

## Review

# Broadening the focus of forest conservation beyond carbon

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## SUMMARY

**Two concurrent trends are contributing towards a much broader view of forest conservation. First, the appreciation of the role of forests as a nature-based climate solution has grown rapidly, particularly among governments and the private sector. Second, the spatiotemporal resolution of forest mapping and the ease of tracking forest changes have dramatically improved. As a result, who does and who pays for forest conservation is changing: sectors and people previously considered separate from forest conservation now play an important role and need to be held accountable and motivated or forced to conserve forests. This change requires, and has stimulated, a broader range of forest conservation solutions. The need to assess the outcomes of conservation interventions has motivated the development and application of sophisticated econometric analyses, enabled by high resolution satellite data. At the same time, the focus on climate, together with the nature of available data and evaluation methods, has worked against a more comprehensive view of forest conservation. Instead, it has encouraged a focus on trees as carbon stores, often leaving out other important goals of forest conservation, such as biodiversity and human wellbeing. Even though both are intrinsically connected to climate outcomes, these areas have not kept pace with the scale and diversification of forest conservation. Finding synergies between these ‘co-benefits’, which play out on a local scale, with the carbon objective, related to the global amount of forests, is a major challenge and area for future advances in forest conservation.**

## Introduction

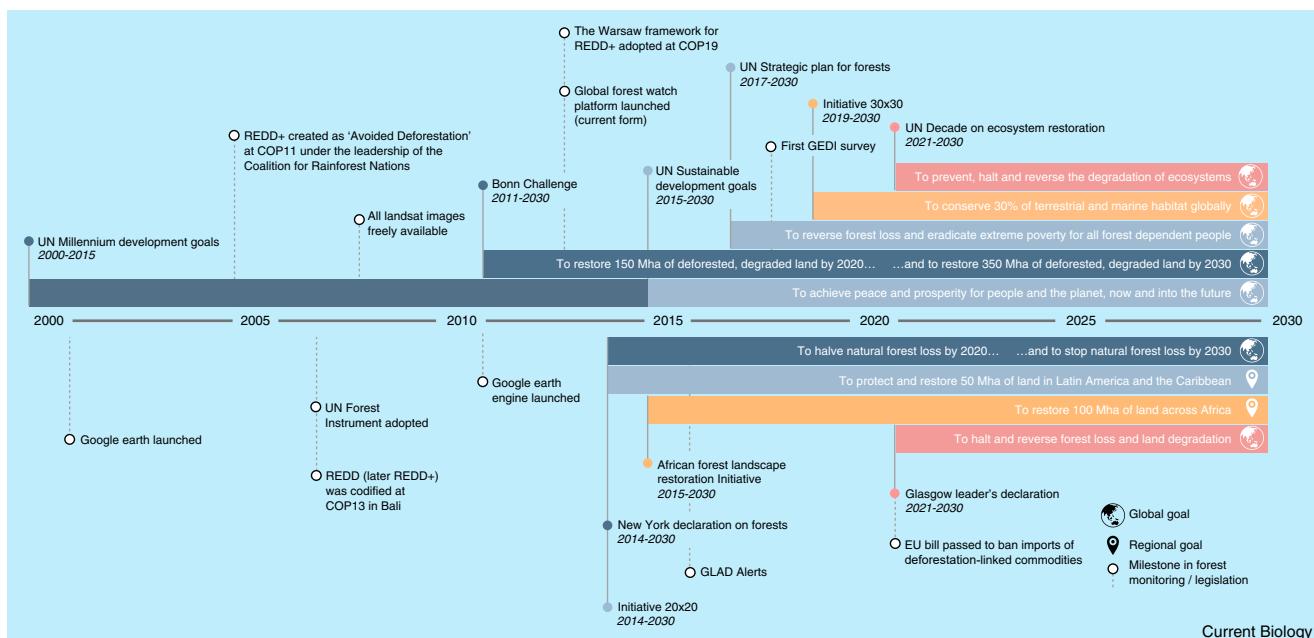
Recent events such as the 2019–2020 mega-fires in Australia<sup>1</sup> or the widely publicized forest fires in the Amazon in 2019<sup>2</sup> have increased the coverage of forests by the global media. But even before these events, forests have come to occupy a central place in public discourse during the unfolding climate crisis<sup>3,4</sup>. The two most frequently examined roles of forests in this context are how much carbon dioxide is released through deforestation and how this can be prevented<sup>5–7</sup>, as well as how much carbon dioxide can be sequestered by reforestation or forest restoration and how this can be achieved<sup>8–10</sup>.

Since the early reports in the 1990s by the Intergovernmental Panel on Climate Change of the United Nations (IPCC)<sup>11</sup>, countries have often leaned towards maintaining or creating biological carbon sinks to offset emissions, rather than drastically reducing emissions from fossil fuel use<sup>12</sup>. Offsetting and carbon credit trading were proposed in the Kyoto Protocol at the Third Conference of the Parties (COP3) in 1997 (Figure 1 and Box 1). Forests began to feature prominently as an important biological carbon sink, largely through the Reducing Emissions from Deforestation and Forest Degradation mechanism (REDD+)<sup>13,14</sup>. REDD+ has since spread worldwide with over 350 projects in 50 countries<sup>15</sup>. Around 2017, REDD+ projects, together with other initiatives that increase carbon sequestration in the

environment and prevent emissions came to be grouped under the umbrella term ‘nature-based climate solutions’ (or ‘natural climate solutions’). Forest-related pathways account for most of the global mitigation potential of natural climate solutions, the estimates of which vary broadly. The more conservative estimates peak at 11.5 Gt of CO<sub>2</sub> equivalent per year until 2050<sup>3</sup>, with forests — largely through preventing deforestation — providing the majority of this potential<sup>4,16–18</sup>.

