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Global spatial coincidence between protected areas and metal mining activities

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ABSTRACT

The global protected area (PA) system has a key role to play in biological conservation, and it is thus vital to understand the factors that are likely to limit this potential. Attention to date has focused foremost on the consequences of biases in the spatial distribution of PAs for their effectiveness and efficiency in representing biodiversity. What is less clear is the extent to which these biases may also have affected the likelihood with which PAs coincide with or are influenced by particular kinds of threatening processes, further undermining their role. An obvious candidate for such concerns is metal mining activities. Here we demonstrate that approximately 7% of mines for four key metals directly overlap with PAs and a further 27% lie within 10 km of a PA boundary. Moreover, those PAs with mining activity within their boundaries constitute around 6% of the total areal coverage of the global terrestrial PA system, and those with mining activity within or up to 10 km from their boundary constitute nearly 14% of the total area. Given the distances over which mining activities can have influences, the persistence of their effects (often long after actual operations have closed down), and the rapidly growing demand for metals, there is an urgent need to limit or mitigate such conflicts.

1. Introduction

Terrestrial protected areas (PAs) are widely regarded as key elements of in situ conservation strategies at local, regional and global scales (Gaston et al., 2008; Margules and Pressey, 2000; MA, 2005). This reflects evidence of their historical success, when compared with areas that are not so protected, in holding significant components of biodiversity within their bounds (Andam et al., 2008; Gaston et al., 2008; Jackson and Gaston, 2008), and in buffering those components from external pressures (Chape et al., 2005). Nonetheless, numerous ways have been identified in which PAs could be improved, including individually in terms of their structure and management (Lockwood et al., 2006) and collectively in terms of their distribution and extent (Brooks et al., 2004; Fuller et al., 2010; Rodrigues et al., 2004). Particular attention has been focused on the frequent tendency for PAs to be biased towards lands at higher elevations, with steeper slopes, lower primary productivity, and/or lower economic worth (Hoekstra et al., 2005; Joppa and Pfaff, 2009). In other words, the tendency for PAs to be designated and established in parts of the landscape in which many (although not necessarily all) potentially competing uses are a priori minimized.

Such existing spatial biases in the distribution of terrestrial PAs are well known to have had important consequences. In particular, they have, often markedly, reduced their effectiveness and efficiency in representing biodiversity (Barr et al., 2011; Chape et al., 2005; Gorenflo and Brandon, 2006; Rodrigues et al., 2004). What is less clear is the extent to which these biases may also have affected the likelihood with which PAs coincide with or are influenced by particular kinds of threatening processes, yet further undermining their role. One obvious candidate for such concerns is metal mining activities, due to their location and environmental impact. For some key metals a high proportion of potentially accessible ore deposits tends, like protected areas, also to be located in topographically more complex areas and at higher altitudes (e.g. Edwards and Atkinson, 1986; Evans, 1993). Moreover, increasing demand (Fig. 1a) and prices (Fig. A.1) are extending these activities into more remote and previously unmined regions (Pulgar-Vidal et al., 2010). Consequently, metal mining activities have become of major export significance to several countries with notably high biodiversity (e.g. Chile, Peru, Zambia, Papua New Guinea; MA, 2005). Indeed, mining activities have proven a threat to a number of PAs, and such proposed activities are one driver of the downgrading, downsizing, and degazettement of PAs (Earthworks and Oxfam America, 2004; Farrington, 2005; Mascia and Pailler, 2011; Phillips, 2001).

Metal mining activities are potentially of major concern for biological conservation because they can be extensive and physically destructive of natural habitats, require infrastructure (e.g. for

