms of land use.
- Inadequate information on the influence of changes in regional land use and climate on the biodiversity and ecological functioning of TMCF.
- Inadequate information on the conservation status, restoration potential, and management strategies of different types of TMCF.

In view of the increased research efforts in TMCF and the need to summarize the increased understanding of their occurrence, value and functioning that has developed since the 1993 San Juan Symposium, the second International Symposium on Tropical Montane Cloud Forests was held in Waimea, Hawai'i in the summer of 2004. The purpose of this book is to report on advances made in various fields since 1993 as presented at the Waimea Symposium. The book is organized around the information gaps described above and includes a total of 72 chapters that range from inventories of biodiversity, through detailed investigations of TMCF hydrometeorological, physiological, and biogeochemical functioning, to studies of the impact of climate change, the potential for sustainable use, and various conservation strategies. The introductory section of the book consists of invited synthesis chapters on topics that are important to all types of TMCF: viz. their global extent and distribution, climatic variability and climate change, the eco-physiology of epiphytes, global and local variation in soil nutrient contents, nutrient cycling and nutrient limitation to forest productivity, and the state of TMCF restoration. An overview chapter of the hydrological functioning of TMCF was not included because such an overview had just been produced prior to the Waimea Symposium (Bruijnzeel, 2005) as part of a state-of-knowledge compilation of tropical forest hydrology (Bonell and Bruijnzeel, 2005). Therefore, the new information on TMCF hydrology, hydrometeorology, and plant physiology presented in the chapters of this book has been combined with earlier reviews (Bruijnzeel and Proctor, 1995; Bruijnzeel, 2005; Tobón, 2009) in the final Synthesis chapter.

The 11 chapters making up the second part of the book focus on regional floristic or animal diversity in TMCF from various parts of the world, including Africa and the Himalayas, two areas that remained under-discussed during the 1993 Symposium. This section also draws attention to the occurrence of Lowland Cloud Forests, a previously unstudied type of cloud forest (Gradstein *et al.*, this volume). Part II is designed to be a useful complement to the various overview publications on Neotropical TMCF diversity listed above.

The core of the book consists of Part III (hydrometeorology, 19 papers), Part IV (nutrient dynamics, eight papers), Part V (water use, photosynthesis, and the soil and water impacts of TMCF conversion to pasture, eight papers) and Part VI (effects of climate variability and climate change, seven papers). As this final topic was in its infancy during the 1993 Symposium (Lugo and Scatena, 1992; Benzing, 1998; Markham, 1998), this latter collection of papers provides a unique synthesis of the current state of play concerning the effects of climate variability and change on TMCF. Last, but certainly not least, Part VII (10 papers) focuses on the potential for, and approaches to the conservation, management, and restoration of cloud forests. This information was largely lacking in 1993 and includes such recent developments as payments for environmental services delivered by TMCF (Tognetti *et al.*, this volume), multi-stakeholder learning initiatives for sustainable forest use (Hofstede *et al.*, this volume), and community-based forest protection (Asbjornsen and Garnica-Sánchez, this volume). The book concludes with a Synthesis chapter that summarizes what we have learned since 1993 and identifies some of the more important remaining issues that need to be resolved to ensure future sustainable use and protection of TMCF.

GLOBAL DISTRIBUTION OF TMCF

Defining cloud forest

Although the biodiversity, ecological, and hydrological values of TMCF have been widely acknowledged, their definition and the delineation of their spatial distribution has remained both a persistent challenge and need (Stadtmüller, 1987; Campanella, 1995; Hamilton *et al.*, 1995; Ashton, 2003; Bach, 2004; Bubb *et al.*, 2004; Martin *et al.*, 2007; Mulligan, this volume). Historically, this problem has been confounded by a myriad of imprecise, overlapping and at times, contradictory definitions of TMCF (Stadtmüller, 1987). One of the major advances since the 1993 symposium has been the recognition and development of definitions for different TMCF types (Bruijnzeel and Hamilton, 2000; Bruijnzeel 2001). These forest types are described below and are based on forest structure, the degree of mossiness and leaf sclerophylly (Grubb, 1977; Frahm and Gradstein, 1991; Bach, 2004; Table 1.1), and observed contrasts in the fraction

Table 1.1 *Summary of key structural characteristics marking the chief tropical (montane) forest types distinguished in the present volume*

