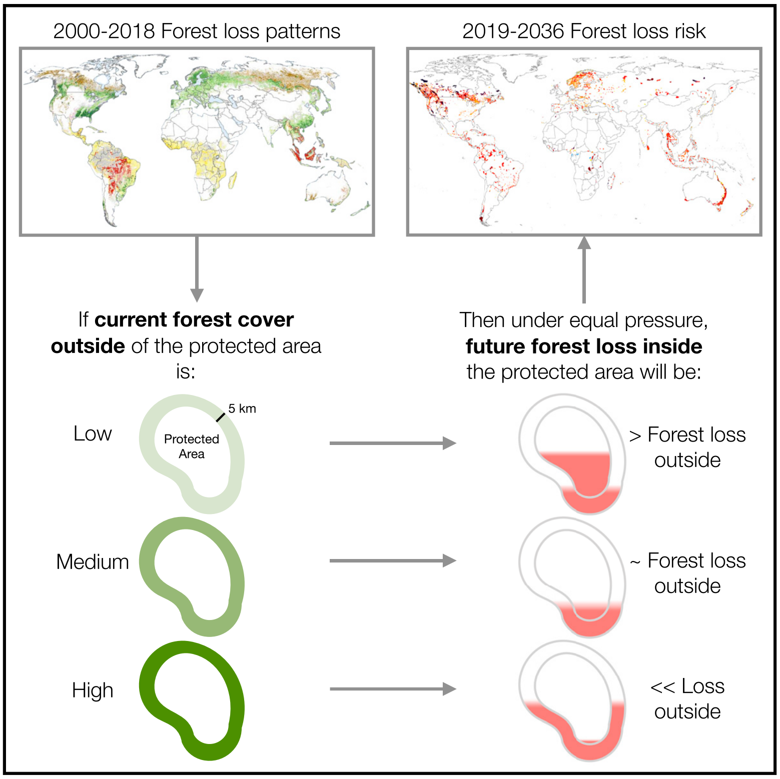
Current Biology

Report

Early warning sign of forest loss in protected areas

Graphical abstract



Highlights

- Low forest cover outside of protected area signals high risk of forest loss inside
- High forest cover outside signals low risk of loss inside, regardless of pressure
- Forest loss risk predictions provided for next 18 years for global protected areas

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In brief

Buřivalová et al. show that a low level of absolute forest cover immediately outside of a protected area signals high risk of future forest loss inside the protected area. When the amount of forest cover outside is >90%, the protected area is likely to experience little to no forest loss, regardless of the pressure in the wider landscape.

Buřivalová et al., 2021, Current Biology *31*, 4620–4626
October 25, 2021 © 2021 Elsevier Inc.
https://doi.org/10.1016/j.cub.2021.07.072

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Report

Early warning sign of forest loss in protected areas

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https://doi.org/10.1016/j.cub.2021.07.072

SUMMARY

As humanity is facing the double challenge of species extinctions and climate change, designating parts of forests as protected areas is a key conservation strategy.[1–4] Protected areas, encompassing 14.9% of the Earth's land surface and 19% of global forests, can prevent forest loss but do not do so perfectly everywhere.[5–12] The reasons why protection only works in some areas are difficult to generalize: older and newer parks, protected areas with higher and lower suitability for agriculture, and more and less strict protection can be more effective at preventing forest loss than their counterparts.[6,8,9,12–16] Yet predicting future forest loss within protected areas is crucial to proactive conservation. Here, we identify an early warning sign of subsequent forest loss, based on forest loss patterns in strict protected areas and their surrounding landscape worldwide, from 2000 to 2018.[17,18] We found that a low level in the absolute forest cover immediately outside of a protected area signals a high risk of future forest loss inside the protected area itself. When the amount of forest left outside drops to <20%, the protected area is likely to experience rates of forest loss matching those in the wider landscape, regardless of its protection status (e.g., 5% loss outside will be matched by 5% loss inside). This knowledge could be used to direct funding to protected areas threatened by imminent forest loss, helping to proactively bolster protection to prevent forest loss, especially in countries where detailed information is lacking.

RESULTS AND DISCUSSION

By analyzing patterns of forest loss across 7,632 terrestrial strict protected areas (International Union for Conservation of Nature [IUCN],[19] category I and II, >1 km^2) and their surrounding 5-km wide landscapes, we found that the amount of forest remaining outside of the protected areas predicts the relationship between future forest loss within the protected areas and outside (Figures 1, 2, and S1). While the available data are not suitable to test whether this correlation reflects a causal relationship, our findings provide critical insight into where efforts to prevent future forest loss within strict protected areas should be focused. To this end, we used our model to estimate the risk of future forest loss in protected areas for 2019–2036 (Figure 3).

