N deposition as a threat to the World's protected areas under the Convention on Biological Diversity

A. Bleeker[a]

W.K. Hicks[b]

F. Dentener[c]

J. Galloway[d]

J.W. Erisman[a,e]

[a] Energy research Centre of the Netherlands (ECN), Petten, The Netherlands
[b] Stockholm Environment Institute (SEI), University of York, UK
[c] European Commission, Joint Research Centre, Ispra, Italy
[d] University of Virginia, VA, USA
[e] VU University Amsterdam, The Netherlands

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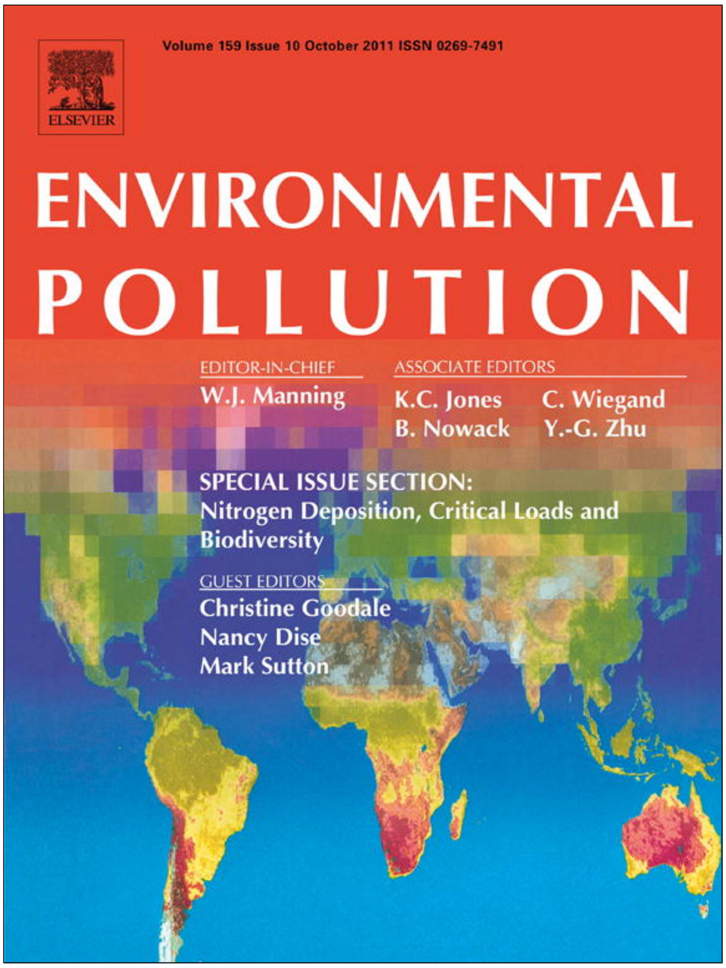

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A. Bleeker [a,*], W.K. Hicks [b], F. Dentener [c], J. Galloway [d], J.W. Erisman [a,e]

[a] Energy research Centre of the Netherlands (ECN), P.O. Box 1, 1755ZG Petten, The Netherlands
[b] Stockholm Environment Institute (SEI), University of York, UK
[c] European Commission, Joint Research Centre, Ispra, Italy
[d] University of Virginia, VA, USA
[e] VU University Amsterdam, The Netherlands

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ABSTRACT

This paper combines the world's protected areas (PAs) under the Convention on Biological Diversity (CBD), common classification systems of ecosystem conservation status, and current knowledge on ecosystem responses to nitrogen (N) deposition to determine areas most at risk. The results show that 40% (approx. 11% of total area) of PAs currently receive >10 kg N/ha/yr with projections for 2030 indicating that this situation is not expected to change. Furthermore, 950 PAs are projected to receive >30 kg N/ha/yr by 2030 (approx. twice the 2000 number), of which 62 (approx. 11,300 km^2) are also Biodiversity Hotspots and G200 ecoregions; with forest and grassland ecosystems in Asia particularly at risk. Many of these sites are known to be sensitive to N deposition effects, both in terms of biodiversity changes and ecosystem services they provide. Urgent assessment of high risk areas identified in this study is recommended to inform the conservation efforts of the CBD.
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1. Introduction

Over the last century human activities led to a dramatic increase in the emission of reactive nitrogen (N) to the environment (Holland et al., 1999; Galloway et al., 2008). In particular, different technological developments increased the rate of crop production in agriculture by means of artificial fertilizer, or industrial production and by fossil fuel burning (Erisman et al., 2008). Although these increases provided a higher standard of living, they have also caused considerable environmental and human health impacts (Vitousek et al., 1997; Townsend et al., 2003; Johnson et al., 2010). Effects of N emissions to the environment are numerous and evidence is available that the different human activities disturb the natural N cycle in a serious way (Galloway et al., 2004). Policy has come into force fighting these negative effects in some regions of the world, mainly in Europe and USA, but the growing human demand for food and energy at a global scale will result in an increasing input of reactive N into the environment (Galloway et al., 2008; Erisman et al., 2008).

Eventually, most of the emitted reactive N to the atmosphere will be deposited to the Earth's surface, either close to the sources (e.g. reduced N) or in remote areas (e.g. chemical transformation and transport of oxidized and reduced N) located far from human activities, where it is often the dominant source of reactive N in N-limited systems (e.g. Phoenix et al., 2006). Once introduced to these systems, this N can then be the cause of different impacts, of which the impact on biodiversity is becoming a major concern. The role of N in biodiversity changes has been studied extensively in Europe and USA, with most research focusing on changes in plant species composition and diversity (e.g. Goulding et al., 1997; Haddad et al., 2000; Bobbink et al., 2010). According to Bobbink et al. (2010) the effect of N deposition depends on: a) the duration, the total amount and the N form of the deposition, b) the intrinsic sensitivity of the (plant) species and c) the abiotic conditions of the ecosystem. Recognition of these aspects resulted in the development of critical loads for N deposition, where a critical load represents an exposure to a pollutant below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge (Nilsson and Grennfelt, 1988). At the global scale, it is becoming increasingly clear that N deposition also plays a role in biodiversity loss alongside other major factors such as land-use change, climate change

* Corresponding author.
E-mail address: a.bleeker@ecn.nl (A. Bleeker).

