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IMPROVING BIODIVERSITY MONITORING USING SATELLITE REMOTE SENSING

Methods in Ecology and Evolution — BRITISH ECOLOGICAL SOCIETY

Understanding and assessing vegetation health by in situ species and remote-sensing approaches

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Abstract

1. Human activities exert stress on and create disturbances to ecosystems, decreasing their diversity, resilience and ultimately the health of ecosystems and their vegetation. In environments with rapid changes in vegetation health (VH), progress is needed when it comes to monitoring these changes and underlying causes. There are different approaches to monitoring VH such as in situ species approaches and the remote-sensing approach.
2. Here we provide an overview of in situ species approaches, that is, the biological, the phylogenetic, and the morphological species concept, as well as an overview of the remote-sensing spectral trait/spectral trait variations concept to monitor the status of VH as well as processes of stress, disturbances, and resource limitations affecting VH. The approaches are compared with regard to their suitability for monitoring VH, and their advantages, disadvantages, potential, and requirements for being linked are discussed.
3. No single approach is sufficient to monitor the complexity and multidimensionality of VH over the short to long term and on local to global scales. Rather, every approach has its pros and cons, making it all the more necessary to link approaches. In this paper, we present a framework and list crucial requirements for coupling approaches and integrating additional monitoring elements to form a multisource vegetation health monitoring network (MUSO-VH-MN).
4. When it comes to linking the different approaches, data, information, models or platforms in a MUSO-VH-MN, big data with its complexity and syntactic and semantic heterogeneity and the lack of standardized approaches and VH protocols pose the

greatest challenge. Therefore, Data Science with the elements of (a) digitalization, (b) semantification, (c) ontologization, (d) standardization, (e) Open Science, as well as (f) open and easy analyzing tools for assessing VH are important requirements for monitoring, linking, analyzing, and forecasting complex and multidimensional changes in VH.

KEYWORDS

biological species concept, earth observation, morphological species concept, multi-source vegetation health monitoring network, phylogenetic species concept, remote-sensing, remote-sensing spectral trait, spectral traits variation concept

1 | INTRODUCTION

An extreme loss of biodiversity has been shown to reduce both ecosystem stability and a range of ecosystem functions (Cardinale et al., 2012). This loss can occur at different levels of biotic organization from the molecular, individual and community levels to that of ecosystems. Accordingly, biodiversity is one central component of the concepts of ecosystem health and integrity (Haase et al., 2018; Müller, 2005; Rapport, Costanza, & McMichael, 1998). These concepts relate to the self-organizing capacity of ecosystems in the presence of stress. Healthy ecosystems can thus be seen as vigorous, diverse systems that are characterized by a high resilience, that is, the ability to quickly return to an initial state following an external disturbance and thus to withstand negative impacts from external influences (Rapport et al., 1998).

Effects of stress, disturbances, and resource limitations on ecosystem health are mostly nonlinear on a spatial and temporal scale, complex, and multidimensional. Evolutionary adaption processes, regional contexts, and stress interactions can impede the understanding and monitoring of ecosystem health (Lausch, Erasmi, King, Magdon, & Heurich, 2016, 2017). Consequently, a holistic approach is required to monitor, analyse, and evaluate ecosystem health. Such an approach should enable landscape managers, decision makers, and politicians to react more quickly and in targeted ways to decreasing ecosystem health and to perform monitoring and data-driven ecosystem management in an effort to stabilize resilience. However, to date, a big discrepancy exists between the requirements and the reality of monitoring: High spatial-temporal exactness and short to long-term timely resolution from local to global scales are needed, that can be recorded cost-effectively, quickly, and comparably, using standardized testing procedures. Moreover, dealing with and managing big and complex monitoring data impedes data retention, linking as well as analyzability.

Here, we focus on vegetation and vegetation health (VH) as the level of primary producers within ecosystems. To record shifts in vegetation diversity (VD) and related shifts in VH, two main monitoring methods are available: (a) in situ or field-based observation and (b) remote-sensing (RS) approaches. In situ observation refers to the direct identification and monitoring of plant species by taxonomists and has been used for VH monitoring for a long time (Mueller, Baessler, Schubert, & Klotz, 2010). In situ approaches are the basis for our present-day understanding of biodiversity, macroecology and biogeography (Violle, Reich, Pacala, Enquist, & Kattge, 2014). Here, plant species are recorded and systematized on the basis of different species concepts (Wheeler & Meier, 2000). However, in-situ approaches on the basis of taxonomic units are spatially and temporally limited when it comes to understanding species responses to stress, disturbances, or resource limitations posed by environmental conditions (Soberón, 2007). While in situ observation has largely been based on taxonomic units, the importance of species traits has recently been recognized and has allowed for a whole new way of understanding fundamental ecological questions, such as “why organisms live where they do and how they will respond to environmental change” (Green, Bohannan, & Whitaker, 2008: 1039). In situ species trait approaches give a complex understanding of species’ potential with respect to different stress levels, disturbances, or resource limitations, adaptation mechanisms, plant fitness or resilience of vegetation. Still, they are limited when it comes to producing extensive conclusions, because in situ mapping is mostly restricted to point samples or small areas and it is costly.