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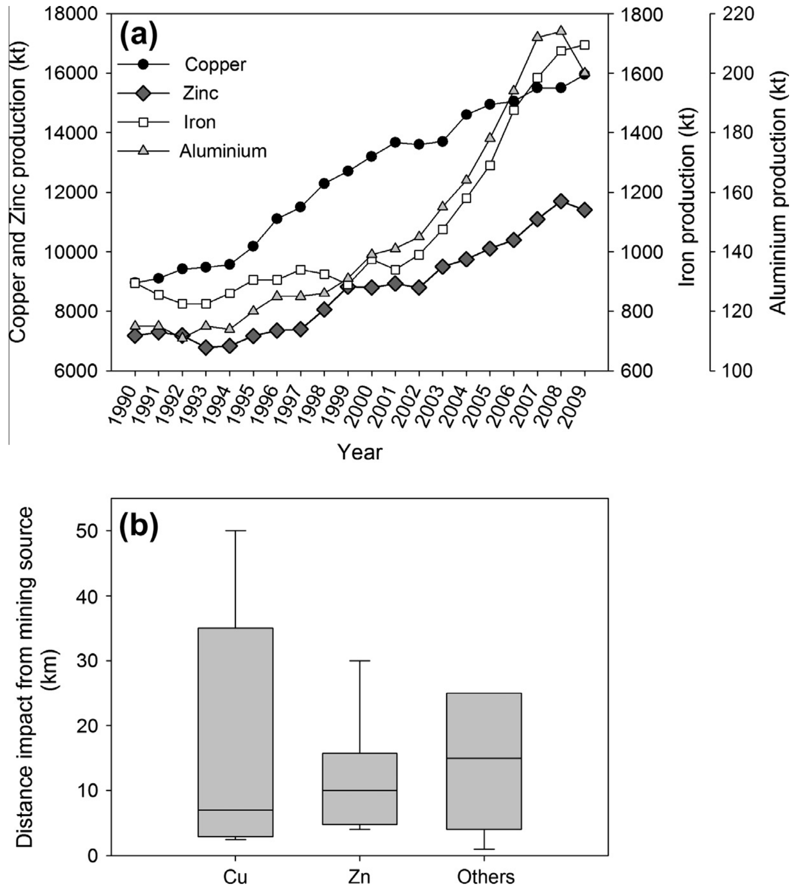

Fig. 1. (A) Annual variation in global production of aluminium, copper, zinc and iron from 1992 to 2010. (Information source: Raw Material Group). (B) Average maximum distance of ecological impacts from mining sources for three different mine types: copper, zinc and others. Fifteen papers that evaluate mining activity impact zones were reviewed (Table 2). Boxes show the median, upper value, lower value, 25th and 75th percentile.

transport) that can extend over yet larger areas (e.g. access roads, rail networks), and can cause both chronic and acute pollution that can persist for many decades (Lefcort et al., 2010). Moreover, this pollution can extend considerable distances from the mine workings themselves, with a new collation of the results of a set of published empirical studies showing effects on the scale of tens of kilometers (Fig. 1b). This raises the potential for PAs to be influenced by metal mine workings that lie well beyond their immediate boundaries.

In this paper, we determine the spatial overlap between terrestrial PAs and mining activities for ore deposits for four metals (aluminium (Al), copper (Cu), iron (Fe) and zinc (Zn)). We determine the variation across the globe both in direct overlaps and in the proximity of mining activities to the boundaries of PAs, which given the 'long reach' of these activities may be just as significant as is the occurrence of active mine workings within PAs.

2. Data and methods

Global maps of the locations of bauxite (for production of Al), Cu, Fe and Zn mines were developed using Rauch (2009) as the baseline dataset. This was updated using information on mining activities obtained from the Raw Material Group (RMG), the world's most extensive mining industry database, containing information on a broad range of legal mining industry entities. The latitude and longitude of mines were determined using company reports, company websites and other available sources. Every updated location was verified using images from Google Earth. The final dataset comprised information on a total of 1418 mines.

Data on the global distribution of PAs were obtained from the World Database on Protected Areas (WDPA, 2010). These data comprise both polygons and point records with associated extents. Following Rodrigues et al. (2004), (i) records were eliminated for marine PAs, and for PAs for which *Status* was indicated as "Proposed", "Recommended" or "Not reported"; (ii) point records were converted into circles of the stated area; (iii) point record circular areas were subsequently merged with those for which original polygon data were provided to generate a common polygon shapefile with a total of 129,422 records; and (iv) for the purposes of overlap analysis, but not for counting numbers and areas of PAs, the polygons that shared a common boundary or overlapped were dissolved. The IUCN Management category in which each PA has been placed was recorded (I – Strict Nature Reserve/Wilderness Area; II – National Park; III – Natural Monument or Feature; IV – Habitat/Species Management Area; V – Protected Landscape; VI – Protected area with sustainable use of natural resources; IUCN, 1994).

