Received: 25 March 2021 | Revised: 20 December 2021 | Accepted: 26 January 2022
DOI: 10.1111/jvs.13119

Journal of Vegetation Science IAVS

FORUM

Fifteen emerging challenges and opportunities for vegetation science: A horizon scan by early career researchers

Abstract

With the aim to identify future challenges and opportunities in vegetation science, we brought together a group of 22 early career vegetation scientists from diverse backgrounds to perform a horizon scan. In this contribution, we present a selection of 15 topics that were ranked by participants as the most emergent and impactful for vegetation science in the face of global change. We highlight methodological tools that we expect will play a critical role in resolving emerging issues by providing ways to unveil new aspects of plant community dynamics and structure. These tools include next generation sequencing, plant spectral imaging, process-based species distribution models, resurveying studies and permanent plots. Further, we stress the need to integrate long-term monitoring, the study of novel ecosystems, below-ground traits, pollination interactions and global networks of near-surface microclimate data at fine spatio-temporal resolutions to fully understand and predict the impacts of climate change on vegetation dynamics. We also emphasize the need to integrate traditional forms of knowledge and a diversity of stakeholders into research, teaching, management and policy-making to advance the field of vegetation science. The conclusions reached by this horizon scan naturally reflect the background, expertise and interests of a representative pool of early career vegetation scientists, which should serve as basis for future developments in the field.

1 | INTRODUCTION

Anthropogenic activities are altering the world's ecosystems, with global change being the most important threat of the 21st century. Climate change, habitat loss and fragmentation, as well as invasive species and pollution, are some of the most important components of global change, acting as major drivers of biodiversity loss worldwide (Franklin et al., 2016). Recent studies have shown that plant species loss is exceeding background extinction rates (Humphreys et al., 2019; Le Roux et al., 2019). This has driven the urgency to address the impacts of global change on vegetation processes. Even if the effects of many of these global change components on vegetation shifts and species displacement have been explored (Tortell, 2020), there remains a lag in identifying how vegetation science is expected to deal with emerging issues related to global change in the coming years.

A recent editorial celebrating the 30th anniversary of the *Journal of Vegetation Science* presented a brief overview of past and expected future trends in research and methods used in the field (Chytrý et al., 2019). Chytrý et al.'s (2019) analysis of 30 years of trends in vegetation science has enabled a formal assessment of upcoming challenges for the field, especially given the urgent threat of global change on vegetation (IPBES, 2019). The article identified important research areas deserving collective scientific attention and highlighted the urgency for a critical and organized assessment of the way forward for vegetation science in a rapidly changing world. Therefore, identifying future challenges, opportunities and research gaps in light of global change is imperative to advance the field of vegetation science.

One way of achieving this is through a horizon scan, whereby topics considered to be emerging issues and opportunities for a particular field are proposed and discussed. Contrary to other exercises, it does not intend to provide a complete overview of the field, but rather to identify which issues and opportunities have not yet been widely explored and that should be prioritized (Sutherland et al., 2021). This is achieved by a representative set of active scientists in the respective research field, aiming to ensure that needs, challenges and limitations for the field are transparently considered. A horizon scan exercise can also provide decision-makers and stakeholders with an informative framework to prioritize which areas of vegetation science to tackle, stimulating the development of collaborative solutions (Sutherland et al., 2020). Although other areas in ecology have carried out such horizon scans (Cooke et al., 2020; Ricciardi et al., 2017; Sutherland et al., 2021), an analysis of this kind for the field of vegetation science has yet to be completed.

We carried out a horizon scan into the field of vegetation science to assess the most important emerging issues in the face of global change. Our aim was to identify topics that could be a challenge or opportunity to advance vegetation science over the next 20 years and to portray the most novel emerging areas within more general topics of vegetation science. As in similar efforts for other disciplines, this exercise does not aim to fully represent the range of knowledge of the field. Because previous horizon scans in ecology have been overly represented by senior researchers from the Global North, in this effort we sought a core group of early career vegetation scientists (featuring different academic backgrounds and career stages), with a diverse geographical representation. We considered this to be particularly important given that a great deal of published, peer-reviewed research is led by early career researchers (Bégin-Caouette et al., 2020), with proven impact on emerging ideas in the field (Bankston et al., 2020). Detailed methods used in the process can be found in the Supporting Information.

To frame our analysis, we began by defining our perspective on the objectives of vegetation science. According to our view, vegetation science aims to:

1. Describe patterns – at different ecological and temporal scales – resulting from underlying processes.
2. Understand and integrate a complex range of biophysical, physiological and ecological processes by which vegetation acts as a driver or response factor in the environment.
3. Integrate different knowledge systems and foster interdisciplinary approaches to promote technological advances for research in vegetation science and innovate the way we manage, protect and restore plant communities.
4. Communicate scientific findings to citizens, stakeholders and decision-makers at any political level in a manner that highlights the role of vegetation as a critical cornerstone for conserving biodiversity and ecosystem services, and in a way that nurtures and heightens the fascination and wonder that plant communities exert on people.

The first two goals have a long history in the field (van der Maarel, 1991), whereas the others have been gaining momentum in recent years. In particular, the need to promote connections and collaborations beyond academics to achieve real impacts in terms of policy, but also in research, was recognized during the discussions at the 62nd Annual Symposium of the International Association for Vegetation Science in Bremen (*IAVS Bulletin* 2020, 1; www.iavs.org) and in a recent editorial by Chytrý et al. (2019). We used these aims to explain not only why each topic from the horizon scan is important, novel and promising for the future of the field, but also how the topic would advance one or more of these aims.

2 | HORIZON SCAN RESULTS

Fifteen topics were retained at the end of the workshop (keywords in Figure 1; topics that were not ranked to be included can be accessed in the Supporting Information). Each of these topics contributes to at least two of the goals we identified for vegetation science and was grouped under three broad non-hierarchical ways for advancing the field (Figure 2). These are: (a) developing new frontiers and data types; (b) improving predictions; and (c) fostering research and policy advancement.

3 | NEW HORIZONS AND TYPES OF DATA FOR THE FIELD

3.1 | Next generation sequencing as a way to advance vegetation science

The development and accessibility of next generation sequencing technology have led to a myriad of opportunities not only to study genetic variation within plant species, but also to unveil hidden diversity and interactions with below-ground organisms closely interacting with vegetation. This method can sequence whole genomes (Narum et al., 2013) and has the capability to genotype hundreds of individuals through the parallel sequencing of millions of reads (Ji et al., 2013). Development in the use of this tool for unveiling the diversity of microorganisms present in soils (Di Bella et al., 2013) and trying to understand the complex networks of interactions with plants associated with many of the underlying processes structuring vegetation (Fierer, 2017; Van Der Heijden et al., 2008) has increased rapidly in recent years. Such knowledge is important because soil microorganisms have been shown to influence plant communities either directly by affecting plant fitness, or indirectly by modulating soil conditions (van der Putten et al., 2016). Next generation sequencing, along with complementary tools such as network analyses and modelling (Vacher et al., 2016), could therefore be used to characterize plant–microbe interactions and their temporal dynamics, to better understand the underlying processes associated with vegetation patterns. Other applications include the study of "hidden" below-ground plant diversity from soil samples using metabarcoding (a method combining DNA taxonomy and next generation sequencing; Hiiesalu et al., 2012), and the use of pollen for identifying species' historical spatial patterns (e.g. postglacial; Napier et al., 2019). Overall, next generation sequencing has the potential to uncover long overlooked interactions and unseen diversity, with significant implications for ecosystem restoration and conservation (Williams et al., 2014; but see Hart et al., 2020).