In contrast to in situ approaches, RS observation is entirely based on spectral reflectance values captured by sensors mounted on drones, airplanes, or satellites. RS approaches for VH monitoring constitute the only approach for a timely, cost-effective, objective, and repeatable recording and assessment of status, stress, disturbance, and resource limitations over the short to long term and for local and global vegetation monitoring (Skidmore et al., 2015; Turner, 2014). Historically, RS evaluations focused on categorizing discrete vegetation units and were the basis of land-use-land-cover classification approaches (Ustin & Gamon, 2010). However, the development of RS techniques with better radiometric, spatial, spectral, directional, and temporal resolution and the enhanced understanding of the importance of spatial heterogeneity and continuous information rather than discrete vegetation units or land-cover classes (Lausch, Blaschke, et al., 2015) to describe processes of stress, disturbances, or resource limitations are opening up new perspectives and new applications of RS in the context of VH.

The RS approach makes it possible to respond to a number of questions related to the status and changes of ecosystem functions, to assess disruptions in ecosystem processes, to measure spatial-temporal shifts in plant phenology (Cleland, Chuine, Menzel, Mooney, & Schwartz, 2007; Garonna, de Jong, & Schaepman, 2016; Jeong, Ho, Gim, & Brown, 2011) to analyse effects of climate change on vegetation (Schimel, Asner, & Moorcroft, 2013) to monitor land-use intensity (Gómez Giménez, de Jong, Della Peruta, Keller, & Schaepman, 2017), land-use changes, landscape fragmentation, infestation and the spread of insect pests in forests and crops, right up to species distribution and richness (α-diversity) (Rocchini, Hernández-Stefanoni, & He, 2015), turnover in species composition (β-diversity) (Baldeck & Asner, 2013; Rocchini et al., 2017), and spatial-temporal heterogeneity in vegetation (Rocchini et al., 2010) as well as phylodiversity (Asner & Martin, 2016), taxonomic (Rocchini et al., 2018), structural (Leitão et al., 2015) and functional (Schneider et al., 2017) VD. But, the RS approach for monitoring VH is limited by the following constraints. Only specific plant traits, trait combinations, and trait variations can be recorded by RS (Lausch, Erasmi, et al., 2016). Moreover, the shape, density, and distribution of plant traits in space and over time determine (a) the spatial, spectral, radiometric, and temporal characteristics of the RS sensors, (b) the choice of the classification method, be it pixel-based or (geographic) object-based approach, and (c) “how the RS algorithm and its assumptions fit the RS data and the spectral traits (ST) of the plant species” (Lausch, Bannehr, et al., 2016).

Consequently, no single approach is suitable for monitoring VH in all its complexity and multidimensionality over short to long-term periods and on local to global scales. With this in mind, the goal of the paper is: (a) To define VH and to introduce methods to measure VH; (b) to identify the key characteristics, differences and commonalities among in situ and RS-based VH mapping approaches and to identify ways of integrating both approaches; (c) to present a framework and crucial requirements for combining in situ and RS-based approaches and the development of a multi-source VH monitoring network.

2 | IN SITU APPROACHES FOR MONITORING VH

Species concepts group individuals according to shared characteristics (Wheeler & Meier, 2000). There are various approaches, with the most important being the biological species concept (BSC; Mayr, 1942) relating to taxonomic diversity; the phylogenetic species concept (PSC; Eldredge & Cracraft, 1980) relating to phylodiversity; and the morphological species concept (MSC; Mayr, 1969) relating to traits and functional diversity.

2.1 | BSC—to measure stress in taxonomic diversity

The BSC defines species on the basis of the ability of individuals to interbreed and have fertile offspring, not on the basis of specific visible (and possibly plastic) traits (Mayr & Ashlock, 1969). This makes the definition of species identity relatively stable. Species are the basis for the quantification of measures of taxonomic diversity from which we can follow changes in biodiversity due to changes in land use or climate. Species richness is positively related to some ecosystem functions, such as productivity (Grace et al., 2016) and enhances the resistance of ecosystem productivity to climate events (Isbell et al., 2015) or to disturbances such as flooding (Wright et al., 2017). Consequently, monitoring taxonomic diversity helps monitoring VH. Even the sole distinction of species by in situ approaches can provide insights into the state of biodiversity and related ecosystem functions. Taxonomic diversity has thus been counted as one of the essential biodiversity variables (EBV) of the Group of Earth Observations Biodiversity Observation Network (Pereira et al., 2013). However, by solely considering taxonomic diversity, we cannot infer information on for example, the rarity of a species or whether it is native, exotic or invasive in a region. Where such information is available (e.g. from national red lists or inventories of invasive species, for example, DAISIE (Pyšek et al., 2010), the distinction of species by in situ approaches can be used for mapping the distribution, spread or decline of for example, invasive species.