To determine the proximity of mines to PAs we overlapped the point locality data for mines and the final merged polygon data for PAs. Those mines that were located within PAs, or within distances of 1 km, 1–5 km and 5–10 km from the boundary of the PAs were accounted. We selected a maximum buffer distance of 10 km to capture potential local to mesoscale effects of mining activities on PAs, whilst acknowledging that longer distance effects can also exist. The coincidence of mine activity within PAs or the buffer distances defined (1 km, 1–5 km and 5–10 km) were compared with a null model in which the same numbers of mines as observed were randomly distributed across the global land masses (including islands but excluding Antarctica), without overlap. This exercise was repeated 100 times, and each individual run was compared to the actual data. This procedure was then carried out separately for each of the six geographic regions of Africa, Asia, Europe, North America, Oceania and South America.

3. Results

Mining activities for Al, Cu, Fe and Zn were widely distributed across the Earth's surface, but with notable concentrations in the Andes range, west North America, eastern Europe, southern Africa,

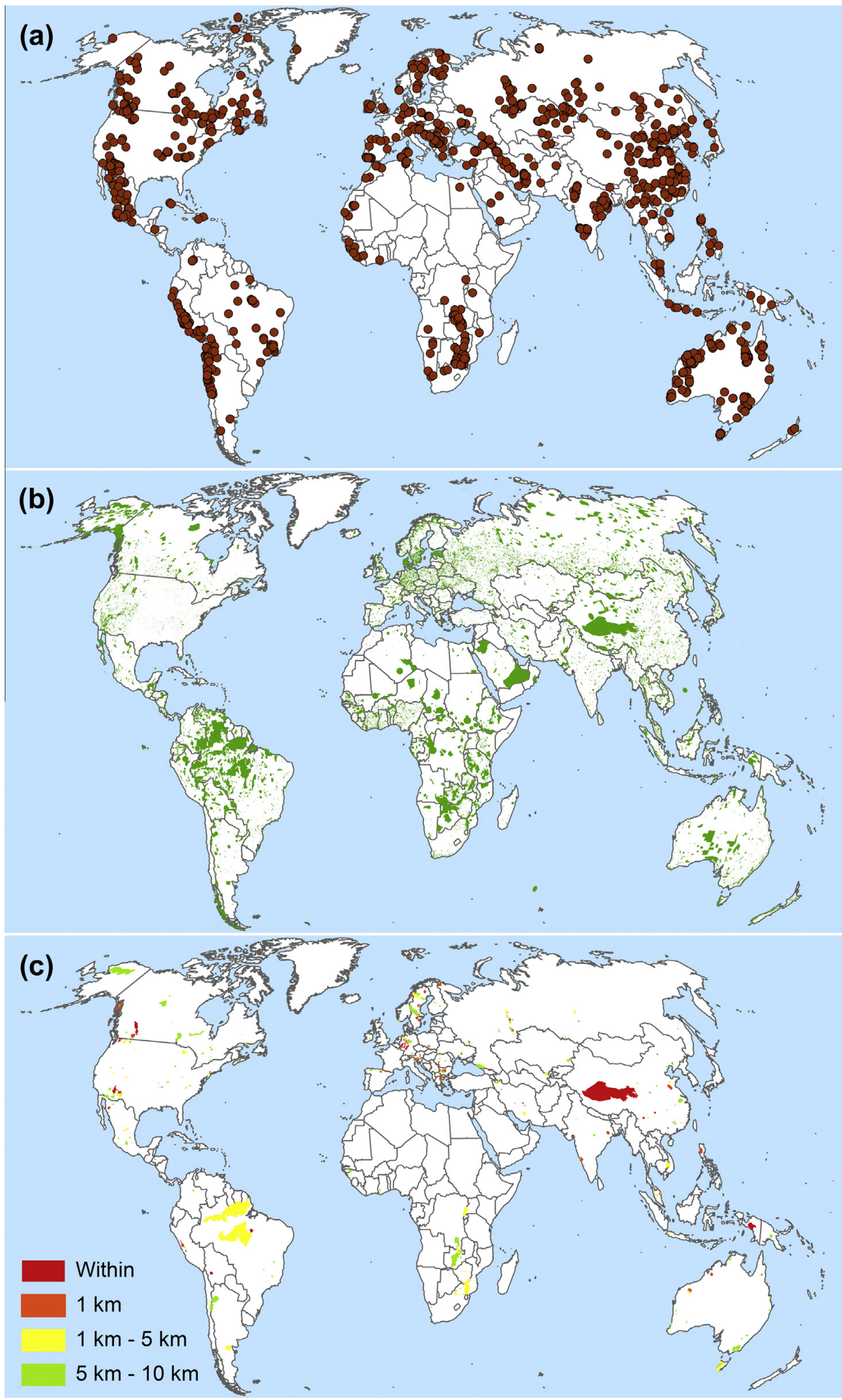

Fig. 2. Global distributions of (A) bauxite, copper, iron and zinc mines, (B) protected areas, and (C) protected areas having mining activities at different levels of proximity (Within: protected areas that completely contain at least one mining activity. 1 km: protected areas located at 1 km distance from at least one mining activity. 1–5 km: protected areas having at least one mining activity at 1–5 km distance. 5–10 km: protected areas having at least one mining activity at 5–10 km distance).

Table 1