At the COP26 in 2021, leaders of over 100 countries that contain more than 85% of the world’s forests committed to working collectively to halt and reverse forest loss and land degradation by 2030, under the Glasgow Leaders’ Declaration on Forests and Land Use. This was backed by US\$20 billion of investments from public and private funds, and largely motivated by climate change<sup>19–21</sup>. At the COP27 in 2022, the Forest and Climate Leaders’ Partnership was launched, with a similar goal of halting forest loss and degradation by 2030 (Figure 1). Global reforestation campaigns and pledges have been launched, culminating for example in the Trillion Tree Campaign, aiming to plant one trillion trees worldwide<sup>22,23</sup>. Even though the scientific basis for such large-scale tree planting has been promptly questioned and refined<sup>24–27</sup>, tree planting for climate purposes remains a globally and politically popular strategy.





**Figure 1. Timeline of major international goals and developments connected to forest conservation.**

Many international goals to stop deforestation and restore habitats are supposed to be achieved by the year 2030. Few goals extend beyond 2030.

At the same time, forest conservation and planting for climate purposes have also started to feature in greenwashing campaigns, including by fossil fuel companies, in land grabs, and violations of the rights of Indigenous Peoples and those dependent on forests for subsistence<sup>28</sup>. Similar criticism has been voiced about global initiatives heavily featuring forests, such as Half Earth or 30 by 30<sup>29,30</sup> (Figure 1), perhaps best summarized by the expression “our nature is not your solution”<sup>29</sup>. Importantly, many of the ambitious treaties, goals and innovative strategies around forest conservation and its financing (Figure 1) were adopted before all countries faced huge costs related to the COVID-19 pandemic, geopolitical tensions, and recent climate-change driven stressors<sup>31</sup>. These tensions serve as a reminder that forests are used by a broad variety of people, are valued for purposes far beyond regulating climate, and that optimizing for carbon does not necessarily uplift all people and maximize all other values of forests<sup>32</sup>.

In this review, we first discuss how the rise in the prominence of forests on the international climate change agenda has been enabled by and encouraged the vast improvements in measuring forests, forest change and the success of influencing forest loss through conservation interventions and policy. Then, we move beyond the concept of forests as predominantly carbon stores and examine the advances — and lack thereof — in other important aspects of forest conservation, namely biodiversity conservation and human health. We conclude by underscoring the necessity for forest conservation science and practice to embrace goals beyond carbon, and for scientists to provide the necessary technology, methods, and policy inputs to maximize the chances that future forests will be resilient and functional under a new climate regime.

### Remote sensing revolutionizes detection of forest changes

Major advances in remote sensing of forest cover and status have transformed which forest conservation issues we are able to detect, how fast and at which scale (Figure 2). Satellite images were used to study land cover and changes as soon as they became available<sup>33</sup>. However, for more than three decades after the first Landsat satellite was launched in 1972, the use of Landsat images in forest science and conservation remained limited, due to high costs and the expertise required to process the images<sup>34</sup>. Understanding where forests are and where they had been recently lost, at a global level, was transformed in 2008 when all archived Landsat satellite images became freely available<sup>34</sup>. This was leveraged by tools enabling non-experts to easily analyze freely available satellite images. For example, the yearly Global Forest Change dataset<sup>35</sup>, derived from Landsat images, is served to the public through intuitive platforms such as Global Forest Watch<sup>36</sup>.

The increasing temporal resolution of satellite images allows for near-real-time monitoring of forest loss. Information on the presence or absence of forests, or, more precisely, tree cover, (Box 2) is now available for the entire terrestrial surface at a 30-meter resolution updated monthly, with 5-meter resolution monthly updates for the entire tropical region<sup>36</sup>. Government agencies, conservation NGOs, communities, journalists — anyone with internet access — can opt to be alerted to new changes in tree cover, for example through the GLAD alert system (Global Land Analysis and Discovery). The newer RADD alerts (Radar for Detecting Deforestation) additionally overcome issues with cloud cover or smoke<sup>37</sup>. Such near-real time deforestation alerts are becoming a common feature in the conservation toolbox. Governments of several countries, including Peru, Brazil and Colombia, have adopted such systems for national use<sup>38,39</sup>.

### Box 1. Recent history of forests at the international climate change negotiations.

At first, the Kyoto protocol (Figure 1) did not sufficiently incentivize the protection of standing forests and the prevention of forest degradation, as carbon credit trading was restricted to plantation forests, ultimately opening the door to further deforestation<sup>208</sup>. Initially, the idea of issuing carbon credits for standing forest was not popular. The debate was dominated by countries that wanted to be allowed to use the credits from protecting forests to offset part of their CO<sub>2</sub> emission reduction obligations. At the same time, there was strong opposition from experts regarding the low additionality of crediting the forests that were not under threat of deforestation, such as many forests in Europe and North America<sup>209</sup>. Despite this initial unpopularity, the Coalition of Rainforest Nations (CRfN), led by Papua New Guinea and Costa Rica, argued that such a scheme could be a cost-effective way of reducing climate change with co-benefits such as poverty reduction, biodiversity conservation, and sustainable development. Ultimately, the initial scheme expanded to Reducing Emissions from Deforestation and Forest Degradation in Developing Countries and the Conservation, Sustainable Management of Forests and Enhancement of Forest Carbon Stocks (REDD+)<sup>209,210</sup>. The central idea was to protect forests in developing countries with the finance created from forest carbon credits, within the carbon markets linked to the post-2012 climate deal<sup>209,211</sup>. At the COP19, UNFCCC parties adopted the Warsaw Framework for REDD+ (Figure 1), with subsequent final decisions adopted at the COP21 in Paris, which provided methodological guidance and requirements for countries to access REDD+ activities<sup>212,213</sup>. The Warsaw Framework required that REDD+ projects are designed and implemented by respecting the principles rooted within the Cancun Safeguards<sup>214,215</sup>. However, no methodological guidance as to how to consider, assess, or verify these was provided<sup>216</sup>. Implementation of REDD+ projects has faced many problems as they are exposed to a wide variety of drivers of deforestation and forest degradation, and different socio-economic contexts<sup>15,217</sup>.