2.2 | PSC—to measure stress in phylodiversity

The knowledge about phylodiversity can provide better understanding of VH (Faith, 1992; Marcon & Hérault, 2015). Measures of phylodiversity (diversity measures based on the evolutionary history of species; Laity et al., 2015) do not necessarily correlate to measures of taxonomic diversity (Schweiger, Klotz, Durka, & Kühn, 2008). Rather, an increase in taxonomic diversity can just as well be accompanied by a decrease in phylodiversity (Knapp, Winter, & Klotz, 2017). Phylodiversity is not distributed randomly across the globe (Sechrest et al., 2002) and is affected by land use (Frishkoff, Karp, M’Gonigle, Hadly, & Daily, 2014; Knapp, Kühn, Schweiger, & Klotz, 2008) climate (Willis, Ruhfel, Primack, Miller-Rushing, & Davis, 2008) biological invasions and extinctions (Knapp et al., 2017). The phylodiversity of plants has been shown to increase the taxonomic diversity of arthropods (Dinnage, Cadotte, Haddad, Crutsinger, & Tilman, 2012) and to support ecosystem functions and stability (Cadotte, 2013; Flynn, Mirotchnick, Jain, Palmer, & Naeem, 2011). It has been suggested as criterion for the establishment of protected areas (Sechrest et al., 2002). In sum, measures of phylodiversity can provide important insights into VH; however, in situ, phylodiversity cannot be monitored directly but needs to be inferred from information on species occurrence.

2.3 | MSC—to measure stress in functional diversity

BSC and PSC distinguish species based on the ability of individuals to interbreed. In contrast, the morphological (Mayr, 1969), the chemotaxonomy (Grube & Kroken, 2016) and environmental species concepts (Hutchinson, 1965) focus on the characteristics of species—the so-called traits—and on the adaptation of species to environmental conditions. Taxonomic measures cannot answer “why organisms live where they do and how they will respond to environmental change” (Green et al., 2008: 1039) but trait-based/functional approaches can.

Plant traits are anatomical, morphological, biochemical, physiological, structural or phenological characteristics of plants (Kattge et al., 2011). As environments differ in the presence and frequency of trait values ("environmental filtering"; Figure 2), traits, their diversity, and their changes can be used to map environmental changes as well as impacts from and responses to environmental and anthropogenic pressures (Carboni et al., 2014; Garnier et al., 2007), such as plant invasions (van Kleunen, Weber, & Fischer, 2010), grazing (Díaz et al., 2007) or eutrophication and fragmentation (Römermann, Tackenberg, Jackel, & Poschlod, 2008). The diversity of traits (i.e. functional diversity) has been shown to support ecosystem functioning (Flynn et al., 2011). The fact that traits both respond to environmental changes and affect ecosystems makes them valuable indicators for VH.

Traits can show plastic responses to environmental changes but can also be evolutionary fixed (Cheptou, Carrue, Rouifed, & Cantarel, 2008). Consequently, in comparison to the BSC, the definition of traits is less stable. Standardized measurements are thus needed to compare traits across sites and scales. However, in situ trait measurements are time consuming and many measurements require laboratory equipment (e.g. measuring leaf nitrogen or chlorophyll content). Nevertheless, a range of traits has been measured by in situ approaches and has been stored in national or global databases (Kattge et al., 2011). Even though such databases exist, the extrapolation of trait patterns remains limited. Only spatially and temporally intensive data collection, such as concentrating data sampling to long-term ecological research sites (Mueller et al., 2010) or monitoring biodiversity-ecosystem functioning experiments (Bruelheide et al., 2014) allow a comprehensive description, explanation and prediction of trait changes and related changes in VH.

3 | REMOTE-SENSING APPROACHES FOR MONITORING VH

RS records biochemical-biophysical, physiognomic, morphological, structural and functional traits at all levels of biotic organization based on the principles of image spectroscopy across the electromagnetic spectrum from visible to microwave bands (Ustin & Gamon, 2010). Compared to the in situ trait approach, RS is unable to detect all traits and trait variations (Homolová, Maenovsky, Clevers, Garcia-Santos, & Schaepman, 2013). Traits and trait variations that can be monitored by RS are called ST (see Figure 1) and spectral trait variations (STV) (see Figure 2) (Lausch, Erasmi, et al., 2016). The approach to monitor VH by RS is called the remote-sensing–spectral trait/STV concept (RS-ST/STV-C).