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and alien invasive species (Sala et al., 2000; Clark and Tilman, 2008; Bobbink et al., 2010; Butchart et al., 2010). However, the extent to which N deposition has an effect on biodiversity, in comparison to the other issues is not yet fully quantified.

Biodiversity loss is a major international concern recognised in the Millennium Ecosystem Assessment and evidenced by the establishment of the United Nations (UN) Convention on Biological Diversity (CBD) in 1992. With the signing of this Convention concern for biodiversity was awarded a higher political profile. With its main objective: '… the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources, …', this legally-binding global treaty commits the international community to addressing biodiversity loss and recognising its significance to society. As part of the CBD the Programme of Work on Protected Areas (POWPA) was established in 2004 to 'support the establishment and maintenance, by 2010 for terrestrial and by 2012 for marine areas, of comprehensive, effectively managed, and ecologically representative national and regional systems of protected areas that collectively, *inter alia* through a global network contribute to achieving the three objectives of the Convention and the 2010 target to significantly reduce the current rate of biodiversity loss at the global, regional, national and sub-national levels'. As such the Protected Areas (or PAs) can be seen as cornerstones of in-situ conservation of biodiversity, by means of protecting representative examples of all major ecosystem types. Following a description from Dudley (2008), PAs can have different functions:

1) Set aside areas, maintaining functioning natural ecosystems (acting as refuges for species and maintain ecological processes), 2) Benchmarks against which we understand human interactions with the natural world, 3) Providing direct human benefits (recreation, genetic potential of wild species and environmental services provided by natural ecosystems) and 4) Essential for vulnerable human societies by conserving places of value such as sacred natural sites. PAs are not only set up by governments, but are also established by e.g. local communities, indigenous peoples, individuals, companies, etc.

In total there are more than 120,000 PAs covering about 12% of the Earth's land area, 6% of the territorial seas and about 0.5% of the extra-territorial seas). Examples of PAs are: national parks, nature reserves, wilderness areas and wildlife management areas. Using the International Union for Conservation of Nature (IUCN) definition, a PA is 'a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystems services and cultural values'; and six IUCN PA categories have been set up (see Table 1). While originally these categories were only intended to help collate data and information on PAs, at present the categories are used for planning purposes, and also for setting regulations and negotiating land and water uses.

Table 1
IUCN classification of Protected Areas (PAs).

Category	Title	Managed for
Ia	Strict Nature Reserve	Science
Ib	Wilderness Area	Wilderness protection
II	National Park	Ecosystem protection and recreation
III	Natural Monument	Conservation of specific natural features
IV	Habitat/Species Management Area	Conservation through management intervention
V	Protected Landscape/Seascape	Landscape/seascape conservation and recreation
VI	Managed Resource Protected Area	Sustainable use of natural ecosystems

Information about the PAs is available via the World Database on Protected Areas (WDPA), which consists of the largest assembly of data on the world's terrestrial and marine protected areas. The WDPA is a joint project of the United Nations Environment Programme (UNEP) and IUCN. The database holds spatial and attribute information from governments and non-governmental organizations on the over 120,000 national and international protected areas. According to the annual report of the programme, the database is used to 'complete the periodic United Nations List of Protected Areas that tracks the status of the world's protected areas' (WCMC, 2008). Among other purposes, the database is also used for environmental impact assessments related to the PAs, as well as international emergency response action planning.

It is well established that N deposition threatens plant diversity in Europe and North America and it is projected to increase in other regions such as the tropics, where much less is known about the sensitivity of ecosystems to N (Phoenix et al., 2006; Bobbink et al., 2010). The growing global production of reactive N and the related increases in N deposition in certain parts of the world, especially Asia, may be affecting the biodiversity of parts of the PAs under POWPA.

The problem is recognised by the Convention on Biological Diversity (CBD) that has N deposition as one of its biodiversity indicators to illustrate progress toward the 2010 biodiversity target to halt biodiversity loss, but this does not identify the sensitive systems (CBD, 2010).

In this paper we therefore evaluate the changing N deposition patterns and the consequences this might have for the PAs. The PAs are overlaid with global estimates of N deposition to allow a preliminary assessment of the extent to which these areas may be under threat from N. The structure of the PA database allows identification of individual PAs that are threatened. Because of this, there is the potential that measures can be taken to protect the PAs from further deterioration. The PAs were not only overlaid with N deposition information, but also combined with information about the World Wildlife Fund (WWF) Global200 (G200) ecoregions (after Olson and Dinerstein, 2002) and Biodiversity Hotspots (Myers et al., 2000), to give a further indication of the potential importance of N deposition impacts on the conservation value of the protected areas. Biodiversity Hotspots (Phoenix et al., 2006) and G200 ecoregions (Bobbink et al., 2010) have previously been overlaid separately with N deposition estimates but this is the first study to combine these assessments with the PAs under the CBD in an attempt to promote assessments of the less studied areas under threat from excess N deposition, so that they may be protected.

2. Global N deposition rates

As mentioned in the introduction, human development patterns are reflected in the changing levels and patterns of N deposition. Due to a lack of global deposition measurements, modelled data that have been validated with available monitoring data as far as possible, are used in this study. These data are the ensemble mean average from a multi-model comparison, where the N deposition estimates of the mean values for 23 different models are used (Dentener et al., 2006); as mean deposition values consistently showed the best comparison with the measurements. The 23 models calculate the deposition at different resolutions, ranging from 1×1 to 3×3 degrees, but the mean values used in this study have a resolution of 1×1 degree. In this study two datasets of total N deposition were used: a baseline dataset for the year 2000 and a dataset derived from applying a 'current legislation' (CLE) scenario to estimate deposition in the year 2030. This scenario was developed by IIASA (International Institute for Applied Systems Analysis) and is described by Dentener et al. (2005). In the early 2000s a number of countries issued legislation on advanced