Forest formation[a]	LERF	LMRF/LMCF	UMRF	SACF
Canopy height	25–45 m	15–33 m	1.5–18 m	1.5–9 m
Emergent trees	Up to 67 m tall	Often absent, up to 37 m	Usually absent, up to 26 m	Usually absent, up to 15 m
Compound leaves	Abundant	Occasional	Rare	Absent
Principal leaf size class[b]	Mesophyllous	Meso-/notophyllous	Microphyllous	Nanophyllous
Leaf drip-tips	Abundant	Present	Rare or absent	Absent
Buttresses	Frequent and large	Uncommon, and small	Usually absent	Absent
Cauliflory	Frequent	Rare	Absent	Absent
Big woody climbers	Abundant	Usually absent	Absent	Absent
Bole climbers	Often abundant	Frequent to abundant	Very few	Absent
Vascular epiphytes	Frequent	Abundant	Frequent	Very rare
Non-vascular epiphytes	Occasional	Occasional/Abundant	Usually abundant	Abundant
(mosses, liverworts)		<10%/25–50%	70–80%	>80%

[a] LERF, lowland evergreen rain forest; LMRF/LMCF, lower montane rain/cloud forest; UMCF, upper montane cloud forest; SACF, sub-alpine cloud forest.
[b] Leaf sizes according to the (1934) Raunkiaer classification system: mesophyllous, 4500–18 225 mm^2; notophyllous, 2025–4500 mm^2; microphyllous, 225–2025 mm^2; nanophyllous, <225 mm^2.
Source: Based on Whitmore (1998) and Frahm and Gradstein (1991).

of net precipitation reaching the forest floor (Bruijnzeel, 2005). Three general TMCF types are recognized (lower montane cloud forest, upper montane cloud forest, and sub-alpine cloud forest) within the widely adopted definition of cloud forests as "forests that are frequently covered in cloud or mist" (Stadtmüller, 1987; Hamilton *et al*., 1995). These definitions also recognize the important influence of temperature and humidity levels on montane forest zonation.

With increasing elevation on wet tropical mountains, distinct changes occur in forest appearance and structure (Table 1.1). In general, the tall and often buttressed trees of the multi-storied *lowland rain forest* (main canopy height 25–45 m, with emergents up to 60 m), gradually give way to *lower montane forests*. With a mean canopy height of up to 35 m and emergent trees as high as 45 m, these lower montane forest can still be quite impressive. Yet, with two rather than three canopy layers, the structure of lower montane forest is simpler than that of lowland forest. The large buttresses and climbers that are so abundant in the lowland forest all but disappear while epiphytes (orchids, ferns, bromeliads) on branches and stems become more numerous with elevation (Whitmore, 1998). The change from lowland to lower montane forest is normally observed at the elevation where the average minimum temperature drops below 18 °C. At this threshold many lowland tree species are displaced by a floristically different assemblage of montane species (Kitayama, 1995). On large equatorial inland mountains this transition usually occurs at an altitude of 1200–1500 m.a.s.l. and coincides with the general range of incipient and intermittent cloud formation (Kitayama, 1995). As elevation increases, the trees become gradually smaller, moss cover on stems increases from 10% to 25–50%, and a *lower montane cloud forest* is observed. With further increases in elevation there is usually a very clear change from relatively tall (15–35 m) lower montane cloud forests to a distinctly shorter-statured (2–20 m) and much more mossy (70–80% bryophytic stem cover) *upper montane cloud forest* (Frahm and Gradstein, 1991). Although these two forest types are not separated by a known or distinct thermal threshold, there can be little doubt that the transition from lower to upper montane cloud forest coincides with the level where cloud condensation becomes most persistent (Grubb and Whitmore, 1966; Kitayama, 1995; cf. Schawe *et al*., this volume). On large mountains in equatorial regions away from the ocean this belt of persistent clouds typically occurs at elevations of 2000–3000 m.a.s.l. (Grubb, 1977; Kitayama, 1995). On small oceanic island mountains and in some coastal mountains this change from lower to upper montane forests may occur at much lower altitudes (see below). Mosses also start to cover rocks and fallen trunks on the soil surface in the upper montane cloud forest zone. With increasing elevation and exposure to wind-driven fog and rain, tree stems become increasingly crooked and gnarled, and bamboos often replace palms as dominant undergrowth species (Kappelle, 1995). The eerie impression of this tangled mass, wet with fog and glistening in the morning sun, has given rise to names like "elfin" forest or "fairy" forest to the more stunted and dwarfed forms of these upper montane cloud forests (Stadtmüller, 1987).

A third major type of TMCF occurs at the elevation where the average maximum temperature falls below 10 °C. Here the upper montane forest gives way to still smaller-statured (1.5–9 m) and

more species-poor *sub-alpine cloud forest* (or scrub) (Kitayama, 1995; Bach, 2004; Hemp, 2006). This forest type is characterized not only by its low stature and gnarled appearance but also by even smaller leaves, and a comparative absence of epiphytes. Mosses usually remain abundant and cloud incidence is still a paramount feature (Frahm and Gradstein, 1991; cf. Schawe *et al*., this volume). On large equatorial mountains the transition to sub-alpine forest is generally observed at elevations between 2800 and 3200 m.a.s.l. (Kitayama, 1995; Hemp, this volume #12; Schawe *et al*., this volume). As such, this type of forest is encountered only on the highest mountains, mostly in Latin America and Papua New Guinea, where it may extend to *c*. 3900 m.a.s.l. (Whitmore, 1998; cf. Hemp, this volume #12).