3.1 | Remote sensing can measure processes, stress, disturbances, and resource limitations

RS can record the status, stress, disturbances, or resource limitations of vegetation over the short and long term on local and global scales, since (modified after Lausch, Erasmi, et al., 2016)

1. processes, stress, disturbances, and resource-limitations cause changes in spectral traits and lead to STV,
2. plant traits are a proxy and filter for status (structure, process, function) and for stress, disturbances, or resource limitations,
3. RS can record direct and/or indirect traits and trait variations on all spatial and temporal scales of vegetation hierarchy (see Figure 2),
4. spectral RS patterns and heterogeneity are a proxy for plant trait diversity and the result of processes, stress, disturbances and resource limitations on plant and vegetation traits.

3.2 | Monitoring stress in phylo-, taxonomic, structural and functional diversity by RS

3.2.1 | Phylogenetic stress by RS

Phylodiversity has been suggested as a proxy of functional diversity because a range of functional traits are heritable; still, heritability does not always apply (Lososová et al., 2016). Inferring facts on phylodiversity from spectral traits should thus only be possible when heritable traits correlate with spectral traits or when spectral traits are heritable themselves (Jetz et al., 2016). Imaging spectroscopy with its high spectral resolutions of 0.4–2.5 μm and more than 20 spectral channels shapes the next generation of plant trait monitoring techniques compared to multispectral RS sensors (Asner & Martin, 2016). By means of imaging spectroscopy at least 21 biochemical elements were identified, like foliar nitrogen content (Knyazikhin et al., 2013), photosynthetic pigments (Ustin et al., 2009), lignin, polyphenols and cellulose or water in leaves (Martin et al., 2018). These elements define the "spectral fingerprint" of plant species and vegetation based on their "chemical phylogeny" or chemical VD (Asner & Martin, 2016; Pandey, Ge, Stoerger, & Schnable, 2017; Ustin, 2013), Schweiger et al. (2018) developed an integrative spectral diversity indicator on the basis of the leaf economic spectrum (Díaz et al., 2015) to predict 97% of phylogenetic diversity in plant species.

3.2.2 | Taxonomic stress by RS

Plant species diversity, heterogeneity and richness are key parameters for describing VH, stability and resilience of ecosystems (Richter, Reu, Wirth, & Doktor, 2016). Therefore, a continuous and consistent recording of taxonomic stress by RS is a crucial method for assessing VH. Due to their high spectral resolution and the recordability of various plant traits, hyperspectral RS techniques are very suitable for discriminating species and their turnover (Rocchini et al., 2017) floristic compositions (Lopatin, Fassnacht, Kattenborn, & Schmidtlein, 2017) spatial heterogeneity (Rocchini et al., 2018) dominant species, functional guilds, invasive plant species (Santos, Khanna, Hestir, Greenberg, & Ustin, 2016) or vegetation types (Laurin et al., 2016; Schmidt & Skidmore, 2003).

However, different taxa can only be discriminated by RS if the taxa can be differentiated by: (a) their chemical, biochemical-biophysical,