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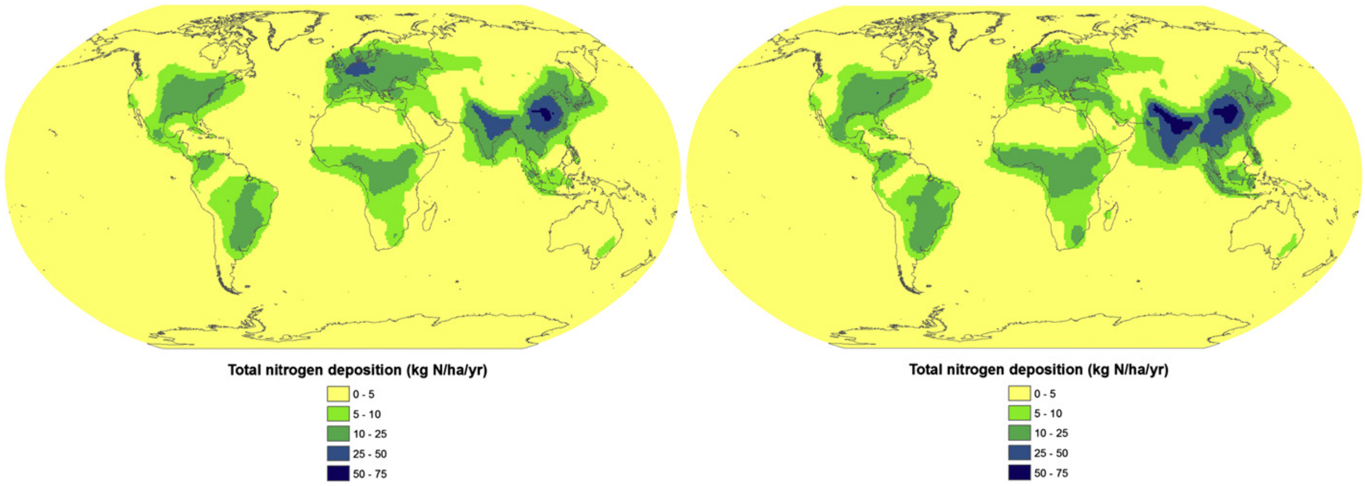

Fig. 1. Spatial distribution of total nitrogen deposition (in kg N/ha/yr) for 2000 (left) and 2030 (right) (after Dentener et al., 2006).

emission controls, affecting the air emissions at regional and global scales. This formed the basis for the CLE scenario, which is consistent with the energy and activity data of the IPCC (Intergovernmental Panel on Climate Change) SRES (Special Report on Emissions Scenarios) B2 scenario. For NH_3, IIASA and IPCC-SRES have no emission scenarios available. Therefore, Dentener et al. used the IMAGE (Integrated Model to Assess the Global Environment) model (Eickhout et al., 2004) with regional assumptions on population increase and agricultural developments from the SRES-B2 scenario, to make a separate estimate for the development of NH_3 emissions. It should be noted that the scenarios represent the future emission situation as envisaged around the year 2000. Therefore, emission abatement legislation that was developed after 2000 is not included in these calculations.

Fig. 1 shows the spatial distribution of the total N deposition for the two years. The maps clearly show an increase in N deposition mainly in areas that are currently showing strong economical growth (e.g. India & China).

3. Classification of the PAs

As already mentioned above, the objectives and management strategies for PAs can differ widely. The IUCN categories (Table 1) do not provide information on how a protected area is governed and also not about the present N deposition status, but give indirect information about the level of protection for individual PAs (I highest and VI lowest level of protection). When distributing the PAs over the different IUCN classes (Fig. 2), most PAs with a known classification are classified as Habitat/Species Management Area (category IV). However, in terms of surface area categories II and VI are the most important (respectively National Park and Managed Resource Protected Area). This difference in the number of sites and surface area of sites is considered carefully in this paper, since there may be large differences when number or surface area data are expressed as percentages, especially since the PAs can have areas up to 925,000 km^2.

Another way of classifying the PAs is by overlaying them with information about the WWF G200 Ecoregions (after Olson and Dinerstein, 2002). G200 Ecoregions are defined as areas containing a distinct assemblage of natural communities and species that constitute priority conservation areas, which if conserved would protect a broad diversity of the earth's ecosystems (see Fig. 3). By overlaying the two datasets the importance of the PAs in terms of potential biodiversity protection can be assessed, and when overlaying them with N deposition data the threat to these PAs (now containing information about their importance) can be assessed. In

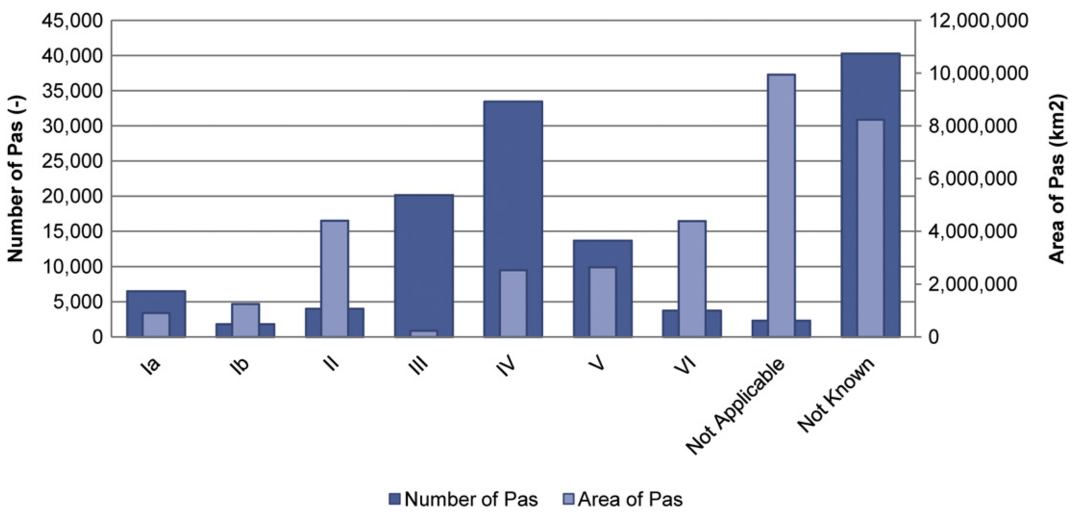

Fig. 2. PA distribution over the IUCN categories and surface areas (in km^2).