In Peru, an Indigenous community incorporated monthly deforestation alerts into their forest patrolling system, which led to a decrease in forest loss, especially in areas with a high risk of deforestation<sup>40</sup>. Across several African countries, the use of GLAD alerts led to an 18% decrease in the probability of deforestation, resulting in the saving of US\$149–696 million in terms of the social cost of carbon<sup>41</sup>.

Previously, remote sensing was limited to detecting the presence or absence of trees (Figure 2). Advances in remote sensing, together with seeing forests as complex systems, have helped detect and better define forest degradation (Box 2)<sup>42,43</sup>. Hyperspectral, very high resolution images, such as DESIS, enable the evaluation of individual tree species traits, such as resource allocation or stress<sup>44</sup>. It is now possible to measure the 3D structure of forests from space: LiDAR (Light Detection and Ranging) missions allow measures of forest structure, canopy height and underlying terrain. The results from GEDI (NASA's Global Ecosystem Dynamics Investigation), analyzed with deep convolutional neural networks, have been used to produce very precise global maps of tree height<sup>45–47</sup>. Together, these advances enable the study of forest degradation from various causes, such as selective logging, insect infestations, understory fires and drought<sup>48</sup>.

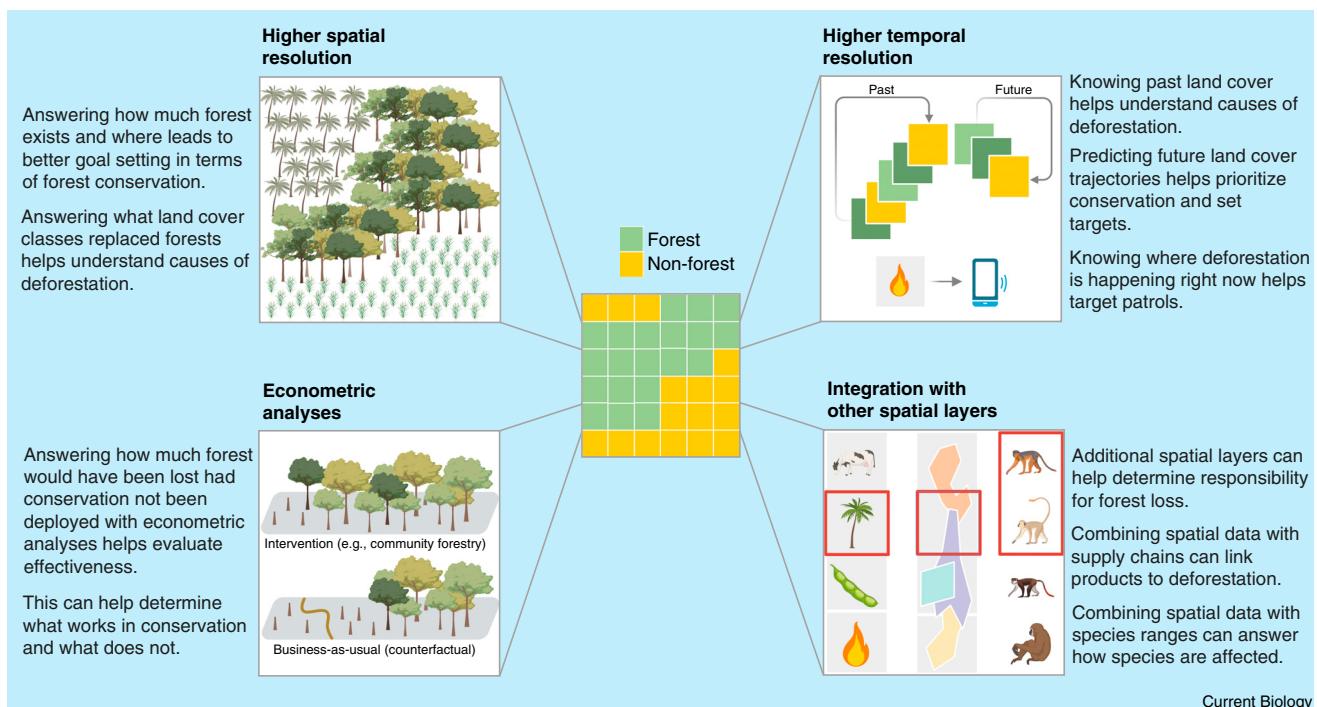
Early detection of forest degradation can improve the prediction of deforestation. In the Brazilian Amazon, the presence of new selective logging roads is connected to a higher likelihood of complete deforestation<sup>49</sup>. Recently, scientists detected 3.46 million km of roads in the Brazilian Amazon<sup>50</sup>. Similarly, early detection of tree mortality could be used in the future to limit and manage die-offs<sup>51</sup>. The ability to quantify ongoing deforestation in a spatially explicit way, as it changes with geopolitical, macro-economic and policy developments, can help the conservation sector to prioritize action<sup>52,53</sup>. For example, in Borneo, deforestation risk maps are based on past correlates of forest loss, such as distance to roads, terrain and soil suitability for agriculture<sup>54</sup>.

Remote sensing, together with carbon-flux towers that measure CO<sub>2</sub> exchange between the forest and the atmosphere

and forest warming or drying experiments, have improved predictions of how climate change will continue to impact various forest types (Figure 3). For example, much of the Amazon basin, being phosphorus limited, may have a lower-than-expected response to the fertilizing effect of increased atmospheric CO<sub>2</sub><sup>55</sup>. In Australia, remote-sensing and modeling studies found that the degree to which water stress leads to tree mortality in Australia has doubled over the last 35 years<sup>55,56</sup>. In boreal forests, remote sensing helped detect the pole-ward advance of trees at the speed of the last glacial maximum<sup>57</sup>. Regardless of our improved predictive ability, climate-induced changes and risks to forests are rarely explicitly considered in nature-based climate solutions. Such oversights may ultimately limit their effectiveness, and future studies should take the changing conditions into account when designing nature-based climate solutions<sup>4</sup>.

