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Synergies and trade-offs between renewable energy expansion and biodiversity conservation – a cross-national multifactor analysis

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Abstract

Increased deployment of renewable energy can contribute towards mitigating climate change and improving air quality, wealth and development. However, renewable energy technologies are not free of environmental impacts; thus, it is important to identify opportunities and potential threats from the expansion of renewable energy deployment. Currently, there is no cross-national comprehensive analysis linking renewable energy potential simultaneously to socio-economic and political factors and biodiversity priority locations. Here, we quantify the relationship between the fraction of land-based renewable energy (including solar photovoltaic, wind and bioenergy) potential available outside the top biodiversity areas (i.e. outside the highest ranked 30% priority areas for biodiversity conservation) within each country, with selected socio-economic and geopolitical factors as well as biodiversity assets. We do so for two scenarios that identify priority areas for biodiversity conservation alternatively in a globally coordinated manner vs. separately for individual countries. We show that very different opportunities and challenges emerge if the priority areas for biodiversity protection are identified globally or designated nationally. In the former scenario, potential for solar, wind and bioenergy outside the top biodiversity areas is highest in developing countries, in sparsely populated countries and in countries of low biodiversity potential but with high air pollution mortality. Conversely, when priority areas for biodiversity protection are designated nationally, renewable energy potential outside the top biodiversity areas is highest in countries with good governance but also in countries with high biodiversity potential and population density. Overall, these results identify both clear opportunities but also risks that should be considered carefully when making decisions about renewable energy policies.

Keywords: air pollution mortality, bioenergy, control of corruption, governance, international investment, offsetting, spatial conservation prioritization, trade-off

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Introduction

There is overwhelming evidence that fossil fuels are the main driver of climate change (IPCC, 2013). In addition, fossil fuels are the single largest source of air pollution (World Health Organization, 2013). Simultaneously, extraction of fossil fuels adds to anthropogenic loss, degradation and fragmentation of habitats, which drives the decline of biodiversity (Pimm *et al.*, 2014). These two major environmental challenges have been addressed in international agreements, setting policy

agendas for achieving medium-term targets for climate change mitigation (the Kyoto protocol, followed by the Copenhagen Accord in 2009; UNFCCC) and for biodiversity conservation (Aichi Targets set by the Convention on Biological Diversity 2010).

Climate change and biodiversity loss represent environmental challenges of global scale. While global coordination among countries is strongly advocated in order to effectively address such global challenges, in practice each country tends to act largely independently from each other (IPCC, 2011; Di Minin & Toivonen, 2015). However, the means to address climate change with internationally coordinated efforts exists, for example in the form of international markets for carbon credits

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(IPCC, 2011; REN21, 2014). To this end, the production and trade of bioenergy (one of the main renewable energy sources) is rapidly expanding within the international energy market (REN21, 2014). Bioenergy is often produced in regions where its production is most cost-efficient, such as tropical areas, and consumed elsewhere, often in industrialized countries where there is high demand for energy and high pressure for reducing carbon emissions (REN21, 2014). This is, however, not presently the case for other rapidly expanding renewable energy sources, such as wind and solar energy, for which technical restrictions on power storage and distribution limit their usage to the areas where they are produced (IPCC, 2011). Because of this, wind and solar energy may have much reduced scope in internationally coordinated energy policies. Conversely, protecting biodiversity can be achieved, given sufficient political will, by means of a globally coordinated effort to expand the global protected area (PA) network (Pouzols *et al.*, 2014).

Current and projected rapid changes towards highly intensive land-use regimes threaten the persistence of biodiversity across large regions of the globe (Foley *et al.*, 2005, 2011). Although renewable energy may represent a potential solution to mitigate climate change, it may also be more land-use intensive per unit of energy produced than other sources, such as nuclear (Brook & Bradshaw, 2014). It thus becomes important that biodiversity loss is not hastened as a side product of energy policies targeted at climate change mitigation. If targets to mitigate climate change are to be met through renewable energy (hereafter RE) expansion, this should not undermine the future prospects for biodiversity conservation as stated by the CBD (Convention on Biological Diversity, 2010).