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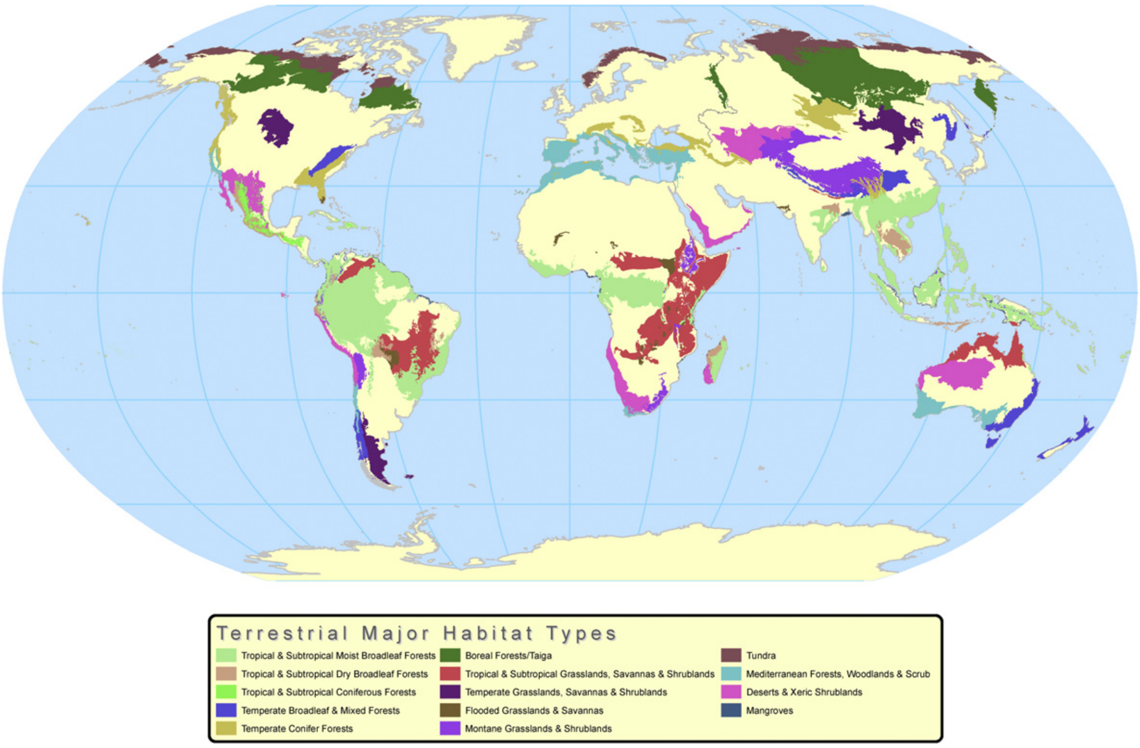

Fig. 3. Overview of the WWF G200 Ecoregions.

total about 23% of the number of PAs can be assigned to a G200 Ecoregion, while this is about 74% in terms of area. When considering the PAs located within the Ecoregions (in terms of Biomes), many of the PAs are located in the Temperate Broadleaf & Mixed Forest ecoregion type, while in terms of area most of them can be found in Tropical & Subtropical Moist Broadleaf Forests (Table 2).

The third way of classifying the PAs is by overlaying them with spatial Biodiversity Hotspot data (see Fig. 4). These Hotspots (Myers et al., 2000) are firstly defined by level of endemism (uniqueness of plants/animals species to an area) and secondly by degree of threat (>70% primary habitat for endemics lost). In total 18860 PAs are located within a Hotspot (15% of the total PAs), representing 9,208,088 km^2 (27% of the total area).

By overlaying the three datasets (PAs, WWF G200 Ecoregions and Biodiversity Hotspots) information is available about the conservation value of the individual PAs and the numbers of endemic species. Together, this shows the importance of these classified PAs when evaluating the exposure to high loads of N deposition.

4. PAs under threat of N deposition

Although the above-mentioned classification systems give some indication of 'conservation importance', they do not give an indication of the extent to which N deposition poses a threat to these systems. In this study we used 10 kg N/ha/yr as a tentative threshold for N deposition effects, based on empirical critical load studies from Europe (Phoenix et al., 2006; Bobbink et al., 2010), although some research suggests that effects may occur over the long-term at chronic levels of N deposition lower than 10 kg N/ha/yr (Clark and Tilman, 2008; Bobbink et al., 2010). It represents a threshold above which changes in ecosystem

Table 2
Distribution of the Protected Areas (PAs) – number and surface area (in km^2) over the WWF G200 Ecoregions, as percentage of the total number/area of PAs within the Ecoregions. Also given are the same numbers, but now as percentage of the total number/area of PAs.

	Percentage of PAs in G200 ecoregions		Percentage of total PAs	
	Number	Surface area	Number	Surface area
Trop. & Subtropical Moist Broadleaf Forests	18	36	4	20
Trop. & Subtropical Dry Broadleaf Forests	1	2	<1	1
Trop. & Subtropical Coniferous Forests	1	5	<1	2
Temp. Broadleaf & Mixed Forests	25	5	6	5
Temp. Conifer Forests	22	4	5	2
Boreal Forests/Taiga	3	6	1	5
Trop. & Subtrop. Grasslands, Savannas & Shrublands	5	14	1	11
Temp. Grasslands, Savannas & Shrublands	2	2	<1	2
Flooded Grasslands & Savannas	0	5	<1	3
Montane Grasslands & Shrublands	2	8	<1	5
Tundra	2	4	<1	5
Mediterranean Forests, Woodlands & Scrub	17	3	4	1
Deserts & Xeric Shrublands	2	5	<1	12
Mangroves	1	1	<1	1
Grand total	100	100	23	74

