Changing lenses to assess biodiversity: patterns of species richness in sub-Antarctic plants and implications for global conservation

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Taxonomic groups and ecoregions shape the “lenses” through which biodiversity is assessed and conserved. A historical bias toward vertebrates and vascular plants in the northern hemisphere underpins how global patterns of biodiversity in terrestrial ecosystems are perceived. Here, we focus on the hitherto overlooked non-vascular flora (liverworts and mosses) in the remote sub-Antarctic Magellanic ecoregion of southwestern South America. We report that: (1) this ecoregion hosts outstanding non-vascular floristic richness, with >5% of the world’s bryophytes on <0.01% of the Earth’s land surface; (2) species richness patterns for vascular and non-vascular plants are inverted across 25 degrees of latitude in Chile; and (3) while vascular plants are 20 times more abundant than non-vascular plants globally and in tropical South America, non-vascular plants are dominant in the sub-Antarctic Magellanic ecoregion and Antarctic Peninsula. These findings have been translated into policy and conservation decisions, including the creation of the Cape Horn Biosphere Reserve in 2005 and the introduction there of “tourism with a hand lens” in the diverse “miniature forests” of bryophytes, lichens, and invertebrates. We argue for consideration of ecoregional- or biome-specific indicator groups, rather than a narrow set of global indicator groups, for designing effective conservation strategies.


Patterns of species richness and endemism used to identify priority areas for biodiversity conservation are strongly biased by our differential knowledge of taxonomic groups, as well as by contrasts in the existence of studies and data among geographical and ecological regions (Isaac et al. 2004; Lawler et al. 2006). In past decades, influential assessments of global priorities for conservation have relied on geographic differences in the concentration of diversity and endemism of vertebrates and vascular plants (Myers et al. 2000; Rodrigues et al. 2004; Lamoreux et al. 2006). Taxonomic bias is also illustrated by the fact that more than 80% of the publications on animal conservation during the past 20 years have been devoted to vertebrate species, despite the fact that vertebrates represent less than 5% of the known faunal diversity (Clark and May 2002). Among vertebrates, birds and mammals (endotherms) are favored, being the focus of more than 70% of published articles, despite the fact that ectotherms (fishes, amphibians, and reptiles) comprise more than 70% of species, and include most of the threatened vertebrate taxa (Bonnet et al. 2002). Attention has not previously been called to analogous taxonomic biases in plant conservation studies. However, preliminary analyses indicate that the majority of publications on plant conservation focus solely on vascular flora. During the past decade, non-vascular plant conservation articles have remained marginal and diversity patterns of non-vascular flora poorly documented (Rozzi et al. in prep).

Regarding biases among geographical and ecological regions in the literature, conservation research has strongly concentrated on the northern hemisphere, with temperate forest biomes of North America and Europe accounting for 30% of publications with a conservation focus (Lawler et al. 2006). In contrast, few studies have

\begin{itemize}
  \item At high latitude ecoregions, non-vascular flora should be included in floristic richness assessments
  \item Reverse latitudinal trends of vascular and non-vascular plant diversity challenge the universality of latitudinal species-richness gradients
  \item Inconspicuous taxonomic groups such as bryophytes can be important in promoting conservation, when their ecological and aesthetic values are understood by the general public and policy makers
  \item Metaphors and narratives generated by ecologists can be powerful tools for promoting local conservation and ecotourism
\end{itemize}

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investigated patterns of species richness in relation to conservation priorities in sub-Antarctic forests, tundra, and adjacent Antarctic ecosystems (Arroyo et al. 2005; Lawler et al. 2006).

What, then, would happen if we were to move outside of these taxonomic, geographical, and ecoregional boundaries? Would a change in the taxonomic and geographical lenses disclose reservoirs of biodiversity that might have remained invisible to conservation biologists? Here, we describe the consequences of changing “biodiversity conservation lenses”, by focusing on the world’s southernmost forest and tundra ecosystems, in the sub-Antarctic region of western South America (Figure 1). In addition, we address the inconspicuous and largely overlooked non-vascular flora comprising liverworts and mosses present in this southern geographic region. The analysis of diversity patterns of this frequently overlooked taxonomic group, in a remote and striking geographical area of evergreen broadleaf forests and tundra, has led us to novel and challenging theoretical and practical questions. In this article, we show how non-vascular and vascular plants display opposite latitudinal species-richness gradients. We argue that conservation should focus on regional patterns of biome-specific biodiversity indicator groups, which are often left out of global assessments.