Climate and the distribution of TMCF

Although the different types of TMCF described in Table 1.1 are recognized in many regions, there is a wide variation in the elevations of TMCF. In general their distributions depend on the upper and lower bounds of clouds and the global, regional, and local factors that influence cloud formation. The transition from lower to upper montane cloud forest, and the thickness of the cloud forest belt itself, is primarily governed by the level of persistent cloud condensation (Grubb and Whitmore, 1966; Frahm and Gradstein, 1991; Kitayama, 1995; Hemp, this volume #12; Schawe *et al*., this volume). The lower elevation of cloud formation, in turn, is determined by the moisture content and temperature of the atmosphere such that the more humid the uplifted air is, the sooner it will condense. With increasing distance from the ocean, air tends to be drier and therefore requires lower temperatures and higher elevations to reach its condensation point. Consequently, the associated cloud base and TMCF vegetation will occur at a higher elevation farther from the oceans. Likewise, at given moisture content, the condensation point is reached more rapidly for cool air than for warm air. Thus, at greater distance from the equator, the average temperature – and therefore the altitude at which condensation and TMCF occurs will be lower (Nullet and Juvik, 1994; Jarvis and Mulligan, this volume).

In addition to the elevation of the cloud *base*, the distribution and extension of the TMCF belt is also governed by the *upper level* of cloud formation which is influenced by global-scale atmospheric circulation. In general, in a large-scale atmospheric circulation pattern (the Hadley cell), heated air rises to great elevations in the equatorial zone, and flows poleward and eastward in the upper atmosphere as it cools. The cool dry air then descends in a broad belt in the outer tropics and sub-tropics from where it returns to the equator. This subsidence reaches its maximum expression at oceanic sub-tropical high-pressure centers and along the eastern margins of the oceanic basins. As the air descends and warms, it forms a temperature inversion that separates the moist layer of surface air (that is being cooled while rising) from the drier descending air above. This so-called "trade wind inversion" (TWI) has a tilted three-dimensional surface that generally rises toward the equator and from east to west across the oceans. Over the eastern Pacific Ocean, the TWI occurs at only a few hundred meters above sea level, e.g. off the coast of southern California. It rises to about 2000 m near Hawai'i and dissipates in the equatorial western Pacific (Nullet and Juvik, 1994). The consequences of the TWI for the occurrence of the upper boundary of montane cloud forest are profound and are another reason why the vegetation zonation on mountains situated away from the equator tends to become compressed (Stadtmüller, 1987). For instance, windward slopes in the Hawai'ian archipelago receive more than 6000 mm of rain per year below the inversion layer. However, at 1900–2000 m.a.s.l., montane cloud forest suddenly gives way to dry sub-alpine scrubs because the clouds are prevented from moving upward by the presence of the temperature inversion (Kitayama and Müller-Dombois, 1994a,b). One of the best-known examples of the TWI and its effect on vegetation zonation comes from the Canary Islands. Situated between 27° and 29° N, a daily "sea of clouds" develops between 750 m and 1500 m which sustains evergreen Canarian laurel forests in an otherwise rather arid environment (Ohsawa *et al*., 1999; cf. Marzol *et al*., this volume; García-Santos, 2007). However, the dry conditions prevailing at the level of the TWI also promote the occurrence of wildfires and thereby help to maintain the upper boundary of TMCF (Hemp, 2005; Martin *et al*., 2007).

Superimposed on these global-scale moisture and temperature gradients are the more local processes that influence the temperature of the air column and thus the "starting point" for cooling. These include the influence of offshore sea surface temperatures, land–sea interactions involving the coastal plain, the size of a mountain and its orientation and exposure to the prevailing winds (Van Steenis, 1972; Stadtmüller, 1987; Jarvis and Mulligan, this volume). The interactions of these local and regional influences on the distributions of TMCF can be quite pronounced. For example, the sheer mass of large mountains exposed to intense radiation during cloudless periods is believed to raise the temperature of the overlying air enough to decrease the lapse rate and enable plants to extend their altitudinal range. This effect is commonly referred to as the "mass elevation" or "telescoping" effect and has been recognized for decades (Van Steenis, 1972; Whitmore, 1998; Figure 1.1). More recent research has indicated that low-stature, mossy, upper montane-looking forests that occur at relatively low elevations (<1000 m.a.s.l.) on some small coastal mountains can be ascribed to the high humidity of the oceanic air promoting cloud formation at very low elevations rather than to a steeper temperature lapse rate (Jarvis and Mulligan, this volume). Further support for this comes from the observation that the effect is most pronounced in areas with high rainfall and thus high atmospheric humidity (Van Steenis, 1972; Bruijnzeel *et al*., 1993). Locally produced inversions can also influence the distributions of cloud