3.2 | Using plant spectral properties to explore vegetation patterns and processes across spatio-temporal scales

Heterogeneity in plant reflectance, namely the profile of light reflected by leaves throughout the electromagnetic spectrum, is an exciting prospect for advancing research in vegetation science by allowing scaling between individual-level observations, and patterns and processes occurring across larger spatio-temporal scales

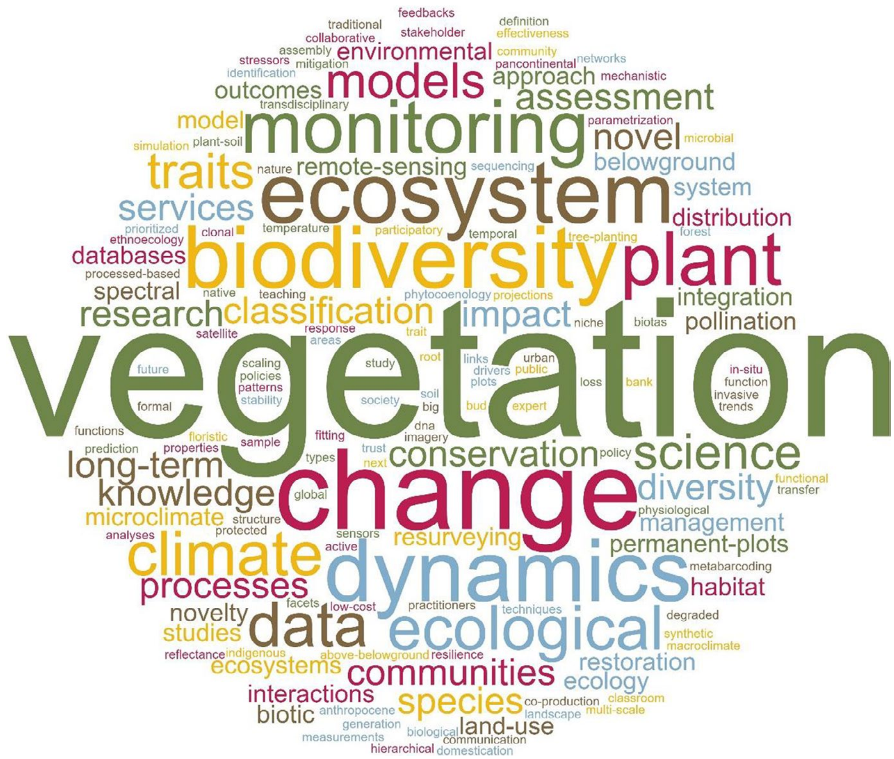

FIGURE 1 Word cloud showing recurring keywords extracted from the 15 highest-ranked topics, selected using the horizon scan methodology. Each topic was described by 10 keywords. Larger words represent the ones most frequently used in keywords from each topic. Colours have no meaning

(Cavender-Bares et al., 2020; Houborg et al., 2015; Ollinger, 2011). At the species level, plant spectral properties could be used to: (a) gather insights on structural and chemical traits (Asner et al., 2015); (b) map alien species (Niphadkar & Nagendra, 2016); and (c) remotely identify plant functional types (Schweiger et al., 2017). At larger spatial extents (e.g. from landscape to global scale), plant spectral properties are promising to detect the effects of environmental changes on vegetation patterns (Laliberté et al., 2020; Rocchini et al., 2010) and predict ecosystem functions over time (Schweiger et al., 2018). However, it is important to stress that these applications depend strongly on the properties of remote-sensing products, namely data spatial and spectral resolution (e.g. multispectral vs hyperspectral images).

Beyond providing a suitable tool to investigate vegetation patterns and processes across spatio-temporal scales, plant spectral properties, in conjunction with remote-sensing advancement, can substantially contribute to improving the monitoring of biodiversity. Indeed, Skidmore et al. (2015) highlighted that modern remote-sensing technologies would allow recurrent assessment of ecosystems' status worldwide (e.g. by providing early warning of habitat loss and fragmentation). Consequently, the significance of remote-sensing products should be given further recognition and support by governments and other agencies (Jetz et al., 2019). Finally, vegetation maps derived from remote-sensing data are a valuable tool to represent complex ecological patterns in a simple and intuitive manner, which can be readily available to a wider (non-scientific) audience. Closer collaborations between remote-sensing experts and vegetation scientists would be beneficial to maximize these approaches for vegetation science.

3.3 | Integrating resurveying studies and permanent plots for regular assessment of long-term ecosystem changes and stability

Collecting temporal vegetation data via resurveying studies and/or permanent plots is a common and particularly important method used for studying community dynamics and assessing human-driven impacts on natural habitats. Resurveying studies, namely the occasional repetition of historical surveys, are a cost-effective approach to detect temporal changes in habitat composition (Hédl et al., 2017). They have the advantage of being able to make use of massive historical information stored in vegetation databases. Yet, they are also considered less accurate because of their reliance on a limited number of time-points and their being prone to inaccurate relocation of historical plots (Verheyen et al., 2018). The latter particularly affects plots that were not permanently marked in the field ("quasi-permanent plots" sensu Kapfer et al., 2017). Permanent plots, by contrast, are more reliable and can detect long-term vegetation trends as well as capture non-linear responses of community composition and functions, which makes them particularly suitable for tracking the stability of ecosystem functions (de Bello et al., 2020). For this reason, they have been listed among the six most important developments in vegetation science (Chytrý et al., 2019). However, they require considerable resources for maintenance, and cannot be easily installed in all ecosystems. Even so, several studies have demonstrated that both approaches are effective at the local scale (see the *Applied Vegetation Science* 2017 Special Feature "Vegetation resurvey"; Hédl et al., 2017 and the *Journal of Vegetation Science* 2020 Special Feature "Permanent Plots in Vegetation Science"; de Bello et al., 2020).