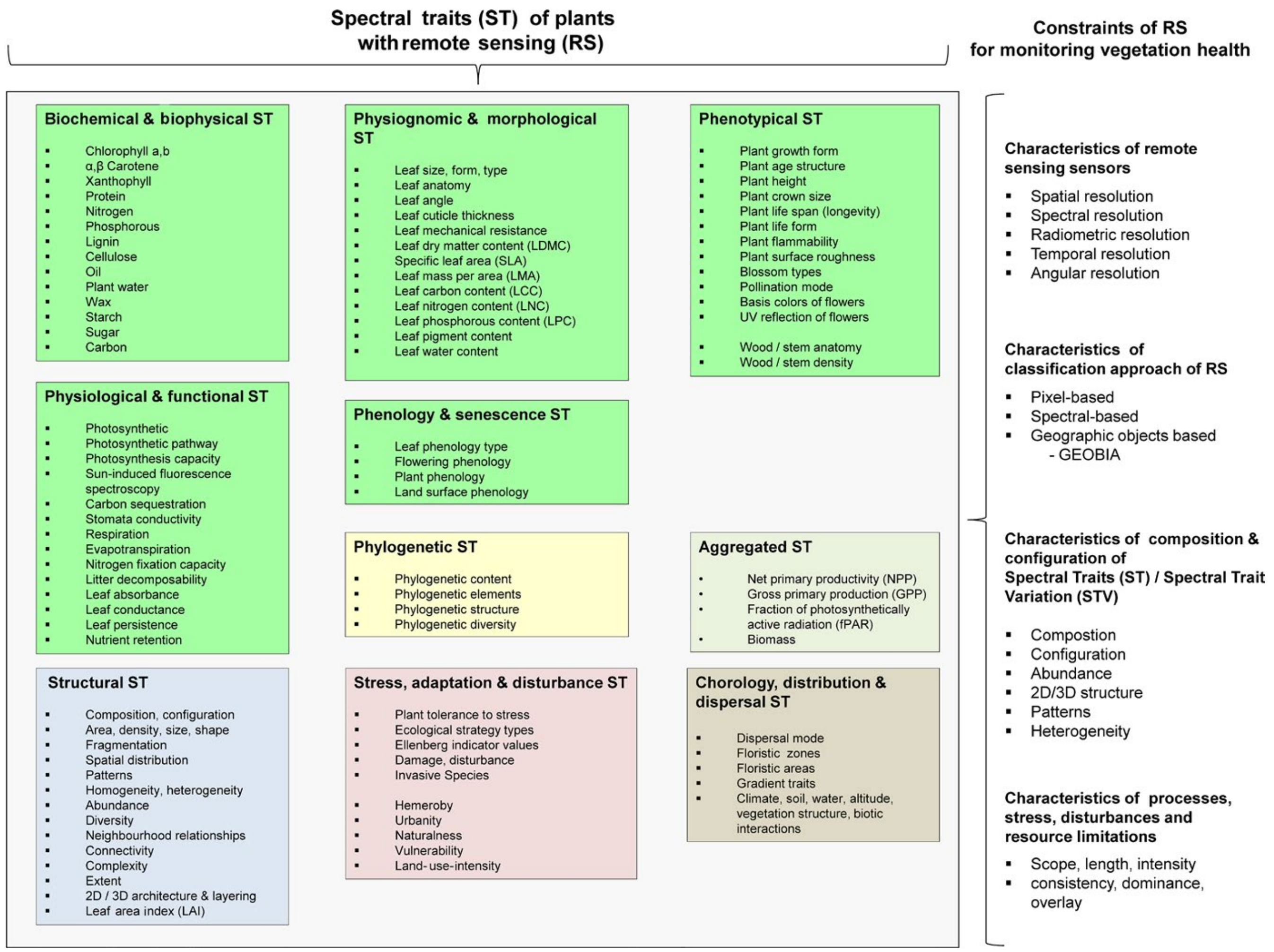

FIGURE 1 Spectral traits for observing and assessing phylogenetic, taxonomic, structural and functional diversity using hyperspectral remote-sensing techniques (modified after (Lausch, Erasmi, et al., 2016). RS: remote sensing

morphometric, geometric or physiology traits, (b) various life-cycle traits like senescence, phenology, flowering period or growth characteristics; (c) if regional specific resource limitations are present, which determine the geographic presence of the plant species, or (4) if taxa can be differentiated by their response to stress, again using traits such as hairy leaves, leaf morphology, cuticula strength, changes to intercellular tissue.

The recording of taxonomic stress by multitemporal RS techniques (a combination of RS sensors with different characteristics such as thermal, optical or radar) as well as multisensor RS techniques (a combination of image data that covers the entire vegetation development) can generally be improved, since different sensors with different sensor characteristics increase the discrimination of various traits.

3.2.3 | Functional stress by RS

Plant traits both respond to and affect environmental conditions and can thus be used as indicators of stress, disturbances and resource limitations. Furthermore, functional VD is closely related to ecosystem processes such as water, matter and energy cycles (all being indicators of ecological integrity (EI) and thus of ecosystem health; (Haase et al., 2018). The open data policy of remote-sensing data and data products (Wulder & Coops, 2014) like Landsat TM or the Copernicus RS mission (Sentinel 1–6) enable scientists to globally record data on the functional composition and diversity of plant communities as a basis for monitoring, understanding, assessing, evaluating and predicting, for example, the productivity of ecosystems (Lees, Quaife, Artz, Khomik, & Clark, 2018) forest biomass (Avitabile et al., 2016) or vegetation productivity patterns (Guay et al., 2014), estimating carbon fluxes (Lees et al., 2018; Schimmel et al., 2015), changes in carbon stocks (Asner et al., 2014) or interactions between biodiversity and carbon stocks (Bustamante et al., 2016). The global variation in leaf respiration in relation to plant functional types, leaf traits and climate (Atkin et al., 2015), the distribution of N in canopies (Balzotti et al., 2016) or the loss of canopy water (Asner et al., 2015) can all be monitored extensively by using RS technologies. Furthermore, there are numerous applications for monitoring shifts in plant traits such as shifts in biochemical traits, photosynthetic activity, plant productivity, phenology, the length of the growing season,