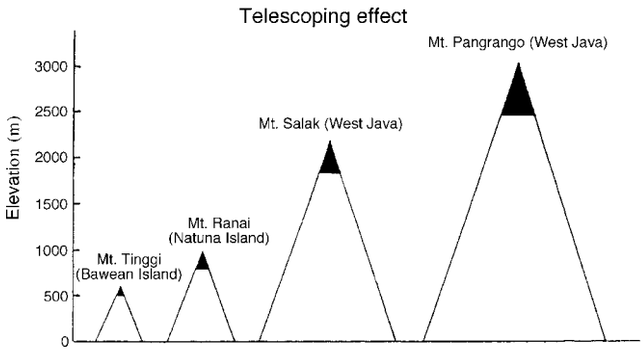

Figure 1.1. The telescoping effect of vegetation zonation on differently sized mountains (after Van Steenis, 1972).

forests, as has been described by Proctor *et al.* (2007) for Mt. Cameroon. Here, fires and active volcanism have created an inversion that limits the upper occurrence of (cloud) forest to a comparably low elevation of *c.* 2200 m despite the large size of this continental mountain (4095 m) and the presence of fertile soils.

Mapping cloud forests

As a result of the complex interactions and the major variations in global- and local-scale influence of climate, topography, and atmospheric circulation briefly described above, the mapping of actual and potential area of TMCF at the global scale is more than challenging (Bubb *et al.*, 2004). Ideally, a global TMCF map would explicitly account for multiple climatic and physiographic factors, including cloud frequency, wind and rainfall patterns, as well as aspect, latitude, altitude, the size of mountains, their distance from the sea, and local vegetation classification. Unfortunately, much of this information has not been available at the spatial scales needed, although this situation is changing rapidly with respect to topography, climate, and cloud occurrence (cf. Jarvis and Mulligan, this volume; Mulligan, this volume; Lawton *et al.*, this volume).

A map of the global distributions of TMCF cannot be compiled from existing national forest assessments because the term "cloud forest" is not commonly or consistently used. Moreover, at least 35 different names have been used to typify cloud forests in the past (Stadtmüller, 1987). In Africa, cloud forests have generally not been distinguished from the broader Afro-montane forest category (Hemp, this volume #12), whereas in Asia and the Pacific region the term "cloud forest" is rarely recognized outside of the "mossy forest" of the Philippines (Penafiel, 1995) and Malaysia (Kumaran *et al.*, this volume). In the Americas, the concept of cloud forest is relatively well known and approximate maps of the distributions of TMCF have been compiled for some Latin countries (see Kappelle and Brown, 2001). However, Mexico is the only country with a national vegetation classification scheme that explicitly includes a category corresponding to "cloud forest" (Vázquez-García, 1995).

Given the limitations in resources and data coverage, different approaches to mapping TMCF have been considered. Maps based on ground-measured *floristic or physiognomic characteristics* have been used to map TMCF at the spatial scales of a single mountain or landscape (Frahm and Gradstein, 1991; Bach, 2004; Hemp, this volume #12) and for mapping of ecotones of TMCF on either side of a ridge (e.g. Lawton and Dryer, 1980; Martin *et al.*, 2007). Other approaches have used elevation as a proxy for the climatic (temperature, rainfall, and fog incidence) and edaphic (soil water status, acidity) conditions that tend to be associated with cloud forest (e.g. Campanella, 1995; Bubb *et al.*, 2004). Whilst this approach is the least data-demanding and therefore particularly suitable for global-scale inventories, it also tends to lump different types of TMCF into a single category. Elevation-based predictions of TMCF occurrence are also complicated by the mass elevation effect (Figure 1.1) and need local or regional calibration. The most complex and data demanding techniques involve mapping according to a set of pre-defined *hydro-climatic characteristics*, such as cloud frequency or water balance (Mulligan, this volume; cf. Lawton *et al.*, this volume).

Areal estimates of cloud forest distribution based on these different techniques can differ substantially and a definitive global-scale map of actual or potential TMCF is still far from being developed. Nevertheless, our knowledge of TMCF distribution has improved significantly since the 1993 San Juan Symposium when the first global maps of TMCF were made by having symposium attendees place tags on maps to identify sites known to have TMCF. The map analysis provided below is a second iteration of work carried out by UNEP–WCMC as a product of the Mountain Cloud Forest Initiative referred to earlier (Aldrich *et al.*, 1997; Bubb *et al.*, 2004), and represents the first major attempt to calculate a global estimated cloud forest distribution. The overall approach followed was to first delineate the potential distribution of TMCF using preset altitudinal limits that are likely to include cloud forests of any kind between 30° N and 30° S (Table 1.2). These altitudinal limits were determined from a database of TMCF sites that was compiled at UNEP–WCMC from literature sources and expert opinion (Table 1.2). The database contains 650 records from 46 countries (Aldrich *et al.* 1997). This information was supplemented by cloud forest altitudinal ranges as reported for several Latin American countries in Kappelle and Brown (2001), and modified further on the basis of comments received from participants during the Waimea Symposium. The area of potential TMCF within these altitudinal bands is likely to include montane rain forests and drier forest types as well as TMCF. A Geographic Information System (GIS) was used to estimate the potential distribution of TMCF as follows:

- A GIS layer of the mountain areas within the altitudinal limits of TMCF for each major mountain range or region was produced from the GIS-base layer of the mountains of the world, using the definition of mountains proposed by

Table 1.2 *Regional groupings of tropical montane cloud forest and the lower and upper altitudinal limits used in the present analysis. See text for details*

Regional groupings	Lower and upper altitudinal limits of cloud forest used in the analysis (m.a.s.l.)
Mexico west of the isthmus of Tehuantepec	2200–3500
Mexico east of the isthmus of Tehuantepec and Central and South America	1800–3500
Caribbean islands and coastal Venezuelan mountains	above 660
Atlantic coast of Brazil	above 700
Galápagos islands and coastal Ecuadorian mountains	above 400
Hawai'i	1000–3000
African Atlantic coast countries	1000–3500
Ethiopia and Albertine Rift mountains, including DR Congo	2000–3500
Kenya and northern Tanzania	1500–3500
Southern Tanzania, Malawi, Mozambique and Réunion	1000–3500
Madagascar	1300–3500
Philippines	1200–3500
New Guinea	2000–3500
Continental South-East Asia, Borneo, Sumatra, Java and Sulawesi	1500–3500
South India, Sri Lanka, other insular Asia–Pacific islands, northern Australia	1000–3500

Kapos *et al.* (2000), i.e. (i) all land above 2500 m.a.s.l., (ii) land between 1500 and 2500 m.a.s.l. and having a slope $\geq 2°$, (iii) land between 1000 and 1500 m.a.s.l. and having a slope $\geq 5°$ or a local elevation range >300 m, and (iv) land between 300 and 1000 m.a.s.l. and having a local elevation range >300 m. This phase utilized the GTOPO30 Digital Elevation Model from the US Geological Survey's EROS Data Center, which has a horizontal grid spacing of 30 arc sec (*c.* 1 km; http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html).

- To convert the potential distribution to actual distribution, the mountain areas within the altitudinal limits of TMCF were combined with a map of tropical montane forest and tropical lowland evergreen forest taken from the UNEP–WCMC global forest inventory. This data-set is comprised of national and regional data from many sources that have been harmonized to display global forest cover in the early 1990s at a resolution of 1 km (Iremonger *et al.*, 1997). Areas of non-forest and non-humid forest were excluded from the TMCF analysis.
- Finally, these base layers were updated using MODIS satellite-based vegetation coverage for the year 2000 (VCF 2000) to represent the actual distribution of TMCF in 2000.

Table 1.3 *Area (km^2) of estimated tropical montane cloud forest (TMCF) by continental region*

Region	Estimated area of TMCF (km^2)	% of global TMCF
Americas	87 626	40.8
Africa	34 328	16.0
Asia	92 676	43.2
Global total	**2 14 630**	**100.0%**

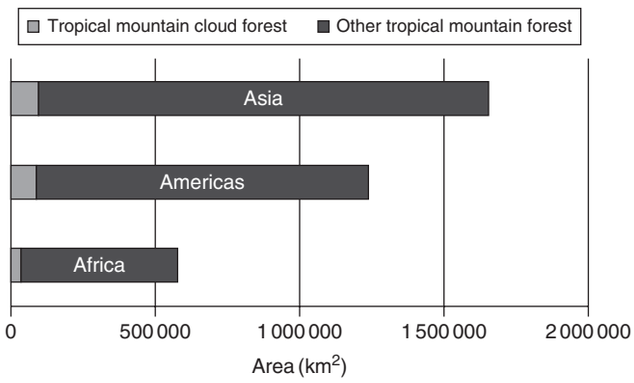

Figure 1.2. Estimated area (km^2) of tropical montane cloud forest and tropical montane forest by continental region.

A significant source of error in this analysis is the variability of forest coverage and classifications used to compile the UNEP–WCMC global forest coverage (Iremonger *et al.*, 1997). This classification system divides the world's forest into 26 major types that reflect climatic zones as well as the principal types of trees. Pertinently, the coverage was derived from national sources and classifications that did not explicitly distinguish TMCF as a separate category, let alone made a distinction between lower or upper montane cloud forest.