Protected areas (hereafter PAs) are one of the main pillars of biodiversity conservation (Watson *et al.*, 2014). According to Aichi target 11 of the CBD, such a network should be expanded to cover at least 17% of the global terrestrial surface by 2020 (Convention on Biological Diversity, 2010). This entails that large areas of the globe, currently under no protection, would be set aside from any, or most, types of development and resource extraction. In a world dominated by an increasing human population, land area available for supplying modern societies with goods and services, including energy and land for biodiversity conservation, is limited and becoming increasingly scarce (Wise *et al.*, 2009; Verburg *et al.*, 2013). Constraints in available land area may restrict options to simultaneously mitigate climate change and protect biodiversity. On the other hand, RE can represent important socio-economic opportunities to societies (Alam Hossain Mondal *et al.*, 2010; IPCC, 2011; REN21, 2014). RE deployment can contribute

towards job creation and wealth (Chien & Hu, 2008), can lead to an improved environment, and thus health quality (World Health Organization, 2013), and can aid rural development by supplying energy through the deployment of decentralized systems in areas with no access to the grid (Alam Hossain Mondal *et al.*, 2010; Boyle, 2012; REN21, 2014). However, in order for these opportunities to be fully exploited, factors such as governance are also important. Poor governance may deter international and national investments, thereby hindering RE deployment irrespective of the cost-efficiency of harvesting RE sources (Komendantova *et al.*, 2012). Furthermore, if not carefully sited, development of RE may cause serious environmental damage (Fargione *et al.*, 2008; Northrup & Wittemyer, 2013). In summary, it is foreseeable that a conflict may arise over the use of land for RE development vs. conservation, but opportunities may also exist (Katzner *et al.*, 2013; Santangeli & Katzner, 2015).

A few studies have investigated the relationship between renewable or traditional energy consumption and national socio-economic factors (such as gross domestic product) across a set of countries (Gan & Smith, 2011; Kocsis & Kiss, 2014; Ohler & Fetters, 2014). Overall, there is a growing body of evidence highlighting the risks and opportunities from RE development at different scales (Fargione *et al.*, 2008, 2010; McDonald *et al.*, 2009; Hong *et al.*, 2013a,b; Brook & Bradshaw, 2014; REN21, 2014). However, a comprehensive cross-national analysis which links RE potential to socio-economic and political factors, while simultaneously considering biodiversity protection, still has not been performed. Such an analysis would help to understand the risks and opportunities emerging from RE development beyond national-level considerations.

Therefore, in this study we consider the RE potential available from solar photovoltaic panels, wind turbines and a dedicated bioenergy crop sited outside the top biodiversity areas (i.e. highest ranked 30% priority areas for biodiversity conservation), and quantify the relationship of this with selected factors such as national wealth, health, governance and biodiversity assets. Our emphasis is in identifying factors that may represent major risks and opportunities to human societies and the environment from the development of RE, accounting for the different impacts on land use and biodiversity expected from the expansion of solar, wind and bioenergy (Fargione *et al.*, 2008, 2010; Northrup & Wittemyer, 2013; Pogson *et al.*, 2013).

In addition, we also consider another important issue that might have serious repercussions towards tackling the biodiversity crisis: whether the expansion of the current PA network will be carried out by each country independently at the national scale or via an

international collaboration. Recent research suggests that the latter option will yield much higher returns on investment for biodiversity conservation (Pouzols *et al.*, 2014). Although there is a pressing need to implement globally coordinated efforts for effective expansion of the PA network (Di Minin & Toivonen, 2015), what is happening in practice is that each country is identifying national areas for PA expansion independently. This implementation pathway is also supported by the CBD (Aichi Targets set by the Convention on Biological Diversity, 2010). It is therefore timely and relevant to understand how these two alternative ways of achieving biodiversity conservation targets through the expansion of the PA network may affect the challenges and opportunities deriving from simultaneous protection of biodiversity and harvesting of RE.

Materials and methods

We calculated land-based solar photovoltaic, wind (hereafter solar and wind) and bioenergy unrestricted potential (see Pogson *et al.*, 2013; for more information) within the 70% fraction of the landscape with least importance for biodiversity conservation in each country (data from Pouzols *et al.*, 2014). We set the 70% threshold for this study because it implies that 30% of each country's land would be excluded from development, allowing for the cost-efficient achievement of global biodiversity conservation targets (Pouzols *et al.*, 2014; Butchart *et al.*, 2015) and a measurable expansion of RE development (Santangeli *et al.*, 2015). Calculations were made in ARCGIS 10.1 (ESRI, Redlands, CA, USA) using the zonal statistics tool and accounting for the change in cell size by latitude. Because there are two commonly recognized alternative means to identify priority areas for conservation (i.e. globally vs. nationally coordinated; see above), we explored the outcomes of using these two alternatives by considering two scenarios: one where priorities for biodiversity conservation have been identified globally without administrative considerations and the other where priorities are identified for each country separately. Both priorities are based on the distribution of c. 25 000 terrestrial vertebrates, 826 terrestrial ecosystems and land-use model for 2040 (for more details, see Pouzols *et al.*, 2014). We hereafter call these two scenarios the global protection scenario and the national protection scenario, respectively.

