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Relationship between Global Warming and Species Richness of Vascular Plants

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We analyzed climatological and geographical variables in 90 countries from the Northern Hemisphere to determine the significant variability of plant species richness as it relates to broad-scale levels of global warming. This variability was quantified by the parameters of temperature and precipitation. Of the 27 temperature variables and 13 precipitation variables, 6 variables had negative influences on species richness while 5 variables had positive impacts. When we estimated the effect of higher temperatures, we found that a 1 or 2°C rise in global warming produced an increase in species richness of 1.6 or 3.2%, respectively.

Keywords: global warming, maximum temperature, minimum temperature, precipitation, species richness increase

Species richness may be evaluated on several different levels, including molecular, species, habitat, or ecosystem (Gentry, 1992; Pimm and Gittleman, 1992; Pimm et al., 1995; Bao et al., 2006; Tripathi et al., 2007; Yi, 2007). It is widely accepted that species is the single most useful unit for assessing such richness, whether carried out locally, nationally, regionally, or globally. A significant impact of global warming is already discernible in plant and animal populations. Moreover, factors that influence the density or range of species, phenology, morphological changes, genetic frequencies, and extinction interact in complex ways (Schall and Pianka, 1978; Walter and Gillett, 1998; Sala et al., 2000; Penuelas and Filella, 2001; Walther et al., 2002; Root et al., 2003).

There is general consensus that an anthropogenic warming signal appears in the long-term climate record. Greenhouse gas emissions may cause a 3-6°C increase in average surface temperatures at the sub-Arctic and temperate latitudes. This is primarily due to the average minimum temperature (T_{MIN}) having risen at twice the rate of the maximum temperature (T_{MAX}) (Gentry, 1992; Vitousek et al., 1997; Kim, 1998; Alward et al., 1999; Williams et al., 2005). Consequently, net primary production might decrease if an elevated T_{MIN} results in higher plant and microbial nocturnal respiration rates without a compensatory rise in photosynthetic capacity. However, if an elevated T_{MIN} leads to longer growing seasons, the opposite may occur. Although trees have responded to global warming in the past – to temperatures higher than they are now – the rate of change predicted for the 21st century is likely to be unprecedented. However, little research has isolated the effects of temperature on vegetation within this scenario (Alward et al., 1999; Chapin et al., 2000). The synergism of a rapid temperature rise and other stresses, in particular habitat destruction, could easily disrupt the connectedness among species and lead to a reformulation of communities that reflect differential changes as well as to numerous extirpations and possibly extinctions (Loreau et al., 2001; Walther et al., 2002; Root et al., 2003). Here, we present the relationships between vascular plant species richness of 90 countries in Northern Hemisphere and their respective temperatures, amounts of precipitation, latitude, or total surface area.

MATERIALS AND METHODS

We analyzed climatological and geographical variables for 90 countries in the Northern Hemisphere, based on data from the 1997 IUCN Red List of Threatened Plants (Walter and Gillett, 1998). Our two objectives included: 1) detecting any significant variability in plant species richness, and 2) determining whether these fluctuations were related to global-scale levels of environmental change. Eleven countries were excluded from this analysis early on because of their very high species richness (0.332 to 3.357) per km^2 within a smaller land area, i.e., <10000 km^2 (these included Antigua and Barbuda, Brunei Darussalam, Comoros, Cyprus, Dominica, Luxembourg, Malta, Mauritius, Seychelles, Singapore, and Trinidad and Tobago). In all, we were able to calculate the richness of vascular plant species per unit area (km^2) for 79 nations. For each country, we collected data for 40 climatological and 2 geographical variables concerning species richness (Walter and Gillett, 1998; WMO, 2005). These involved average daily minimum temperature (°C) (T_{MIN1}-T_{MIN12}); average daily maximum temperature (T_{MAX1}-T_{MAX12}); average total precipitation (mm) (P_1-P_{12}); average annual minimum temperature; average annual maximum temperature; average annual temperature; average annual precipitation, both rain and snow (mm); *Country's land surface area* (km^2); and *Latitude* (°). The subscripts 1 to 12 indicated January through December. Those variables were entered into a backward stepwise multiple regression that used the number of vascular plant species per km^2 as the dependent variable. Climatological variables were based on monthly averages for the 30-year period from 1971 to 2000.

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RESULTS AND DISCUSSION

For 79 countries in the Northern Hemisphere, vascular plant species richness showed large variability, ranging from 377 to 51220 species per country, or 0.0003 to 0.2896 species per km^2. Average richness was 6,311 species per country and 0.0331 species per km^2 (Table 1). Variability declined while richness gradually increased as one moved from Arctic to Equator regions.