A second source of error lies in using the GTOPO30 Digital Elevation Model in mountainous regions, which gives a single value of altitude for a 1-km grid cell. Thus, these altitudinal belts are based on kilometer-scale regional patterns and do not include the smaller-scale variations in aspect and exposure that are known to be important (Grubb and Tanner, 1976; Lawton and Dryer, 1980; Weaver, 1995; cf. Häger and Dohrenbusch, this volume).

Using the elevation- and publication-based approach described above, the estimated global area of TMCF (of all categories) is about 215 000 km^2 (Table 1.3 and Figure 1.2), which is approximately 0.14% of the Earth's land surface and 1.4% of the total area

Table 1.4 *Estimated area of tropical montane cloud forest as a percentage of all tropical forest and tropical mountain forest. Areas of tropical (mountain) forest based on Iremonger* et al. *(1997) and Kapos* et al. *(2000). The calculations of Kapos* et al. *(2000) of the areas of the world's mountain forest included altitudinal ranges from 300 m to above 4500 m.a.s.l.*

Region	All tropical forest (km^2)	TMCF as % of all tropical forest	Tropical mountain forest (km^2)	TMCF as % of all tropical mountain forest
Americas	7 762 359	1.1%	1 150 588	7.6%
Africa	4 167 546	0.8%	544 664	6.3%
Asia	3 443 330	2.7%	1 562 023	5.9%
Global total	**15 373 235**	**1.4%**	**3 257 275**	**6.6%**

of the world's tropical forests (Table 1.4). This estimate of the total area of TMCF is considerably less than the only other published figure of *c.* 500 000 km^2 of cloud forests in the humid tropics (Bockor, 1979). The estimate is also less than Kappelle and Brown (2001) their estimate of a potential extent of 750 000 km^2 for Latin America alone. The present estimate is also less than the recent estimates of hydro-climatically defined cloud forest using satellite measures of cloud frequency as derived by Mulligan (this volume) who also discusses several reasons for this discrepancy. Nevertheless, the present results are considered to represent a conservative estimate of the global extent of actual, not potential, TMCF and to accurately reflect their relative distribution (Figures 1.3–1.5).

Of all the TMCF mapped, 43% occur in Asia (including northern Australia and Oceania), 41% in the Americas (including the Hawai'ian archipelago), and 16% in Africa (Table 1.3). TMCF is also a relatively scarce habitat amongst all forest types in tropical mountain regions, occupying an estimated 7.6%, 6.3%, and 5.9% of the Tropical Mountain Forest biome in

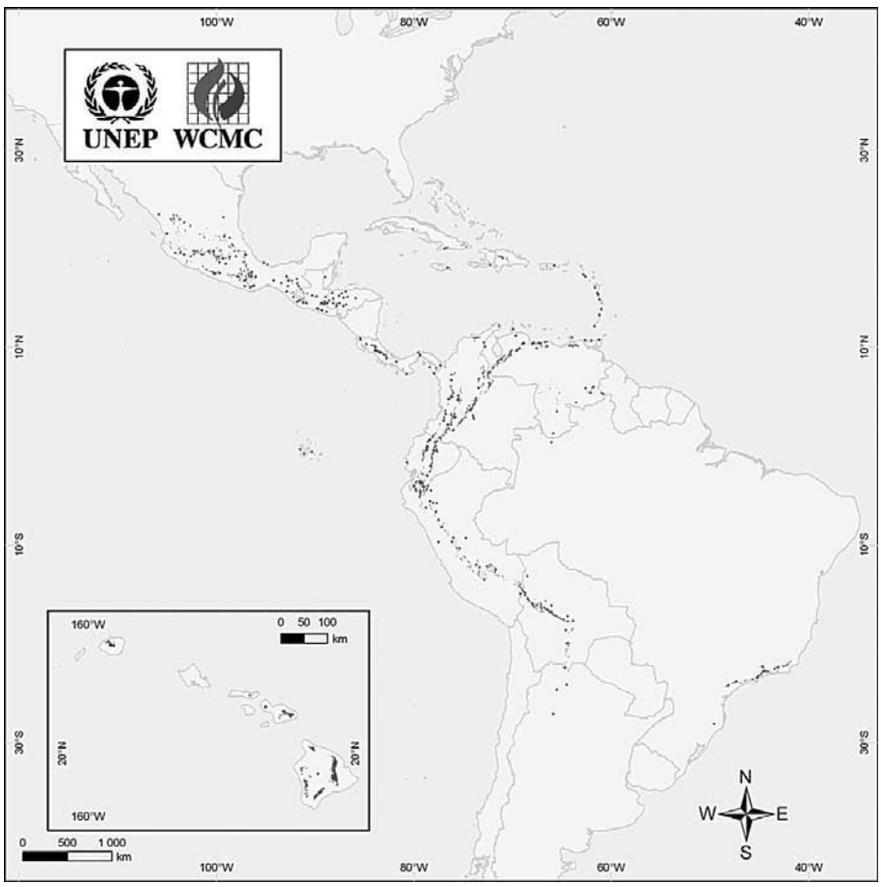

Figure 1.3. Estimated tropical montane cloud forest distribution in the Americas (including the Hawai'ian archipelago), based on the altitudinal ranges listed in Table 1.2 (areas in red) and known cloud forest site locations from Aldrich *et al.* (1997) (green dots). (See also color plate.)