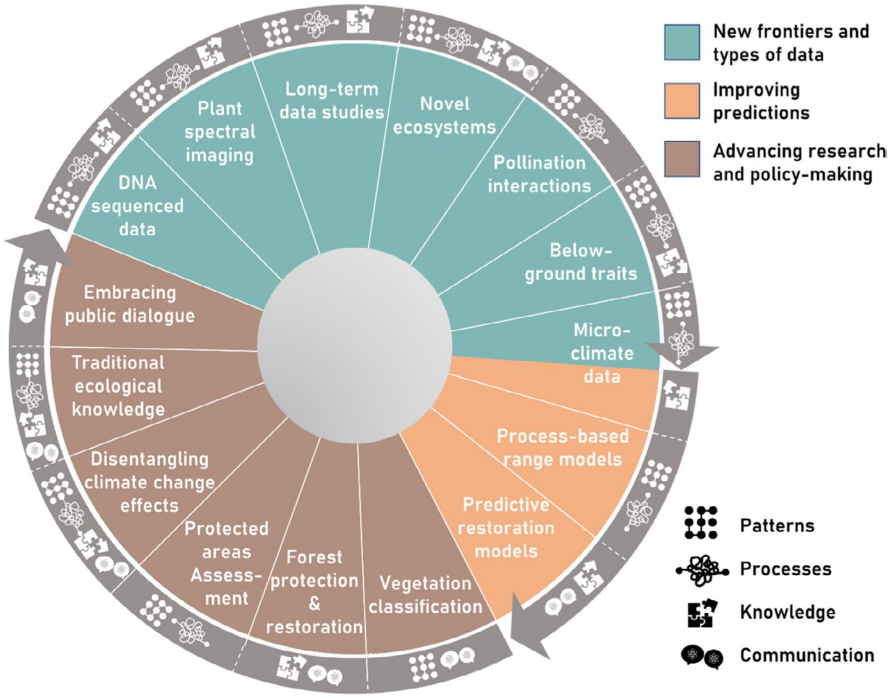

FIGURE 2 Fifteen topics considered to be emergent and most impactful by the horizon scan for vegetation science. Each topic was identified to contribute to at least two of the goals we recognized for the field (i.e. in a concise way: to describe patterns, understand processes, integrate different knowledge systems and communicate science); the goals are represented as symbols (see legend in the lower right corner), so that the outer part of the graph shows, for each topic, its contribution in terms of specific goals. Different colours indicate the non-hierarchical ways in which each topic can develop in the field (i.e. developing new frontiers and data types, improving predictions or advancing research and policy-making; see caption in the upper right corner). The grey arrows represent how new frontiers and types of data help improve predictions in vegetation science, which in turn aid the advancement of research and policy and drive further developments in collecting data for the field

The need to quantify biodiversity trends and reach global conclusions about their consequences on ecosystem functioning, has led to an increase in data syntheses built by collating and analysing time-series data sets recorded at individual locations around the world (Dornelas et al., 2014; Gonzalez et al., 2016; Vellend et al., 2017). Although promising, this approach has proven to have several shortcomings (Cardinale et al., 2018), including the: (a) lack of a specific focus on plants; (b) lack of appropriate spatial representation; and (c) short duration and/or poor periodicity of the underlying time-series. Most importantly, although depicting global trends, large syntheses often do not convey insights that can be easily employed in conservation at the habitat scale. In light of the current biodiversity crisis, a fundamental and valuable challenge for vegetation science will be to integrate information from resurveying studies and permanent plots worldwide to produce regular, habitat-specific assessments about long-term vegetation changes and ecosystem stability. This will imply efforts towards harmonizing different procedures and methods, and building collaborative databases (see the recent, high-quality and vegetation-specific initiatives LOTVS [https://lotvs.csic.es]; and ReSurveyEurope [http://euroveg.org/eva-database-re-survey-europe]). Simultaneously, it will finally allow quantification of single habitats that are changing, testing for the drivers of such changes, and eventually contribute to complying with supranational reporting obligations (e.g. reporting under article 17 of the Habitats Directive; European Commission, 1992) and/or produce synthetic, although highly valuable knowledge (Janssen et al., 2016), to be employed in directing both conservation and policy efforts.

3.4 | Novel ecosystems as an opportunity to understand the effects of global change stressors

Global change components modify biophysical factors influencing plant interactions. This creates new drivers and stressors that can impact community assemblages (Komatsu et al., 2019), which are difficult to predict as they often have synergistic non-linear effects (Rillig et al., 2019) leading to so-called ecological novelty. Ecological novelty is the emergence of novel species assemblages that differ significantly from a known reference and may not be reversible to a pre-degradation desired state (Heger et al., 2019). Novel ecosystems can be found in, for example, agricultural landscapes, forestry plantations and post-mining landscapes. They often challenge the dichotomy of native/invasive species and force vegetation scientists to reconsider whether diverse novel biotas have ecological value (e.g. in terms of presence of rare and endangered species, species diversity and ecosystem services) (Borhidi et al., 2012) that are worth conserving (Thomas, 2020).

Novel ecosystems dominated by invasive species, for instance, can allow us to explore the underlying processes by which vegetation responds to global change stressors. Urban environments are both a very promising prospect and a challenge for vegetation science, because they offer opportunities for the conservation and study of diversity (Klaus, 2013; Kowarik, 2011) and ecosystem services (Palliwoda, et al., 2017), but at the same time they constitute a major threat to biodiversity (Aronson et al., 2014). Compared with other novel ecosystems, human-dominated habitats share more compositional similarities globally, than with their surrounding matrix (Olden et al., 2018). Therefore, they constitute an ideal broadscale experiment to elucidate the role of anthropogenic stressors on plant community dynamics and the formation of new biotas. Far too little is known about which urban species combinations will thrive in a continuously changing future, or whether the urban heat and urban drought island effects will result in climate change impacting urban ecosystems most severely (Chapman et al., 2017). Thus, vegetation science needs to deviate from the single focus on "pristine" systems and move toward understanding how global change will impact the world's biota, by learning from these emerging novel ecosystems and considering new perspectives from non-specialists living in urban areas. Given the continuous trend of migration to cities, the study of and communication about novel ecosystems in urban settings and their value for people, are important to increase the appreciation for vegetation in society (see also topic "Embracing public dialogue to increase the relevance and robustness of vegetation science").

3.5 | Incorporating pollination interactions into vegetation studies

Pollination by animals occurs in almost all terrestrial ecosystems of the world. It plays a crucial role in the survival of both plant and pollinator species, and is an important ecosystem service (Winfree et al., 2011). Despite this, relationships between plants and pollinators have rarely been considered in vegetation studies (E-Vojtkó et al., 2020). Plant interactions have generally been assessed by considering only those interactions related to competition for space or soil nutrients (Sargent & Ackerly, 2008). Increasing evidence shows that interactions mediated by pollinators are as important as other biotic interactions in shaping patterns of species richness and occurrence in terrestrial ecosystems (Fantinato et al., 2018a; Heystek & Pauw, 2014). Therefore, pollination interactions together with other mutualistic interactions that are often disregarded (e.g. plant–disperser interactions, plant–microbe interactions), should be incorporated into vegetation studies to develop a conceptual framework that recognizes their role in shaping vegetation processes and the role of vegetation in supporting mutualistic partner assemblages. Studies should adopt a scaling approach, addressing pollination issues from single interactions to the landscape scale. Such an approach will enable the identification of pollination emergent properties involved in the self-organizing capability and resilience of terrestrial ecosystems (Fantinato et al., 2018b; Hackett et al., 2019).