Forest loss in and around protected areas intensified between 2000 and 2018

Our planet's strictest protected areas lost much more forest than they gained over the first 18 years of this millennium (3.3 percentage points lost, 0.07 gained), corroborating findings by previous studies.[6,16,20,21] The difference in loss and gain is particularly concerning, given that in the dataset we used[22] gains are often in the form of monoculture plantations,[23] which have a far lower conservation value than natural forest.[24,25] We therefore disregarded forest gains in the following results. Some forest loss is expected from natural disturbances such as fire, typically followed by natural succession and forest regrowth, which can, however, take decades to centuries to reach pre-fire structure, composition, and function.[26] Worryingly, we found that the average forest loss in protected areas increased over time, except in Europe and North America (Figures 4 and S3).

Forest loss was even greater within 5 km of the boundary of a protected area, hereafter "outside" (7 percentage points lost, 0.46 gained). Such forest loss is in many cases due to legal and responsibly planned activities, but it is worrisome that it accelerated over time on all continents (Figures 4 and S4), suggesting an increasing extent of natural forest disturbance or human use. This pattern shows that the increasing isolation of forests documented between 1980 and 2000[21] continued in the following two decades.

Forest cover around protected area predicts future loss within

Our results show that a simple indicator—the amount of forest cover left outside of a protected area—can help predict the risk of future forest loss within the protected area, regardless of the

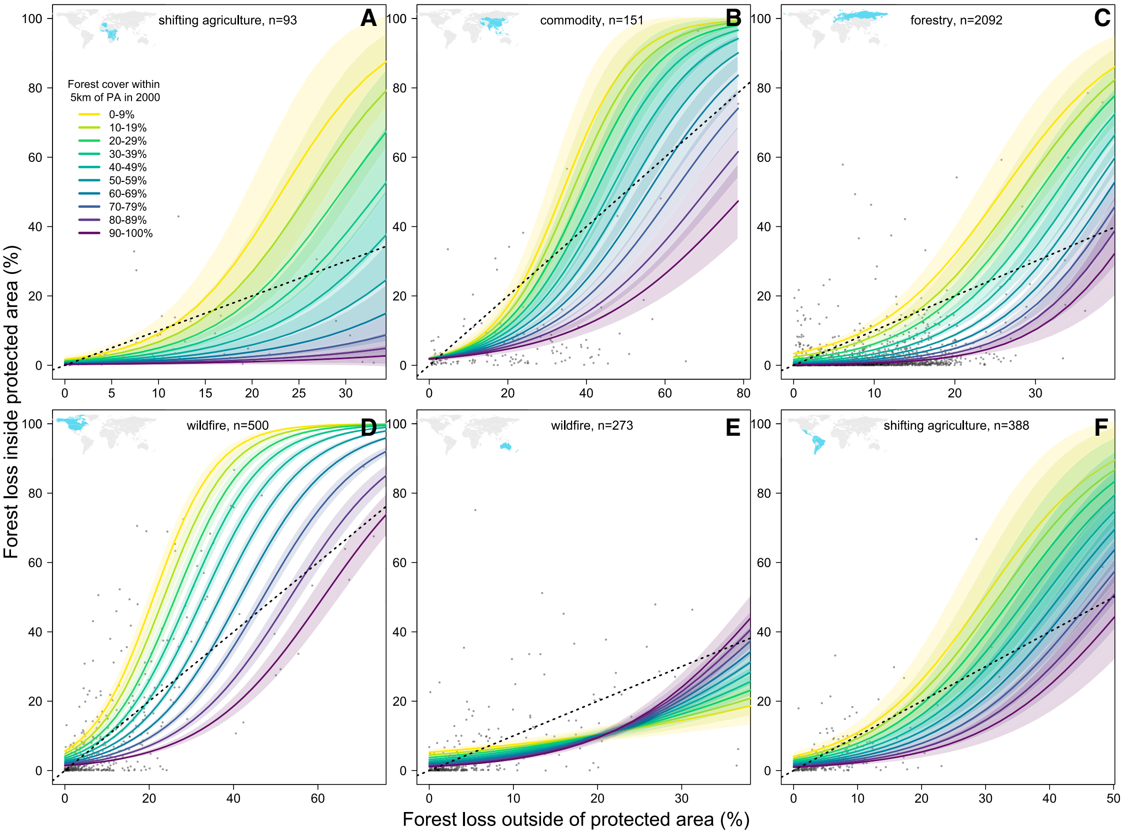

Figure 1. Forest loss inside protected areas (2000–2018) is correlated with loss outside (within 5 km), and this relationship is modulated by how much forest cover was left outside at the beginning of the study

Colors represent the percentage of forest cover outside of the protected area in 2000. The fitted lines and shaded areas (95% CI) are representative of protected areas of median size and median forest cover inside in 2000, and one example of a common driver of forest loss within protected areas on that continent:[18] shifting agriculture in Africa (A), commodity-driven deforestation in Asia (B), forestry in Europe (C), wildfire in North America (D) and Oceania (E), and shifting agriculture in South and Central America (F); countries included are highlighted in blue (see also Figure S1). Gray dots represent all relevant protected areas from a category (e.g., North America, forestry); please note that variance therein is further explained by variables that are fixed in this figure (area, forest cover inside in 2000). Black dashed line represents equal forest loss inside and outside.

magnitude of the pressure (Figures 1 and 2). Based on how much forest is left outside the protected area, we can predict the nature of the relationship between forest loss outside and inside. The total (2000–2018) forest loss inside protected areas is correlated with several interacting variables. First, the size of the protected area has a high explanatory power (when considered individually in a linear regression of log-transformed variables, adj. $R^2 = 0.57$, $p < 0.001$, intercept = −7.33, slope = 1.26, d.f. = 7,630). To focus on additional variables, in the following results, we accounted for area by using the percent of forest loss inside the protected area as a response variable. We still included area as an explanatory variable to test for potential second-degree effects.