### Broadening forest conservation strategies and participation

Who does and who pays for forest conservation has changed dramatically in the last decade. This change is due to the increased need for forest conservation globally, as well as the greater availability and accessibility of effective forest monitoring tools. Sectors and people previously considered as separate from forest conservation are now playing an important role<sup>58</sup>. Forest conservation has moved from the domain of NGOs, governments and a limited number of industries (e.g. forestry), to practically everyone. From agroindustry linked to formerly forested lands, banks and the financial sector to fossil fuel companies, many more organizations are incentivized to pursue forest conservation<sup>59–61</sup>. Companies making commitments to forest conservation targets extend beyond those with direct links to deforestation, now including sectors such as finance, aviation, technology or entertainment<sup>62,63</sup>. This expansion of the constituency and goals of forest conservation has required and stimulated a wider range of forest conservation strategies, such as moratoria on deforestation, certifications of sustainable forestry and voluntary agreements<sup>64–66</sup>.



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**Figure 2. Developments in remote sensing have led to and been encouraged by major advances in forest conservation.**

Instead of being able to distinguish only broad land cover categories (e.g., forest and non-forest), we can now distinguish finer land use types, at a higher temporal resolution, and integrate data on forests with other data types to ask conservation questions. Created with BioRender.com.

The broadened constituency of forest conservation has been enabled by the possibility to assign responsibility for deforestation to specific industries, individual companies or properties<sup>5,67</sup>. In Indonesia, for instance, the palm oil and timber industries were found to be responsible for ~1 and ~3.7 million hectares of deforestation, respectively, between 2000 and 2010<sup>68</sup>. Such insights put pressure on consumers, industries and the government of Indonesia, which ultimately led to a moratorium on all new plantation and logging permits from 2011 to 2021<sup>69,70</sup>. Simultaneously, many companies began to pledge zero deforestation commitments. For example, Asia Pulp and Paper, one of the biggest timber plantation companies in Indonesia, announced that from 2013, all clearance of natural forest would be suspended<sup>71</sup>. In Brazil, sector-wide quantification of responsibility for deforestation contributed to the declaration of the Soy Moratorium in 2006<sup>72</sup>, and later a government pledge to reduce gross deforestation in the Legal Amazon by 80% by 2020, compared to 1996–2005. Since then, hundreds of companies, countries and other entities have made ambitious zero deforestation pledges. These are typically not legally binding, and therefore subject to change. Additionally, in many cases, the mechanisms for implementing and evaluating such commitments are ambiguous in terms of committing to zero net or zero gross deforestation<sup>71</sup>. Such pledges are useful, but ultimately it is necessary to hold individual companies accountable to ensure effectiveness<sup>59,73</sup>.

For certain commodities, such as palm oil, soy, or beef, it is possible to trace deforestation from the land, through several intermediaries, all the way to producers, which could be used by consumers to make purchasing decisions<sup>67</sup>. Such information is becoming publicly available through online tools, e.g. Trase<sup>74</sup>,

and several governments and country blocks — most recently the European Union — have banned the sourcing of commodities linked to deforestation<sup>70</sup>. Moving beyond forest cover, timber sourcing from tropical countries has also been newly linked to responsibility for biodiversity at a company level, although such analyses are currently rare<sup>75</sup>.

#### Land titling and Indigenous Peoples

The significant role of Indigenous Peoples and local communities in forest conservation is becoming more widely recognized. Several factors are contributing to this recognition, including activism by Indigenous Peoples, research showing that people have been an influential part of the majority of forest landscapes for thousands of years<sup>76</sup> and the acknowledgement that a substantial amount of Earth's remaining intact forests are on the lands of Indigenous Peoples<sup>77</sup>.

Together with development and social justice goals, the recognition that Indigenous Peoples and local communities are often effective at protecting forests has led to numerous land titling initiatives. Such programs, which take on additional importance when determining the beneficiaries of REDD+ and other mitigation-related payments, are beginning to be evaluated using rigorous econometric analyses. For example, formally recognizing land tenure by Indigenous Peoples in the Peruvian Amazon reduced forest clearing by more than three-quarters, and forest disturbance by two-thirds<sup>78</sup>. In Colombia, recognizing collective land rights of Afro-Colombian communities led to reduced forest loss<sup>79</sup>. Across tropical regions, forests with a higher presence of Indigenous Peoples show lower deforestation and degradation than non-protected areas<sup>80</sup>. Yet, in Indonesia, the national social forestry program, which gave community land titles, often in

### Box 2. Changing definition of forests

Despite the advances in remote sensing — and possibly also thanks to them — there is a lack of global agreement on concepts fundamental to forest conservation, such as the definitions of forests, deforestation, forest degradation, and reforestation. The way people define forests has changed substantially over the last two decades, due partially to the improvements in technology (what is possible to measure) and to the broadening of whose voices are considered when definitions are drawn. One definition of forests, commonly used for international purposes, was proposed by the Food and Agriculture Organization<sup>218</sup>. According to it, forest is: “land spanning more than 0.5 hectares with trees higher than five meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use.” This definition is now seen as too narrow and biased (Christmas tree plantations are forests, but teak plantations are not) and simultaneously too broad for conservation and climate purposes. For example, specifying a threshold of 10% canopy cover could result in substantial forest degradation being allowed to happen without a forest losing its status<sup>219,220</sup>. Some scientists propose that we cannot — and should not — strive for one universal definition of a forest, because any such definition will necessarily be based on the management objective and the values the defining party places on the forest<sup>221</sup>. Instead, they propose to define forests using a set of key criteria for different purposes: the forest’s value for timber, value for carbon, improving livelihoods of forest-dependent people, whether the forests are natural or planted, whether they are pre-existing or new, continuous or fragmented, and whether they consist of native or non-native species<sup>221</sup>. The fact that the definitions of forests, deforestation, and degradation are evolving concepts has had consequences for the forest conservation sector, particularly in climate change mitigation. Depending on how forests are defined, countries and companies have been able to prove net zero deforestation to fulfil requirements for funding<sup>222</sup>. In other cases, artificially inflating historical deforestation baselines can lead to wasting carbon credits for little additionality<sup>6,106</sup>. A technological solution to this issue may be to count tree cover loss, or indeed individual trees, rather than having to define forests<sup>6,9</sup>. The Global Forest Watch platform switched to this terminology (tree cover loss, instead of forest loss), which can be helpful in terms of carbon accounting. Yet, it does not resolve issues around the biodiversity impacts of forest degradation or loss, ecological functioning, and the many other societal and ecosystem values that might differ between collections of trees and forests, depending on how the latter are defined.