Percentage of total metal mines observed within different levels of proximity (buffers) from protected areas (PAs) in different geographic regions, compared with a null model. Column 'Randomization larger than observed' indicates how many times the percentage of mines within PAs and buffers as determined from a null model was higher than the percentage observed.

Geographic region	PAs buffer	Percentage of mines within PAs and buffers (cumulative percentage)	Percentage of mines within PAs and buffers by null model (mean ± SD)	Percentage of randomization larger than observed (%)
Global	Within	6.7	12.15 ± 1.07	100
	1 km	2.89 (9.59)	1.82 ± 0.56	0
	1–5 km	10.51 (20.1)	6.71 ± 0.59	0
	5–10 km	13.75 (33.85)	7.71 ± 0.63	0
Africa	Within	3.81	11.5 ± 2.7	100
	1 km	0.76 (4.57)	0.87 ± 0.74	34
	1–5 km	22.9 (27.47)	3.86 ± 1.65	0
	5–10 km	16.03 (43.5)	4.47 ± 1.88	0
Asia	Within	7.71	11.44 ± 1.54	99
	1 km	1.74 (9.45)	1.01 ± 0.49	5
	1–5 km	4.72 (14.17)	4.36 ± 0.99	31
	5–10 km	10.45 (24.62)	5.82 ± 1.28	0
Europe	Within	16.35	12.09 ± 2.31	3
	1 km	10.28 (16.63)	3.03 ± 1.19	0
	1–5 km	17.75 (44.38)	12.05 ± 2.13	0
	5–10 km	18.22 (62.6)	11.77 ± 2.66	0
N. America	Within	3.04	7.68 ± 1.62	99
	1 km	1.14 (4.18)	2.61 ± 0.87	91
	1–5 km	12.93 (17.11)	9.7 ± 1.86	7
	5–10 km	15.97 (33.08)	11.28 ± 1.77	3
Oceania	Within	0	10.52 ± 2.46	100
	1 km	2.52 (2.52)	2.26 ± 1.13	31
	1–5 km	9.43 (11.95)	7.52 ± 2.11	19
	5–10 km	13.21 (25.16)	7.03 ± 2.13	0
S. America	Within	6.42	21.13 ± 3.29	100
	1 km	1.61 (8.03)	1.39 ± 0.75	25
	1–5 km	5.22 (13.25)	5.05 ± 1.47	42
	5–10 km	12.05 (25.3)	6.21 ± 1.50	0

East Asia and Australia (Fig. 2a). The distribution of PAs was less clumped, but with particularly high coverage in north-east South America, western North America, northern and central Europe, southern-central Australia and East Asia (Fig. 2b).

