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Current and future opportunities for satellite remote sensing to inform rewilding

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Abstract

Rewilding has been suggested as an effective strategy for addressing environmental challenges such as the intertwined biodiversity and climate change crises, but there is little information to guide the monitoring of rewilding projects. Since rewilding focuses on enhancing ecosystem functionality, with no defined endpoint, monitoring strategies used in restoration are often inappropriate, as they typically focus on assessing species composition, or the ecological transition of an ecosystem towards a defined desired state. We here discuss how satellite remote sensing can provide an opportunity to address existing knowledge and data gaps in rewilding science. We first discuss how satellite remote sensing is currently being used to inform rewilding initiatives and highlight current barriers to the adoption of this type of technology by practitioners and scientists involved with rewilding. We then identify opportunities for satellite remote sensing to help address current knowledge gaps in rewilding, including gaining a better understanding of the role of animals in ecosystem functioning; improving the monitoring of landscape-scale connectivity; and assessing the impacts of rewilding on the conservation status of rewilded sites. Though significant barriers remain to the widespread use of satellite remote sensing to monitor rewilding projects, we argue that decisions on monitoring approaches and priorities need to be part of implementation plans from the start, involving both remote sensing experts and ecologists. Making use of the full potential of satellite remote sensing for rewilding ultimately requires integrating species and ecosystem perspectives at the monitoring, knowledge-producing and decision-making levels. Such an integration will require a change in know-how, necessitating increased inter-disciplinary interactions and collaborations, as well as conceptual shifts in communities and organizations traditionally involved in biodiversity conservation.

Introduction

Our environment is breaking down, taking with it the foundations of our economies, food security, health and quality of life (Steffen et al., 2018). A number of crises underpin this breakdown, such as rapid changes in climatic conditions and unprecedented biodiversity loss; many of these are fundamentally connected. For example, human-induced climate change is leading to a loss of biological diversity, but the loss of biodiversity driven by climate change and other anthropogenic pressures (such as land use change) is deepening the climate crisis, with reduced species abundance, local extinctions, as well as the rapid degradation and loss of ecosystems such as mangroves, tropical forests, peatlands and seagrass (Pörtner et al., 2021). These losses are having major impacts on our planet's ability to store carbon, as well as on nature and people's ability to adapt and cope with changing climatic conditions (Pettorelli et al., 2021). Scientific advice from international scientific panels such as the International Panel on Climate Change (IPCC) and the International Platform on Biodiversity and Ecosystem Services (IPBES) could not be clearer: we need rapid bold collective action to transform economies to achieve a low-carbon, sustainable, biodiverse future (IPBES, 2019; IPCC, 2022).

As the planet's life-support systems are fast approaching a danger zone for humanity (Persson et al., 2022), it is fundamental that we not only promote a different path for development underpinned by the sustainable use of natural resources but that we also acknowledge that our ability to tackle current societal challenges is closely linked to our ability to retain and increase biodiversity (Strassburg et al., 2020). Such a realization has recently led to an increase in calls for large-scale ecological restoration projects, as exemplified by the Bonn Challenge, which aims to restore 350 million ha of degraded and deforested lands by 2030, and the launch of the United Nations Decade on Restoration, which aims to spur actions to prevent, halt and reverse the degradation of ecosystems on every continent and in every ocean (Pettorelli et al., 2021).

Rewilding, broadly defined as the recovery of self-organizing and self-sustaining ecosystems shaped by natural processes, is increasingly being considered as a cost-effective environmental management option to bend the curve of biodiversity loss, with the potential for enhancing both biodiversity and ecosystem services such as carbon sequestration and climate regulation (Cromsigt et al., 2018; Pettorelli et al., 2018a). As a conservation approach, it has gained substantial traction in the past few years, with, for example, the International Union for the Conservation of Nature (IUCN) having launched both an inter-commissional working group on rewilding and a rewilding thematic group under the Commission on Ecosystem Management. Several rewilding projects are currently being implemented in multiple countries around the world, with the number of launched projects having increased significantly in the past few years, particularly in Europe (Pettorelli et al., 2019).