According to our final model (quasi-binomial generalized linear model, 7,549 d.f., McFadden's pseudo $R^2 = 0.45$), forest loss (%) inside the protected areas between 2000 and 2018 was correlated with (1) total forest loss outside, (2) the initial forest cover outside in 2000, (3) size of the protected area, (4) initial forest cover inside, (5) continent, and (6) the most likely driver of forest loss in that protected area (Table S1; Figures 1, 2, and S1). On all continents, the relationship between forest loss outside and inside was non-linear, meaning that forest loss inside was disproportionately higher when there was more loss outside (Figures 1 and S1).

High levels of forest cover outside a protected area were correlated with a low likelihood of future forest loss within the protected area (Figures 1 and S1). For example, in African protected areas of median size, under threat from smallholder agriculture, and that had an initially extensively forested surrounding landscape (>90%), subsequent forest loss within the protected areas was low over the next 18 years (0.0%–1.1%, 95% CI range; Figure 1), even at substantial rates of forest loss outside during the same period (10%, or ~0.55% $year^{-1}$). For similar protected areas with surroundings that were 50% forested in 2000, 10% forest loss outside translated to 0.9%–3.0% forest loss inside over 18 years. However, a similar protected area with only 20% forest cover outside, under the same outside forest loss pressure (10%), was likely to lose 3.0%–6.9% of forest inside (Figure 1). These differences were even more pronounced under severe forest loss pressure (Figures 1, 2, and S1).

The correlation between forest loss inside and outside is not surprising, as forest loss is often auto-correlated.[27–30] In general, a protected area is likely to suffer from similar (but non-identical)

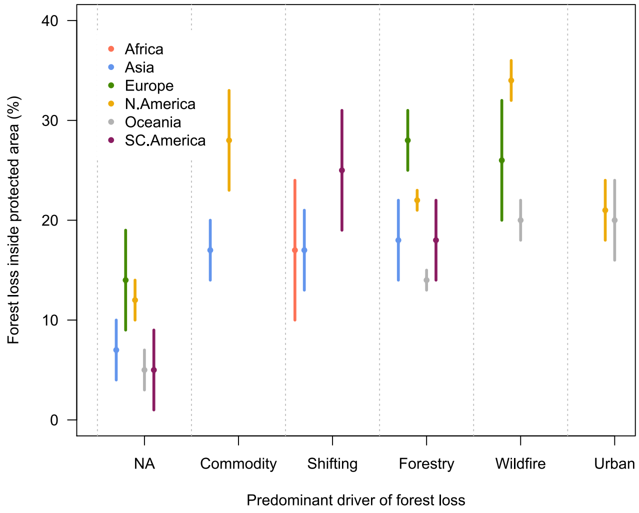

Figure 2. Forest loss inside protected areas differs according to the predominant driver of forest loss

NA, unknown driver of forest loss; Commodity, commodity-driven deforestation; Shifting, shifting agriculture on each continent, represented by different colors (N.America, North America; SC.America, South and Central America). Means (dots) and 95% CI (lines) are parameter estimates from a quasi-binomial model, for protected areas of median size on each continent, with median initial forest cover, 30% forest loss outside, and 50% initial forest cover outside. These values correspond to one point (30% on the x axis, along dark green) in Figure 1 (see also Figure S4).

disturbance pressures, both natural and anthropogenic, as the landscape it is embedded in.[31,32] Broad-scale factors such as global commodity prices, national environmental policy, and climate influence the magnitude of pressure on forests.[33] Such pressures mean that forest loss inside and outside of protected areas is often correlated, but multiple local factors modify this relationship.[30,34] For example, the land inside a protected area might be poorly suited to agriculture or less susceptible to fire than the surrounding area due to differences in accessibility, soil, or vegetation type.[13] Importantly, this relationship can also be modified by the protected area's status, that is, the protected area can have the desired effect of preventing forest loss.[7,8,35] However, it can also trigger the unintended consequence of displaced forest loss into the vicinity.[11,13,36]

Our results present an important advance in the understanding of how the relationship between loss inside and outside changes depending on how much forest is left outside, as well as on the geographic location and the predominant cause of forest loss in the landscape. Importantly, we do not show whether the amount of forest cover outside the protected area is causally linked to the forest loss inside, and we do not show whether maintaining high forest cover outside of the protected area will prevent future forest loss inside. Hence, our results must not be interpreted as goals. For example, it is incorrect to say, "If we maintain 90% forest cover within 5 km around the protected area, no forest loss will occur within the protected area." Rather, our results should be interpreted as "taking the temperature" of the protected area. For example, "A protected area recently lost half of its surrounding forest. Even though it had a historically low rate of forest loss, we should now anticipate higher forest loss within the protected area." Ultimately, reducing forest loss requires managing the underlying drivers, but our analyses can help identify where to focus such efforts if resources are limited.