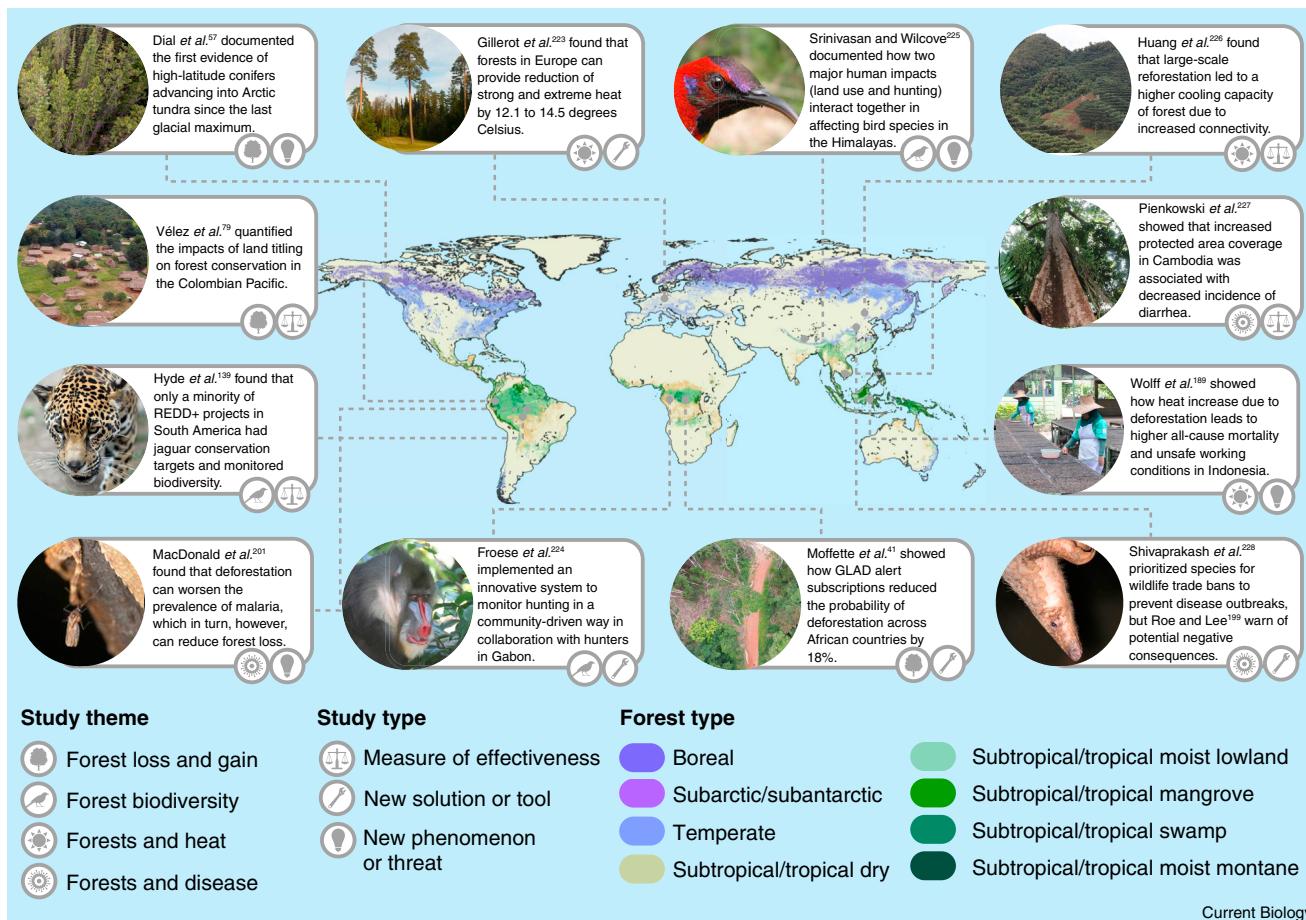
zones with a high deforestation pressure, led to increased deforestation compared to a baseline<sup>81</sup>. In the Brazilian Amazon, small and medium landholdings had increased deforestation in response to the Terra Legal land titling program<sup>60</sup>. A meta-analysis on a small sample size found that whereas land titling and reform initiatives did not reduce deforestation, Indigenous protected land led to better outcomes than all other strategies considered, including payments for ecosystem services, protected areas or sustainable use areas<sup>82</sup>. Although evaluating changes in deforestation rates in response to land titling programs can yield useful information, it should not be interpreted as evidence of success or failure of such programs. Land titling can be a step towards rectification of land-based injustice, a pre-condition of several other forest conservation strategies, or a preventative measure against landgrabs<sup>83,84</sup>, but one cannot recognize somebody’s rights to land and then judge them for not managing it according to a global goal.