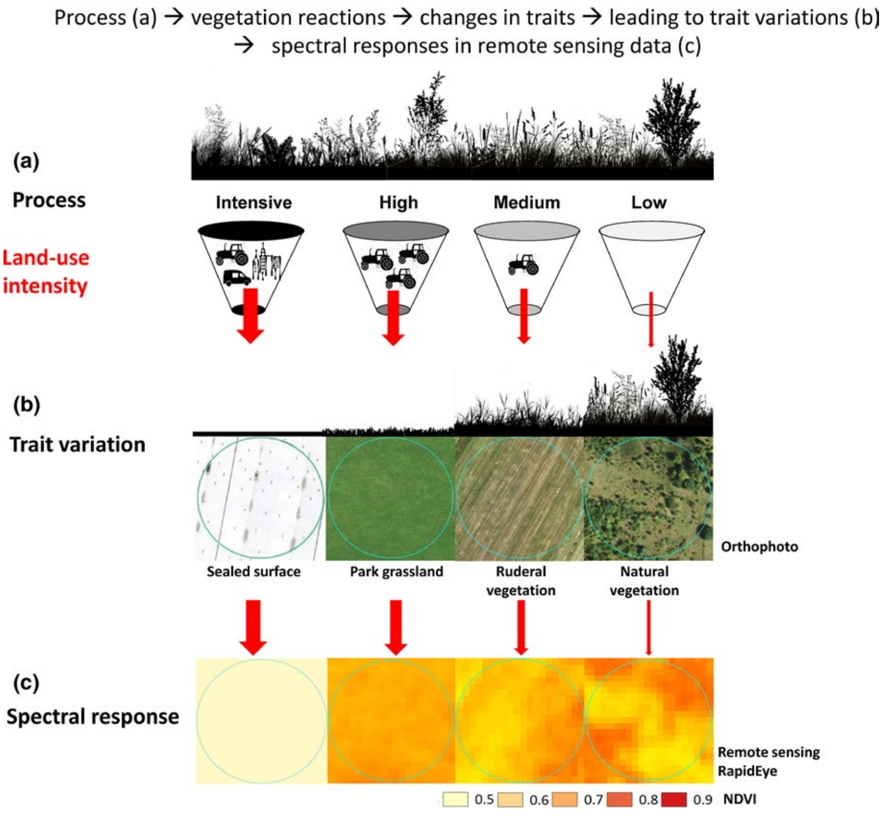

FIGURE 2 Illustration of environmental filtering of vegetation by processes of land-use intensity and how remote sensing can monitor this. (a) Processes of land-use intensity lead to reactions in the vegetation and changes in traits, which lead to (b) trait variations with the result of (c) the spectral response that can be measured using remote-sensing data. NDVI (Normalized Difference Vegetation Index) is a proxy for the spectral trait—chlorophyll content (modified after Wellmann et al., 2018)

the variation in carbon dioxide exchange, and carbon balance or greening response (Garonna et al., 2016). An extensive overview on this is provided in (Lausch, Erasmi, et al., 2016).

The "Fluorescence Explorer Satellite" (FLEX) is currently being developed and is financed and established by European Space Agency (ESA). It is scheduled for use after 2022 (Kraft, Del Bello, Bouvet, Drusch, & Moreno, 2012). It features a high spectral resolution of 0.3–3.0 nm to directly measure solar-induced chlorophyll fluorescence as an indicator of photosynthetic conditions and to provide estimates of global photosynthetic activity and CO_2 fluxes (Kraft et al., 2012). The development of high temporal and spectral resolution for future applications is underway: the first hyperspectral satellite EnMAP, the hyperspectral/thermal combination HyspIRI and the multispectral/hyperspectral RS combination HISIRI, or a multi-sensor combination with RADAR and thermal radiometer like the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station.

4 | COUPLING OF IN SITU AND RS APPROACHES BY METHODS OF DATA SCIENCE

No monitoring approach alone is sufficient, comprehensive, cost-effective, and flexible enough to perform VH monitoring from local to global scales and for short to long-term processes as well as to monitor changes in phylo-, taxonomic and functional diversity and to assess the stress and resilience of ecosystems. Therefore, the development of a multisource vegetation health monitoring network (MUSO-VH-MN) is necessary where multi-source data and different monitoring approaches can be linked in an effort to compensate for the shortcomings of one approach with the advantages of another and to achieve additional benefits for VH monitoring. A future MUSO-VH-MN therefore should contain the following elements: (a) the integration of multisource data and platforms, (b) the coupling of monitoring approaches and (c) Data Science as a bridge for coupling (Figure 3), (modified after Lausch et al., in review).