Our results were robust for shorter time steps, too: fitting the same global model to 2001–2006, 2007–2012, and 2013–2018, with initial state of forest cover outside the protected areas set to 2000, 2006, and 2012, respectively, yielded similar parameter estimates and explanatory power as fitting the model for the full study period (quasi-binomial generalized linear model, 7,549 d.f., McFadden's pseudo R^2 = 0.46, 0.49, and 0.43 for the three periods, respectively). Similarly, our results were robust across wider and narrower surroundings of the protected areas: using 10 and 2.5 km widths yielded similar parameter estimates and explanatory power as using 5 km (McFadden's pseudo R^2 = 0.47 and 0.41 for 10 and 2.5 km, respectively).

Regional and forest loss driver-related differences

The amount of forest cover outside of the protected area was an important predictor of future forest loss risk, especially where commodity production and shifting cultivation were the main causes of forest loss in and near protected areas (Figures 1A, 1B, 1F, 2, and S1). Similarly, forest cover outside of a protected area was important where forestry was the main cause of forest loss, but not in Asia and Oceania (Figures 1C and S1). Wildfire was a particularly common driver of forest loss in protected areas in the Americas, and the amount of forest cover left outside of protected areas played an important role in North America, but not in Oceania (Figures 1D, 1E, and S1).

In the case of shifting cultivation,[18] which is most common in Central America and Africa (Africa also has on average the largest protected areas), it is possible that forest presence outside protected areas "postpones" forest loss due to shifting agriculture within the protected areas themselves. As less land is available for new agricultural plots, farmers may have no choice but to use land in protected areas.[37] Another explanation could be an increasing accessibility of the protected area when more land around it is cleared, particularly close to new roads constructed for selective logging.[38]

There are two main reason why the amount of forest cover outside helps predict future forest loss in protected areas embedded in agroindustrial landscapes, with crops such as oil palm, acacia, rubber, and soy in South America and Asia. First, plantations that neighbor protected area may encroach into the protected areas, due to conflicting land claims, ignoring land boundaries, and spatial contagion.[29,39] Second, commodity production might affect forest loss indirectly: once most of the landscape surrounding the protected area is converted to agroindustry, local smallholder farmers may enter the protected area for subsistence farming. Industrial land owners often have greater enforcement power than under-funded and under-staffed protected areas, so encroaching onto a protected area may be less dangerous for a smallholder farmer than onto a commercial plantation.[40] Whereas forest loss in protected areas affected by shifting agriculture is typically followed by forest regrowth when fields are left fallow,[26] resulting in secondary forests (not measured in our analysis), commodity-driven forest loss almost always results in permanent deforestation.[41]

Forestry was an important driver of forest loss in protected areas on all continents except Africa (Figures 1 and S1). In