Although related, rewilding is expected to be conceptually different from traditional ecological restoration (du Toit & Pettorelli, 2019), in the sense that rewilding aims at enhancing the functioning of ecosystems, rather than reaching a particular compositional or structural state. As such, the monitoring of rewilding projects and the definition of success are in many respects uncharted territory, as, for example, how to best detect and track changes in ecosystem functioning is still open to debate, with very little experience to draw from (Schulte to Bühne et al., 2022; Torres et al., 2018). Practical and comprehensive guidance on how to monitor the impacts of rewilding efforts has so far been limited, with existing recommendations including (1) adapting guidance from organizations such as IUCN and the Society for Ecological Restoration on how to audit restoration projects, which requires setting up a benchmark and comparing the level of ecosystem integrity between the chosen benchmark and the rewilded site (Torres et al., 2018), and (2) using species distribution models to assess the potential level of colonization by new species (Mata et al., 2021).

Over the past decades, satellite remote sensing has shown increased utility for providing information on the state of, and pressures on, biodiversity at a landscape, regional, ecosystem, continental and global spatial scales (Pettorelli, 2019) and could, amongst other things, offer promising avenues for the cost-effective monitoring of ecosystem processes and functions (Pettorelli et al., 2018b) making satellite-based monitoring approaches particularly well suited to inform rewilding projects. Indeed, proponents of rewilding often emphasize that rewilding takes place at large spatial scales, making satellite remote sensing a well-suited instrument for monitoring rewilding, given its wall-to-wall coverage of the Earth's surface. In addition, many satellite missions have been generating data for decades (e.g. the Landsat archive going back more than 40 years in many places), allowing for changes in ecosystem dynamics (such as phenology) to be observed.

To date, however, little practical guidelines and recommendations are available to practitioners to gauge the benefits and limitations of using satellite remote sensing technology to quantitatively assess the impacts of a rewilding scheme on ecosystem composition, structure and functioning. Discussions as to how satellite data could help address current knowledge and data gaps in rewilding science are also lacking. To address these gaps, we here provide an up-to-date, interdisciplinary perspective on the current and future prospects of satellite technology to inform the monitoring and evaluation of terrestrial rewilding projects (Fig. 1). There are many ways in which satellite data can inform rewilding efforts, such as helping monitor changes in land cover, ecosystem functioning and the level of various human-induced disturbances in and around rewilding sites. In this contribution, we review established avenues and highlight new developments that have a high potential to make a difference to practitioners and policymakers. Although satellite data have become increasingly popular in applied ecology, they are still underused. Hence, we also discuss current barriers to the democratization of satellite-based approaches in rewilding science and practices and identify possible ways to overcome some of these limitations.

Satellite Remote Sensing and the Monitoring of Rewilding and Other Restoration Projects: Status and Limitations

How does satellite remote sensing currently inform rewilding?

The rewilding of a degraded area is expected to transform ecosystem structure, composition and functioning, altering the distribution of habitats for multiple species. The

