Original research article

Can temporal and spatial NDVI predict regional bird-species richness?

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ABSTRACT

Understanding the distribution of the species and its controls over biogeographic scales is still a major challenge in ecology. National Park Networks provide an opportunity to assess the relationship between ecosystem functioning and biodiversity in areas with low human impacts. We tested the productivity–biodiversity hypothesis which states that the number of species increases with the available energy, and the variability–biodiversity hypothesis which states that the number of species increases with the diversity of habitats. The available energy and habitat heterogeneity estimated by the normalized difference vegetation index (NDVI) was shown as a good predictor of bird-species richness for a diverse set of biomes in previously published studies. However, there is not a universal relationship between NDVI and bird-species richness. Here we tested if the NDVI can predict bird species richness in areas with low human impact in Argentina. Using a dataset from the National Park Network of Argentina we found that the best predictor of bird species richness was the minimum value of NDVI per year which explained 75% of total variability. The inclusion of the spatial heterogeneity of NDVI improved the explanation power to 80%. Minimum NDVI was highly correlated with precipitation and winter temperature. Our analysis provides a tool for assessing bird-species richness at scales on which land-use planning practitioners make their decisions for Southern South America.

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1. Introduction

Human activities are worldwide modifying natural ecosystems in different ways and scales (Peñuelas et al., 2013), such as the combined effects of land use change, fire, grazing pressure, and human accessibility that threatens South America natural heritage (Jarvis et al., 2010). Land use planning policies offer an alternative to attenuate these threats by the regulation

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Table 1

Summary of satellite information to predict bird species. Results from a SCOPUS search with the words (NDVI or SPOT or MODIS or LANDSAT) and (bird/avian biodiversity or bird diversity) that predict bird species. The numbers in each column represent the number of papers. The list of papers is reported in Appendix 1 (see Appendix A).

Predictor		Bird species		Spatial extent		Biome		Country/Region		Satellite/Sensor	
NDVI	31	Richness	27	Local	27	Temperate forest	15	USA	15	Landsat	24
Land cover	8	Composition	11	Regional	16	Tropical forest	8	Canada	4	SPOT	11
Habitat structure	4	Presence	10	Continental	1	Multiple	6	Asia	9	MODIS	5
fPAR	2	Abundance	5			Grassland/savannah	5	Europe	6	AVHRR	3
						Desert	4	S. America	3		
						Urban	3	C. America	3		
						Wetland	2	Oceania	3		
						Boreal forest	1	Africa	2		
						Tundra	1				

of different production activities in a finite landscape. These policies require linkages with sound scientific knowledge to provide real alternatives to current land use (Müller and Opgenoorth, 2014), and deep commitment with land owners to succeed, however are often difficult to implement (Seghezzo et al., 2011).

Species diversity is often used to define conservation priorities (Kim and Byrne, 2006). Species diversity at regional scales can be derived from field surveys, museum records, or the habitat distribution of species (Rahbek and Graves, 2001; Hawkins et al., 2003b; Dunn and Weston, 2008). An alternative is to use a proxy for environmental variables such as potential evapotranspiration or annual mean temperature (Cueto and De Casenave, 1999; Hawkins et al., 2003b; Bellocq and Gómez-Insausti, 2005) sheltered under the productivity–diversity hypothesis (Evans et al., 2005b). This hypothesis states that productivity (i.e. the main input of available energy to ecosystems which is the result of plant photosynthesis) limits the number of species present in ecosystems (Mittelbach et al., 2001; Hawkins et al., 2003a). However, the shape of this productivity–diversity relationship is not universal as it had been noted for bird-species diversity and ecosystem productivity in different biogeographical regions (Hawkins et al., 2003b). Therefore, other potential mechanisms may also operate at large scale such as the heterogeneity–diversity hypothesis that states that differences in habitat composition determines difference is species composition (Kerr et al., 2001).

Satellite images provide low cost and large scale assessment for spectral variables that can be linked with incoming energy to ecosystems, and thus to productivity (Kerr and Ostrovsky, 2003). Annual primary production (or plant productivity) is highly correlated with the normalized difference vegetation index (NDVI) (Garbulsky et al., 2010), a spectral proxy for the fraction of photosynthetic active radiation absorbed by the vegetation (Myneni et al., 2002). Methods to estimate primary production from satellite images included the NDVI, the available photosynthetic active radiation and efficiency conversion models. Time series starting at the 1970s and global coverage provide temporal and spatial NDVI variability.