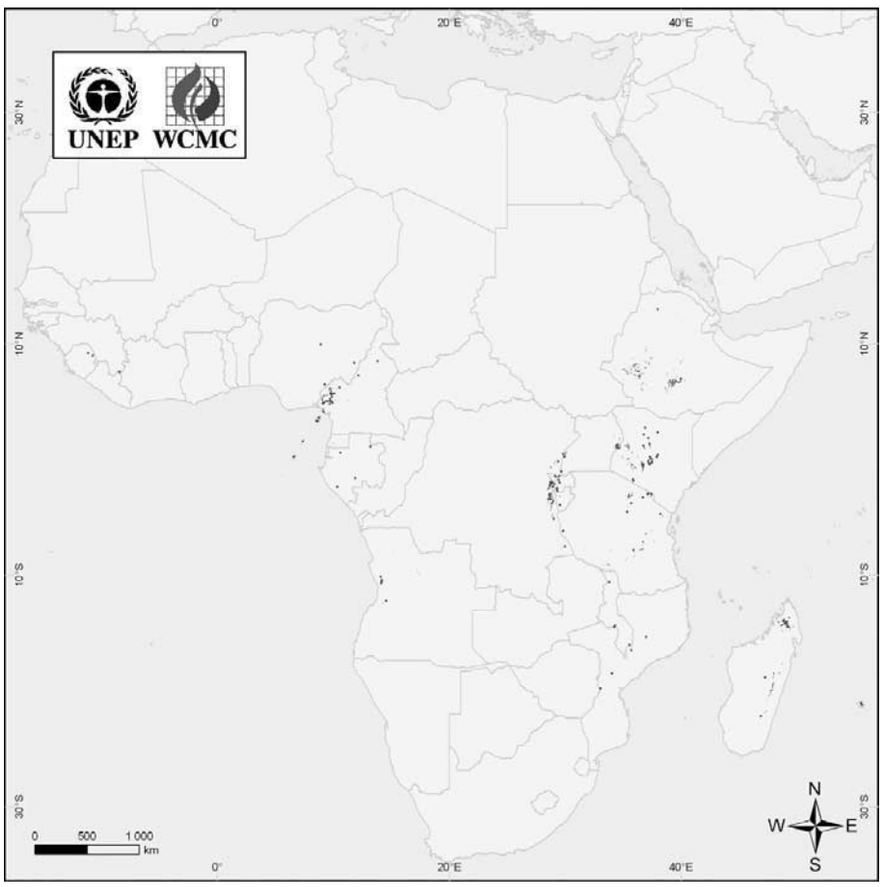

Figure 1.4. Estimated tropical montane cloud forest distribution in Africa, based on the altitudinal ranges listed in Table 1.2 (areas in red) and known cloud forest site locations from Aldrich *et al*. (1997) (green dots). (See also color plate.)

the Americas, Africa, and Asia, respectively (Table 1.4 and Figures1.3–1.5). One of the most noteworthy results of this analysis is the large extent of existing TMCF in Asia, principally in Indonesia and Papua New Guinea (Figure 1.5).

EMERGING ISSUES

Whilst there have been considerable advances since 1993 in our knowledge of the regional variability in TMCF biodiversity and in our understanding of TMCF hydrological, physiological, and ecological functioning, this continues to be a critical "decision time" for TMCF. Their actual distributions are still poorly defined and they continue to be threatened in a variety of ways, the most important of which are, arguably, conversion to pasture and various forms of agriculture on the one hand, and climatic drying and all its ecological implications on the other (Bubb *et al*., 2004; Pounds *et al*., 2006; Zotz and Bader, 2009). As the recognition of the value of TMCF as treasure houses of biodiversity, protectors against soil erosion, and providers of a steady supply of high-quality water continues to increase, so does the need for land managers and policy-makers to determine which forests under their jurisdiction are the most diverse and valuable biologically; which ones are the most susceptible to landsliding and soil erosion upon clearing, which forests provide the best water supplies, and which degraded TMCF have the best chances for recovery? As such, there is a great need for site-specific information on TMCF for incorporation in conservation and management plans.