4.1 | Data, networks and platforms

The MUSO-VH-MN should integrate the following data and site survey platforms. *Species/habitats:* Data of site surveys for species, species lists, metabarcoding, microgenomics (Bush et al., 2017), Phenotyping (Deans et al., 2015), data from museums, lysimeter, plant phenomic facilities (Furbank, 2009), controlled environmental facility—Ecotron's (Lawton et al., 1993), long-term ecological research (Mueller et al., 2010), spectral laboratory experiments, biodiversity ecosystem functioning experiments (Bruelheide et al., 2014), *Remote sensing:* Optical (multispectral, hyperspectral), thermal, Radar, LiDAR data, laboratory, tower, camera traps, wireless sensor networks, drones, close-range, air- and space-borne RS platforms, *Additional:* linking monitoring databases, networks, citizen science information, abiotic (soil, water, air), social and economic information.

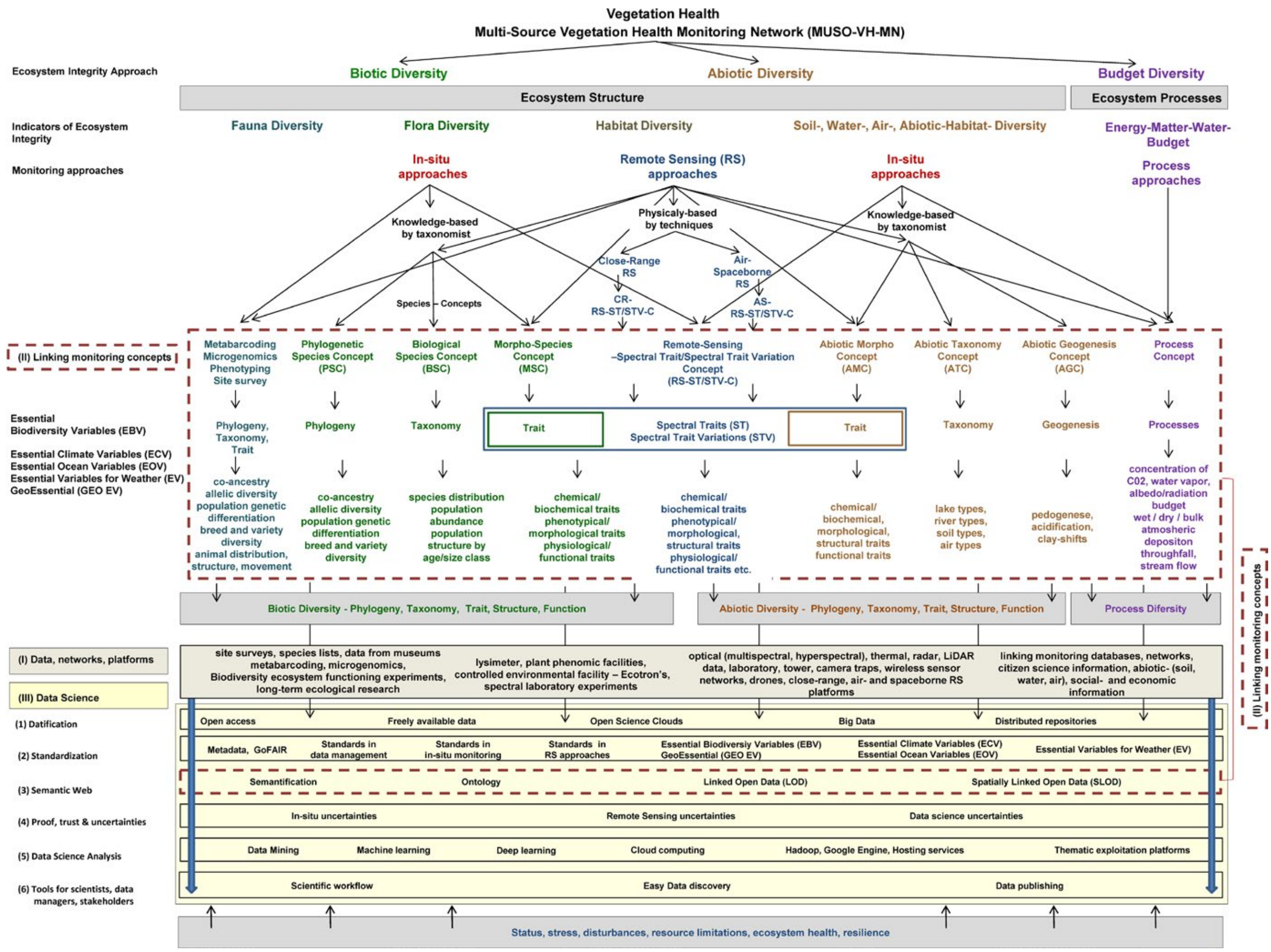

FIGURE 3 Illustration of the components that need to be included for a future multi-source vegetation health monitoring network: (I) integration of existing data, networks and platforms, (II) linking of existing monitoring approaches as well as (III) the use of data science as a bridge for handling and coupling big forest health data with volume, velocity, variety and veracity, close-range remote-sensing–spectral trait/spectral trait variation-concept, air-scaceborne remote-sensing-spectral trait/spectral trait variation-concept

4.2 | Linking monitoring approaches

Future site-based long-term research and monitoring concepts necessitate the linking of different approaches, namely: (a) for vegetation monitoring—the Biological (BSC), the Phylogenetic (PSC), and the MSC, (Jetz et al., 2016), (b) the concepts of phenotyps (Deans et al., 2015), (c) for abiotic and process monitoring—the concept of EI (Haase et al., 2018) and (d) for RS-ST/STV-C (Lausch, Bannehr, et al., 2016).

4.3 | Data science as a bridge

When it comes to developing a MUSO-VH-MN, big data, complexity and syntactic and semantic heterogeneity and the lack of standardized approaches, protocols, as well as data management are all challenging. This is where Data Science comes in as a bridge: (a) digitalization, (b) standardization, (c) Semantic Web, (d) testing of uncertainties, (e) Data Science analysis, and (f) open and easy analysis tools for assessing VD are all crucial requirements for a better use, understanding, and analysis of complex and multidimensional VD. Specifically, this means:

1. *Digitalization:* VD information has to be computer producible, connectable, readable, and evaluable, allowing for a cost-effective, error-free and standardized processing and semantic linking of complex and multidimensional VD information to understand new patterns, interactions and processes in ecosystems. Important components are: Open Access for tools, software, algorithms, instruments or platforms, freely available data and data policy for species, RS (Wulder & Coops, 2014) and abiotic data, development of Open Science Clouds like the European Open Science Cloud (Ayris et al., 2016), familiarization with big data and distributed repositories.