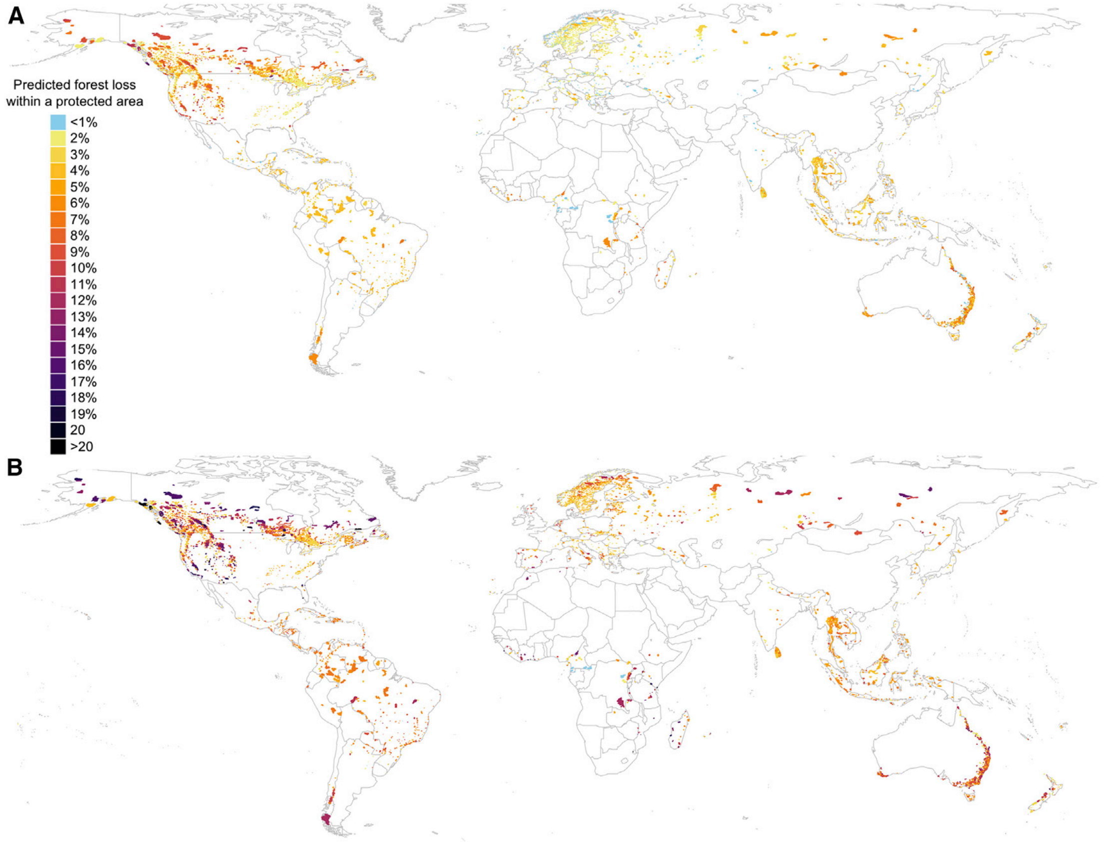

Figure 3. Predicted risk of future forest loss (2019–2036) inside protected areas (IUCN I and II)

(A) Scenario whereby protected areas' surroundings will experience a 7% forest loss, similar to average forest loss between 2000 and 2018.
(B) Doubling (14%) of forest loss in surroundings over the next 18 years.
 See also Figure S2.

general, the more forest remaining outside of the protected area, the less likely the protected area was to subsequently lose forest cover, but this was not the case in Asia and Oceania (Figures 1 and S1). In Asia, our results may be driven by the world's largest reforestation scheme—the Grain for Green program in China, which has dominated land use change there in the last two decades.[25,42] Variations in the precise relationships on different continents could be also due to forestry practices, which range from low-intensity selective logging of natural forests to repeated clear-cutting of monoculture stands, or difference in the adherence to protected areas rules.[43] Forestry is often intertwined with wildfire and other natural causes of forest loss, such as insect outbreak or windfall (not measured separately here).[44]

Some countries allow forestry interventions even within IUCN category I and II protected areas. For example, in central Europe, salvage logging sometimes follows natural disturbances,[45] and in the western United States, fuel reduction is conducted to reduce the intensity of fires.[46] Whereas such interventions are not likely to be detectable in our dataset, they may have an indirect effect on forest loss due to wildfire, which is a common cause of forest loss in protected areas, especially in North America and Oceania (Figures 2D and 2E). For example, in the northern Rockies (USA), large fires have become more common in recent decades due to warmer temperatures and earlier snowmelt.[47] In Oceania, neither the amount of surrounding forest cover nor surrounding loss was correlated with forest loss within protected areas embedded in urbanizing landscapes, which we cautiously interpret as reluctance by planners and the public to deforest protected areas for construction (Figure S1).

Risk hotspots for future forest loss in protected areas

Projecting our results to the future suggests that if forest loss outside of protected areas remains at the same level (7%) over the next 18 years (2019–2036) as over the last 18 years (Scenario A), 67% of protected areas worldwide would likely lose less than 1% of their forest cover (Figure 3A). That is an optimistic estimate because it would require the forest cover surrounding *all* protected areas to be maintained at 7%, rather than an average 7% forest loss. The non-linear nature of the relationship between forest loss inside and outside of protected areas (Figure 1) means that lower-than-average forest loss in one area does not make up for a higher-than-average loss in another area. If forest loss pressure doubles in protected area surroundings (i.e., 14% of forest outside is lost in 2019–2036, Scenario B), only 25% of protected areas worldwide would lose <1% of their forest cover and 3% would lose more forest inside than outside. Almost 20% of protected areas would lose >5% of forest cover (Figure 3B), resulting in a substantial release of carbon into the atmosphere and biodiversity losses.