Approximately 6.7% of mines were located within the boundaries of PAs, which although substantial, was less than expected by chance (Table 1). These overlaps mainly occurred in Europe, followed by Asia, South America and North America (Fig. 2c). Approximately 2.9%, 10.5% and 13.8% of mines respectively, were located within 1 km, 1–5 km and 5–10 km distance bands from the PA boundaries, leading to a total of 27.2% lying within 10 km of a PA. In all cases this was greater than expected by chance (Table 1). Focusing on individual geographic regions, only Europe had a higher percentage of mines within PA boundaries (16.4%) than expected by chance (Table 1). Similarly, only Asia had a higher percentage of mines within 1 km of a PA boundary (1.7%) than expected by chance (Table 1). However, in all six geographic regions there was a higher percentage of mines within 1–5 km and 5–10 km of a PA boundary than expected by chance (Table 1).

The occurrence of mining activities within PAs depends on their IUCN management category (IUCN, I–IV) ($\chi^2 = 33.91$, $df = 5$, $p < 0.001$). PAs in more permissive categories (IUCN, IV–VI) contained a higher than expected frequency of mines within their bounds than those in more strict categories (IUCN, I–III). This dependence was not explained by the geographic regions in which PAs were located ($\chi^2 = 26.64$, $p = 0.15$) [Fisher's exact test with simulated p-value by a Monte Carlo test by 2000 iterations].

Considering mines separated by their metal production type (i.e. Al, Cu, Fe and Zn), at a global scale the percentages of mines lying within PAs were lower than expected by chance for all metals (Table A.1). However, the percentages lying within 1 km, 1–5 km, and 5–10 km of a PA boundary were higher than expected for Cu, Fe and Zn (Table A.1). These co-occurrences were distributed mainly in Africa, Asia and North America (Fig. A.2–A.5). In Africa the percentage of mines within PAs was higher than expected for Al, and within 1 km, 1–5 km and 5–10 km of a PA boundary for Cu. In Asia, the percentage of mines within PAs was higher than expected for Zn, and within 5–10 km of a PA boundary in all cases except for Al. In Europe the percentage of mines within PAs was higher than expected by chance for Zn, and within 1 km, 1–5 km, and 5–10 km of a PA boundary in all cases except for Al within the 1 km distance band. For neither North nor South America were the percentages of mines lying within PAs higher than expected by chance for any of the metals, although percentages within the 5–10 km distance band were higher than expected by chance in all cases, except for Fe in North America and Al in South America.

Addressing the coincidence of mines and PAs from an alternative perspective, those PAs with mining activity within their boundaries constitute 6.1% of the total areal coverage of the global terrestrial protected area system (Table A.2). Those with mining activity within 1 km, 1–5 km, and 5–10 km of their boundary constitute 0.1%, 5.9%, and 1.9% of worldwide PA land cover, and those with mining activity within or up to 10 km from their boundary constitute 14% of the total area. South America, followed by Asia and North America, exhibited the highest areal land cover of PAs that overlapped with mining activities within the four distance buffers (Table A.2).

4. Discussions

Studies of the threats to terrestrial PAs arising from human resource exploitation have focused heavily on potentially 'renewable' ecosystem goods and services (e.g. forestry, harvesting of wildlife;

e.g. Andam et al., 2008; Craigie et al., 2010; Gaston et al., 2008; Gaveau et al., 2007). Here the key issues are the degree to which such areas serve effectively to attract, limit or displace these activities by virtue of their being protected. For non-renewable resources some of the challenges are similar and others somewhat different. Moreover, for the metal mining activities considered here those challenges need to be evaluated carefully because, as we have shown, they can influence a substantial proportion of the terrestrial PA estate: approximately 7% of mines for the four key metals directly overlap with PAs, a further 27% lie within 10 km of a PA boundary, those protected areas with mining activity within their boundaries constitute about 6% of the total areal coverage of the global terrestrial protected area system, and those with mining activity within or up to 10 km from their boundary constitute 14% of the total area.