3.6 | Plants upside down: a multidimensional approach for vegetation science

Widely accessible trait data covering a large range of species (e.g. TRY; Kattge et al., 2020) have contributed greatly to the advancement of vegetation science (Chytrý et al., 2019). However, trait values are still not uniformly available across plant compartments and functions. Whereas most studies and inferences using functional traits are based on the local, regional and world leaf economic spectrum (see Wright et al., 2004), below-ground traits, including roots, clonal and bud bank traits, have been neglected in many ecosystems (but see, Klimešová et al., 2017). Below-ground traits probably scale up to affect community- and ecosystem-level dynamics, by adding additional ecological and independent dimensions of plant functional variation. These dimensions are largely related to below-ground processes and pathways (Bardgett et al., 2014; Freschet et al., 2021; Weigelt et al., 2021), such as on-spot persistence, recovery after disturbance and space occupancy. Furthermore, below-ground traits are essential for understanding how such processes and pathways drive species distribution, dominance and trade-offs in plant communities affecting ecosystem properties (Laughlin et al., 2020, 2021). Below-ground traits such as morphological and physiological fine roots traits can also shed light on how plant–soil feedback holds the rapid transformation of soil carbon stock to a carbon sink globally (van der Putten et al., 2013; De Deyn et al., 2008), mainly through mediating soil biota activities shaping the carbon pathway in soil (Rossi, 2020). The recent publication of standardized protocols for plant modularity traits (Klimešová et al., 2019) and root traits (Freschet et al., 2020) has led to new scientific perspectives for collecting traits of below-ground organs related to key processes that help us to understand the complex variation in plant ecosystem pathways (Laughlin et al., 2021). Below-ground trait patterns tend to differ from their above-ground counterparts (Ottaviani et al., 2020; Weigelt et al., 2021) and thus, explaining ecosystem functions by weighting plant communities' above-ground traits is potentially misleading when inferring below-ground functions. Yet, broadscale empirical evidence of how below-ground traits influence species interactions, plant–soil feedback and ecosystem process pathways is still needed. Overall, the measurement of below-ground plant functional traits, their variability and proper scaling at the community (see Ottaviani et al., 2020) and ecosystem level will feed emergent fields of vegetation science, including functional biogeography and the study of ecosystem functioning and services.

4 | IMPROVING PREDICTIONS IN THE FIELD

4.1 | The need for fine spatio-temporal resolution near-surface microclimate data

Accurately predicting and tracking how plants will redistribute in the future because of climate change calls for a need for fine spatio-temporal resolution near-surface (microclimate) data, in contrast to widely used coarse-resolution, free-air temperature (macroclimate) data. Microclimate data are essential to adequately describe plant–climate interactions, particularly because certain species, such as low-stature plants or understory vegetation, are more influenced by micro- than macroclimate conditions (De Frenne et al., 2021; Potter et al., 2013). Furthermore, there is increasing evidence that the biotic response of plant communities to climate change is locally determined by microclimate alterations, while being partially decoupled from macroclimate trends (Lenoir et al., 2017; Zellweger et al., 2020). Global coverage of spatio-temporally fine-resolution climate data will lead to a better understanding of how microclimatic changes affect plant biodiversity and vegetation dynamics. For example, by allowing identification of microclimate refugia and stepping stones that affect species redistributions (Dobrowski, 2011; Lembrechts & Lenoir, 2020; Zellweger et al., 2020), or by integrating the impact of temporal climate dynamics, such as extreme weather events. In addition, high-resolution microclimate data are needed to infer how these vegetation dynamics affect climate in return (e.g. through changes in albedo) (Lembrechts & Nijs, 2020).

One way to approach this is by using data collected with microclimate sensors, which provide hundreds of in situ temperature and/or moisture measurements per day, at the ground and near-surface level. Such measurements have overcome many critical limitations typical of macroclimate data for studying vegetation processes (Lembrechts et al., 2019). Linking high-resolution environmental data – ideally also on other parameters such as light, nutrients, pH – with long-term and wide-extent data on species community dynamics (Lembrechts, 2020), will allow us to better understand past and current changes and make more accurate predictions for the future. Ideally, these long-term monitoring efforts will be combined with physiological experiments that reveal the link between microclimate and vital processes such as seed germination and survival, which in turn would allow mechanism-based understanding and prediction of species dynamics (Lembrechts, 2020).

4.2 | Big-data driven parametrization of process-based species distribution models for global change research

Plant species have responded individualistically to climatic changes in the past (Davis, 1976), leading to the disaggregation of historic plant communities and transient species compositions (Burke et al., 2019). Predicting range dynamics and habitat suitability for many individual plant species may thus help forecast how existing plant communities disaggregate and reassemble into transient and potentially novel communities, as the current climatic changes progress. Projections of species range shifts often deploy correlative species distribution models (SDMs). SDMs fit statistical models describing the relationship between a species' distribution and present-day environmental conditions, then use these relationships to project areas of potential occupancy (Elith & Leathwick, 2009). However, SDMs do not explicitly represent the physiological or demographic mechanisms that control species distributions, thereby limiting their transferability into conditions outside the training data domain, for example, into future climates (Evans et al., 2015). By contrast, process-based SDMs use equations that prescribe how lower-level physiological or demographic processes influence species distributions. This enhances their transferability and usefulness in assessments of climate change impact, and allows for a mechanistic explanation of distribution patterns. The application of process models has been limited in the past by the laborious measurements required to parametrize the processes in the models, but this is now changing. The creation of global databases of species distribution and trait data (e.g. BIEN, GBIF, GIFT, TRY and sPlot; https://bien.nceas.ucsb.edu/bien/; www.gbif.org/; Bruelheide et al., 2019; Kattge et al., 2020; Weigelt et al., 2020), in conjunction with strategies for hierarchical and inverse parameter estimation from these data, makes it possible to parametrize process-based models for thousands of species (Evans et al., 2016). Indeed, recent work showed that inferring the physiological parameters of a physiological SDM from species distribution data produces parameterizations that significantly enhanced the model's transferability over correlative SDMs (Higgins et al., 2020, 2021). The application of process-based models will certainly increase in the near future, given that model parametrization is no longer a limiting factor for many species. For instance, Conradi et al. (2020) parameterized the same physiological SDM model for 23,500 plant species of different growth forms to model African biomes and their future change. Beyond assessment of climate change impact, increasing the knowledge on how environmental changes influence physiological performance outside the currently narrow number of well-studied organisms will also contribute to biodiversity conservation, for example, when dealing with rare or threatened species. Eventually, estimation of the physiological niche parameters of many species will have a broader application in studies of trait evolution and diversification (Larcombe et al., 2018).