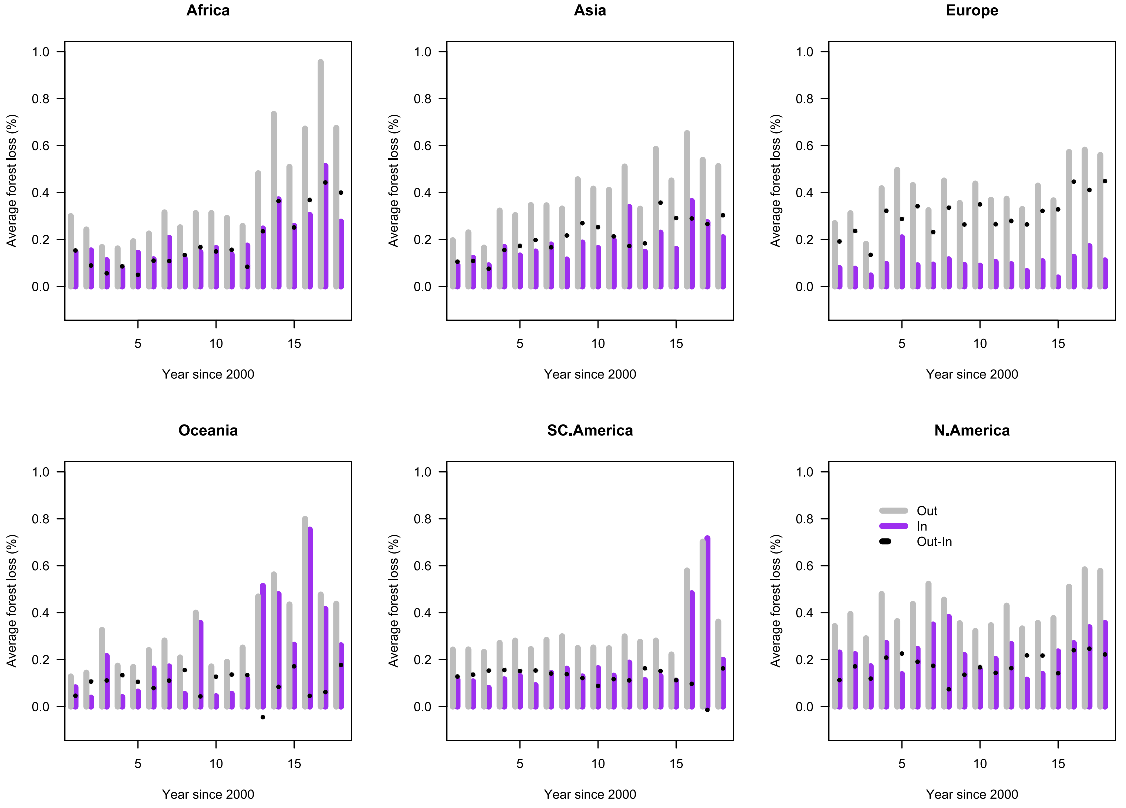

Figure 4. Average yearly forest loss in protected areas (purple) and their 5 km surroundings (gray), and the difference between them (black), for different continents between 2000 and 2018

Negative values of black dots mean that forest loss inside protected areas was on average higher than in their 5 km surroundings in a given year. SC.America, South and Central America; N.America, North America. See also Figures S3 and S4.

Within Madagascar, a global biodiversity hotspot,[48] two National Parks may be at a heightened risk of forest loss: Ankarafantsika and Kirindy Mitea National Parks. Under the business-as-usual scenario of 7% forest loss outside, we project that these national parks will lose 4.7% (3.2–7.0 95% CI) and 4.4% (3.2–6.1), respectively, of forest cover over the next 18 years. Within the Congo Basin, Virunga National Park in eastern Democratic Republic of Congo stands out with a projected 7.9% (3.7–17.0) forest loss. The largest national park in the Congo Basin, Bassin de la Lufira, is projected to lose 3.4% (2.1–5.4) of its forest. In Asia, the Khan Khentii and Tengis-Shishged National Parks in Mongolia may lose 8.6% (4.9–15.0) and 8.4% (4.8–14.5) forest, respectively, due to wildfire, and the Tesso Nilo National Park in Indonesia may lose 4.8% (3.4–7.0) of forest under continuing pressure from the agroindustry. In the Amazon, among those at highest risk is the Defensores del Chaco National Park in Paraguay, with 4.1% (3.0–5.5) forest loss. In Europe, no protected areas are, according to our results, likely to lose >3% of forest. In North America, many protected areas are likely to lose substantial amounts of forest due to wildfire.

Conclusion

We show that the remaining amount of forest cover outside of a protected area—a variable that is relatively easy to measure and can be derived from freely available data—can help predict the strict protected area's risk of subsequent forest loss, at a time-scale of the next 6–18 years (Figures 1 and 3). Even protected areas that are currently well preserved might be at a high risk of forest loss in the coming years if they have recently undergone substantial forest loss in their surroundings. National agencies could use our results to direct resources to their country's protected areas according to their predicted risk and prioritize pro-active conservation actions. Such preventative conservation actions should address the root cause of forest loss in the area that causes future forest loss within the protected area.[49] Predicting and preventing forest loss in protected areas, and beyond, is pivotal in the 21st century's fight against climate change and mass extinction of species.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2021.07.072.

ACKNOWLEDGMENTS

We thank Joshua Daskin, He Yin, and Tatiana Maeda for help and advice.

AUTHOR CONTRIBUTIONS

Z.B. designed the study and carried out GIS analyses, Z.B. and U.S. carried out statistical analyses, and S.J.H. and V.C.R. contributed substantially to results interpretation and methodology and conceived of additional analyses. All authors contributed to writing the manuscript.