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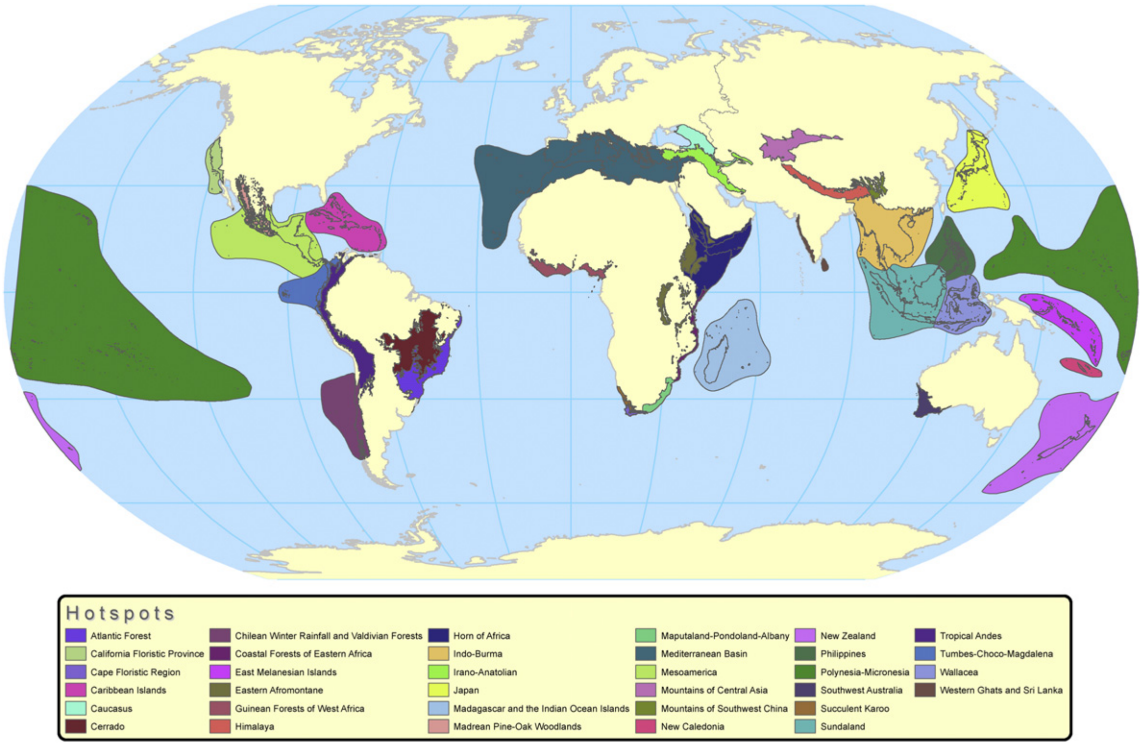

Fig. 4. Overview of the Biodiversity Hotspots.

functioning may occur (Bobbink et al., 1998; Bouwman et al., 2002) but it must be stressed that this threshold is predominantly based on experimental studies conducted on temperate ecosystems (see Discussion). Dentener et al. (2006) estimated that about 10% of the area of world's natural vegetation was exposed to N deposition exceeding 10 kg N/ha/yr for 2000, while this is estimated to be 15% for 2030. However, this estimate was based on an overlay of the deposition dataset with the crude classification of land cover by the Global Land Cover 2000 dataset (http://www.-gvm.jrc.it/glc2000), and does not discriminate between the different vegetation types and/or classifications (which formed the motivation for this work).

Fig. 5 gives an overview of the number of PAs (classified according to the IUCN system) exposed to the different 2030 deposition levels. Of the 126,069 PAs recorded in the WDPA, in 2030 50,805 (40%) will be exposed to N deposition higher than 10 kg N/ha/yr. About 8% of the PAs will be exposed to levels equal to twice the threshold value. Most of the exceeded situations are expected to be in IUCN category IV ('Habitat/Species Management Area'). However, when expressing the PAs and their corresponding deposition classes in terms of area, about 11% of the PA area will be exposed to deposition higher than 10 kg N/ha/yr (which is consistent with Dentener et al., 2006; however, their exceeded area was related to all global nature area) and about 2% of the area exposed to levels higher than 20 kg N/ha/yr.

Fig. 5 shows that in 2030 a large number of PAs will be exposed to deposition higher than 10 kg N/ha/yr. Fig. 6 and Table 3 show this

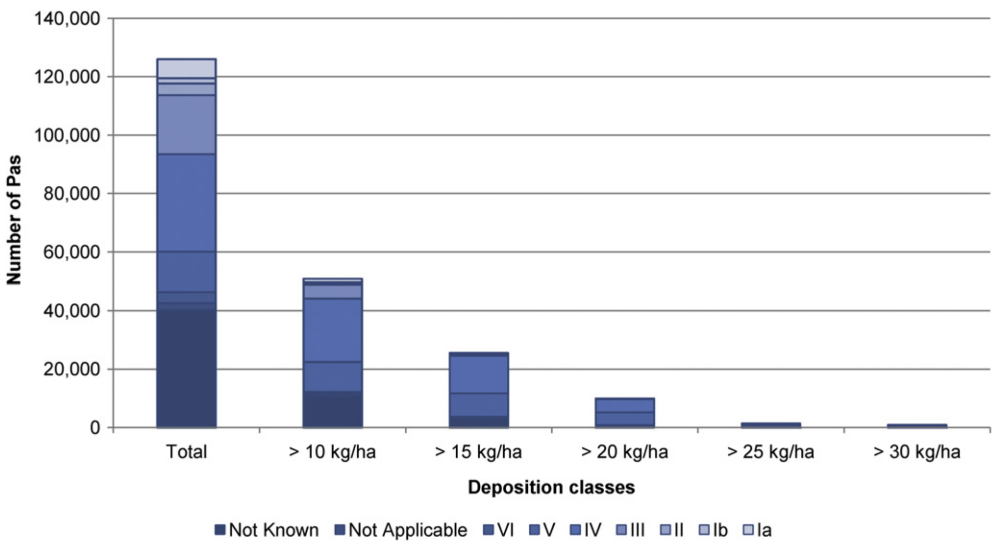

Fig. 5. Number of PAs distributed over IUCN categories and deposition classes for 2030.