4.3 | Predictive vegetation science for the UN Decade on Ecosystem Restoration 2021–2030

In 2019, the United Nations (UN) General Assembly proclaimed 2021–2030 as the Decade on Ecosystem Restoration (https://undocs.org/A/RES/73/284). This multilateral commitment provides an opportunity to set aside a significant fraction of the global land surface for a lasting provision of ecosystem services and biodiversity conservation. For these functions to last, the species combinations used in restoration projects now must be compatible with projected future abiotic and biotic conditions (Choi, 2007). These include warmer temperatures, altered precipitation and disturbance regimes, elevated atmospheric CO_2 concentrations and nutrient inputs, and both novel and lost biotic interactions. A challenge for vegetation scientists will be to describe vegetation states that are both in a dynamic equilibrium with future biophysical conditions and maximize the targeted function, so that restoration practitioners can implement anticipatory measures that direct vegetation trajectories towards such states (Young & Duchicela, 2021). This will require a blend of physiology- and demography-based dynamic vegetation simulation models that can be parametrized for a large number of candidate species. At the same time, these models should allow users to explore succession outcomes under alternative climate scenarios, restoration measures (including rewilding) and species combinations. Developing such models poses a challenge. Vegetation scientists will need to find the right balance between generality and adaptability to local context, and identify key gaps in process representation and parameterization early to divert science resources to fill them. Yet we consider that such models are on the horizon. For instance, existing process-based models of plant growth and demography could be linked and parametrized for large numbers of species with inverse and hierarchical modelling tools that utilize databases on species distributions, traits and phylogenies (Conradi et al., 2020; Evans et al., 2016). The UN Decade on Ecosystem Restoration is an opportunity for vegetation science to position itself as a key discipline for reaching the UN's Sustainable Development Goals.

5 | RESEARCH AND POLICY ADVANCEMENT

5.1 | Classification stability in vegetation science

Vegetation classification has traditionally focused on vegetation types, yet the uncertainty of these types has prompted criticisms, leading to the urgent need for creating stable classifications. A step forward in this direction is the recently published, first comprehensive hierarchical floristic classification system for the whole vegetation of Europe (Mucina et al., 2016). This classification includes vascular plant, bryophyte, lichen and algal communities, and classifies these vegetation types at the alliance level. This effort, however, represents a compromise between local and/or regional classification systems. The lack of formal definitions for all vegetation types still makes processing new data a challenge. This lack of consensus in terms of classification affects not only our understanding of vegetation and ability to compare among different regions, but also other applied areas of vegetation science such as conservation, where categorizing can be useful to develop targeted actions for a specific vegetation type or habitat.

Increasingly available large vegetation databases (Chytrý et al., 2016; Sabatini et al., 2021) and computer processing power are now leading to emerging classifications based on formal definitions (Bonari et al., 2021; Gholizadeh et al., 2020; Landucci et al., 2020; Marcenò et al., 2018; Peterka et al., 2017; Willner et al., 2017), thus overcoming this historical challenge. Such expert-system based classifications are also extending to habitats (sensu EUNIS; Chytrý et al., 2020), although there is still a need to have a set of unequivocal formulas beyond European vegetation types. Therefore, future advancement of vegetation classification will be likely associated with the development of expert systems arising from synthetic analyses across continents that will describe vegetation patterns over large scales to foster nature conservation.

5.2 | Halting forest degradation by targeted restoration in prioritized ecosystems

Forest ecosystems help control regional climate, support biodiversity and connect indigenous people to nature (Watson et al., 2018). However, forest cover is decreasing steadily in many areas due to changes in land use, leading to deforestation and degradation. Recent data released in 2019 show that the world lost 2.8% more primary forest than in the previous year and indicates that low-income countries are affected disproportionately by deforestation (Global Forest Watch, https://www.globalforestwatch.org/), particularly in inaccessible areas. The need to stop deforestation has been recognized globally, especially of tropical forests, which are hotspots of biodiversity and have a significant role in carbon sequestration (Myers et al., 2000; Sullivan et al., 2020). By monitoring deforestation drivers and their impacts, vegetation science should be key in understanding the extent of vegetation changes in forests at both the spatial and temporal scale, which is critical to support successful restoration programmes. The emergence of easily accessible tools can help these efforts in low-income countries. For instance, the International Climate and Forest Initiative (NICFI), financed by the Norwegian government, has made freely available high-resolution image maps covering 64 countries and these are expected to be updated monthly (https://www.planet.com/nicfi/). This tool offers an opportunity for monitoring areas that lack the means to access expensive imaging (see topic "Using plant spectral properties to explore vegetation patterns and processes across spatio-temporal scales"), although such information would also need to be ground truthed.

Targeted ecosystem restoration is an effective tool to mitigate the loss of forest ecosystems (Bastin et al., 2019; IPBES, 2019). In this context, vegetation science should provide solid background knowledge to ensure that these efforts are carried out with care, that the right species mix is selected considering reference vegetation types, but also suitability to the current biophysical conditions. Recent publications aiming to identify areas with the biggest possible benefits and cost-effective consequences to optimize tropical forest restoration (Brancalion et al., 2019) have led to a narrow emphasis on just planting trees to mitigate climate change. Such studies have been criticized for incentivizing large-scale tree plantations in the wrong places (e.g. in savannas) or with the wrong species (e.g. using non-native species). Indeed, massive tree plantations can increase fire risk, lead to plant invasions, further land degradation, endanger sustainable development (Bond et al., 2019; Nuñez et al., 2021) and native species extinctions (Veldman et al., 2019). The message of planting trees as the only way to mitigate global change-driven impacts disregards the value of other threatened species-rich ecosystems covering large areas (e.g. grasslands and wetlands) that perform important ecosystem functions. Furthermore, restoration success can only be warranted by active knowledge transfer between all stakeholders including scientists, local communities and policy-makers (Baker & Eckerberg, 2016) to ensure this effort is carried out with care. The overall goal of restoration projects should be to enhance native biodiversity, benefiting local communities as well as protecting other valuable non-forested ecosystems (Di Sacco et al., 2021).

5.3 | Evaluating the effectiveness of protected areas in conserving plant communities

Although protected areas are recognized as the pillars of global conservation efforts, their ecological outcomes are currently being questioned (Watson et al., 2014). This highlights the necessity of analysing their effectiveness (Watson et al., 2016) to improve the way we manage and protect biodiversity. However, there is still confusion related to the definition of "effectiveness" and thus, scarce assessments of the effectiveness of protected areas in conserving biodiversity (especially those focusing on vegetation). Most of the studies formally aiming at evaluating the effectiveness of protected areas have quantified their efficiency through, for instance, gap analyses assessing biodiversity hosted in protected versus non-protected areas (Araújo et al., 2007; Dimitrakopoulos et al., 2004; Fois et al., 2018; Maiorano et al., 2015). Instead, evaluating the effectiveness of protected areas should assess whether or not pre-established biological outcomes have been reached (Biró et al., 2018; Sperandii et al., 2020), which requires long-term data. This should be done using a counterfactual approach, that is, comparing outcomes obtained with and without conservation interventions (Maron et al., 2013). Among other factors, the effectiveness of protected areas depends on whether and how they are managed. Therefore, evaluations should account for management effectiveness, that is, "the extent to which management is protecting values and achieving goals and objectives" (Hockings et al., 2006). In addition, specific challenges that need to be addressed when monitoring protected areas include combining remote-sensing and field sampling approaches, as well as effectively using resources such as satellite imagery, permanent plots, resurveying studies and other appropriate techniques (Jones & Lewis, 2015) (see topics "Using plant spectral properties to explore vegetation patterns and processes across spatio-temporal scales" and "Integrating resurveying studies and permanent plots for regular assessment of long-term ecosystem changes and stability").