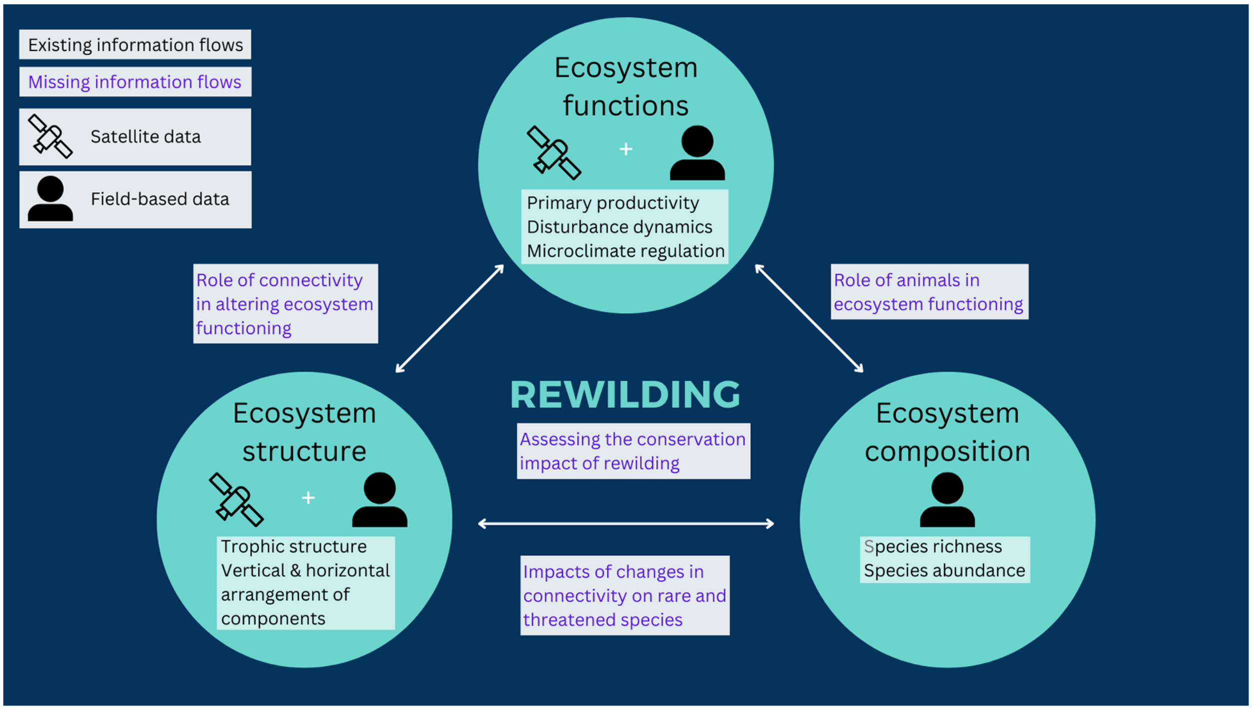

Figure 1. Overview of existing and missing information flows for rewilding monitoring. Field-based and satellite data already provide complementary information on the different dimensions of ecological change occurring as a result of rewilding. Satellite data could also help elucidate the relationships between different dimensions of ecological change.

utility of satellite data to map ecosystem and habitat distribution in different realms and at various spatial resolutions is well established (Pettorelli, 2019), and studies that have made use of satellite data to assess the biodiversity outcomes of rewilding projects, and restoration projects more broadly, have so far primarily focused on land cover mapping, land cover change detection and changes in the availability of suitable habitats as informed by satellite imagery (see e.g. Dombrovski et al., 2022; Mata et al., 2021; Regos et al., 2016; Zielke et al., 2019). Examples of such applications include the use of very high-resolution imagery (e.g., Quickbird, Worldview) to characterize the response of woodlands to mechanical restoration (Meddens et al., 2016); and the use of passive (Wu et al., 2020) or active sensors (Chen et al., 2018) to compare the outcomes of different restoration treatments.

Tracking changes in ecosystem structure involves providing information on the distribution of structural components (e.g. number of water bodies in a given terrestrial ecosystem), as well as describing horizontal and vertical arrangements. The horizontal arrangement typically refers to fragmentation metrics (e.g. number of fragments, distance between fragments; Fahrig, 2003) whilst vertical structure typically refers to the arrangement of the canopy in the vertical dimension, which is a key component of habitat quality for many species. Changes in satellite-derived metrics of ecosystem structure as a result of restoration or rewilding projects have rarely been reported in the literature, though exceptions do exist, particularly when it comes to the restoration of forests (see e.g. Camarretta et al., 2020 for a review of the use of passive and active sensors to capture structural attributes at the tree- and stand-level). For example, LiDAR data have been used to track changes in vertical vegetation structure on abandoned agricultural fields over time (Broughton et al., 2021).

Similar to land cover and land cover change, the tracking of primary productivity dynamics from space has been the subject of many scientific studies since the launch of the Landsat program, with many satellite-based vegetation indices, including the normalized difference vegetation index (NDVI), having been shown to indirectly relate to this key ecosystem process (Pettorelli, 2013). Despite this popularity, few studies have looked at the impacts of rewilding projects, or unintentional rewilding as a result of human land abandonment, on primary productivity dynamics as tracked by NDVI (but see Sikorska et al., 2021; Schulte to Bühne et al., 2022). This is surprising, as rewilding often includes reintroducing or increasing populations of large herbivores, and the remote monitoring of primary productivity dynamics can help assess the impacts of increasing herbivory on vegetation (Navarro et al., 2020).