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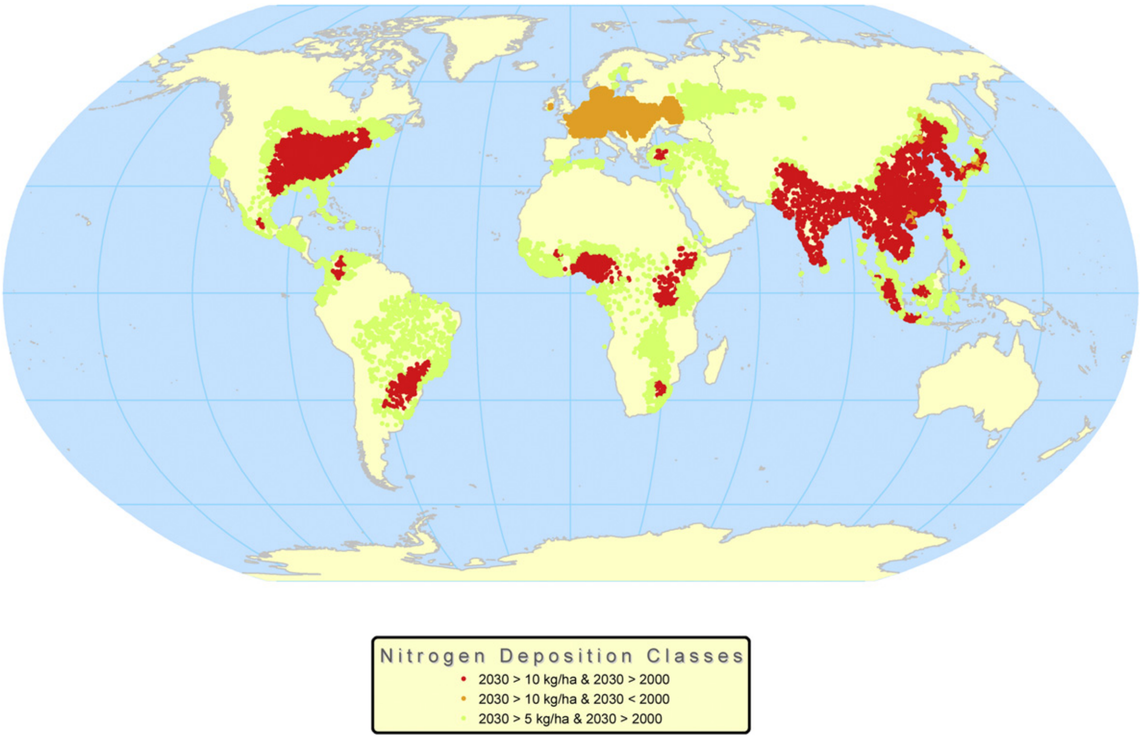

Fig. 6. Distribution of deposition classes (see text for details).

Table 3
Number and surface area of PAs (both absolute and as percentage of total) for the three classes shown in Fig. 6.

Class		Number of Pas		Surface area of Pas	
			% of total	Km^2	% of total
1. Red	2030 > 10 kg N/ha/y & 2030 > 2000	13,570	11	3,059,400	9
2. Orange	2030 > 10 kg N/ha/y & 2030 < 2000	37,240	30	588,600	2
3. Green	2030 > 5 kg N/ha/y & 2030 > 2000	29,290	23	10,435,600	30

again, but now in a different way: it shows the deposition change between 2000 and 2030 as well, giving insight in possible exposure situations beyond 2030. The situation with depositions higher than 10 kg N/ha/yr is shown in the first two classes, for two situations where: the first class (red) >10 kg N/ha/yr in 2030, and 2030 > 2000; and the second class (orange) >10 kg N/ha/yr in 2030, 2030 < 2000. These two classes thus show two exceedance situations, but distinguishing between increasing and decreasing deposition between 2000 and 2030. A third class (green) is also shown: >5 kg N/ha/yr but <10 kg N/ha/yr in 2030, 2030 > 2000. This shows the sites where the N deposition may still be below the 10 kg N/ha/yr threshold, but the deposition is increasing between 2000 and 2030, indicating those sites that might be under threat in the near future. Another 23% of the sites and 30% of the area will be subject to deposition levels higher than 5 kg N/ha/yr and lower than 10 kg N/ha/yr, with 2030 values higher than 2000 values (i.e. increasing deposition).

The PA database also holds information about the possible listing under one of the International Conventions. Table 4 shows an overview of these Conventions and the number/area of PAs falling under them. In total about 2% of the PAs (2329 in total), which represents about 30% of the PA area, are listed in the context of one of the International Conventions. Most of these sites are registered as being part of the Ramsar Convention (Wetlands of International Importance): 1567 out of the 2329 sites. Most of the area is however registered under the UNESCO-MAB Biosphere Reserve: about 5,400,000 km^2. Of these different ‘Convention sites’,

Table 4
Number and percentage of PAs and their surface area (in km^2) within different International Conventions and exceedance of 10 kg/ha/yr in 2030.

Conventions	Number of PAs	Surface area of PAs (in km^2)	Number of PAs (in % >10 kg N/ha/yr)	Surface area of PAs (in % >10 kg N/ha/yr)
ASEAN Heritage	30	103,900	56	58
Barcelona Convention	20	90,800	10	<1
UNESCO-MAB Biosphere Reserve	510	5,373,600	27	8
Wetlands of International Importance (Ramsar)	1570	1,567,000	27	9
World Heritage Convention	210	2,807,000	23	28
Grand total	2330	9,943,000	27	14

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Table 5
Percentage of number of PAs (and of surface area between brackets) within WWF G200 Ecoregions/Biomes with depositions higher than x kg/ha/yr in 2030.