5.4 | Disentangling the effects of climate change and other drivers on vegetation change

Disentangling climate change from other drivers of vegetation change acting at multiple spatial and temporal scales (Ferner et al., 2018; Ricklefs & Jenkins, 2011) is notoriously difficult. There are some useful statistical tools that could be employed. These include temporary sample plot inventory data, which are widely used along with various statistical means, such as variance partitioning (Moura et al., 2016) and structural equation modelling (Ferner et al., 2018). However, these methods are limited by the complexity of the natural systems that scientists aim to understand. For instance, climate change effects are evidenced over long periods (> 30 years) and existing climatic data used in modelling (WorldClim data, E-OBS data, etc.) are often not localized enough to meet the requirements for understanding complex vegetation ecosystems at various spatial scales (Dietrich et al., 2019). Hence, the use of emerging tools available to vegetation scientists to monitor changes over long periods of time (e.g. remote sensing and permanent plots), combined with high-resolution climatic data and increasingly available novel statistical analysis, should offer a better aid for disentangling various drivers of change. This opportunity is particularly important for areas harbouring a high percentage of the world's biodiversity, where local communities may be impacted by changes in vegetation-related resources, and where the lack of accessibility or limited financial means can hinder complex experimental approaches (Barlow et al., 2018).

5.5 | Managing vegetation through the integration of traditional ecological knowledge into research and public policy

Evidence suggests that conventional scientific approaches to land management have failed to address environmental complexity and heterogeneity (Adams et al., 2014; Klooster, 2002). Conversely, traditional ecological knowledge, including local, peasant, traditional and indigenous forms of ecological knowledge (Berkes & Folkes, 1994; Sierra-Huelsz, 2020), has a distinct rationale underlying vegetation management. In traditional societies the fundamental motivation for vegetation and landscape management is aimed at ensuring a food supply throughout the year (Berkes & Folke, 1994), in a more sustainable way. Traditional land management goals are based on continued empirical practice and have the benefit of providing an understanding of complex ecological patterns and processes at different spatio-temporal scales, such as effects on plant harvesting, cycles of plant availability, and alteration in the structure and function of plant communities (Adams et al., 2014). In recent years there has been increased interest in understanding the human footprint on landscapes considered "pristine" because of their high biodiversity and the important ecological services they provide. Research on traditional use of biodiversity and life history related to the land has revealed that many places considered pristine are actually highly modified environments. These landscapes emerge as the result of sustained management by traditional societies but lack the disruptive outcomes of industrialized productive systems that lead to degradation (Clement et al., 2015; Ferreira et al., 2019; Turner et al., 2013). Because traditional ecological knowledge has historically proven to provide long-lasting livelihoods to human societies (Toledo & Barrera-Bassols, 2008), it also emerges as an alternative for sustainable living (Trisos et al., 2021) and vegetation management. Some examples include the aboriginal use of fire in Australian bushlands (Ruane, 2018), highly diverse agroforestry systems in

Mexico (Moreno-Calles et al., 2013) and landscape management in Amazonia (Franco-Moraes et al., 2019). The struggle to bridge knowledge systems will require efforts to secure knowledge mobilization, translation, negotiation and practice (sensu Peterson et al., 2018). Hence, a major challenge for vegetation management will not only include efforts for integrating different knowledge systems into research and public policies, but prior to this, recognizing that traditional ecological knowledge has been deliberately ignored and subjugated, in contrast to western knowledge (Merçon & Roldán-Clarà, 2021), despite it building environmental understanding over centuries (Ayre & Mackenzie, 2013). Incorporating traditional ecological knowledge into vegetation research could be strengthened by highlighting sustainable advantages in environment, social and economic aspects to support further innovative policies and decision-making (Diver, 2017; Ludwig & Macnaghten, 2020).

5.6 | Embracing public dialogue to increase the relevance and robustness of vegetation science

Conventional teaching styles and insufficient science communication can play a role in public distrust of science, which may impact science-driven policy. On average, one-sixth of the world's population have low levels of trust in science (Wellcome Trust, 2018), which can be higher in countries or regions of high-income inequality. In the United States, although public confidence in scientists has remained stable for decades (National Science Board, 2018), positive perceptions of science vary between social, political and economic societal groups (American Academy of Arts and Sciences, 2018). This indicates the need to rethink the way in which scientists communicate science with students, policy-makers and society, but also the way we approach teaching. That is, acknowledging that there is no one-size-fits-all approach in teaching and science communication. Several approaches can help reach these goals, such as extension activities (Raynor et al., 2019), the use of translational ecology (Enquist et al., 2017) or, most importantly, improving public understanding of the scientific process (Hoskins, 2020).

For vegetation science, suitable actions may include initiatives aimed at improving human perception and understanding of the importance of vegetation patterns and processes in everyday life (i.e. recognizing and shortening the plant blindness bias; Jose et al., 2019). To be successful, efforts to mitigate impacts derived from global change in the near future must encompass the perception and partnership with local communities (Lima & Bastos, 2020). Namely, vegetation scientists must engage local communities in the process of generating knowledge, from developing research aims to discussing and interpreting results (Enquist et al., 2017). Community–researcher collaborations may increase local-community understanding about the scientific process, with an aim to enhance environmental policies derived from evidence-based research. The interaction between researchers, stakeholders, traditional communities and the general public is also extremely valuable in bringing real-world complexity into research practice and in stimulating creativity and innovation. Therefore, we suggest that the participation of stakeholders in research should be incorporated in the research design phase and promote participation throughout the project development process and beyond.

6 | DISCUSSION

All topics in our horizon scan for vegetation science contribute to advancement of the field by addressing challenges, opportunities and research gaps (summarized in Table 1, Figure 2). One-third of the topics considered to be emergent and significant for vegetation science were related to an array of rapidly developing methodological tools (next generation sequencing, plant spectral properties, process-based range models, as well as resurveying studies and permanent plots). Although many are already used in the field, their improvement and wider application are expected to lead to further developments in terms of understanding and predicting patterns and processes related to vegetation in the near future (Chytrý et al., 2019). To better understand vegetation dynamics, we propose directing attention to aspects and community types that have been mostly disregarded by vegetation science. That is, moving away from focusing on only above-ground patterns and near-natural communities, to incorporating semi-natural, degraded and novel ecosystems, as well as below-ground traits and pollination interactions. We emphasize the future significance of global networks of near-surface microclimate data at fine spatio-temporal resolutions, process-based range models, as well as a blend of physiology and demography-based distribution models to improve the accuracy and predictability of the impacts of global change on vegetation dynamics.