Similarly, the use of NDVI to inform restoration projects remains relatively limited, although interesting exceptions can be found (see e.g. Hausner et al., 2018; Kim et al., 2015). More broadly, and despite rewilding efforts being centred on the functioning of ecosystems, including the facilitation of new processes as well as the enhanced functioning of existing processes, literature documenting changes in ecosystem functioning because of rewilding (or restoration) remains relatively scarce.

What are the barriers to the use of satellite data in rewilding projects?

Though satellite data has become a standard tool in ecological research over the past decades, its use in monitoring environmental protection and restoration strategies, including rewilding, remains limited, for a number of reasons. Some of the barriers to the use of satellite data in rewilding projects are discussed below (Fig. 2).

Importance of monitoring for rewilding

Rewilding is a conservation approach that seeks to establish self-organizing, self-sustaining ecosystems, with no commitment to align ecosystems' structure, composition or functioning with specific ecological or historical benchmarks. As such, questions are sometimes raised about the necessity to monitor rewilding projects and their outcomes, especially so given the difficulties and costs associated with biodiversity monitoring. There are however several reasons why monitoring should be part of any rewilding project's implementation plans. First, although uncertainty about ecosystem trajectory characterizes rewilding, rewilding is defined as broadly aiming to enhance ecosystem functions, and existing rewilding projects have so far been associated with clear targets (Pettorelli et al., 2018a). These aims and targets are part of the information communicated to funders, local communities, policy makers and other stakeholders when seeking support to establish and implement a project; they represent commitments that need to be honoured and reported on. Second, rewilding is characterized by a high level of unpredictability in its ecological outcomes, and projects could pose a number of issues and risks to local communities and neighbouring restoration projects. The ability to communicate early about the likely trajectory an ecosystem may take, and the associated risks this may pose, is key to securing local communities' long-term engagement and support with rewilding initiatives. Such assessments can only be made if rewilding sites are comprehensively and regularly monitored.

Perceived and established capacity issues

The increased appetite for rewilding approaches in conservation can be broadly understood as being part of a