Satellite images have been proved as useful tools for monitoring species distribution and their habitats (Leyequien et al., 2007; Kosicki and Chylarecki, 2012). Studies that predicted bird diversity used NDVI, the enhance vegetation index (EVI), land cover, and habitat structure (Table 1) as proxies of vegetation characteristics. Satellite images were used to predict in most cases bird-species richness, but also bird-species composition, presence and abundance (Table 1). Most studies were performed in temperate forests and local scales, and concentrated primarily in the northern hemisphere for the most developed regions of the world (Table 1). Among these studies, those who evaluated NDVI (or EVI) and bird-species richness at regional scales or larger scales, found that mean annual NDVI (Bonn et al., 2004; Evans et al., 2005a; Phillips et al., 2008; Rowhani et al., 2008; Phillips et al., 2010; Kennedy et al., 2014), or summer/spring NDVI (Hawkins, 2004; Yamaura et al., 2011) were good predictors; and that an increase in the interannual variability in primary production (as captured by NDVI) led to a decrease in species richness (Rowhani et al., 2008). On the contrary, winter NDVI was not a good predictor for bird-species richness or population size (Sarasola et al., 2008; Yamaura et al., 2011), and it was only relevant after land cover categories to explain bird diversity in Canada temperate forest (Coops et al., 2009b). Several studies found that the spatial heterogeneity of vegetation was also as good as a predictor for bird diversity (Bergen et al., 2007; Coops et al., 2009b; Bacaro et al., 2011; Culbert et al., 2012; Price et al., 2013) and even at small spatial scales was the most relevant than energy related variables (St-Louis et al., 2009). Besides the utility of satellites images to estimate species richness, few studies focused on South America to understand the relationships between bird richness and vegetation function at biogeographic scales. Here, we tested if bird-species richness can be predicted with spatial and temporal variables descriptive of productivity, obtained from the NDVI using a dataset from the National Park Network of Argentina (Garbulsky and Paruelo, 2004). We focused on bird species because it is the taxonomic group for which there are more field observations and because it is relevant to define conservation priorities.

2. Materials and methods

We analyzed the relationship between bird species richness and a satellite derived NDVI and its spatial and temporal variance for 33 protected areas of the National Park Network of Argentina (NPNA) (Table S1). The NPNA is relatively well characterized in terms of bird diversity and their vegetation dynamics based on satellite imagery (Chebez et al., 1999; Garbulsky and Paruelo, 2004; Administración de Parques Nacionales, 2011) and represents all major natural biomes of

Argentina, from deserts to tropical forests. The NPNA spans a mean annual precipitation gradient from 139 to 1981 mm/yr and a mean annual temperature gradient from 6.2 to 25.4 °C (Table S1). Also primary production ranges widely between 83 and 1700 g m^{-2} yr^{-1}, and contrasting seasonality between tropical and temperate biomes (Garbulsky and Paruelo, 2004).

For each protected area of the NPNA, we used a single value of bird species richness. Bird species richness for each area represented the sum of all species ever recorded. Bird inventories range from the beginning of 20th century, and include field and museum collections and observations by ornithologists (Chebez et al., 1999; Administración de Parques Nacionales, 2011). We used bird diversity inventories compiled by Chebez et al. (1999) and by the Biodiversity Information System developed by the National Park Administration from Argentina (www.sib.gov.ar; Table S1).

For each protected area belonging to the NPNA, we analyzed mean and temporal variability of the NDVI, as a surrogate for productivity in the ecosystem. We identified a variable number of pixels (81, 162 or 243) depending on the size and heterogeneity of vegetation in each protected area (Table S2). We obtained NDVI data from MODIS sensor (MODerate resolution Imaging Spectroradiometer) on board the Terra satellite (ORNL DAAC, 2014). The NDVI is a normalized spectral index derived from the reflectance of the vegetation in red and infrared portions of the spectrum (Tucker, 1979). Data was composed by one NDVI value for each 16 days period from 2000 to 2011 at 250 m spatial resolution (MOD13Q1 product).