We calculated the fraction of energy potential (over the total) available outside the top biodiversity areas for each country. We did so separately for each of the three RE sources (solar, wind and bioenergy) and for each of the two scenarios for the identification of priority areas for biodiversity conservation. This resulted in six variables that were used as the response variables in separate statistical models. We restricted the scope of this study to the terrestrial realm because data for off-shore wind potential were lacking, and because possible impacts of marine energy development on biodiversity are yet to be fully understood (Inger *et al.*, 2009). Similarly, we did not consider hydropower because of the lack of available detailed global

data on its potential, and also because its rate of expansion is declining after most of the potential sites have already been exploited in many regions of the world (Boyle, 2012).

We then selected a set of factors (see Table 1 for descriptions) that may indicate opportunities and risks, to society and the environment from RE deployment. The first group of factors is related to national governance and wealth, because they may influence ability to harvest RE (Komendantova *et al.*, 2012). These factors (see Table 1 for data sources) are political stability and absence of violence/terrorism (hereafter political stability), human development index (hereafter HDI) and corruption perception index (hereafter CPI). We also considered population density and percentage of agricultural land, which may constrain RE deployment, as renewables are more land-use intensive than many other energy sources, such as nuclear (Brook & Bradshaw, 2014). RE may negatively impact biodiversity (Fargione *et al.*, 2010; Northrup & Wittemyer, 2013), even if implemented outside of the top priority areas for biodiversity protection. Thus, we also considered the biodiversity potential of each country (see Table 1). Air pollution mortality was also considered, because the use of RE produces much less air pollution than traditional sources like fossil fuels or inefficient biomass combustion (IPCC, 2011), thereby benefitting human health. Finally, we considered overall energy consumption of each country, with the aim of verifying whether the RE potential in the 70% fraction of landscape correlates to the energy consumption level of a country.

We built six separate beta regression models using the *betareg* package (Cribari-Neto & Zeileis, 2010) in R software v. 3.0.3 (R Core Team, 2013). The response variable (i.e. the sum of energy potential outside the scenario-dependent top biodiversity areas divided by the total energy potential within each country) was separately calculated for each of the three RE sources and for the two scenarios for identifying PAs, thus resulting in six response variables (Fig. 1). Each response variable was used in a separate model with the same set of explanatory variables (see Table 1). The response variable varies from zero, where none of the potential for RE is available outside the top biodiversity areas (i.e. all potential is within the top 30% landscape fraction), to one, where all the RE potential of the country is concentrated outside the top biodiversity areas. Because the response is a proportion, it is appropriate to assume a beta distribution with a logit link function (Cribari-Neto & Zeileis, 2010). We excluded all countries for which the overall national potential was equal to zero for the particular RE considered (i.e. $N = 78$ countries for solar, 92 for bioenergy and 65 for wind under the global protection scenario, and $N = 86, 100$ and 81, respectively, for the national protection scenario) as they have no relevance for this study that focuses on factors related to RE development and biodiversity conservation. These countries were all of very small size.

Energy consumption, population density and HDI were log-transformed to reduce the spread of the data (Zuur *et al.*, 2009). Before fitting the models, we checked for collinearity using variance inflation factor (VIF) analysis. All variables had a VIF value lower than 3, indicating low collinearity levels and no need for excluding any of them from the models (Zuur *et al.*, 2009). We then built six separate full models,

Table 1 List of explanatory variables in the beta regression models, their description, unit, year of the data and source of the data

Factors name	Description	Unit	Year	Source
Human Development Index (HDI)	Composite index of health (life expectancy), education (years of schooling) and wealth (gross national income per capita)	Index from 0 = least developed, to 1 = most developed	2012	World Bank
Corruption Perception Index (CPI)	An index measuring the perceived level of corruption in the public sector of a country	Index from 0 = highly corrupt, to 100 = least corrupt	2012	Transparency International
Political stability	Index based on perceptions of likelihood of political instability and/or politically motivated violence, including terrorism	Index from -2.5 = high instability, to 2.5 = high stability	2012	World Bank
Air pollution mortality	Count of deaths related to air pollution	Deaths per 100 000 capita	2008	WHO
Population density	The density of the population in each country	No. People per km ²	2012	World Bank
Energy consumption	Overall yearly consumption of energy	Quadrillion Btu	2010	EIA
Biodiversity potential	Composite index of relative biodiversity potential of each country based on species representation and their threat status, and the diversity of habitat types present in each country	Index from 0 = no potential, to 1 = maximum potential	2012	World Bank
% Agricultural land	The fraction of land in each country covered by farmed land	Percentage over the total land area	2012	World Bank

Data from World Bank retrieved from www.govindicators.org, data from WHO (World Health Organisation; www.who.int), data from EIA (U.S. Energy Information Administration; www.eia.gov), data from Transparency International (www.transparency.org).

one for each RE source and protection scenario combination. Next we applied model selection based on the Akaike's information criterion (AIC), followed by multimodel inference and averaging (Burnham & Anderson, 2002) using the *MUMIN* package in R (Barton, 2014). We derived averaged coefficients and *P*-values for each variable from across the set of best-ranked models (i.e. with $\Delta AIC < 4$; listed in Table S1). The models had a sample size of 155, 161 and 143 units for solar, wind and bioenergy, respectively, under the global protection scenario, and of 151, 153 and 140 units, respectively, under the national protection scenario.