When multiple regression models were used to evaluate this variability, the model R^2 was 0.431 when country species richness per km^2 was analyzed as the independent variable. This variability could be explained by the 11 variables related to temperature and precipitation.

$$\textit{Vascular Plant Species Richness} \text{ (per km}^2) = (-10.425-91.905(T_{MIN2})+86.491(T_{MIN3})-58.451(T_{MAX5}) +164.015(T_{MAX10})-230.298(T_{MAX11})+136.367(T_{MAX12}) -3.766(P_3)-1.222(P_7)+6.026(P_{10})-4.457(P_{11}) +4.010(P_{12})) \div 10{,}000 \; (R^2 = 0.431;\ P < 0.001) \quad (1)$$

Of the 27 temperature variables and 13 precipitation variables assessed here, 6 variables such as T_{MIN2}, T_{MAX5}, T_{MAX11}, P_3, P_7, and P_{11} had negative influences on species richness while 5 variables such as T_{MIN3}, T_{MAX10}, T_{MAX12}, P_{10}, and P_{12} had positive effects. At least across the temperate to polar regions, substantial evidence has been found on a geographical scale for a broadly positive, monotonic relationship between richness and energy availability (Currie and Paquin, 1987; Turner et al., 1988; Currie, 1991; Rutherford et al., 1999; Gaston, 2000; Stevens et al., 2004). The correlates for plants tend to be measures of both heat and water, e.g., actual evapotranspiration and net primary productivity, whereas for terrestrial, and perhaps marine, animals, the best correlates are quantifiers of heat, such as average annual temperature and potential evapotranspiration. For example, the species richness of trees in East Asia, temperate Europe, and eastern North America increases with primary productivity (Adams and Woodward, 1989). Moreover, there is a good correlation between January isotherms and the distribution of northern tree species. Low winter temperatures are the main limiting factor for frost-sensitive trees in continental regions, while high winter temperatures are an important limiting factor for some continental species that avoid coastal areas with mild winters.

$$\textit{Vascular Plant Species Richness} = 10064 - 129.754\ (\textit{Latitude}) \; (R^2 = 0.08;\ P < 0.01) \quad (2)$$

$$\textit{Vascular Plant Species Richness} = 5211.929 + 0.00101\ (\textit{Country area}) \; (R^2 = 0.11;\ P < 0.01) \quad (3)$$

Latitude and *Country area* had negative and positive influences on species richness, with R^2 values of 0.08 and 0.11, respectively, according to *Eq*. 2 and 3 (Fig. 1A, B). Lower-latitude sites showed greater richness than did higher-latitude sites. This latitudinal gradient in species richness, however complex it might be, is a consequence of spatial variation in both the immigration and extinction of species (Pianka, 1966; Rohde, 1992; Givnish, 1999; Gaston, 2000; Ohlemuller and Wilson, 2000). For very large land masses, the effects of speciation and regional or global extinction will predominate, and immigration and emigration will be less important. Three possible explanations have been advanced for why this latitudinal gradient might nonetheless be expressed: 1) low productivity/energy availability at high latitudes reduces the species richness they would gain as a result of area alone

Table 1. Averages for plant species richness, land area, latitude, annual temperature, and annual precipitation from 79 countries on 4 continents within the Northern Hemisphere.

Continent	No. of countries	Species richness	Area (km^2)	Latitude (°)	Average annual temperature (°C)	Average annual precipitation (mm)
Africa	20	3270	733439	13.3	24.5	1115.7
America	15	11760	1604862	19.3	20.9	1281.7
Asia	21	8809	1224387	28.9	19.6	1064.5
Europe	23	3122	922169	50.8	9.9	639.8

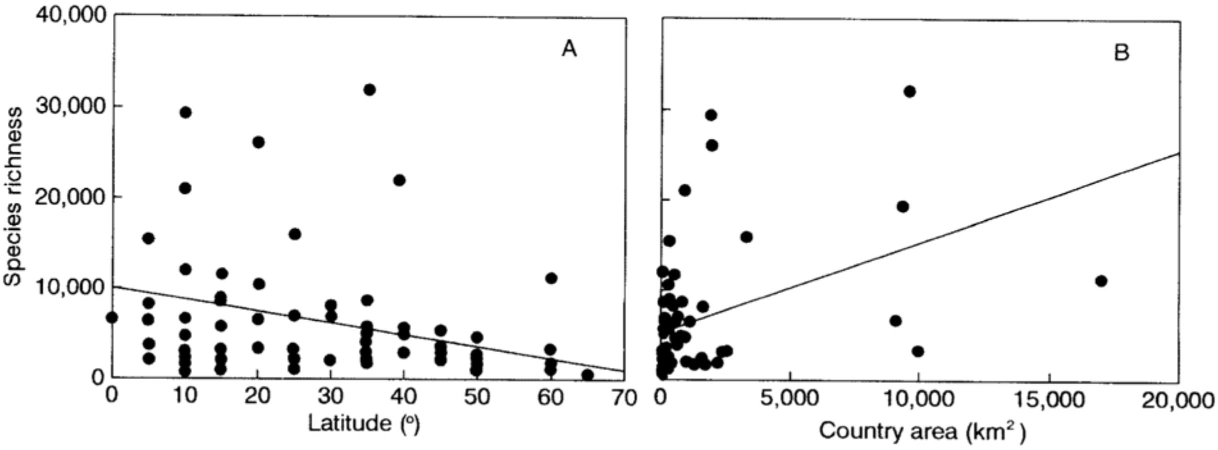

Figure 1. (**A**) Relationship between species richness and latitude for 79 countries in Northern Hemisphere. (**B**) Relationship between species richness and country area. Regression lines are shown in *Eq*. 2 and 3.