We processed NDVI data to estimate annual and seasonal averages, and the temporal and spatial heterogeneity inside each protected area. Mean NDVI (meanNDVI) is the NDVI average for the 12-years time series and it is used as a proxy for ecosystem productivity. Minimum and maximum NDVI for the whole analyzed period (minNDVI and maxNDVI) are proxies for the lowest and highest incoming available energy amounts in each ecosystem. To estimate minNDVI and maxNDVI we identified the highest and lowest 16-day values of NDVI within a year and averaged them along the 12 years. The difference between maxNDVI and minNDVI (ampNDVI) was a proxy for the seasonality on ecosystem functioning, and we estimated one per year and the 12 years average. The weighted ampNDVI (wampNDVI) expressed in a relative scale (0–1) the seasonal dynamic of vegetation, and was obtained as the ratio between ampNDVI/meanNDVI; we estimated one per year and the 12 year average. Also, we estimated the inter-annual dynamics of meanNDVI, minNDVI, maxNDVI, ampNDVI and wampNDVI (sdmeanNDVI, sdminNDVI, sdmaxNDVI, sdampNDVI and sdwampNDVI) as the standard deviation along the 12 years of data as proxies for the stability of vegetation dynamics. Finally, we estimated the spatial heterogeneity of each area as the range between the first and fourth quartiles (qrtl_NDVI) and the 10 and 90% percentiles (perctl_NDVI) of the NDVI for the whole national park. For qrtl_NDVI and perctl_NDVI we used a single image (July 2014) which covered the whole national park. qrtl_With NDVI and perctl_NDVI we seek to represent the different habitat types after their functional characteristics. In addition, we gathered temperature and precipitation ancillary data from the closest meteorological stations to each national park. Climatic data was provided by the National Meteorological Service of Argentina (www.smn.gov.ar). We performed a stepwise analysis using MATLAB (Mathworks, MA) to identify which satellite derived variable best explained bird diversity, and simple regression between climatic and NDVI variables.

3. Results

Bird-species richness from the protected areas four folded from the Patagonian steppe to the rainforest of northeastern Argentina. National parks in arid ecosystems had 139 bird species in average, followed by temperate forests in Patagonia (144 species), grasslands (226 species), tropical forests and savannas (263 species) and rainforests with 379 species in average. Los Cardones and Baritú were particularly high and low in their diversity in relation to their biome average (Table S1).

Minimum NDVI (minNDVI) was the variable that best explained bird-species richness. minNDVI accounted for 75% of bird species variability, which was 1.6, 2.4 and 2.6 times larger than the variability accounted by meanNDVI, sdwampNDVI and maxNDVI respectively (Table 2 and Fig. 1). A stepwise analysis identified the minNDVI and its spatial heterogeneity (described as the interquartile range of NDVI; qrtl_NDVI) as the two most significant variables ($P < 0.005$ for both cases) (Table 2 and Fig. S1). Together these variables accounted for 80.7% of total variance. The inclusion of the spatial heterogeneity (qrtl_NDVI) in the model reduced the residual mean square error in 12.5% and increased the variance explained in 6.6%. The final model was

$$\text{Bird species richness} = 93.1 + 374.5 \text{ minNDVI} - 208.0 \text{ qrtl\_NDVI}. \tag{1}$$

Minimum NDVI ranged from 0.02 to 0.80 with lower values for Patagonian temperate forest and deserts, and higher values for grassland, sub-tropical forests and savannas and tropical forests. Minimum NDVI was positively related to the accumulated mean annual precipitation ($r^2 = 0.738$; $P < 0.0001$) and minimum temperature ($r^2 = 0.604$; $P < 0.0001$) (Fig. 2). qrtl_NDVI ranged from 0.03 to 0.65 with highest values (qrtl_NDVI > 0.4) for national parks with temperate forests (except Los Glaciares) and mountain areas with wide altitudinal ranges (Campo de los Alisos). qrtl_NDVI for most other parks were below 0.2.

4. Discussion

The minimum seasonal value of the photosynthetic fraction of vegetation (minNDVI) was a good predictor for bird-species richness in areas of Argentina with low human impact. The National Park Network of Argentina is aimed to protect

Table 2

List of variables estimated from normalized difference vegetation index (NDVI) and their relationship with bird species richness. Results from regression analyses where variable were evaluated individually, and from a stepwise analysis where all variables were combined. Ref: Mean, minimum, maximum, amplitude and weighted amplitude of NDVI (meanNDVI, minNDVI, maxNDVI, ampNDVI, and wampNDVI), interquartile and 10–90 percentile of NDVI (qrtl_NDVI and perctl_NDVI).