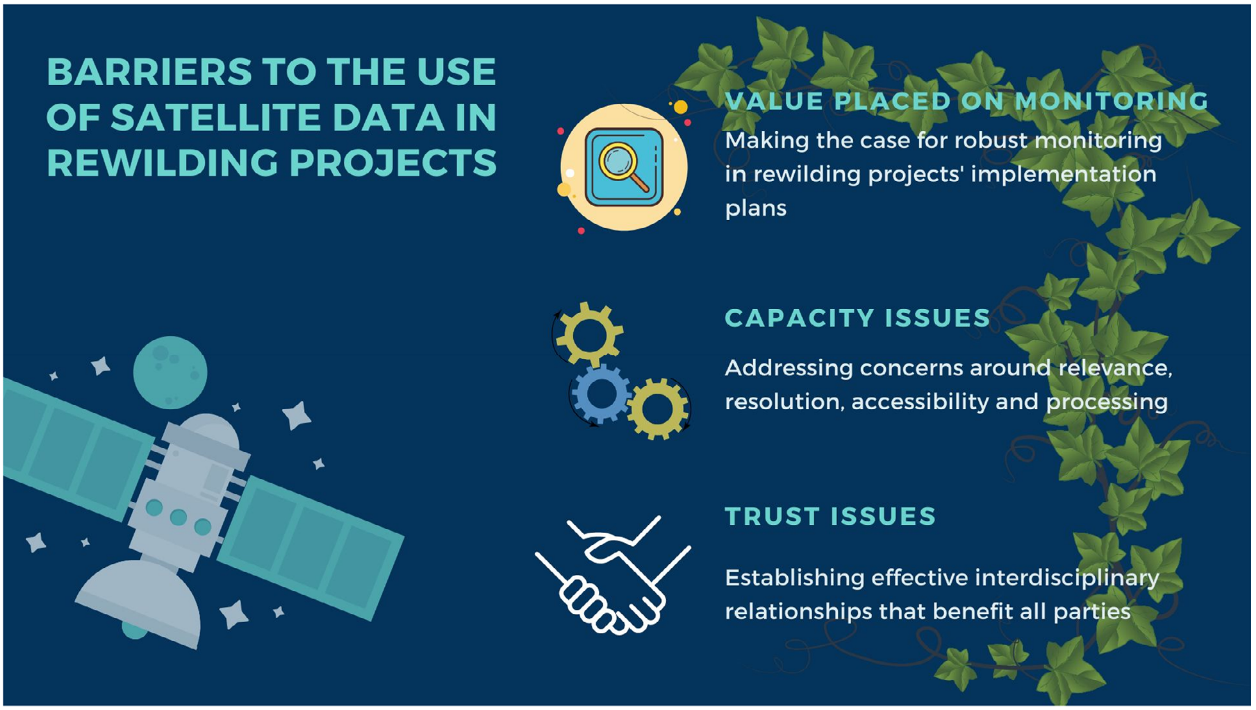

Figure 2. Barriers to the use of satellite data in rewilding projects.

wider interest in, and focus on, ecosystems and ecosystem conservation over the past decade, as opposed to the species-focused approach that characterized the previous decades of conservation biology. The shift being relatively recent, many scientists and practitioners are still having to learn about ecosystems, ecosystem dynamics and ecosystem monitoring, being primarily trained in species-based approaches and knowledge. Satellite data may therefore be wrongly perceived by many as being inadequate or inaccessible to inform rewilding projects on the ground, with common assumptions including satellite data always needing to be of very high (i.e. <1 m) resolution (and thus not free) to be useful, or satellite data always requiring very high-performance computers to be manipulated and interpreted. Other concerns that may hamper the use of satellite data by projects for their monitoring and reporting include data access and limited training opportunities that help set common references across communities of both scientists and practitioners.

Trust

High-resolution satellite data and user-friendly platforms for satellite data analyses have become widely accessible to scientists and practitioners all around the world, enabling anyone to build a land cover map for known rewilded sites globally. Increasingly, maps derived from satellite images are constructed by those who may not be very familiar with the sites they are looking at, or those whose familiarity with remote sensing analyses may be limited. Improved access to data and algorithms has certainly helped satellite technology to be part of the big data revolution in wildlife management, but it has also increased the likelihood that important contextual information and analytical steps are missed, and wrong conclusions produced. These risks, associated with a perception by some that satellite remote sensing aims to replace existing monitoring methods used in rewilding projects, such as expert-led assessments, or field-based data collection, can lead to decreased trust by stakeholders in the approach and results; without trust, much of the work performed generally ends up being dismissed and not used to guide management.

Opportunities to Address Current Knowledge Gaps

Rewilding aims to impact many different levels of ecological organization, from single species (e.g. reintroducing a large herbivore to a site; Naundrup & Svenning, 2015) to landscape-level functioning (e.g. restoring floodplain dynamics; Brown et al., 2018). Ecological changes across different levels interact, creating often complex and unanticipated changes (Maris et al., 2018; Tree, 2017). A key challenge for rewilding projects is to understand how these broad ecological principles manifest across widely varying ecological contexts. Satellite remote sensing can play a key role in bridging the gap between the species perspective, which focuses on population dynamics, habitat occupancy and individual species-species interactions, and the ecosystem perspective, which focuses on flows and stocks of matter and energy at large spatial scales and interactions in trophic networks, to gain a better understanding of the ecological changes brought about by rewilding (Fig. 1). To demonstrate this point, we identify below three knowledge gaps in rewilding science that could benefit from the use of satellite remote sensing to monitor rewilding projects.

Gaining a better understanding of the role of animals in ecosystem functioning

Trophic complexity underpinning good ecosystem functioning is key to rewilding. Yet, our understanding and ability to assess how much control different animals exert over ecosystem functioning on the one hand (Ellis-Soto et al., 2021), and how rewilding affects habitats, altering animal impacts in space and time, on the other (Contos et al., 2021; Fuhlendorf et al., 2009) remains limited, hindering the development of rewilding practices. Satellite remote sensing data allows the derivation of relevant information for a wide range of ecosystem functions, providing an avenue for monitoring changes in ecosystem functioning in rewilding sites (Freitag et al., 2021; Pettorelli et al., 2018b; Zhang et al., 2021). Satellite remote sensing also offers key opportunities to characterize how species use their environment at multiple scales, enabling, for example, the derivation of information that can help contextualize animal-mediated nutrient translocation within and between ecosystems (Ellis-Soto et al., 2021). For instance, changes in the distribution of suitable habitats for focal animal species over time can be monitored based on changes in remotely-sensed ecosystem structure and function (Arenas-Castro & Sillero, 2021). Being able to monitor fluctuations in habitats in space and time is especially important for understanding the impact of novel species, or species with a potentially large impact on whole ecosystem functioning, allowing affected communities (both human and non-human) to respond to these changes. Such knowledge could help prioritize interventions to enhance ecosystem functioning in degraded sites, whilst improving our ability to predict, for example, the ecosystem consequences of predator introduction (Ellis-Soto et al., 2021).