Given the complexities, advances, and information gaps described above, what are the main issues and questions that this book will address? For convenience, the major issues that affect TMCF can be roughly categorized into three broad and interrelated groups, viz. (i) biogeography and biodiversity; (ii) biophysical and ecological processes; and (iii) management issues and strategies. The key questions per broad category include:

Biogeography of TMCF

- Is it possible to identify the regions and areas with the greatest diversity in TMCF flora and fauna? Do these relationships vary between "maritime" and "continental" settings?

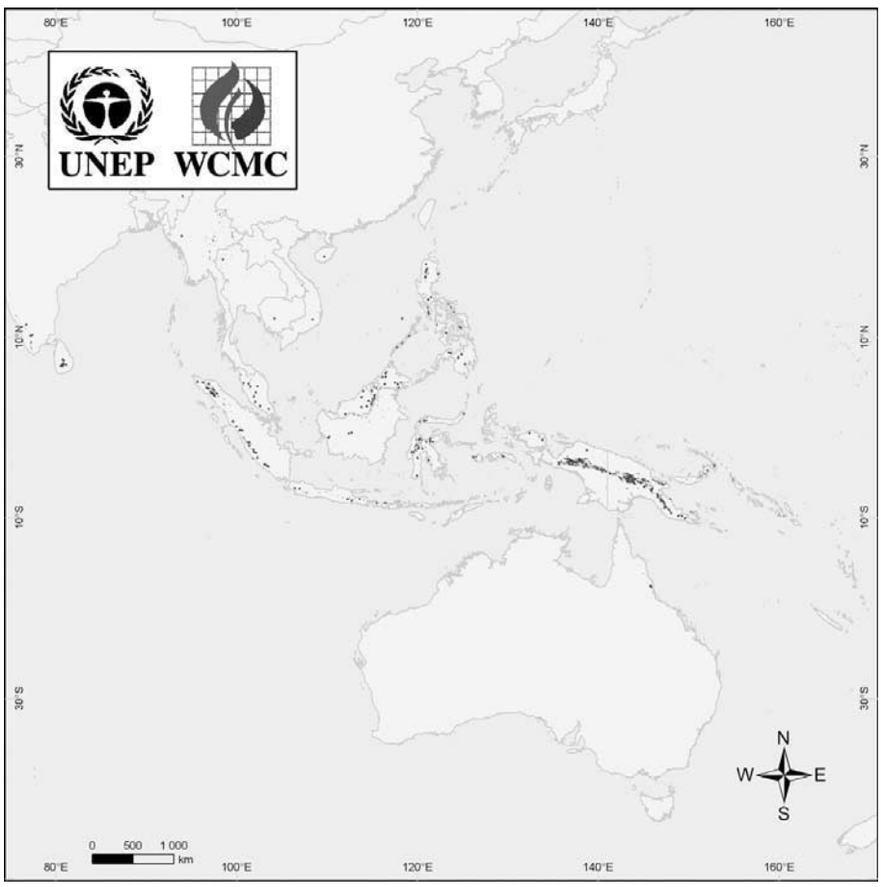

Figure 1.5. Estimated tropical montane cloud forest distribution in Asia (including northern Australia and Oceania), based on the altitudinal ranges listed in Table 1.2 (areas in red) and known cloud forest site locations from Aldrich *et al*. (1997) (green dots). (See also color plate.)

- Is it necessary on hydrological or ecological grounds to distinguish between lower and upper montane forests when mapping TMCF? And if so, what are the remotely sensed, modeled, and field data that can be used to distinguish between lower, upper, and sub-alpine TMCF?

Biophysical processes in TMCF

- What are the absolute and relative amounts of cloud water interception (*CWI*) and wind-driven rain (*WDR*) in different types of TMCF? Are there predictable regional and forest-type related patterns in *CWI* and *WDR*? How can these be measured and their spatial and temporal distributions modeled?
- What is the water use (evapotranspiration) and carbon uptake (photosynthesis) of different types of TMCF? Do similarly statured forests at different elevations cycle water, carbon, and nutrients at similar rates?
- How are annual and seasonal water yields and ecosystem services affected by converting different types of TMCF to pasture, annual crops, or coffee plantations?
- Are there important differences in soil nutrient levels, soil water status (e.g. degree of waterlogging), and aluminum or hydrogen toxicity between different types of TMCF? How do these differences relate to above-ground forest biomass and overall ecosystem productivity? How do soil resources change with land-cover change?
- How are different types of TMCF affected by climatic drying and a reduction in precipitation? What ecosystem component or function is most affected? Is the extent of climatic drying in TMCF mostly caused by local, regional, or global processes? Do these relationships vary between "maritime" and "continental" settings?

Management strategies for sustaining TMCF

- What is the present conservation status of TMCF? Where are these forests threatened the most and why?
- Which ecosystem components (e.g. ornamental plants, bryophytes, anoline species, large mammals) are the most vulnerable, and which are the most resilient to human activities or climatic drying?