| Category	Variable	Regression analysis		Stepwise analysis		
		R^2	P	Slope	SE	P
Annual	meanNDVI	0.47	<0.001	−36.0	76.5	0.64
Seasonal	maxNDVI	0.29	0.001	−20.7	50.66	0.69
	minNDVI	0.75	<0.001	374.5	33.0	≪0.001
	ampNDVI	0.06	0.179	−11.5	55.9	0.84
	wampNDVI	0.20	0.009	17.5	32.6	0.60
Inter-annual	sdmeanNDVI	0.01	0.647	−135.5	456.9	0.77
	sdmaxNDVI	0.06	0.179	−374.7	472.9	0.44
	sdminNDVI	0.01	0.661	−5.5	256.0	0.98
	sdampNDVI	0.03	0.364	24.5	266.1	0.93
	sdwampNDVI	0.31	<0.001	10.1	110.3	0.93
Spatial	qrtl_NDVI	0.09	0.080	−208.0	53.6	≪0.001
	perctl_NDVI	0.14	0.036	11.2	97.6	0.91
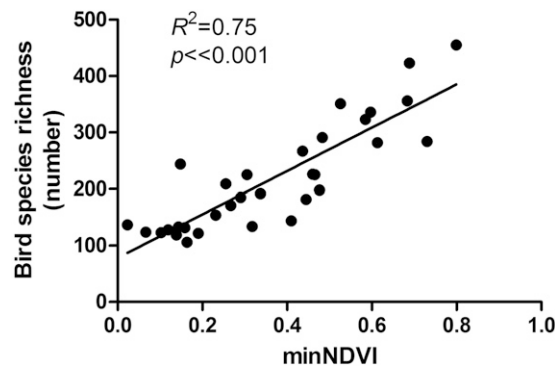
Fig. 1. Relationship between minimum annual value for NDVI (minNDVI) and bird species richness for the National Parks of Argentina. Each symbol represents one national park.

pristine portions of landscape without human use and is perceived as the natural condition for each ecosystem (Garbulsky and Paruelo, 2004; Roldán et al., 2010). Minimum NDVI was typically achieved in winter, the time of year in which energy to ecosystem is incoming at a slowest rate. The inclusion of spatial heterogeneity of NDVI improved the explanation power of the analysis. The spatial heterogeneity of NDVI was used here to track the diversity of habitats within a national park. The interquartile range of NDVI (qrtl_NDVI) tracked differences in habitats highly represented within a protected area. For the National Parks in Patagonia habitat heterogeneity included temperate forests, deserts, and high mountain habitats. Habitats with a different NDVI and/or present in small proportion within a protected area were detected by the difference in the 10–90 percentile, but this measure of the heterogeneity was not relevant in the analysis.

The observed relationship between minNDVI and bird-species richness can be primarily explained by the diversity–productivity, and secondarily by the heterogeneity–diversity hypotheses. The first hypothesis states that the number of species increases with the available energy; and although it had been studied for many years large discrepancies still remain (Hawkins et al., 2003a). In Argentina, bird diversity was strongly related with temperature and weakly related with precipitation (Rabinovich and Rapoport, 1975), two proxies for available energy to ecosystems. Mean July temperature had similar power to predict passerine diversity than mean annual temperature (Rabinovich and Rapoport, 1975). Similarly in our study, minNDVI reflected winter (July) vegetation green cover, and was highly correlated with minimum temperature. Our results suggest that the minimum energy available within a year may be the limiting factor to bird diversity. Minimum available energy can be easily estimated from remote sensing data but it is not commonly included to predict bird-species richness. Among those studies that explored the relationship between satellite images and bird species, few evaluated winter NDVI (Sarasola et al., 2008; Coops et al., 2009b; Yamaura et al., 2011), besides the relevance of seasonal variability to bird diversity (Rowhani et al., 2008; Coops et al., 2009a; Apellaniz et al., 2012; Filloy and Bellocq, 2013).

The second hypothesis states that the difference in habitat composition determines the difference in species composition. As few species are present in a habitat, as the number of habitats increases, so does the number of species (Kerr et al., 2001). After accounting for the effect of available energy, habitat heterogeneity was a relevant factor in this study. Even if habitat heterogeneity played a major influence to explain mammals and butterflies species richness at regional spatial scales, this hypothesis remains less explored than the energy–diversity hypothesis (Kerr and Packer, 1997; Kerr et al., 2001). The use
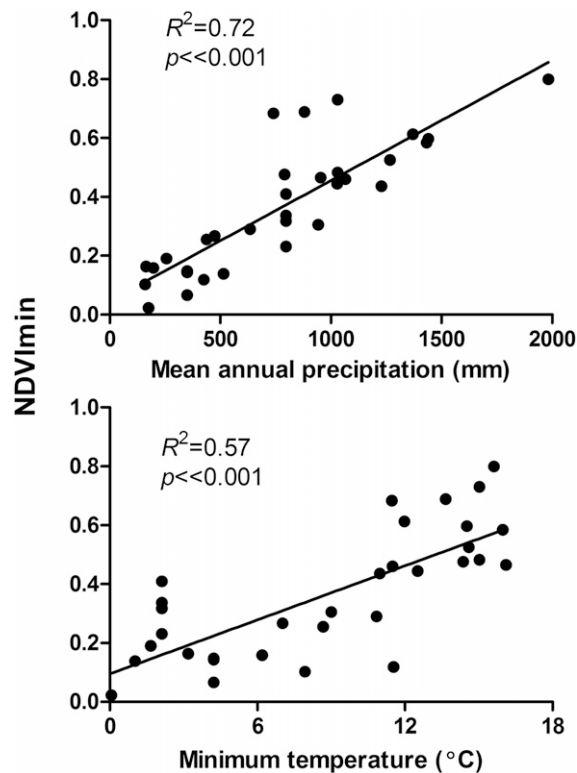
Fig. 2. Relationship between minimum NDVI (NDVImin) and environmental variables for the National Parks in Argentina. Each symbol represents one park.