**Figure 1.** The sub-Antarctic (or sub-polar) Magellanic ecoregion, showing the full extent of evergreen rainforests (green) and Magellanic moorland (gray) from Cape Horn to Penas Gulf in Chile. Located on Navarino Island, south of Tierra del Fuego, Omora Ethnobotanical Park launched a bryoflora conservation program with international collaboration in 2000. As the research, education, and conservation center for the Cape Horn Biosphere Reserve (WebFigure 1), Omora Park serves as a long-term ecological research site of a nascent Chilean Long Term Ecological Research network, supported by the Chilean Institute of Ecology and Biodiversity (IEB; www.ieb-chile.cl; see Rozzi et al. 2006a).

Since 2000, we have been conducting a series of floristic inventories in the region of Cape Horn, which, when combined with previously published data, indicate that more than 5% of the world’s bryophytes are found on less than 0.01% of the Earth’s land surface, at the southern tip of the Americas. Along the narrow southwestern archipelagic margin of Chile, between Cape Horn (56°S) and Penas Gulf (49°S; Figure 1), 818 bryophyte species (He 1998; Villagrán et al. 2005) have been recorded from the approximately 15 000 km² of moorland, bogs, forests, glaciers, and alpine ecosystems, this humid and fragmented coast harbors 450 moss and 368 liverwort species (including hornworts; Figure 2; WebTable 1).

Ongoing work suggests that the species richness of this group is likely to grow, as several additions to the bryophyte flora of Cape Horn Archipelago await formal description, including three new species of *Schistidium* (Grimmiaceae; W Buck in prep). Current phylogeographic studies are shedding new light on the isolation of populations of possibly widespread species, leading to the recognition of additional endemic taxa (MacDaniel and Shaw 2003; Figure 2b). According to recent floristic and taxonomic studies, more than 50% of liverwort and moss species are endemic to the temperate rainforests of southern South America (Engel 1978; He 1998; Buck 2000; Matteri 2000; Villagrán et al. 2005; Figure 2d). Moreover, several endemic bryophyte genera are monotypic (Matteri 2000). Thus, we contend that the combination of high bryophyte species diversity, including many geographi-
and 58% of 778 moss species known to Chile (Figure 3a; WebTable 1). Analysis of latitudinal patterns of floristic richness in Chile from 18° to 56°S indicates that more than 50% of bryophyte species (> 500) have a northern distribution limit in the archipelago region, around 41.5° S. Further north (38.5–30.5° S), species richness (estimated for each Chilean Administrative Region) declines to fewer than 100 species of liverworts, and fewer than 250 species of mosses. Finally, in the deserts of northern Chile (19.5–27.5° S), bryophytes are nearly absent and highly restricted (Figure 3a).

Vascular plants, in contrast, fail to exhibit such a dramatic decline in species richness toward the desert region, with nearly 1000 species in each Administrative Region (Figure 3a). The Chilean vascular flora reaches its peak richness in the transition from Mediterranean climate zone to temperate forest zone, between 30.5° and 41.5° S (Figure 2a).

**Inverse latitudinal diversity patterns in non-vascular and vascular flora of Chile**

The high number of bryophyte species in southernmost South America results from a clear trend toward increased species richness at higher latitudes along the southwestern margin of the continent; the sub-Antarctic Magellanic archipelago contains 67% of 549 liverworts and 58% of 778 moss species known to Chile (Figure 3a; WebTable 1). Analysis of latitudinal patterns of floristic richness in Chile from 18° to 56°S indicates that more than 50% of bryophyte species (> 500) have a northern distribution limit in the archipelago region, around 41.5° S. Further north (38.5–30.5° S), species richness (estimated for each Chilean Administrative Region) declines to fewer than 100 species of liverworts, and fewer than 250 species of mosses. Finally, in the deserts of northern Chile (19.5–27.5° S), bryophytes are nearly absent and highly restricted (Figure 3a).

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Colombia, and Ecuador, NV/V ratio is < 0.05 (i.e., the number of vascular plant species exceeds by 20 or more the species richness of non-vascular plants; Figure 3b; WebTable 2). The NV/V ratio increases to 0.14 and 0.25 in more temperate countries such as Argentina and Chile. In the sub-Antarctic region, in turn, this ratio rises to 1.06 (Figure 3b), as the number of bryophyte species slightly surpasses the number of vascular plants.