	>10 kg/ha/yr	>15 kg/ha/yr	>20 kg/ha/yr	>25 kg/ha/yr	>30 kg/ha/yr
Tropical & Subtropical Moist Broadleaf Forests	34 (12)	21 (5)	17 (4)	11 (2)	7 (1)
Tropical & Subtropical Dry Broadleaf Forests	31 (40)	19 (34)	13 (15)	9 (8)	6 (6)
Tropical & Subtropical Coniferous Forests	16 (92)	8 (<1)	8 (<1)	7 (<1)	5 (<1)
Temperate Broadleaf & Mixed Forests	58 (51)	33 (24)	13 (9)	<1 (4)	<1 (3)
Temperate Conifer Forests	57 (23)	6 (5)	<1 (4)	<1 (2)	<1 (<1)
Boreal Forests/Taiga					
Tropical & Subtropical Grasslands, Savannas & Shrublands	20 (11)	2 (1)	<1 (<1)	<1 (<1)	<1 (<1)
Temperate Grasslands, Savannas & Shrublands	33 (5)	10 (1)			
Flooded Grasslands & Savannas	18 (8)	2 (3)	1 (2)		
Montane Grasslands & Shrublands	19 (15)	6 (11)	3 (3)	1 (2)	<1 (<1)
Tundra					
Mediterranean Forests, Woodlands & Scrub	2 (1)				
Deserts & Xeric Shrublands	6 (3)	5 (3)	4 (1)	2 (<1)	2 (<1)
Mangroves	13 (12)	6 (9)	6 (8)	3 (7)	1 (4)

Table 6
Percentage of surface area of PAs within WWF Ecoregions Global Status classes and different deposition classes in 2030.

Global Status	Deposition classes				
	>10 kg/ha/yr	>15 kg/ha/yr	>20 kg/ha/yr	>25 kg/ha/yr	>30 kg/ha/yr
Critical	26	10	5	3	2
Vulnerable	10	2	1	<1	<1
Stable/Intact	5	3	1	1	<1

about a third are exposed to deposition higher than 10 kg N/ha/yr. In terms of area this is about 14% of these sites. The ASEAN Heritage sites show the highest percentage exceedance: about 60% (both in number of sites and in area).

Table 5 shows the distribution of the PAs (both in number and area) over the different G200 Ecoregions and the earlier mentioned deposition classes. For the temperate forest systems more than 50% of the PAs are exposed to depositions higher than 10 kg N/ha/yr. Also for the tropical systems a relatively high number of PAs are exposed to this load. In terms of area this changes only slightly, but still large parts of the temperate and tropical systems are exposed to levels higher than 10 kg N/ha/yr.

In the WWF Ecoregions database, also a ‘Global Status’ was assigned to each of the Ecoregions. This Global Status represents a 30-year prediction of the future conservation status, given the current conservation status and some trajectories into the future. Table 6 shows the comparison between the Global Status and the different deposition classes and is expressed as percentage of the area of the different PAs for 2030 projected N deposition estimates. The higher proportion of the area of PAs exposed to higher deposition classes (i.e. >10 kg N/ha/yr) is in the Critical class, with about 26%, 19% and 5% in the Critical, Vulnerable and Stable/Intact classes respectively. Since N deposition is not an issue when determining the Global Status, it becomes clear that high N deposition levels

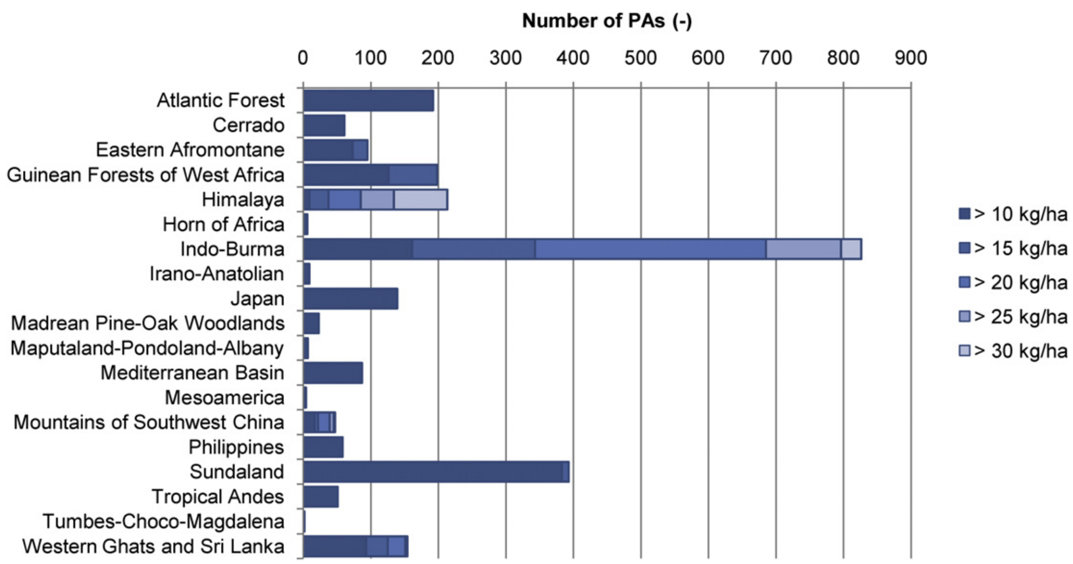

Fig. 7. Number of PAs with exceedance of x kg/ha/yr and located within Hotspots in 2030.

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Table 7
PAs per G200 Regions and Hotspots (number and surface area) with N deposition >30 kg N/ha/yr. in 2030.

Number of PAs with >30 kg N/h/yr	Hotspots			
G200 Regions	Himalaya	Indo-Burma	Mountains of Southwest China	Grand Total
Eastern Himalayan broadleaf and conifer forests	4			4
Hengduan Shan conifer forests			2	2
Naga–Manapuri–Chin Hills moist forests		10		10
Southeast China–Hainan moist forests		20		20
Terai–Duar savannas and grasslands	16			16
Western Himalayan temperate forests	10			10
Grand total	30	30	2	62
Surface area (in km^2) of PAs with >30 kg N/ha/yr	Hotspots			
G200 Regions	Himalaya	Indo-Burma	Mountains of Southwest China	Grand Total
Eastern Himalayan broadleaf and conifer forests	1326			1326
Hengduan Shan conifer forests			39	39
Naga–Manapuri–Chin Hills moist forests		1054		1054
Southeast China–Hainan moist forests		4953		4953
Terai–Duar savannas and grasslands	2808			2808
Western Himalayan temperate forests	1134			1134
Grand total	5268	6007	39	11314

coincide with other threats to biodiversity (e.g. land-use change, deforestation and biomass burning). For the classes Vulnerable and Stable/Intact the relative importance of N as a threat increases and measures to prevent degradation of the biodiversity in those areas can thus focus more on reducing the N inputs. This does not hold for the Critical class, since a combination of threats seems to be ‘acting together’, which requires a wider approach in dealing with them.