of remote sensing tools largely improved the ability to quantify patterns of habitat heterogeneity at large scales (Kerr et al., 2001). For birds, habitat heterogeneity quantified by satellite images was scale dependent (Price et al., 2013), and found to be relevant at local (Bergen et al., 2007; St-Louis et al., 2009; Bacaro et al., 2011; Price et al., 2013) and regional scales (Coops et al., 2009b; Culbert et al., 2012). Finally, the hypotheses diversity and habitat heterogeneity or available energy had been tested simultaneously thanks to the use of satellite images since they can provide data for both analyses. Even if the relative relevance of each factor varied (e.g. St-Louis et al., 2009, Culbert et al., 2012) energy and habitat heterogeneity are commonly included (Bergen et al., 2007; Coops et al., 2009b; St-Louis et al., 2009; Bacaro et al., 2011; Culbert et al., 2012).

The relationship between NDVI and bird-species richness represented a simple and inexpensive way to estimate bird diversity at large scales in southern South America. Minimum NDVI and the interquartile NDVI can be obtained from freely available MODIS data, and just three parameters provide the estimation of bird diversity (Eq. (1)). The regional boundaries for which this equation can be used are defined by the biomes included in the National Park Network of Argentina, which are desert, grassland, temperate forest, savannah and tropical forest; similar biomes can be found in Chile, Uruguay, and southern Bolivia, Brazil, and Paraguay, thus making the equation suitable for these regions. Beyond these limits, it should be of limited use: in tropical regions of South America bird diversity can be higher, or in other continents the relationship between energy and bird-species richness can differ markedly (Hawkins et al., 2003a). We developed a spatial relationship between NDVI and bird richness (Chebez et al., 1999; Administración de Parques Nacionales, 2011). This difference between the time series for NDVI and the unique data for bird diversity constrains our ability to understand dynamic relationships between these two variables. Alternatives to the use of Eq. (1) as a surrogate for bird diversity are using birdwatchers records such as eBird (ebird.org) or EcoRegistros (www.ecoregistros.org) but extrapolations on species distributions need to be processed to generate bird species richness. The advantage of the birdwatchers records is that they show real instead of potential bird diversity, and the disadvantage is that many areas threatened by human activities have low densities of birdwatchers, such as the case of the Subtropical Forest of Chaco (Jarvis et al., 2010; Seghezzo et al., 2011). Other alternatives include the use of bird diversity maps generated by more complex models that include climatic variables and topographic variables (Rabinovich and Rapoport, 1975; Rahbek and Graves, 2001; Hawkins et al., 2003a) or compilations of bird species (Jenkins et al., 2013).

Human activities impact both sides of the bird diversity–NDVI relationship. Human dominated landscapes such as agro-ecosystems, impact both the number of bird species (Weyland et al., 2012), and the ecosystem functioning (Guerschman et al., 2003). Crops and forested areas often change bird habitat heterogeneity which impact the number of bird species (Weyland et al., 2012). Annual crops have lower values of minimum NDVI than natural grasslands, while perennial crops have higher values in temperate Argentina (Guerschman et al., 2003). In the tropical forests, crops may have maximum NDVI

higher than natural forest, but a much lower minimum NDVI. Field observations of bird-species richness from agricultural areas may be useful to test this model in highly human managed areas. If the relationship holds the same, it would support the idea that the minimum available energy is a relevant determination of the bird-species richness. However, it is more possible that in agricultural areas human management differentially modifies energy over bird diversity, making minNDVI as a surrogate for bird richness unsuitable for these areas and other approaches may result in better estimators (Cueto and De Casenave, 1999; Apellaniz et al., 2012; Weyland et al., 2012). In conclusion, minNDVI can be used as a surrogate for bird-species richness for large scales at a relative low cost. Thus, minNDVI could meet the demand of managers who seek establishing land use priorities for conservation in areas with scarcely modified.

Acknowledgments

Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.gecco.2015.03.005.

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