Our results also show that in agreement with Chytrý et al. (2019), to better tackle future challenges it is necessary to develop a common baseline for field vegetation classification, for global vegetation conservation and management efficacy assessment. More must be done to curb the loss of plant diversity and mitigate the ongoing impacts of global change components (CBD, 2020). In the proposed topics we offer suggestions on how to evaluate and improve the results of conservation and restoration efforts. Although our horizon scan focused on halting degradation and promoting restoration of forest ecosystems, we note the importance of preserving and restoring other highly valuable ecosystems such as grasslands and wetlands, which are in need of urgent protection and are often threatened by afforestation projects (Dudley et al., 2020). We also identified the urgent need to substantially change the way we approach vegetation monitoring, research, management and teaching. To accurately assess the impacts of global change drivers, such as climate change, we stress the need of finding affordable ways to monitor understudied areas of exceptional conservation interest, particularly in countries with limited financial resources.

Integrating traditional forms of knowledge into research, using a multi- and transdisciplinary approach is long overdue in the field. Further, encouraging people to appreciate the wide diversity of vegetation types and to participate in research

TABLE 1 Fifteen topics selected in this horizon scan for vegetation science

Topic	Aims	Contribution of the topic to addressing future challenges, opportunities, or research gaps
Next generation sequencing as a way to advance vegetation science	Patterns	Describing patterns of intraspecific genetic variation, unveiling hidden plant diversity and historical vegetation patterns
	Processes	Allowing understanding how interactions with below-ground diversity influence ecological processes structuring vegetation
	Knowledge	Unveiling complex networks of interactions with below-ground organisms (e.g. microorganisms)
Using plant spectral properties to explore vegetation patterns and processes across spatio-temporal scales	Patterns	Scaling between individual plant observations and worldwide vegetation patterns
	Processes	Detecting effects of environmental changes on vegetation, monitoring plant biodiversity and predicting ecosystem functions over time
	Knowledge	Bringing together vegetation scientists and remote-sensing experts to produce maps representing complex vegetation patterns in an intuitive manner
Integrating resurveying studies and permanent plots for regular assessment of long-term ecosystem changes and stability	Patterns	Describing patterns of temporal dynamics in plant communities
	Processes	Assessing drivers of temporal changes and evaluating their impact on the structure and functions of natural habitats
	Knowledge	Building integrated and harmonized temporal databases to effectively monitor the conservation status of habitats and comply with supranational reporting obligations
Novel ecosystems as an opportunity to understand the effects of global change stressors	Patterns	Characterizing novel species assemblages (e.g. urban vegetation) and assessing their ecological value
	Processes	Exploring the underlying processes by which vegetation responds to global change stressors (e.g. urbanization and temperature changes)
	Knowledge	Understanding the role of anthropic activities, social aspects and novel environmental conditions in the formation of new biotas
	Communication	Increasing societal appreciation for vegetation by communicating the value of novel ecosystems in urban settings
Incorporating pollination interactions into vegetation studies	Patterns	Unveiling how pollinator-mediated interactions shape vegetation patterns
	Processes	Understanding how pollination-mediation interactions influence plant occurrence and community attributes and identifying pollination properties involved in the self-organizing capability and resilience of terrestrial ecosystems
Plants upside down: a multidimensional approach for vegetation science	Patterns	Describing patterns of below-ground plant functional diversity
	Processes	Understanding the influence of below-ground traits on community- and ecosystem-level processes and dynamics (e.g. space occupancy, post-disturbance recovery)
	Knowledge	Advancing our knowledge of species interactions, plant–soil feedbacks and ecosystems processes pathways
The need for fine spatio-temporal resolution near-surface microclimate data	Patterns	Improving our understanding on how plant–microclimate interactions determine current distribution of vegetation
	Processes	Enhancing the forecast of future plant redistribution under climate change
	Knowledge	Revealing interactions between microclimate and vegetation changes
Big-data driven parametrization of process-based species distribution models for global change research	Patterns	Explaining the distribution of many species with the lower-level demographic or physiological processes that are represented in the models
	Processes	Allowing extrapolation beyond the training data domain, for example, into potentially no-analogue future climates
Predictive vegetation science for the UN Decade on Ecosystem Restoration 2021–2030	Knowledge	Guiding vegetation trajectories towards desired states during restoration using simulation models, in the context of future biophysical conditions
	Communication	Bringing together practitioners, modellers, and vegetation scientists to develop suitable models, balancing generality and adaptability to local context
Classification stability in vegetation science	Patterns	Reaching stable, expert-based definitions of vegetation types
	Communication	Enhancing our understanding of global vegetation patterns and improving the efficacy of targeted conservation actions

TABLE 1 (Continued)

Topic	Aims	Contribution of the topic to addressing future challenges, opportunities, or research gaps
Halting forest degradation by targeted restoration in prioritized ecosystems	Knowledge	Properly targeting species and areas suitable for forest restoration
	Communication	Working closely with local communities and policy-makes to enhance diversity during restoration and prevent further degradation
Evaluating the effectiveness of protected areas in conserving plant communities	Patterns	Evaluating different patterns (ecological, geographical, but also socio-economical) of protected areas effectiveness
	Processes	Assessing the extent to which protected areas contribute to the maintenance of ecological functions and processes, as well as to the delivery of ecosystem services
Disentangling the effects of climate change and other drivers on vegetation change	Patterns	Monitoring changes in vegetation patterns resulting from climate change impacts
	Processes	Increasing our understanding of climate change impacs on vegetation dynamics
	Knowledge	Using a combination of vegetation and temperature sampling techniques across time, with statistical tools to disentangle climate change impacts on vegetation
	Communication	Including local communities in the monitoring and studying of climate change impacts on vegetation-related resources
Managing vegetation through the integration of Traditional Ecological Knowledge into research and public policy	Patterns	Understanding the structure and function of plant communities through the lens of traditional management
	Processes	Unveiling the how traditional knowledge and forms of biodiversity management impact the underlying processes influencing vegetation patterns
	Knowledge	Recognizing the value of subjugated knowledge systems and integrating their insights to support vegetation management strategies, policy and decision-making
	Communication	Allowing for active exchange and communication among stakeholders (especially local and or indigenous people)
Embracing public dialogue to increase the relevance and robustness of vegetation science	Knowledge	Reaching a more integrated, diverse, and inclusive view of the vegetation science and increasing scientific literacy
	Communication	Translating ecological complexity to increase citizens' interest in vegetation patterns and processes; enhancing public understanding of the scientific process

Each topic contributes to at least two of the aims defined for the advancement of vegetation science by addressing challenges, opportunities, or research gaps for the field.

production by making vegetation science more accessible to communities is essential for the advancement of the field. A recently developed interactive database of vegetation photographs aimed at addressing this (particularly for online teaching during COVID-19-related lockdowns) could pave the way to more easily accessible vegetation information and encourage public interest in the field (Fleri et al., 2021). Stakeholder engagement may ultimately enable scientists to progress toward improving predictive modelling, leading to more effective vegetation management, teaching, and evidence-based policies.