Indigenous Peoples’ and local communities’ rights are affected by old and new forest conservation strategies and goals, beyond land titling<sup>84</sup>. Conservation has extended beyond ‘fortress conservation’ of strict protected areas towards a variety of strategies, including community forest conservation, decentralized forest management, payments for ecosystem services, less strict protected area categories, sustainability certification schemes and other effective area-based conservation measures<sup>85</sup>. Yet, some of these new conservation strategies are criticized for repeating the mistakes of fortress conservation<sup>86</sup>. Many protected areas have been established by forced eviction of communities, often by colonial powers, with negative consequences to this day<sup>84,87</sup>. Households close to protected areas often lose economic opportunities by losing access to the land, without always gaining new opportunities. Where forest access

is replaced by alternative opportunities, like ecotourism, these can be an unreliable source of income<sup>88,89</sup>. In Tanzania, this has disproportionately impacted the poorest members of society<sup>90</sup>. In China, households neighboring the giant panda biosphere reserve also experienced higher levels of human-wildlife conflict, which led to lower crop production<sup>91</sup>, similar to evidence from India and Tanzania<sup>92,93</sup>. ‘Neoprotectionist’ initiatives<sup>86</sup>, such as ‘half Earth’, which aims to protect half of all land and sea area for biodiversity conservation, large-scale reforestation programs that are not locally led, as well as nature-based solutions in general, have all been criticized for not considering the needs and values of local communities and Indigenous Peoples’ rights<sup>3,28,29,84</sup>. Critiques of these approaches suggest that alternatives should seek to disentangle conservation approaches from capitalism<sup>86</sup>, design and implement solutions for and by local communities<sup>94</sup>, and in general include more social scientists and political ecologists in conservation teams<sup>32</sup>.

### Evaluating and communicating forest conservation

The wider range of conservation strategies, coupled with better remote sensing data, has enabled the application of more sophisticated and rigorous econometric analyses to examine their effectiveness<sup>95</sup>. Forest conservation is becoming more evidence-informed, rather than based on factors such as personal or organizational preference, current fashion, anecdotal evidence, inertia or good intention<sup>96–98</sup>. Impact evaluations have refined the common assumption that declaring a forest protected will reduce forest loss and that impact could be inferred directly from the extent of protected area. Initially, most impact evaluations used satellite images to compare forest loss inside and outside of protected areas<sup>99–101</sup>. If forest loss was higher outside than inside, the protected area would be considered effective in preventing deforestation. Currently, more nuanced

**Figure 3. Recent advances in forest conservation.**

Studies exemplifying recent advances in forest conservation science, across four themes (forest loss and gain, biodiversity, heat, and health) and three approaches (identifying a new phenomenon or threat, developing a new solution or tool, and measuring the effectiveness of a solution). Image credits: Rhett Butler, Zuzana Burivalová, Umesh Srinivasan. Map source: IUCN Red List Habitat Classification Scheme (V3.1). For more detail on the mentioned studies, see<sup>41,57,79,139,189,199,201,223–228</sup>.

and robust analyses, in a causal inference framework, are becoming standard<sup>95,102</sup>. Using econometric methods, scientists can estimate additionality — how much deforestation has been actually prevented due to the establishment of a protected area or another conservation measure — eliminating many confounding factors, such as the tendency of protected areas to be established in more remote or steep locations with lower suitability for agriculture<sup>103</sup>.

Conservation is rarely done in an experimental way<sup>104</sup>. Thus, determining additionality typically relies on quasi-experimental approaches, such as propensity score matching, difference-in-difference(-in-difference), instrumental variables and synthetic control methods, i.e. techniques that better enable assigning a cause to an effect<sup>105,106</sup>. These techniques are increasingly used to evaluate whether an intervention led to a decline in forest loss in a variety of forest conservation strategies, including protected areas<sup>103,107</sup>, payments for ecosystem services<sup>108,109</sup>, REDD+<sup>106</sup>, forest certification<sup>110,111</sup>, community-based forest management<sup>112,113</sup>, zero deforestation pledges and deforestation moratoria<sup>70,114</sup>. In general, rigorously evaluated impact estimates tend to be smaller than less rigorously evaluated ones<sup>106</sup>.

This is due to several factors, such as: leakage, whereby deforestation is displaced to an area outside of the intervention<sup>72</sup>; higher deforestation rates in anticipation of a new intervention<sup>60</sup>; low baseline deforestation due to poor agricultural suitability or lack of other pressures<sup>115</sup>; a decreasing nationwide deforestation trend due to other policies and interventions (possibly in combination with the examined intervention); commodity prices; broader geopolitical trends<sup>106</sup>; or outright ineffectiveness. For example, in the case of REDD+ projects, studies have shown mixed results. Randomized control trials in Africa showed that paying households to reduce deforestation was effective, but it was ineffective if the payments were unconditional<sup>104,116</sup>. One REDD+ intervention in Amazonia reduced deforestation rates by 50% relative to matched control sites<sup>117,118</sup>, whereas other studies showed little impact<sup>106,119</sup>. A recent global study evaluating the effectiveness of voluntary REDD+ projects demonstrated that in the first five years of implementation, deforestation and degradation within project areas was reduced by 47% and 58%, respectively, compared to matched counterfactual areas<sup>21</sup>.

Several deforestation moratoria and zero deforestation pledges have now also been rigorously evaluated. According

to a triple difference analysis, the moratorium in Indonesia directly caused dryland areas within the moratorium to gain only 0.65% more forest between 2011 and 2018 compared to areas outside the moratorium, and there was no significant reduction in deforestation on peatlands<sup>120</sup>. It is possible that this lack of a substantial effect is due to a general decline in deforestation across Indonesia<sup>120</sup>, which could be due to lower commodity prices between 2012 and 2019<sup>121</sup>, or the influence of regional weather conditions. In Brazil, once the soy moratorium was implemented, scientists were able to detect and quantify the leakage of deforestation to the Cerrado<sup>114,122</sup>, ultimately making legislation more complete and effective.