(Rosenzweig, 1995; Roy et al., 1998), 2) zonal immigration of tropical species into temperate regions smoothes out species-richness gradients (Blackburn and Gaston, 1997; Rosenzweig and Sandlin, 1997), and 3) greater local climatic variability at high latitudes effectively increases the area of ecoclimatic zones that species can actually occupy, because it requires that individuals have broad environmental tolerances. Many different mechanisms have been suggested for generating the systematic latitudinal variation in those processes (Brown and Lomolino, 1998). These include reasons based on chance, historical perturbation, environmental stability, habitat heterogeneity, productivity, and interspecific interactions.

Area is almost certainly an important contributor to latitudinal gradients in species richness. Indeed, this parameter has a pervasive effect on patterns of biodiversity. In *Eq.* 3, *Country area* showed positive impacts on richness (Fig. 1B). However, tests of the area model have been limited, and have seldom sought the signal for the influence of area on latitudinal gradients when controlling for other factors. Moreover, that model is insufficient as a sole explanation.

We found weak relationships between species richness and average annual minimum temperature, average annual maximum temperature, average annual temperature, or average annual precipitation. This may have been due to the high variability in annual temperature and precipitation, both of which were poorer predictors of species richness than monthly T_{MIN}, T_{MAX}, and P.

Figure 2 presents a comparison of the species richness observed with that calculated from the predictive model (*Eq.* 1). Applying a t-test on the null hypothesis, we found that the observed values and the predicted values were the same, such that the null hypothesis was not rejected ($P < 0.995$).

Over the past 100 years, the global average temperature has increased by approximately 0.5°C, and is projected to continue rising at a rapid rate (Kim, 1998; Houghton et al., 2001). To estimate the effects of this trend in the Northern Hemisphere, we also investigated the changes in species richness, assigning their measured data as the 100% value and increasing each 0.1°C in *Eq.* 1 (Fig. 3). Here, temperature rose by 0 to 2.0°C, with richness also increasing linearly in parallel with temperature (Fig. 3). This 1 and 2°C increase in global warming translated into an increase in species richness of 1.6 and 3.2%, respectively, while the 50-yr and 100-yr elevation in air temperature was associated with a richness increase of 0.4 and 0.8%. Likewise, decadal climate warming can play a role in the thermal adaptation and acclimation of plants. Species richness may increase as a consequence of greater productivity and energy availability in regions with high T_{MAX} values and low latitudes (Chapin et al., 2000; Root et al., 2003). Therefore, because there is evidence of a positive relationship between species richness and global warming, we can apply these results to the modeling and monitoring of local biodiversity, speciation, extinction, and species movement.

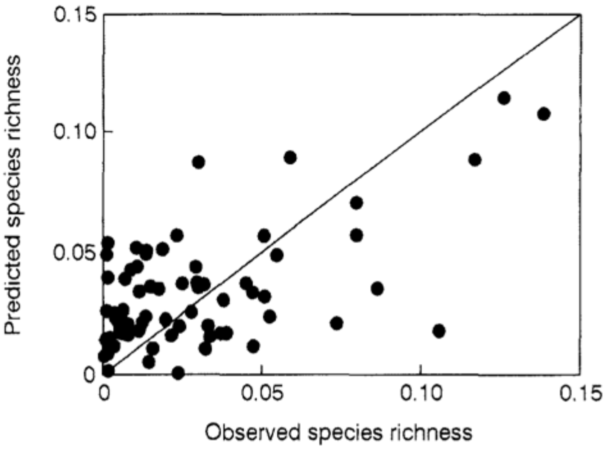

Figure 2. Relationship between observed and predicted species richness, based on multiple regression model. Diagonal line demonstrates equality between predicted and observed values.

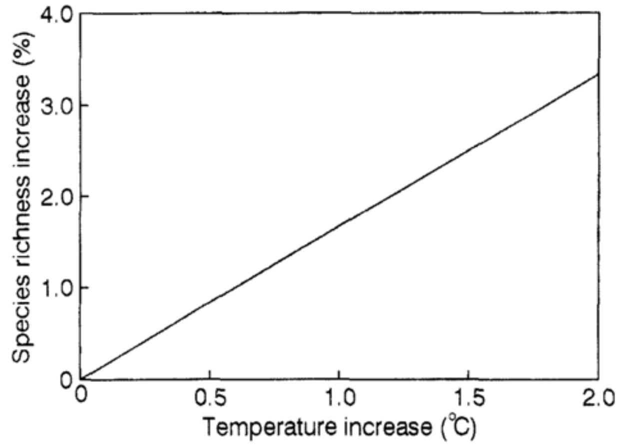

Figure 3. Alterations in species richness from Northern Hemisphere as consequence of changes in T_{MIN}, T_{MAX}, and P.

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