First, in the main, any overlap between the distribution of the resource and that of PAs is typically much less likely to be a consequence of the designation of the PA per se (as can, for example, be the case when this results in the increase or maintenance of the numbers of a particular species of organism) for metal mining activities than for many renewable resources. Nonetheless, as demonstrated by metal mining activities, this coincidence can be marked. There is less mining activity within the bounds of PAs than expected by chance, which likely follows from a combination of a reduced likelihood of PAs being established in areas where mining activity is already present and also of mining activities being established in areas where PAs are already present. Nonetheless, there remains some substantial overlap between mining activities and PAs (Tables 1, and A.2), which is reflected in the pressures both for altering the status of some existing PAs and for licensing mining activities within them (Farrington, 2005; Mascia and Pailler, 2011). This almost certainly follows from PAs being established in areas in which the demands for many other forms of land use such as urbanization, agriculture and logging, are often substantially reduced (Hoekstra et al., 2005; Joppa and Pfaff, 2009). Not surprisingly, PAs in more permissive IUCN management categories (IUCN, IV–VI) contained a higher than expected frequency of mines within their bounds than those in more strict categories (IUCN, I–III). Second, because of the nature of practically and economically accessible metal deposits, there are arguably limited opportunities for the substantial displacement of mining activities away from the regions in which many PAs have been established. This results in the greater than expected occurrence of mining activities within relatively short distances of the boundaries of PAs (Table 1). Not surprisingly, the aggregated distribution of mining activities (Fig. 2a) coincides with metal-rich zones that resulted from geologic processes such as plate convergence, collision tectonics and extensional tectonics (Edwards and Atkinson, 1986). These high density ore deposit regions have been named Metallogenic Provinces (Parker, 1984), which offer good opportunities for exploration of new ore deposits and thus allocation of mining activities .

There have been repeated calls to redesign the global PA system (or, more realistically, its regional and national constituent parts) so that it better reflects conservation needs (e.g. Fuller et al., 2010; Rodrigues et al., 2004). However, whilst some have proposed that this should be done by a combination of degazettement of existing areas that contribute too little (particularly relative to their cost) and establishment of entirely new areas (e.g. Fuller et al., 2010), it seems likely that changes will occur principally by the latter expansion. There seems little prospect of degazettement of large numbers of PAs in close proximity to mining activities being motivated principally by conservation considerations. This places a high priority on limiting the environmental impacts of mining activities both within and beyond the immediate bounds of operations, and particularly the atmospheric and water-borne spread of pollutants.

Third, the threats to PAs from mining activities operate on spatial scales that are seldom considered in the context of the impacts of exploitation of renewable resources. Habitat changes beyond PA boundaries can have important influences through effects on overall patch sizes and on ecosystem functioning (through, for example, changes in rainfall; Webb et al., 2006), and the killing of individuals of more wide-ranging species when outside PAs can have important effects on their population sizes within those areas (Woodroffe and Ginsberg, 1998). However, it is clear with regard to mining activities both that influences can routinely occur over distances of tens of kilometers (Fig. 1b), and that many PAs and much of the PA estate occur within such proximity of those activities. Of course, the magnitudes of the impacts of metal mining activities and the distances at which these impacts act vary depending on a range of factors (method of extraction, topography, presence or not of refinery). Equally, the potential impacts of mining highlighted by the analyses reported here are based solely on legal activities, operating under regulated standards. There are likely to be additional threats from illegal and artisanal mining (Collen et al., 2011; Laurance et al., 2012).

Fourth, the difficulties that the non-random co-occurrence of mining activities and PAs may present are undoubtedly heightened by the combination of rising metal prices, increasing scarcity of some kinds of metal deposits, and the economic potential now held in previously non-viable deposits. Given these pressures, it is more urgent than ever to generate effective approaches that promote

Table 2
Summary of examples of published studies that evaluate the extent of impact of mining activities on various ecological and environmental variables.