Results

Global protection scenarios

First, we analysed RE potential of countries in the light of globally coordinated biodiversity priority areas, which are based on analysis of global distributions of species (Pouzols *et al.*, 2014). We found considerable uncertainty regarding the best model within the set of model combinations considered for solar, wind or bioenergy, with no model having an AIC weight >0.25 (Table S1). The top-ranked models (i.e. with $\Delta AIC < 4$)

were able to explain 15–22% of the variation in RE potential available outside the top biodiversity areas defined according to the global protection scenario for expanding the PA network. Overall, the set of factors and their relative importance derived after multimodel averaging were very similar for solar, wind and bioenergy (Fig. 2 left and Table 2). Potential for solar, wind and bioenergy concentrated outside the top biodiversity areas was negatively related to HDI, but unrelated to political stability or the CPI (see Table 2).

We also found that RE potential outside the top biodiversity areas was negatively correlated to biodiversity potential (i.e. the presence of threatened species and diverse habitats; Table 2). This was consistent among the three RE sources considered. Although this result may suggest an opportunity for expanding RE development in countries where biodiversity potential is low, it also has a negative counter-side. This result also suggests that, in countries of high biodiversity potential, most RE is concentrated within the top 30% areas of highest priority for biodiversity conservation. This highlights a potentially very high risk to biodiversity from RE expansion. Additionally, in the case of bioenergy,

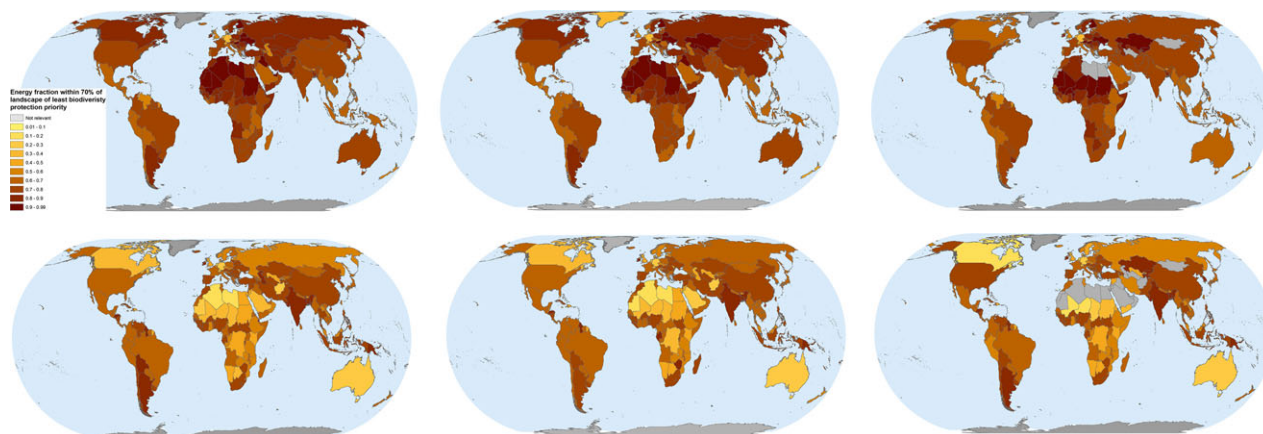


Fig. 1 The fraction of national renewable energy potential within the lowest 70% biodiversity priority areas, for solar (left column), wind (centre) and bioenergy (right) based on globally (upper row) and nationally (lower row) coordinated identification of priority areas for biodiversity. These are the six response variables used in the models (see Materials and methods). Note that in practice the modelling was based on a slightly restricted set of countries compared to that shown in this figure as some countries were excluded from the modelling due to missing data for one or more of the explanatory variables tested. The same legend applies consistently through all the six figures. Grey colour shows countries for which the response variable was not calculated (see Materials and methods).

but not for solar and wind, potential outside the top biodiversity areas is also positively correlated with an increasing percentage of agricultural land (see Table 2). Although this could mean that open landscape is available for producing bioenergy where its potential is highest, it may also indicate competition with land used for food production.

We also found that the fraction of energy potential outside the top biodiversity areas is negatively related to population density for all three RE types, but not or very weakly related to the energy consumption of a country (Table 2). The former result seems encouraging in the light of developing large-scale RE plants in areas of low biodiversity conservation value within countries with low population density where competition for land may not be a limiting factor.

Finally, we found that the potential for solar, wind or bioenergy outside the top biodiversity areas is highest in countries with high air pollution mortality (Table 2). This suggests an opportunity to improve air quality and mitigate climate change by harvesting RE while preserving the best areas for biodiversity conservation.