DECLARATION OF INTERESTS

We declare no conflicts of interest.

Received: February 16, 2021
Revised: June 1, 2021
Accepted: July 28, 2021
Published: August 18, 2021

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
Google Earth Engine	[50]	https://developers.google.com/earth-engine
R version 4.0.3	[51]	https://www.r-project.org/
R package olsrr version 0.5.3	[52]	https://cran.r-project.org/web/packages/olsrr/index.html
R package maps version 3.3.0	[53]	https://cran.r-project.org/web/packages/maps/maps.pdf
Other		
World's protected areas	[54]	https://www.protectedplanet.net/en
Global Forest loss	[17]	https://earthenginepartners.appspot.com/science-2013-global-forest
Global Forest loss by driver	[18]	https://science.sciencemag.org/content/361/6407/1108/tab-figures-data

RESOURCE AVAILABILITY

Lead Contact

Further information should be directed to and will be fulfilled by the lead contact, Zuzana Buřivalová (burivalova@wisc.edu).

Materials Availability

This study did not generate new unique reagents.

Data and code availability

- This paper analyzes existing, publicly available data. The accession numbers for the datasets are listed in the key resources table.
- All original code is available in this paper's supplemental information (Methods S1).
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

For our analyses, we used the databases listed in the Key resources table: the World Database of Protected Areas, the Global Forest Change Dataset, and a dataset on global forest loss drivers.

METHOD DETAILS

Protected areas

We analyzed the World Database of Protected Areas (WDPA), which contains polygons that specify the position, size, and shape of most of the world's protected areas.[55] While this database is not exhaustive, it is the most complete and regularly updated one at a global scale.[56,57] We selected designated terrestrial protected areas that were classified as IUCN category I or II, because other categories are typically small (III, IV), may permit management activities causing forest loss (V, VI), or maintain low forest cover as part of the management plan (IV). Given our focus on forest cover change, we excluded protected areas that had < 10% of forest cover at the start of our analysis in 2000, and those that were smaller than 1 km^2. We also excluded protected areas with missing or corrupt IDs and geometries. In total, there were 257,543 protected areas, of which 239,152 were terrestrial, of which 19,923 were classified as IUCN category I or II, of which 11,654 were > 1 km^2 and had complete geometries, of which 7632 had > 10% forest cover in 2000.

The 'outside' of protected areas

Strict protected areas are often surrounded by less stringently protected areas, which are sometimes formally designated as another IUCN category (e.g., V and VI). Such landscapes are often expected to 'buffer' the strict protect area cores from various threats, including forest loss. In other cases, the surrounding landscape is not formally protected. Here we analyze the forest cover immediately outside of a protected area, i.e., within 5 km, regardless of its designation as a buffer zone in the protected area's management plan or the WDPA. Such areas are often used by local communities and visitors for recreation, subsistence or commercial activities, such as selective wood extraction, non-timber forest product harvest, small holder agriculture, or hunting.[58] We emphasize that there are many conservation benefits of PAs' surroundings, such as increasing the effective population size and territory of species, connecting two strictly protected areas, reducing the edge effects, etc.[58] However, in this paper we focus on the forest loss within the strict protected areas themselves, because we assume that they have a higher conservation value than their surroundings. Equally, we do not seek to establish which IUCN category is better at preventing a forest loss, a question that has been answered by other studies.[16]

Forest cover and loss

We quantified forest cover and loss from 2000 to 2018 using the 30-m resolution Global Forest Change dataset.[22] For each protected area and its surrounding outside area separately, we quantified the fraction of the area classified as forested in 2000, annual forest loss, and total forest loss over the 18 years (expressed as fraction of the protected area). Forest loss is defined in the dataset we used as "a stand-replacement disturbance or complete removal of tree cover canopy," whereby forest is defined as vegetation higher than 5 m (see Hansen et al.[22] for details). These definitions, which have been criticized[23] and defended,[59] have two important implications for our study: First, in our analysis we did not include data on forest gain from the Global Forest Change dataset, which sometimes reflect new monoculture plantations (e.g., Acacia, oil palm, teak), rendering the forest gain data problematic for our purposes, as monoculture plantations have little conservation value.[23] We only present forest gain in the overall statistics. A related limitation is that some of the pixels classified as forest in 2000 may have been mature monoculture plantations. Whereas such mature plantations have likely a lower conservation value than a diverse forest, meaning that their loss may be of a lower consequence than a loss of a natural forest, we argue that such loss is nevertheless notable when it occurs within a strict protected area, where clear cutting is typically not allowed.