If we consider the flora of the Antarctic Peninsula (> 60° S), the NV/V ratio increases to 33.5. This high NV/V ratio results from the fact that only two native vascular plant species (Deschampsia antarctica and Colobanthus quitensis) occur on the islands of the Scotia Ridge and along the western coast of the Antarctic Peninsula (Lewis-Smith 1996). In contrast, 67 native non-vascular plant species have been recorded in the same territory, including 27 liverwort (Bednarek-Ochyra et al. 2000) and 40 moss species (Putzke and Batista-Pereira 2001). Consequently, non-vascular flora becomes the dominant plant group at high latitudes in southern South America and Antarctica.

The observed shift in NV/V ratio with increasing latitude in southwestern South America might be associated with historical and ecological factors. Small Pleistocene refugia may have favored survival of non-vascular over vascular plants during repeated glacial cycles (Villagran 2005). This, together with the ability of mosses to tolerate high levels of desiccation and low temperatures (Longton 1982), may have facilitated their survival in micro-refugia within glaciated zones. Following glacial retreats, mosses are often the first plants to colonize the

Figure 3. (a) Latitudinal patterns of species richness in non-vascular and vascular plant species in Chile. Values on the vertical axis are for median south latitude for each of the 12 Chilean Administrative Regions (shown on the map at left). The sub-Antarctic Magellanic ecoregion corresponds to the southernmost Region XII, shown in dark blue. The non-vascular to vascular plant species ratio (NV/V; dotted line) is positively correlated with latitude (rs = 0.92, P < 0.001). (b) Within South America, NV/V increases southward from 0.03 in Colombia to > 1 in the sub-Antarctic Magellanic ecoregion. See WebTables 1 and 2 for species numbers and NV/V ratios.

Non-vascular and vascular plant species ratio in southern South America and Antarctica

To better visualize the contrasting latitudinal patterns of vascular and non-vascular species richness, and to facilitate comparisons with other regions of South America, we define the non-vascular/vascular (NV/V) plant species ratio. As illustrated in Figure 3a, NV/V ratio significantly increases with latitude in Chile (Spearman’s rank correlation; rs = 0.92; P < 0.001), from close to 0 in the northern desert to slightly > 1 at the southern tip of the Americas. The roughly even NV/V ratio at high latitudes in South America contrasts sharply with the much richer vascular floras of tropical South America. In Brazil, Colombia, and Ecuador, NV/V ratio is ≤ 0.05 (i.e., the number of vascular plant species exceeds by 20 or more the species richness of non-vascular plants; Figure 3b; WebTable 2). The NV/V ratio increases to 0.14 and 0.25 in more temperate countries such as Argentina and Chile. In the sub-Antarctic region, in turn, this ratio rises to 1.06 (Figure 3b), as the number of bryophyte species slightly surpasses the number of vascular plants.

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newly exposed ground and bare rocks (Schofield 2000), as can be seen on glacial moraines today (Figure 2b). Finally, patterns of plant species diversity in sub-Antarctic regions are shaped in part by dominant wind currents that favor long-distance dispersal of bryophyte and lichen spores and asexual reproductive structures (such as fragments of mature individuals or special reproductive bodies like gemmae) over propagules of vascular plants (Muñoz et al. 2004). Similarly, in the northern hemisphere, the non-vascular flora prevails in Arctic Alaska (Longton 1982). Thus, the trend toward NV/V ratios \(\geq 1\) at higher latitudes seems to be a general phenomenon, which contrasts with an average NV/V ratio of 0.05 at a global scale (based on the figures of 300,000 vascular versus 15,000 non-vascular plant species). If non-vascular plants dominate the high-latitude floras in both hemispheres, then sub-Antarctic and sub-Arctic biodiversity assessments may require a transformation of the prevailing “botanical lens”, as the focus on vascular plants will continue to make the high floristic diversity of these ecosystems “invisible” to both scientists and decision makers.