National protection scenarios

Our second set of analyses replicates the first one, with the exception that national biodiversity priority areas are based on country-specific analysis of national distributions of species and ecosystems (Pouzols *et al.*, 2014). In these analyses, an area can be assigned high priority if it includes species that are nationally rare even if the same species are globally common. Also, unlike the

global analyses, each country has exactly 30% of land in top biodiversity priority areas and 70% in low priority areas. Here, we also found considerable model uncertainty (Table S1), and the amount of variance explained by the best-ranked models was slightly smaller than that of models presented above, at around 10% (Table S2). The set of factors and their relative importance derived after multimodel averaging was very similar for different forms of RE considered here, but the significant variables were different from the previous global protection scenario (Fig. 2). For the national protection scenario, potential for solar, wind and bioenergy concentrated outside the top biodiversity areas was negatively related to CPI and positively related to political stability and population density, and, for bioenergy only, it was positively related to the biodiversity potential across countries (Table 3 and Fig. 2 right).

Under nationally coordinated expansion of the PA network, the proportion of RE outside the top biodiversity areas is highest in countries with good governance (i.e. low CPI and high political stability), which is encouraging for the reconciliation of RE production and biodiversity conservation. The counter-side of this finding is that there may be a threat to biodiversity in countries with poor governance and where most of the RE potential is concentrated within the top 30% biodiversity areas. Contrary to the global protection scenario, here we found that RE potential outside the top biodiversity areas appears positively correlated to population density (Table 3). Consequently, if areas of high value for biodiversity protection are identified independently for each country, high RE potential will be available