2. *Standardization:* Data, information, tools, algorithms, models, data management, and monitoring of approaches have to be standardized, administered, stored, processed, updated as well as linked and evaluated with other platforms and

networks. The basics of metadata management reflect the principles of Findability, Accessibility, Interoperability and Reusability (Wilkinson, Dumontier, Aalversberg, Appleton, & Axton, 2016). The concepts of EBV (Pereira et al., 2013), essential climate variables or semantic-based platforms like GFBio (https://www.gfbio.org) are leading the way for standardization.

3. *Semantic web:* Linking complex and multidimensional VD information, tools, approaches, data, scales, RS platforms, models in a semantic-enabling way according to the standards of the World Wide Web Consortium (Berners-Lee, 2006). Important elements are: semantification (Berners-Lee, 2006), ontologization (Madin, Bowers, Schildhauer, & Jones, 2008) and Linked Open Data approaches (Lausch, Schmidt, & Tischendorf, 2015).
4. *Proof, trust and uncertainties:* Most methods, data or models used in data science introduce a certain degree of uncertainty. Consequently, methods of testing uncertainties are required for in-situ, RS-monitoring data and Data Science approaches.
5. *Data-science-analysis:* The digitalization of the world and necessitates the use and familiarization with Big Data and its four characteristics: Data volume, velocity, variety and veracity. Data Science analysis thus requires methods of Data Mining, Machine learning, Cloud computing, Hadoop, Google Engine, Hosting services and Thematic exploitation platforms.
6. *Tools for scientists, data managers and stakeholders:* Open and easy management and analysis tools, comprehensible scientific workflows as well as easy and constantly up to date data publishing tools for analyzing and assessing MUSO-VH-MN information are imperative for an applicable and implementable decision-making support system for authorities, stakeholders and politicians.

5 | CONCLUSION

VH is multi-dimensional and only partially understood due to its complexity. So far there is no existing monitoring approach that can sufficiently assess and predict VH and its resilience on its own. To establish a multi-source VH monitoring network in the future, the following main elements should therefore be considered: (a) the integration of existing data, networks and platforms, (b) the linking of all existing monitoring approaches as well as (c) the use of Data Science as a bridge for handling and coupling big forest health data with volume, velocity, variety and veracity.

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AUTHORS’ CONTRIBUTIONS

All authors contributed to the development and writing of the manuscript.

DATA ACCESSIBILITY

I confirm that my manuscript does not include any data.

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