Factoring in connectivity

A key species-ecosystem interface relevant to rewilding is connectivity (Torres et al., 2018). Connectivity is shaped by landscape-scale ecosystem structure, but it varies by species: a habitat mosaic that can easily be traversed by one species may be impenetrable for another (Baguette et al., 2013). Connectivity between rewilding sites and the wider landscape will govern much of the ecological change occurring in response to rewilding. This includes community re-organization through the arrival of new (novel or native) species (Grau et al., 2020), as well as the spread of species from the rewilded site into the wider landscape, especially of potentially high-impact species such as predators (Garcia-Lozano et al., 2020).

There are two key gaps in knowledge regarding the role of connectivity in rewilding. First, understanding species movements in and out of rewilded sites is especially important where rewilding takes place next to sensitive areas, such as small populations of highly threatened species, that may be adversely impacted. Satellite imagery can aid in monitoring rewilding-driven changes in ecosystem aspects that shape species-specific landscape connectivity (Baumann et al., 2020; Root-Bernstein & Svenning, 2017; Torres et al., 2017). This is key to understanding how connectivity changes across the landscape, and across time, thereby allowing potential flows of rewilding benefits and costs to humans and biodiversity to be taken into consideration when planning or adapting to rewilding projects (or ecosystem restoration more broadly; Koh et al., 2013).

Second, it is unclear how changes in connectivity will shape ecosystem function. The arrival of novel species, or changes in species abundance, will alter the trophic structure of an ecosystem, which could have long-term effects on ecosystem function. In marine ecosystems, increasing trophic complexity (i.e. more and more diverse interactions between species) is overall expected to lead to increases in ecosystem functioning (Mora et al., 2014), but this relationship does not necessarily apply everywhere (Valiente-Banuet et al., 2015). Ecosystem functioning shapes flows of benefits and harms to all species in an ecosystem, including humans (IPBES, 2019), so understanding the impact of connectivity on ecosystem functioning is important to predicting the effects of rewilding on socio-ecological systems.

Assessing the impacts of rewilding on the conservation status of rewilded sites

Rewilding initiatives are expected to benefit biodiversity, leading to more ecologically complex and more resilient ecosystems. A multitude of variables and indicators are relevant to assessing the ecological outcomes of rewilding projects, but these need to be integrated into a framework that helps us conclude whether the conservation status of rewilded ecosystems has improved or not. That synthetic information is key to secure long-term engagement and political support for rewilding globally.

Nearly a decade ago, the IUCN adopted the Red List of Ecosystems (RLE) Categories and Criteria as a robust and consistent tool for monitoring the risk status of ecosystems in order to plan appropriate conservation actions (Bland et al., 2016; Keith et al., 2013). This protocol aims to estimate the probability of ecosystem collapse over a specified time frame (Keith, 2015), thus providing an interesting metric for tracking changes in conservation status for a given ecosystem, including rewilded ones. Many data sources are relevant for RLE assessment, including satellite remote sensing, which can deliver ecologically relevant, long-term datasets suitable for analysing changes in ecosystem area, structure and function at the temporal and spatial scales relevant to risk assessment protocols (Murray et al., 2018). Thus, a key benefit of the RLE framework is its ability to cope with a diversity of biodiversity data, including satellite data. So far, very little has been done in terms of using RLE assessments to track the impacts of restoration (which it is ideally suited for) or rewilding approaches on ecosystems, even though such an integrative approach could provide practitioners with an alternative to having to make sense of potentially conflicting trends in different biodiversity metrics.