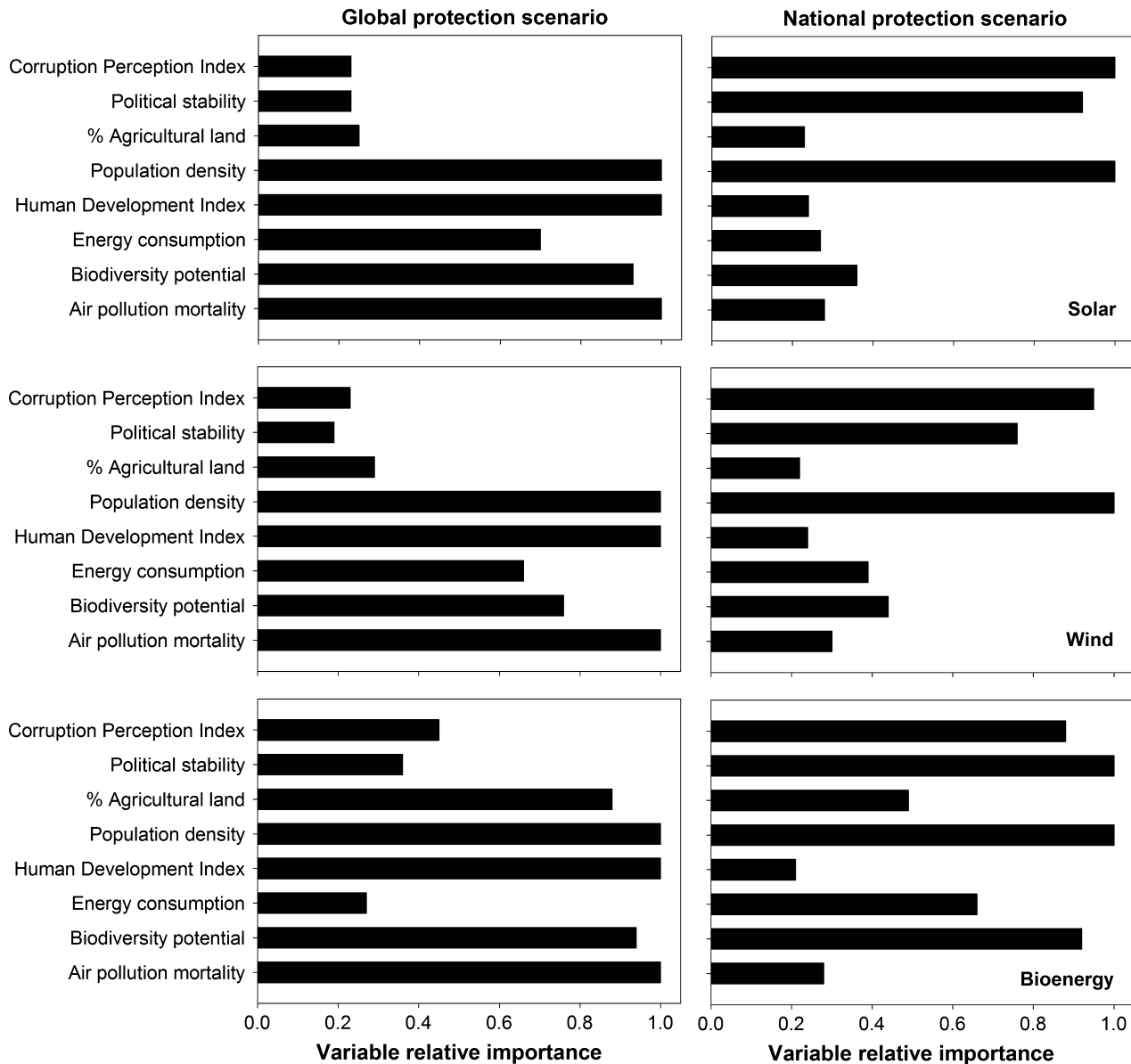


Fig. 2 The relative importance of each factor as they link to the potential fraction for solar, wind and bioenergy (upper, central and lower row, respectively) outside the top biodiversity areas (i.e. outside the highest ranked 30% priority areas for biodiversity conservation) based on the global protection scenario (left column) and national protection scenario (right column; Pouzols *et al.*, 2014). The values are derived from model averaging and multimodel inference based on the best-ranked models according to Akaike’s information criterion (Tables 2 and 3, and Tables S1 and S2). Higher values indicate higher importance of the factor.

outside the top biodiversity areas in the most densely populated countries. While this may imply challenges due to limited land available for RE production in general, it may also represent an opportunity for producing RE where most people live, thereby limiting the need for energy storage and transport.

Ultimately, the positive correlation between RE potential outside the top biodiversity areas and national biodiversity potential contrasts with the findings for global biodiversity priorities. Under the national biodiversity

conservation scenario, it appears that countries with high biodiversity potential also have high opportunities for harvesting much of their national RE outside the top biodiversity areas (Table 3). In these countries, biodiversity-rich areas cover more than 30% of the landscape.

Discussion

We combine information on potential for expanding RE with detailed data on priority areas for biodiversity

Table 2 Results of the models (showing model-averaged coefficients and standard errors, Z- and P-values across beta regression models) using the fraction of renewable energy potential available outside the top biodiversity areas identified based on the global biodiversity scenario (i.e. globally coordinated ranking of areas for biodiversity conservation). For details and interpretation of the variables, see Table 1

Variable	Solar				Wind				Bioenergy			
	Beta	SE	Z	P-value	Beta	SE	Z	P-value	Beta	SE	Z	P-value
Intercept	2.144	0.348	6.17	<0.001	2.089	0.341	6.12	<0.001	2.593	0.409	6.33	<0.001
Air pollution mortality	0.013	0.004	3.07	0.002	0.015	0.004	3.50	<0.001	0.015	0.005	2.85	0.004
Biodiversity potential	-0.007	0.003	2.09	0.037	-0.007	0.003	1.92	0.055	-0.007	0.003	2.26	0.024
Energy consumption	0.151	0.077	1.97	0.049	0.149	0.079	1.88	0.060	0.069	0.089	0.78	0.438
Human development index	-1.661	0.647	2.57	0.010	-1.879	0.620	3.03	0.002	-2.250	0.836	2.69	0.007
Population density	-0.110	0.038	2.86	0.004	-0.095	0.038	2.52	0.012	-0.207	0.049	4.22	<0.001
% Agricultural land	0.001	0.002	0.61	0.545	0.002	0.002	0.86	0.389	0.006	0.003	2.18	0.029
Political stability	0.024	0.060	0.41	0.685	-0.011	0.058	0.19	0.852	0.071	0.074	0.95	0.340
Corruption perception index	0.001	0.003	0.44	0.657	0.001	0.003	0.48	0.634	0.005	0.004	1.34	0.181

Values in bold font depict significant variables for each of the three renewable energy sources.

Table 3 Results of the models (showing model-averaged coefficients and standard errors, Z- and P-values across beta regression models) using the fraction of renewable energy potential available outside the top biodiversity areas identified based on the national biodiversity scenario (i.e. independent nationally developed ranking of areas for biodiversity conservation). For details and interpretation of the variables, see Table 1

Variable	Solar				Wind				Bioenergy			
	Beta	SE	Z	P-value	Beta	SE	Z	P-value	Beta	SE	Z	P-value
Intercept	0.394	0.266	1.48	0.140	0.373	0.274	1.36	0.173	-0.243	0.442	0.55	0.583
Air pollution mortality	0.003	0.004	0.78	0.436	0.004	0.004	0.91	0.366	0.004	0.007	0.64	0.519
Biodiversity potential	0.004	0.003	1.12	0.263	0.004	0.004	1.25	0.213	0.011	0.005	2.08	0.037
Energy consumption	-0.051	0.077	0.67	0.505	-0.094	0.083	1.13	0.257	-0.212	0.114	1.87	0.062
Human development index	-0.481	0.707	0.68	0.496	-0.506	0.692	0.73	0.465	0.162	1.124	0.15	0.885
Population density	0.134	0.044	3.05	0.002	0.119	0.044	2.68	0.007	0.280	0.072	3.87	<0.001
% Agricultural land	0.002	0.002	0.66	0.510	0.002	0.002	0.78	0.437	-0.005	0.004	1.37	0.172
Political stability	0.153	0.070	2.18	0.029	0.134	0.068	1.97	0.049	0.396	0.111	3.57	<0.001
Corruption perception index	-0.009	0.004	2.46	0.014	-0.008	0.004	2.18	0.029	-0.012	0.005	2.31	0.021