When looking at the distribution of the Hotspots over deposition classes higher than 10 kg N/ha/yr, they largely coincide with the exposed PAs within G200 Ecoregions. Fig. 7 gives an overview of the number of sites located within the Biodiversity Hotspots that are exposed to different levels of N deposition. In total about 2600 sites are exposed to deposition higher than 10 kg N/ha/yr, with 111 of them exposed to levels higher than 30 kg N/ha/yr (respectively 1,700,000 and 25,000 km^2). These high levels occur in Asia; more specifically the Himalaya, Indo-Burma and Southwest China region.

5. Discussion and conclusions

We have shown in this study how the different sites from the UNEP Protected Areas Programme are exposed to varying levels of N deposition. Between 2000 and 2030 deposition levels change and in large parts of the world will increase due to intensified activities (mostly related to agriculture and fossil fuel burning) in those regions (e.g. Asia, South America, Africa) to meet the demands for food, animal feed and energy. This deposition may seriously affect the integrity of the PAs, since high inputs of N can result in different effects that can be a threat to the biodiversity of ecosystems and the services they supply to human populations (e.g. Greenhouse Gas regulation).

Different classification systems of the PAs have been used in this study, which (to some extent) can also be treated as levels of ‘conservation importance’. These systems are: IUCN Classification, WWF G200 Ecoregions and Conservation International Biodiversity Hotspots. For all these systems there are sites exposed to deposition classes ranging from low to as high as 30 kg N/ha/yr. Even in the less sensitive (tropical) systems, changes in plant species composition can be expected for these high levels of deposition (see below).

As a first general way of expressing the vulnerability of the different ecosystems, we used a deposition threshold, based on available critical loads predominantly from temperate ecosystems in Europe, of 10 kg N/ha/yr in this study. Recent work from Bobbink et al. (2010) showed that this critical load may vary considerably. For ecosystem types like ‘Polar desert’, ‘Alpine tundra’, ‘Alpine/sub-alpine scrub and grassland’ and ‘temperate forest’ the critical load may be as low as 5 kg N/ha/yr, while for ecosystem types like ‘temperate grasslands’ it may be as high as 30 kg N/ha/yr. For tropical systems is was not possible to derive a critical load, but Bobbink et al. (2010) state that deposition higher than 20–30 kg N/ha/yr may potentially seriously affect the ecosystems in these regions. For example, in China, manipulation experiments suggest that N deposition has the potential to influence the species richness of the under-storey of temperate and tropical forests [Bobbink et al., 2010].

When combining the deposition information with the PAs and listing them according to the different classification systems, it becomes clear that for all these systems there are sites that are exposed to high N deposition rates, even greater than 30 kg N/ha/yr (in total about 950 sites with a total surface of 180,000 km^2). With a special focus on these 950 sites, 62 of them are registered as both a Hotspot and a G200 region. Table 7 shows these PAs, both in number of sites and area. The 62 sites represent a total surface of about 11,300 km^2, and most of them are forested or grassland areas according to the G200 classification. According to Bobbink et al. (2010), this implies that the deposition level of 30 kg N/ha/yr will most likely result in changes in the species composition in these areas, even when taking uncertainties in deposition calculations and critical loads into account.

With respect to the deposition calculation, we have to be aware of the fact that the presented deposition maps (Fig. 1) are the result of averaging the estimates of 23 models. This means that there is variation in the deposition estimates for specific locations when taking the individual model estimates into account. Although Dentener et al. (2006) showed that the mean values on average show the best comparison with measurements, a global model will not be adequate in calculating local (PA scale) situations in sometimes very high deposition areas near farms or industrial activities. For these specific situations the variations in the deposition can be large and should be explored further. Furthermore, due to lack of dry deposition data the model outcomes cannot be validated with respect to dry deposition, which dominates the total deposition in source regions.

Not only deposition calculations can show large uncertainties for specific locations, for many ecosystems around the globe adequate information about critical loads is not available. It is therefore recommended that some PAs should be studied more

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closely to determine if they are currently indeed being impacted or are at risk, with a focus on the 62 PAs that are mentioned in Table 7. Also the potential for using the critical loads approach in some of the temperate areas outside of Europe and North America should be investigated further, especially in Asia where deposition is already high and evidence of effects is just starting to emerge (see Bobbink et al., 2010).

Despite the uncertainties that have been mentioned, we conclude that significant areas of the UNEP Protected Areas Programme are receiving deposition values above critical thresholds and that is set to increase in the future, especially in Asia (Galloway et al., 2004). Some of these Protected Areas are known to be sensitive to N deposition impacts, are of high conservation value and have high numbers of endemic species, and are therefore highly important in terms of safe guarding a healthy conservation status. However, not only N deposition is a threat to PAs. PAs are also known for the potential loss of rights, land or access to resources and eventually even the displacement of local population. While the direct influence of the population may be reduced in this way, the indirect influence of N emissions from agricultural, transport and industrial activities outside of PAs can still occur through N deposition. PAs are by definition managed in order to protect the biodiversity they contain. Management in this case is always a trade-off between protecting the conservation and the population needs. Indeed, some of the PAs receiving high levels of deposition may well have important ecosystem services affected, such as pollination, regulation of water quality and of GHG fluxes. However, some N effects can also be positive (e.g. N deposition fertilization of forestry increasing carbon sequestration in the tropics (Chen et al., 2010), so more research is required to identify those PAs where additional management is necessary to better balance these different needs. For example, it has been shown that projected future N deposition to grasslands in China and India may be sufficient to promote possible benefits for carbon sequestration and forage production, however, these may be offset by declines in plant biodiversity caused by these biomass gains, thus necessitating careful management if ecosystem service delivery is to be maximized (Lee et al., 2010).

In conclusion, the results of this paper show that N deposition is a significant and growing issue for biodiversity in many parts of the world, especially in Asia. And, although a recent report on the CBD indicators of biodiversity decline (Butchart et al., 2010) shows that the growth in global deposition of reactive N indicator may have slowed in recent years, it is important to look at N deposition impacts on a region by region or even a site by site basis, as the sensitivity of terrestrial ecosystems to N deposition effects and deposition characteristics are often very site specific.

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