The use of RLE assessments to assess the impacts of rewilding on ecosystems could however be challenging, as positive changes in RLE status imply that the composition, structure and/or functioning of a given ecosystem type (Keith et al., 2022) has improved. Because of climate change and other drivers of global change environmental change, successful rewilding projects may yet include situations in which ecological communities become radically different, and ecosystems transition to a new ecosystem type (which would correspond to ecosystem collapse in RLE assessments). This could include transitions to a different yet known ecosystem type, or (in extreme situations) transitions to novel ecosystems that have no historic precedent. In such situations, biotic and abiotic changes will need to be judged based on the effects they have on the long-term autonomous functioning of an ecosystem and not merely by fidelity to any particular ecosystem type.

Interestingly, there have been efforts to identify ecological variables that can track the capacity of an ecosystem to function autonomously, such as trophic complexity, disturbance dynamics and connectivity (Perino et al., 2019; Torres et al., 2018). These variables have already been applied to expert-based assessments of rewilding success; however, the scaling up of this framework has proven difficult (Segar et al., 2022). In situations where ecological communities and ecosystem types are potentially altered in response to changes in environmental conditions and management approaches (e.g. through the adoption of rewilding), RLE assessments could be combined with such a framework to measure the impacts of rewilding on the conservation status of rewilded sites. For instance, the conceptual ecosystem models underlying RLE assessments could be used to guide the identification of meaningful indicators of autonomous ecosystem function for an ecosystem in transition. In addition, data on ecosystem distribution and functioning, as well as data on abiotic and biotic threats collected as part of RLE status assessments could be used to track spatio-temporal changes in such indicators (including trophic complexity, disturbance dynamics and/or connectivity).

Conclusions

Satellite remote sensing enables access to important information about the changes in ecosystem composition, structure and functioning instigated by rewilding initiatives (Table 1). It provides scientists and practitioners with a synoptic landscape perspective that is more difficult or expensive to achieve via other methods; this includes being able to track large-scale disturbances such as floods and fires, and broad changes in vegetation cover at large spatial scales (Pettorelli et al., 2018b). Being able to access such information can enrich expert-led or field data-based assessments, for instance by providing information about the spatial distribution of indicators of habitat quality of key species (Regos et al., 2022).

Integration of in situ knowledge from local stakeholders and expert knowledge from a range of disciplines, including remote sensing analysts, is key for correctly interpreting satellite information and capitalizing on the opportunities that satellite remote sensing has to offer to rewilding science. Establishing effective interdisciplinary relationships that build on everyone's interests and benefit all parties can however be challenging (Pettorelli et al., 2014), requiring for example actors to extend their networks and reach out to new communities; devote time to appreciate others' constraints and priorities, and establish common reference frames and understanding of each other's work. This could be achieved via a dedicated network whose explicit aim is to improve collaboration between rewilding practitioners and policy makers on the one hand and satellite remote sensing experts on the other. Ultimately, removing the barriers between the species and the ecosystem perspective, in terms of data, methodologies and professional communities of scientists and practitioners, is key to ensuring that the full potential of satellite remote sensing data for informing rewilding projects can be realized.

Table 1. Non-exclusive list of examples of situations where satellite remote sensing data can support the monitoring of different types of ecological change in rewilded sites, alone or in combination with expert-led assessments and field-based data.

Level of ecological organisation	Aspects of rewilding being monitored	Opportunities for satellite remote sensing to support monitoring
Species	Species occurrence, behaviour and performance	Monitoring invasive plant species distribution. Using species distribution models informed by species observations and remotely sensed environmental variables to predict species distribution at large spatial scales.
	Habitat distribution and conditions (e.g. food and shelter)	Providing wall-to-wall information about spatial and temporal changes in habitat availability and quality.
	Species interactions	Mapping hotspots of species interactions by combining species habitat maps.
Ecosystem	Distribution and condition of ecosystems	Providing wall-to-wall information about spatial and temporal changes in ecosystem(s) distribution and condition
	Ecosystem functioning (e.g. primary productivity)	Track changes in defined ecosystem functions using established indicators.
Combined	Movement/dispersal of single or multiple species	Wall-to-wall connectivity mapping.
	Impact of species on ecosystem processes or structure	Scaling up knowledge about site-level species impacts for whole-landscape assessments.

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