Values in bold font depict significant variables for each of the three renewable energy sources.

protection and relate it to factors that may represent opportunities, but also risks from developing RE at a cross-national level. We show that very different opportunities and challenges emerge if the priority areas for biodiversity protection are identified globally or designated nationally and separately by each country.

Opportunities for and risks in harvesting RE while protecting biodiversity

Global protection scenarios. The results suggest that there is great scope for developing RE in countries with high development needs (i.e. with low HDI), where the energy potential fraction outside of most important biodiversity areas is highest. In countries with high development needs, about 1.3 billion people lack access to

electricity and rely on heavily polluting energy sources for needs such as heating and cooking on inefficient fires and stoves in confined spaces (World Energy Outlook, 2011). This, altogether, contributes a large fraction of GHG emissions, poor air quality and consequent human mortality that could be reduced with a shift towards renewables (World Health Organization, 2013). This is indeed possible, because unlike traditional energy sources, including most fossil fuels and nuclear, RE sources, such as wind, solar and bioenergy, are well suited for deployment in decentralized systems (Boyle, 2012). Their deployment in rural areas of countries with high development needs can bring not only clean electricity and improvements to air quality and health, but can also contribute to job creation (REN21, 2014). Clearly, harvesting solar and wind would require

investments, as well as know-how, which may be lacking in less developed countries. However, we show that there is no apparent significant relationship between RE potential outside the top biodiversity areas and governance factors, such as political stability and CPI (but see however findings from the national protection scenario below). This suggests that there are countries suitable for development of renewables with high energy potential outside of their most important biodiversity areas.

Our finding that the countries with highest RE potential outside the top biodiversity areas are also less densely populated may be interpreted as an opportunity, but it also entails technical challenges owing to energy transport and storage. Here, land may be comparatively easily available for the deployment of renewable energies, which typically require more area per unit of energy generated than other sources (Brook & Bradshaw, 2014). However, the same result also suggests an impending threat to biodiversity, as the most densely populated countries have highest RE potential concentrated within the top 30% biodiversity priority areas. This threat appears even more serious given that we also found the national biodiversity potential to be negatively, albeit weakly, correlated with RE potential outside the top biodiversity areas. In other words, countries with highest biodiversity potential have most of their RE opportunities concentrated within their most valuable areas for biodiversity protection. In these countries, it will be challenging to protect the great biodiversity asset of global importance while providing clean energy from renewables (this outcome is however not apparent under the national protection scenario). Under such challenging conditions, a shift towards an energy mix that would be more heavily based on nuclear energy may represent a compromise worth considering for balancing the need of biodiversity conservation, energy production and climate mitigation (Brook & Bradshaw, 2012, 2014).

The positive, albeit weak, relationship between bioenergy potential outside the top biodiversity areas and the proportion of agricultural area within a country may indicate an opportunity for harvesting bioenergy where the land is already farmed without impacting on key areas for biodiversity conservation. In practice, this is challenging because bioenergy production requires among the largest amount of area per unit of energy generated (Brook & Bradshaw, 2014) and the land area, even of marginal land, that could be spared to bioenergy production is limited. This implies that large expansion of bioenergy will inevitably subtract land from other uses of critical importance for society (e.g. food production). This may result in impacts (e.g. expansion of anthropogenic land uses) that may spill over areas of key importance for biodiversity, such as

primary forests in tropical areas (Fargione *et al.*, 2010; Wich *et al.*, 2014; Santangeli *et al.*, 2015). Many such areas have previously been identified as biodiversity hotspots (Myers *et al.*, 2000), key sites with species in imminent danger of becoming extinct (Alliance for Zero Extinction sites; www.zeroextinction.org) and sites with natural habitats of irreplaceable biodiversity value (Gibson *et al.*, 2011). Many such areas are rapidly losing natural intact vegetation, particularly where the land is deemed suitable for agriculture (Sloan *et al.*, 2014). Setting aside land for bioenergy cultivation in these regions will not only cause biodiversity loss, but may also fail to provide significant amounts of energy or mitigate changes in global climate (Fargione *et al.*, 2008; Pogson *et al.*, 2013). In already farmed areas of high soil productivity, conversion to bioenergy production will inevitably compete with food production and possibly hasten the recent phenomenon of land grabbing in the developing world (Rulli *et al.*, 2013; Nelson *et al.*, 2014). Given the steadily increasing global demand for food, low-carbon energy sources other than bioenergy, such as solar, wind and nuclear (Brook & Bradshaw, 2014), should be considered in countries where conflicts over limited land may arise. However, bioenergy is among the few RE sources that could provide power for transportation using existing infrastructures. If produced in open landscapes of low biodiversity value, bioenergy could contribute to reducing the GHG emissions associated with land, sea and air transportation (REN21, 2014).