**The Cape Horn Biosphere Reserve**

Our findings on the sub-Antarctic Magellanic non-vascular flora, combined with the invention of an innovative ecotourism activity to appreciate this flora (“tourism with a hand lens”; Panel 1), provided strong support for the proposal to create the Cape Horn Biosphere Reserve (WebFigures 1 a,b). This proposal involved 5 years of research and negotiations, led by scientists from Omora Ethnobotanical Park (Panel 1) and a broad array of regional, national, and international institutions, with the common goal of integrating the protection of the southernmost ecosystems in the Americas (Rozzi et al. 2004). The designation of the Cape Horn Biosphere Reserve by UNESCO in June 2005 documents how the less conspicuous taxonomic groups can motivate the protection of whole ecosystems. Today, the Chilean government recognizes the new Cape Horn Biosphere Reserve as a model for implementing the three main goals of the Convention of Biological Diversity (conserving biodiversity, equitable sharing of its benefits, and sustainable use of biodiversity), through the integration of research, education, and conservation (Rozzi et al. 2006 a,b). In this manner, the tiny mosses and liverworts of Cape Horn helped to establish the largest Chilean biosphere reserve (4.9 million ha), representing long-term and novel institutional arrangement to preserve this valuable ecosystem.

**Lessons learned**

The case study of the sub-Antarctic non-vascular flora in southern South America presented here suggests five points of general applicability. First, we argue for the use of “ecoregional- or biome-specific” indicator groups, rather than a narrow set of global indicator groups, when assessing regional biodiversity patterns. In defining prior-
ity areas for conservation of marine ecosystems, it would make little sense to use vascular plants as an indicator group rather than algae. As a direct corollary, if we are concerned about the biodiversity of high latitude biomes group rather than algae. As a direct corollary, if we are concerned about the biodiversity of high latitude biomes, the non-vascular flora should be given the greatest weight in the floristic assessments. Our findings of high species richness and endemism in the sub-Antarctic Magellanic non-vascular flora (which was overlooked prior to this study), and the considerably different trends seen in vascular and non-vascular land-plant species richness along a broad latitudinal gradient in southwestern South America, highlight the limitations arising from the use of a restricted set of common indicator species to identify conservation priorities across the globe.

Second, the opposite latitudinal trend of vascular and non-vascular land-plant diversity in this area raises questions about the universality of latitudinal species-richness gradients and should stimulate new comparative studies of distribution patterns across different taxonomic groups. The distribution of land-plant diversity in Chile raises further questions regarding the definition of “hotspots” based solely on vascular plant or vertebrate diversity patterns, because such concepts implicitly assume that species richness among different taxonomic groups are positively correlated. While species richness in most groups of terrestrial organisms increases toward the equator, we show here that non-vascular plant species richness exhibits the opposite trend across 40 degrees of latitude in Chile.

Third, inconspicuous taxonomic groups, such as bryophytes, can play important roles in promoting conservation when their ecological and aesthetic values are understood by the general public and policy makers. The high diversity of sub-Antarctic Magellanic non-vascular flora was critical in making the case for the establishment of the Cape Horn Biosphere Reserve in June 2005. Bryophytes, although very small organisms in comparison to charismatic megaflora and large tree species, have the potential for becoming emblematic flora at other subpolar latitudes.

Fourth, our experience suggests that the interdisciplinary and inter-institutional approach can be successful in translating the scientific discovery of an austral species richness center for bryophytes into conservation action, stimulating new research questions in the process. This feedback between biodiversity research and conservation was organized into a four-step cycle, which integrated (1) generation of new scientific knowledge, (2) its communication, (3) in situ education and ecotourism activities, and (4) the creation of a “garden of the miniature forests of Cape Horn”, displaying and conserving in situ sub-Antarctic non-vascular flora (Panel 1). Scientific technical publications with narratives for the general public and a visit by the then President of Chile were instrumental in creating national and international awareness of the charm of these little-known plants for ecotourism in the remote Cape Horn region. Further, the concept of “tourism with a hand lens” and the metaphor of the “miniature forests of Cape Horn” illustrate an innovative approach to communicating locally relevant scientific research to promote effective regional conservation.

Finally, in our experience, international partnerships enhance research and education programs. Creating a program focused on non-vascular plant diversity in the sub-Antarctic Magellanic region without international collaboration would have been difficult because of the lack of trained Chilean bryologists and taxonomists (cf Simonetti et al. 1995). In turn, collaboration among international and Chilean institutions and scientists with different cultural experiences and fields of expertise was essential for promptly translating novel scientific knowledge into regionally and globally significant conservation actions, leading to the creation of the world’s southernmost biosphere reserve.

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References


Buck W. 2002. Preliminary key to the mosses of Isla Navarino,
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