The process of forest conservation — from detecting an issue, proposing a solution, evaluating it, to adjusting the solution<sup>123</sup> (Figure 3) — is transformed by faster and broader communication. Activists and scientists are better able to directly communicate with the public via social media, and traditional media outlets cover conservation issues more often<sup>2,124</sup>. Global Forest Watch has helped make deforestation a newsworthy event, as it is something journalists can and do report on, increasing public pressure on companies, governments, and conservation organizations. This could in turn expand the constituency of forest conservation<sup>124,125</sup>. What works and what does not work in forest conservation is increasingly shared beyond the peer-reviewed literature, in a more systematic way. The platform conservation evidence (<https://www.conervationevidence.com>) for example collates and synthesizes scientific evidence on which conservation actions, many of which are related to forests, work for specific conservation outcomes<sup>126</sup>. Another platform, conservation effectiveness (<https://www.conervationeffectiveness.org>)<sup>127</sup>, visualizes evidence on higher-level forest conservation strategies and presents the evidence in terms of positive, negative and neutral outcomes for a variety of environmental, social and economic metrics<sup>85</sup>. In addition, the ‘Collaboration for Environmental Evidence’ promotes systematic reviews on individual forest conservation strategies<sup>128</sup>.

The forest conservation sector has a better opportunity than ever before to learn from the successes and failures of previous projects<sup>82,129</sup>. Yet, there remains a substantial knowledge gap in the understanding of how evidence from one study, gathered in a specific conservation context, translates to a different context<sup>130</sup>. Most forest conservation interventions are highly tailored solutions to local problems. Whereas meta-analyses can help estimate an overall effect of a conservation strategy, such overall effects do not guarantee that the same gains will be made in a new context<sup>129</sup>.

### Forest biodiversity, human health and other co-benefits

Climate change has put forests at the forefront of the international agenda, and yet this has worked against a more comprehensive view of the role of forest ecosystems, encouraging a focus principally on the presence or absence of forests or individual trees (Box 2). Other ecosystem services and forest values, such as water regulation, soil protection, non-timber forest production, biodiversity protection and benefits to human wellbeing, are often seen as secondary ‘co-benefits’ of forest protection, important but not driving large forest conservation initiatives<sup>131</sup>. How we maximize co-benefits — particularly biodiversity and human health, which often depend on the type and location of

forests — with the carbon objective, which depends on total biomass, is a major challenge and likely an area for advances in forest conservation in the future<sup>132</sup>.

### The need for new biodiversity monitoring tools

Assessments of biodiversity have not been able to keep pace with the scale and diversification of forest conservation. Advances in remote sensing have mostly been used to assess plant diversity or habitat that might be suitable for animals<sup>44,133</sup>, but monitoring forest fauna itself has remained elusive at the necessary scale. This is problematic because animal biodiversity is affected by human impacts beyond habitat loss visible on satellite imagery. Hunting, selective logging, mining and invasive species impact biodiversity without drastically changing the presence or absence of forests<sup>134</sup>. Yet, with nature-based climate solutions permeating a large, diverse but often fragmented area of the world’s forests, detailed biodiversity monitoring is beyond the scope of most projects. Carbon-focused projects typically monitor biodiversity either in an *ad hoc* and limited basis or not at all, despite its importance and proposed frameworks to do so<sup>135,136</sup>. For example, despite its large footprint, the co-benefits of REDD+ for biodiversity conservation are still uncertain and understudied, even for charismatic and keystone species such as jaguars<sup>129,137–144</sup> (Figure 3). However, until there is a cost-effective tool to verify the ‘co-benefits’ of biodiversity conservation under nature-based climate solutions, REDD+, or any predominantly carbon-oriented projects, it is unlikely that these will be taken up by the new powerful players in forest conservation, such as large corporations and financial institutions. Such tools are also sorely needed to prevent the latter from using biodiversity co-benefits for greenwashing<sup>3,145</sup>.

The exponential growth in studies using bioacoustics and environmental DNA meta-barcoding (eDNA) has contributed to the development of cost-effective tools to monitor forest biodiversity<sup>146,147</sup>. These techniques can complement remotely sensed images from satellites and camera traps. Camera trapping in forests<sup>148–150</sup> has advanced most recently in the detection of arboreal species and analytical techniques<sup>151,152</sup>. Yet, forests harbor many species that are hard to observe visually or capture with camera traps. Bioacoustics relies on using the sounds that individual species make to monitor their presence, absence and behavior<sup>146</sup>. In the field of bioacoustics, ecoacoustics or soundscape ecology uses entire soundscapes — all the sounds emanating from a landscape — to evaluate changes in the vocalizing communities<sup>153,154</sup>. Sound-based technology is particularly useful in tropical forests due to the low visibility within them and their high number of vocalizing species<sup>155</sup>. Soundscape analyses have been used to prioritize forest sites for conservation<sup>146</sup>, evaluate the impact of human use on biodiversity<sup>156–158</sup>, monitor restoration or regeneration of habitats<sup>159,160</sup>, monitor and prevent poaching of animals<sup>161,162</sup> and document the advance of invasive species in forests<sup>163</sup>. While bioacoustics is a rapidly growing field, with scientists still developing best practices in data collection, analysis and interpretation<sup>164,165</sup>, it has the potential for continuous monitoring at selected sites, as well as targeted surveys, and investigations in a causal inference framework<sup>165–167</sup>.

Environmental DNA (eDNA) meta-barcoding from forest habitats helps detect species, including those that are hard to observe and do not vocalize, by extracting DNA from water,

soil, malaise traps, blood-feeding organisms, and most recently from air<sup>147,168–170</sup>. For example, in a survey of Amazonian mammals with eDNA, traditional techniques (e.g. pitfalls, mist nets) and camera traps, found that meta-barcoding detected the highest number of species, at the lowest per-species cost<sup>171</sup>. In forestry, eDNA could be particularly suitable for monitoring freshwater organisms, as certified forestry operations are often responsible for monitoring how harvest and effluents from their mills impact freshwater systems<sup>172</sup>. Environmental DNA is also increasingly used in monitoring the progress of forest restoration<sup>173</sup>. Similarly to bioacoustics, analytical techniques are rapidly evolving<sup>170,174</sup>. Although there are no standardized global best practices as of yet, several individual countries have national guidelines<sup>175</sup>.