There were many insightful topics that were not short-listed among the 15 presented here (reported in the Supporting Information to ensure transparency). These were not ranked as highly for various reasons, such as specificity (e.g. focused only on Europe), or because they were considered to be already too well explored to be emerging. The topics include linking on-the-ground insights from in situ studies into terrestrial ecosystem models, using conceptual models to implement more efficient rangeland management tools, integrating new knowledge or available data to test well-established ecological theories, monitoring and protecting Europe's endangered habitats, categorizing largely understudied aquatic plant lifeforms and managing alien invasive plant species in aquatic systems. Interestingly, topics addressing the way we conduct science related to the accessibility of publications (preprints and open access policies) and the challenges to early career researchers given current academic practices were not ranked high. Although these are not scientific questions or topics specific to vegetation science, they indirectly impact the future of the field by shaping science accessibility, demography and geographic representativity. Upon discussions during the workshop, several participants mentioned that although these were indeed important, they were not exclusive to the field, and therefore were considered less impactful in the context of this horizon scan. However, all participants agreed that vegetation science also needs to acknowledge the career uncertainties of early career researchers (Woolston, 2020a, 2020b), which have proven to foster unhealthy practices and, in many cases, harassment or bullying (Burke, 2017; Evans et al., 2018; Powell, 2016). Dealing with these issues should be considered urgent given the current "leaking pipe" leading to the loss of early career researchers from academia (Coleman & Radulovici, 2020).

The significance of our emergent topics is not only restricted to the field of vegetation science, but rather, these can also contribute to addressing shortfalls in biodiversity knowledge (Hortal et al., 2015), or answering fundamental questions related to ecology in a broader sense, such as those posed in Sutherland et al. (2013). Among the 100 fundamental questions listed for the advancement of ecology, Sutherland et al. (2013) asked how well we can predict community properties and responses to environmental changes by using simple traits. Here we propose that this can be accomplished only by incorporating below-ground traits. We also argue that we can predict responses to environmental change (e.g. climate change) by means of process-based models, given that parametrization is becoming easier for an increasing number of species. We discuss the need to use a combination of spectral properties, microclimate data and long-term data, to combine multiple scales and types of monitoring for robust ecological inferences (Sutherland et al., 2013). Such data could also increase our knowledge on how spatial and temporal heterogeneity influence diversity at different scales. The proposed opportunity of incorporating the study of novel ecosystems in vegetation science would aid in understanding the relevance of assembly rules in the context of biological invasions. To the question posed by Sutherland et al. (2013) on how to provide insights into how the structure of ecological interaction networks affect ecosystem functioning and stability a question, we proposed integrating pollination networks to the study of vegetation. To account for feedback between human behaviour and ecological dynamics in ecological models, we assert that this could be accomplished by including traditional knowledge and incorporating all stakeholders into the research (model) generating process from the beginning.

Topics raising issues and opportunities similar to those included in this work have also emerged in recent horizon scans for conservation. As in our horizon scan, Sutherland et al. (2021) identified the issue with planting trees as a way to mitigate climate change through restoration and also stated that the areas where this effort can be carried out should be identified with great caution. DNA sequencing technologies also emerged in one of the Sutherland et al. (2019a) topics, as a tool for using plant microbiome understanding in restoration efforts. Older horizon scans anticipated that data from satellites and remote sensing would become increasingly available at low cost or for free, enabling monitoring of changes in tropical rain forests and other land-cover types to inform climate change mitigation (Sutherland et al., 2014). As with other studies using the horizon scan method, we acknowledge that the selection and ranking of topics could be biased by the research interests of the participants (Sutherland et al., 2019b). Yet, little evidence was found to support this claim across horizon scans for conservation because the method, replicated here and explained in detail in the Supporting Information, was designed to minimize biases (Sutherland et al., 2019b). Furthermore, the topics selected are not assigned as priority over others. Rather we aim to provide a foundation to stimulate future discussion in the field. To further minimize biases, our horizon scan included a diverse range of participants from a geographical, career stage and gender stand. Repeating this methodology in the future, with new participants, should reduce bias further.

7 | CONCLUSIONS

We identified topics that are expected to emerge, or gain momentum, in the field of vegetation science over the next 20 years. Using a bottom-up approach, we drew upon a diverse group of early career vegetation scientists to provide insights into the research needs of the global field of vegetation science, while acknowledging the urgency of addressing the impacts of global change on vegetation and plant diversity. All of our topics addressed at least two of the aims we identified for the field, including describing and understanding ecological patterns and processes by which vegetation acts as either a driver or response in the environment, integrating traditional knowledge systems, fostering interdisciplinary approaches and improving the way we communicate science. We identified tools that could help us overcome these challenges, including improving predictions and advancing research, management and evidence-based policy in vegetation science. In this context, our initiative appeals to reducing a substantial geographic representation gap in the field and promoting a variety of perspectives to advance vegetation science.

KEYWORDS

climate change, early career scientists, global change, horizon scan, methodological tools, vegetation dynamics

ACKNOWLEDGEMENTS

We would like to thank the IAVS for their support in organizing the workshop in October. FAY is grateful to J. Jeschke for his suggestions and advice on logistics for the horizon scan. FAY would like to thank the support of the Rising Star Junior Fellowship in the Department of Biology, Chemistry and Pharmacy of the Freie Universität and specially the women's representative office at the Department of Biology, Chemistry and Pharmacy of the Freie Universität (Frauenbeauftragte BCP) for providing financial support for childcare during Germany's COVID-19 lockdowns. Without this help, working on this manuscript would have not been possible during these hard times. We acknowledge PhD grants from Fundação de Amparo à Pesquisa do Estado de São Paulo - FAPESP (2018/09054-0) to GD, from Conselho Nacional do Desenvolvimento Científico e Tecnológico- CNPq (141715/2018-9) to JT, from an Indonesia Endowment Fund for Education (LPDP) Scholarship to MJMH, from the Ministry of Education, Science and Technological Development of the Republic of Serbia granted to TŠ, from the Slovenian Research Agency (ARRS) to FK and from Mexico's CONACyT (CVU: 348078) to CXPV. Finally, we would like to acknowledge N. Mason, M. Chytrý and one anonymous reviewer for their insightful comments, which have helped improve this manuscript. Open access funding enabled and organized by ProjektDEAL. Open Access Funding provided by the Freie Universität Berlin.

AUTHOR CONTRIBUTIONS

FAY developed the study concept and original draft. FAY and MGS led the organization of the workshop and writing. FAY, MB, TC and MGS worked on the conceptual parts of the manuscript. All authors contributed with suggestions and writing of one or more topics, discussed the results and provided feedback. ZP revised and edited the final version of the manuscript.

DATA AVAILABILITY STATEMENT

All information that supports the findings of this study are openly available either in the manuscript or in the Supporting Information.

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How to cite this article: Yannelli, F.A., Bazzichetto, M., Conradi, T., Pattison, Z., Andrade, B.O., Anibaba, Q.A., et al (2022) Fifteen emerging challenges and opportunities for vegetation science: A horizon scan by early career researchers. *Journal of Vegetation Science*, 33,e13119. https://doi.org/10.1111/jvs.13119