Authors	Mine type	Ecological/environmental effect	Maximum distance impact from mining source (km)
Hernández et al. (1999)	Pyrite	Bird mortality	25
Vásquez et al. (1999)	Copper	Macroalgae abundance	3
Razo et al. (2004)	Copper–gold, lead–zinc–silver	Heavy metal concentration	5
Telmer et al. (2006)	Copper	Heavy metal concentration in lake sediments	50
Yakovlev et al. (2008)	Nickel	Soil quality	25
Kodirov and Shukurov (2009)	Copper and zinc	Heavy metal concentration in soil	4
Kuznetsova (2009)	Copper	Collembola communities in coniferous forests	7
Lafabrie et al. (2009)	Cobalt	Heavy metal concentration in seagrass	5
Taylor et al. (2009)	Copper, zinc and lead	Downstream water quality	30
Bonifait and Villard (2010)	Peat	Odonate abundance	1
Chauhan (2010)	Zinc	Deforestation	11[a]
Huang et al. (2010)	Copper and zinc	Water acidity and heavy metal concentration	10
Katpatal and Patil (2010)	Coal	Flooding	15
Lefcort et al. (2010)	Copper and zinc	Stream insect diversity and abundance	2.5[a]
Vodyanitskii et al. (2011)	Copper	Decrease of soil quality	30

[a] Distance impact was calculated as the perimeter of a circle with stated area mining impact.

Table 3
Measures from mitigation hierarchy and example of potential actions to be taken.

Mitigation measure	Example of action
Avoidance	To avoid infrastructure in priority areas for biodiversity using spatial planning methods
Minimization	Establishment of ecological corridor and buffer zones
Restoration	To restore connectivity between patches of habitats within landscapes. Reforestation
Offset	Environmental compensation policies and payment of ecosystem services schemes

mitigation measures to minimize the impacts of mining activities. Indeed, within the mitigation hierarchy of avoidance, minimization, restoration and offset there are a variety of different measures that should be considered during the planning of mining projects (Quintero and Mathur, 2011) (see Table 3 for examples). Avoidance measures are taken to prevent adverse effects on biological diversity. Minimization measures reduce the duration, intensity or spatial extent of effects which cannot be avoided. Restoration refers to the rehabilitation of ecosystems adversely affected by mining activities. Offsets are measures taken to compensate any negative effect on biological diversity that cannot be avoided, minimized, or restored (BBOP, 2010). A successful initiative that has utilized these mitigation measures is the Smart Green Infrastructure (SGI) project led by the World Bank in Tiger Range Countries. This large international project has identified the infrastructure of mining activities as one of the major contributors to the degradation of tiger habitat (Quintero et al., 2010). Several mitigation measures have been promoted in order to avoid, minimize, restore and compensate any negative effects of previous and future extractive activities. Other similar initiatives are the Mining, Minerals and Sustainable Development (MMSD) and the Sustainable Energy, Oil, Gas and Mining Unit (SEGOM) programs of the World Bank. These initiatives provide evidence that mitigation measures for mining projects are feasible, although more political will and resources are required to ensure implementation worldwide.

Finally, the present study, based on four key metal mine distributions, strongly suggests that metal mining activities are a potential threat to the global PA network, and that it is likely that the overlap between PAs and mines will increase in the future. The incorporation of mines for other key metals and illegal activities would almost certainly increase the frequency of overlaps between mines and PAs, amplifying the magnitude of this important land use trade-off.

5. Conclusion

Studies to date have highlighted two important consequences of biases in the spatial distribution of PAs for their ecological performance. The first, and negative, consequence is the typically lower capture of biodiversity features, that is lower representation, than might have been achieved by alternative distributions (Araujo et al., 2007; Brooks et al., 2004; Rodrigues et al., 2004; Scott et al., 2001). The second, and positive, consequence is the often lower threat, or greater persistence, faced by biodiversity features within PAs than beyond their bounds (Andam et al., 2008; Gaston et al., 2008; Joppa and Pfaff, 2010). By contrast, our analyses identify an example where the spatial distribution of PAs has served to increase the threat to their biodiversity. The global terrestrial PA system has been effective at displacing metal mining activities from within its bounds, either because PAs or mines have been established such that overlap between the two has been reduced. However, given the higher than expected proportion of mines in the close surroundings of PAs, and the distances over which mining activities can have influences, it is highly likely that the conservation performance of a significant proportion of PAs is being affected.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2013.02.003.

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