Camera trapping, bioacoustics, eDNA, as well as various drone-borne sensors, such as thermal infrared cameras<sup>176</sup>, are changing how we can evaluate the status of forest biodiversity, invisible from satellite images. Advances in Artificial Intelligence, such as the use of Convolutional Neural Networks, has vastly improved the possibility of detecting individual species or anomalies from soundscapes, images, or DNA samples<sup>177–179</sup>. However, the biodiversity monitoring breakthrough is more complex than the satellite image revolution, for several reasons: global coverage with any of the current technologies is unlikely, leading to a variety of sensors deployed with different settings, making them not entirely compatible. This in turn has made it difficult to have global databases of harmonized, near-real-time biodiversity data, equivalent to Global Forest Watch<sup>180</sup>, which leads to a lower uptake of biodiversity measures by those involved in the new, broader suite of forest conservation approaches. These drawbacks could be partially overcome by citizen science projects implemented through platforms such as eBird, iNaturalist, or Zooniverse<sup>181</sup>, which often take data collection heterogeneity explicitly into account. After the 2019/2020 bushfire season in Australia, citizen scientists for example helped rapidly map fire severity and biodiversity recovery<sup>182</sup>. While most projects are local or national, several successful international efforts exist, such as the Great Southern Bioblitz<sup>183</sup>, which generated over 190,000 observations in the southern hemisphere over four days in 2021. Not all biodiversity monitoring needs can be fulfilled by citizen science<sup>181</sup>, it can nevertheless provide meaningful ways to connect with forests and nature in general, and thus further broaden who is involved in conservation<sup>184</sup>.

### Human health

Even though conserving forests for human health has been promoted since the 1970s, it recently gained traction as evidence is growing for its effectiveness in, for instance, improving food security, reducing disease burden or bolstering mental health<sup>185</sup>. Forest loss and degradation can have negative consequences for public health, disproportionately impacting people living in areas with high mean annual temperatures, poor access to healthcare, and lack of temperature-regulating infrastructure<sup>186</sup>. Two notable areas of advancement are the role of forests in modulating micro- and macro-climate and zoonotic disease spillover.

Deforestation can dramatically increase local temperatures, beyond the change resulting from global climate warming<sup>187</sup>. In the Xingu region of the Amazon, conversion of forest to crops resulted in additional warming due to lower net surface radiation

and latent heat flux and higher sensible heat flux<sup>188</sup>. The Berau regency in Indonesia lost 17% of its forest cover between 2002 and 2018, which resulted in a 0.95°C increase in daily maximum temperatures, leading to a ~8% increase in all-cause human mortality<sup>189</sup>. In the same region, workers in deforested areas spent more time under heat strain compared to workers in a forest, affecting their productivity and health<sup>190,191</sup>. The additional warming impact increases with the scale of forest loss – the highest warming typically occurs in the largest deforested patches<sup>192</sup>. The resulting changes to thermoregulation and precipitation rates can lead to an increase in extreme weather events, including heatwaves<sup>193,194</sup>.

Forest fragmentation is linked to increased zoonotic disease spillover, as disease vectors are forced into closer contact with humans or domestic animals, which can serve as ‘bridges’ or intermediate hosts<sup>195</sup>. Over the last 50 years, deforestation has been linked to the emergence of the Zika virus, Nipah virus and Ebola fever, which have a combined death toll of over 16,600<sup>196,197</sup>. The COVID-19 pandemic has demonstrated the danger posed to human health by such emerging infectious diseases, which can also have further knock-on effects on conservation efforts. For example, COVID-19 impacted how we could safely monitor biodiversity and disrupted ecotourism<sup>198</sup>. At the same time, it promoted strict bans on wildlife trade<sup>199</sup>. Recent advances show that deforestation affects zoonotic disease spillover in complex ways<sup>200</sup>. For example, forest loss can both increase and decrease malaria prevalence, partially depending on the stage of deforestation<sup>201</sup>. At the same time, better forest conservation can worsen public health through increased human-wildlife conflict and loss of access to forest resources, such as medicinal plants or nutrients from bushmeat<sup>3,202,203</sup>. As such, global conservation initiatives may have a positive impact on public health or conservation on a global scale but at the expense of the health of local communities. Although forest conservation can be an important lever for public health outcomes<sup>186</sup>, the complexity of the underlying mechanisms means that true win-win solutions are likely to be found only through close collaborations between local communities and scientists from the disciplines of conservation, disease ecology, public health, environmental justice, and social science, amongst others<sup>185,204,205</sup>. There are several emerging approaches which aim to incorporate the connection between public health and environmental protection, including ‘one health’ and ‘planetary health’<sup>185,206,207</sup>.

### Conclusion

Given the intertwined trends of increased global interest in forests and the advances in forest monitoring, it is likely that forest conservation is changing more rapidly at present than ever before. Attention to the role of forests in mitigating the impacts of climate change is creating opportunities to increase and diversify forest conservation activities. New science and technologies are being developed and used to address this diversification. Ultimately though, forests still compete with alternative land-uses for local economic primacy, while facing pressures from climate change. Economic values placed on ecosystem services could help adjust this balance but major challenges in effectively connecting forest conservation projects to service markets, e.g., for climate mitigation, substantively limits their impact. Moreover, putting a monetary value on the climate mitigation role of forests

can lead to prioritizing carbon storage over other important forest related goals such as biodiversity conservation and human health outcomes. A purely economic view of forest value can also be fundamentally misaligned with the views and values of many citizens, including Indigenous Peoples and grassroot environmental NGOs. Increasing awareness of the multiple public benefits provided by forests will likely continue to keep forests high in public dialogue within the United Nations' decade of ecosystem restoration. Many global forest goals are supposed to be achieved by 2030, and international as well as community leaders should be looking beyond 2030, learning from past successes and failures. Forest conservation science teams — composed of both natural and social scientists — must continue finding new ways to creatively balance the global and local needs of humans for healthy and resilient forests, embracing the diversity of stakeholders and the underlying and changing ecology of these critical ecosystems.

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#### DECLARATION OF INTERESTS

The authors declare no competing interests.

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