Interestingly, potential of solar, wind and bioenergy outside the top biodiversity areas is greatest in countries with high air pollution mortality. Outdoor air pollution is considered one of the major environmental risks to human health, possibly responsible for an estimated 3.3 million premature deaths per year globally, the majority of which occur in developing countries (World Health Organization, 2013). Reducing air pollution will lead to a reduction in diseases such as stroke, lung cancer and heart disease, as well as chronic and acute respiratory diseases such as asthma (World Health Organization, 2013). Particularly in developing countries, most air pollution is caused by inefficient combustion of coal and diesel fuel (World Energy Outlook, 2011). Improving access to modern, efficient and clean energy technologies with limited air pollution and GHG emissions, such as RE, should thus be at the top of national policy agendas (World Energy Outlook, 2011).

National protection scenarios. The findings based on national independently developed biodiversity priority areas highlight a potentially great opportunity, because countries with good governance appear to have most of their RE resources concentrated in areas of low biodiversity value. These countries, because of their good

governance, may attract large international investments that could allow harvesting a large fraction of the available RE sources where they do not impact key biodiversity areas. It is, in fact, relatively well known that international investors are reluctant to support projects in countries with poor governance (i.e. high corruption and political instability; see e.g. Zhao *et al.*, 2003). In addition, and opposite to the findings from the global protection scenario, here we show that RE potential outside the top biodiversity areas positively correlated with population density. This may suggest a further opportunity, especially in the short term. Although technologies for storing and transporting the energy are developing fast (Boyle, 2012), they may not yet be advanced enough to allow efficient harvest, storage and transport of large amounts of RE from remote areas. In the light of this, the availability of large amounts of RE concentrated outside the top biodiversity areas and within highly populated countries means that a large part of that RE can be efficiently harvested and used locally without major restrictions imposed by energy transport and storage. This could ultimately allow a large contribution towards tackling climate change while maintaining a path towards reaching global biodiversity and sustainability targets (Aichi Targets set by the Convention on Biological Diversity, 2010). However, this scenario, based on the national designation of priority areas for biodiversity conservation, was recently found to yield very inefficient results for biodiversity protection, compared to internationally coordinated conservation measures (Pouzols *et al.*, 2014; Di Minin & Toivonen, 2015). Therefore, we caution that the opportunities for harvesting RE under the national biodiversity scenarios may, in fact, represent only suboptimal solutions for biodiversity conservation at the global scale.

Policy implications

Renewable energies are perhaps one of the major drivers of future land-use change, but also a represent a key solution to address climate change. Recently, their deployment has been increasing rapidly among the developing and emerging nations of Central and South America, Africa and Asia, where targeted energy policies have recently been enacted (REN21, 2014). Here, we show that the best opportunities, but also the biggest challenges, for harvesting RE while protecting biodiversity are largely dependent on the way in which priority areas for biodiversity conservation are designated (i.e. the global vs. national protection scenario). Under the globally coordinated protection scenario, most challenges and also opportunities concentrate in the developing world, where renewables may also contribute to improve human health. Conversely, the national protec-

tion scenario highlights large opportunities for harvesting RE while protecting biodiversity in the countries with good governance and high population density.

These findings thus underscore important policy implications for improving the quality of the environment and the quality of life for people. Ultimately, only by choosing a globally coordinated framework for actions will it be possible to effectively address challenges related to global climate change and biodiversity loss in a timely manner, while simultaneously allowing for the sustainable development of societies in the developing world. Failure to coordinate actions globally would most likely jeopardize national efforts for tackling climate change and biodiversity protection, with irreversible negative consequences for the health of ecosystems and humans alike.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. This file includes all of the supporting material associated to the printed version of the main paper by Santangeli *et al.* 'Synergies and trade-offs between renewable energy expansion and biodiversity conservation – a cross-national multi-factor analysis' published in *Global Change Biology Bioenergy*.

Table S1. Best-ranked models ($\Delta AIC < 4$) used for the multi-model averaging and inference for the global biodiversity priority areas.

Table S2. Best-ranked models ($\Delta AIC < 4$) used for the multi-model averaging and inference for the independent national biodiversity priority areas.