Second, the Global Forest Change dataset does not distinguish between a temporary forest loss, followed by regeneration through natural succession, and a permanent forest loss, due to the conversion of forests to other types of land use change. To address this issue, we analyzed the likely causes of forest loss in each protected area, using a global dataset based on spatial patterns on satellite imagery between 2001 and 2015 to classify forest loss due to wildfire, forestry, commodity driven deforestation (e.g., oil palm plantations), shifting agriculture, and urbanization.[18] We optimistically assumed that forest loss due to wildfire, forestry, and shifting agriculture is temporary and followed by at least some degree of forest regrowth, whereas commodity driven deforestation and urbanization is permanent. For each protected area, we calculated the most frequent cause of forest loss. A limitation of this dataset is that its time span is shorter than our study period (15 out of 18 years), but that time span still provided us with a reasonable confidence in the main cause of forest loss.

QUANTIFICATION AND STATISTICAL ANALYSIS

We examined whether the relationship between the total forest loss (2000-2018) inside and outside of a protected area was modulated by the total amount of forest outside of a protected area in 2000, and other variables (Table S1). Our null hypothesis was that forest loss inside is linearly correlated with forest loss outside, and that the slope of this correlation does not differ depending on the absolute amount of forest left on the outside (dashed line in Figures 1 and S1). In our quasi-binomial generalized linear model, in addition to main effects (Table S1), we included the following two way interactions: *i)* Continent and Forest cover inside PA, *ii)* Continent and Forest cover outside PA, *iii*) Continent and Forest loss outside PA, *iv*) Forest loss driver and Forest cover outside PA, *v*) Forest loss driver and Forest loss outside PA, *vi*) Forest loss driver and Continent, *vii*) Forest cover outside PA in 2000 and Forest loss outside PA. A quasi-binomial generalized linear model is appropriate in our case, as our response variable is bound by 0 and 1, and is not normally distributed. Moreover, compared to a linear regression, a quasi-binomial model is more stringent, as it inflates standard errors, thereby reducing the significance of the model terms.

All variables concerning forest cover or forest loss are expressed as percentages of the protected area's geographic area (i.e., a 100 km^2 large protected area that had 50 km^2 of forest in 2000, of which 10 km^2 were subsequently lost, the forest cover in 2000 is 50%, and forest loss is 10%, not 20%). In the quasi-binomial model, percentages are expressed as fractions. Preliminary analysis showed that large amount of variance in forest loss is explained by the size of the protected area (see Results and discussion), we therefore decided to control for area in a standardized way for all forest cover related variables.

Sensitivity analysis

We fit the same model to three time periods: 1) forest loss in PA between 2001 and 2006, with the state of the PA surrounding in 2000, 2) forest loss in PA between 2007 and 2012, with the state of the PA surrounding in 2006, and 3) forest loss in PA between 2013 and 2018, with the state of the PA surrounding in 2012. We also repeated the entire analysis for two additional buffer widths – 10km and 2.5 km, in order to evaluate the robustness of our findings.

Future risk

Using the model for the full 18 years (i.e, 2001-2018) and the status outside of each PA in 2018, we parameterized two future forest loss scenarios, expressing different levels of forest loss pressure. In scenario A, 7% of forest cover outside of the PA is lost over the next 18 years, corresponding to the global average of forest loss outside of protected areas between 2000-2018. In scenario B, 14% is lost (twice the global forest loss rate we found for 2000-2018). Using our model, we estimated the amount of forest loss within each protected area under each scenario. Not all continents have all types of forest loss; for example, Europe and North America have little shifting agriculture. We only estimated forest loss inside protected area for combinations of continents and forest loss drivers represented by at least 50 protected areas. For forest loss drivers underrepresented on a given continent, we used a mean value for that continent in the prediction maps.

Spatial autocorrelation

We tested for spatial autocorrelation by deriving a correlogram of residuals at different distances, under 100 permutations, using the ncf package in R.[60] We found significant spatial autocorrelation at the shortest lag (Figure S2), however, the level of autocorrelation was too small (< 0.1) to warrant accounting for explicitly in our model. We note that other studies found substantial spatial auto-correlation in whether or not individual pixels are affected by forest loss in protected areas,[28] but those studies differ from our case, in that for us one datapoint represented one protected area so that we did not have very short lag distances.

Other factors

Forest loss within protected areas is affected by many underlying and proximate causes, including national policy, local and global commodity prices, infrastructure construction, and others.[60] Such causes vary and interact differently in each locality,[60] and we did not seek to explain why certain drivers of forest loss impact a particular protected area. Instead, our aim was to map the patterns and main drivers of changes in forest loss in protected areas and outside, in order to create an early warning system based on the remaining forest cover outside of the protected area, that might precede higher forest loss rates in the protected area itself. Preventing forest loss is not the only measure of success of protected areas; many other environmental and socio-economic variables are just as important,[14] particularly biodiversity.[30] However, no global datasets independent from forest cover exist for them to allow analyses.

Degazetting, downsizing and downgrading of PAs

Some of the protected areas that are included in our study may have been larger in 2000,[61] and we did not account for that, because we analyzed protected area boundaries from 2018. Such downsizing might happen, among other reasons, due to high demands for land.[61] We therefore assume that this would result in an underestimate of the forest loss rate, because protected areas that had been downsized during our study period may have suffered higher forest loss rates than we estimate by using their downsized extent in 2018.