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How Essential Biodiversity Variables and remote sensing can help national biodiversity monitoring

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HIGHLIGHTS

- National biodiversity state indicators correspondence with EBVs was assessed.
- EBV approach revealed gaps in the current biodiversity monitoring scheme.
- Monitoring could be improved by using remote sensing applications and EBV approach.
- Four EBVs could benefit substantially from the use of remotely sensed data.
- Three new EBV-candidates were suggested to describe ecosystem function more comprehensively.

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ABSTRACT

Essential Biodiversity Variables (EBVs) have been suggested to harmonize biodiversity monitoring worldwide. Their aim is to provide a small but comprehensive set of monitoring variables that would give a balanced picture of the development of biodiversity and the reaching of international and national biodiversity targets. Globally, GEO BON (Group on Earth Observations Biodiversity Observation Network) has suggested 22 candidate EBVs to be monitored. In this article we regard EBVs as a conceptual tool that may help in making national scale biodiversity monitoring more robust by pointing out where to focus further development resources. We look at one country –Finland –with a relatively advanced biodiversity monitoring scheme and study how well Finland's current biodiversity state indicators correspond with EBVs. In particular, we look at how national biodiversity monitoring could be improved by using available remote sensing (RS) applications. Rapidly emerging new technologies from drones to airborne laser scanning and new satellite sensors providing imagery with very high resolution (VHR) open a whole new world of opportunities for monitoring the state of biodiversity and ecosystems at low cost. In Finland, several RS applications already exist that could be expanded into national indicators. These include the monitoring of shore habitats and water quality parameters, among others. We hope that our analysis and examples help other countries with similar challenges. Along with RS opportunities, our analysis revealed also some needs to develop the EBV framework itself.

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1. Introduction

In addition to climate change, biodiversity loss is recognized to pose one of the most serious threats to human well-being (GBO-4, 2014; MA, 2005; Rockström et al., 2013). Up to date biodiversity monitoring is crucial because of: (1) social–ecological systems are ultimately the result of and dependent upon biodiversity, ecosystem functioning, and biosphere processes (i.e. *socio-economic, utilitarian reasoning*); (2) high-quality biodiversity data is an essential building block of many disciplines and environmental models that attempt to explain the world *per se* (*curiosity, scientific reasoning*) and; (3) biodiversity is included in environmental policies at many levels—people in societies have decided to protect biodiversity and report on this progress (*policy demand for monitoring and reporting, institutional reasoning*). Besides these human-focused reasons of explaining why biodiversity matters, the fundamental rationale is that biodiversity underpins ecosystem functioning (Hooper et al., 2012).

The launching of the concept of Essential Biodiversity Variables (EBVs) has stimulated progress to unify and harmonize biodiversity monitoring globally (CBD Subsidiary Body on Implementation, 2016; GEO BON, 2015a, b; Pereira et al., 2013; Pettorelli et al., 2016) and revitalized aspirations of constructing an encompassing global biodiversity index with an analogy from the stock markets (Brummitt et al., in press; cf. Balmford et al., 2005). The aim of EBVs is to find measurable parameters for all relevant dimensions of biodiversity, to attain consensus on what to monitor, and, subsequently, to decide where to focus the limited monitoring resources. The suggested top-level classes of EBVs are *Genetic composition*, *Species populations*, *Species traits*, *Community composition*, *Ecosystem structure* and *Ecosystem function* (UNEP/CBD/SBSTTA/17/INF/7, 2013; Pereira et al., 2013). Although the focus of EBV development has so far been on global and supranational monitoring, the approach can also be applied to a national level and even lower geographical or administrative scales. Since biodiversity is primarily a phenomenon of local eco-evolutionary processes, it can best be recognized and managed on a national or regional level. Looking at EBVs from a national monitoring perspective –having to think in practice which monitoring data sources and remote sensing techniques could be used to provide the information needed –also serves to make the EBVs more concrete.

The development of national, continental scale and global biodiversity indicators has received increasing interest after the turn of the Millennium. Individual countries started from different outsets. Countries like The Netherlands (Wondergem and Klein, 2010) and Finland (Auvinen and Toivonen, 2006) began by collecting data from all relevant monitoring schemes and building a comprehensive set of indicators based on them. Other countries linked biodiversity indicators from the beginning with political goals (e.g. Sweden's Environmental Objectives; Ministry of the Environment Sweden 2013). In contrast, Switzerland developed a whole new purpose-build monitoring scheme for biodiversity (Hinterman et al., 2002). At international level, one of the first ambitious attempts to make a multi-country set of biodiversity indicators was the Streamlining European Biodiversity Indicators 2010 (SEBI2010) project coordinated by the European Environment Agency (Biała, et al., 2012). The SEBI2010 project was also important for developing global biodiversity indicators for the Convention on Biological Diversity (CBD). After the launching of the Aichi Biodiversity Targets in 2010, the Biodiversity Indicator Partnership (BIP) has developed a global set of indicators which focuses on monitoring the 2020 Aichi targets in particular www.bipindicators.net/globalindicators; (CBD, 2014).

It is important to note the historical background against which EBVs have been introduced. As Geijzendorffer et al. (2015) remark, EBVs are a theory-driven and rather academic approach to biodiversity monitoring. On the contrary, much of previous indicator work has been practically oriented and data-driven. The previous work aims to provide at least some kind of answer to the question of reaching the biodiversity targets that have been set. In the case of Finland, all useable, relevant, and geographically comprehensive monitoring data were amassed and a collection of indicators was created on that basis. Steps are now taken both nationally and internationally to link indicators more closely to targets as seen by the Aichi Targets Passport created by the BIP (above). Perhaps time is now ripe to also look at our monitoring and indicator schemes from the theory-driven EBV perspective in order to find existing gaps and biases.

Technical development of remote sensing applications is another important reason why the establishment of comprehensive biodiversity monitoring schemes, covering relevant aspects of EBVs, is achievable today (Pettorelli et al., 2016). Growing amounts of remote sensing data are freely available. *In situ* data are also increasingly stored in GIS platforms and new observations accumulate all the time (Vihervaara et al., 2012, 2013). Combining remotely sensed and *in situ* data in modelling is a promising approach to fill in gaps in biodiversity monitoring (GEO BON, 2015a, b; CBD Subsidiary Body on Implementation, 2016). In addition, the applicability of automated environmental monitoring data is increasing. For instance, methods for DNA sampling in freshwater and ecological network studies are being developed (e.g. Thomsen and Willerslev, 2015) –however, in this paper, we limit our discussion to remote sensing. Even though remotely sensed data have been produced already dozens of years, its use (and usability) in biodiversity monitoring has been narrow and limited.

2. Aims of the study

Given the present economic limitations in many countries it is not very realistic to aim to launch new monitoring programmes based on large-scale field work. In Finland, it has been estimated that some 70% of all biodiversity monitoring was done on a voluntary basis at the turn of the Millennium (Toivonen and Liukko, 2005), and this percentage is likely to have grown since due to budget cuts. It seems unrealistic to get government funding for any new field-based monitoring schemes as even many of the present monitoring programmes are at risk of being discontinued. Therefore, the most promising sources of new monitoring data lie in remote sensing and other automated or semi-automated data collection methods.

The aims of this paper can be presented as three consecutive steps. First, we look at the existing set of Finnish biodiversity indicators in the light of EBVs –how well do the indicators correspond to second-level EBV subclasses? How many and how strong interlinkages can be found? In cross-tabulating national indicators with EBVs we also hope to point out possible needs to develop the EBV classification further.

Second, we search for gaps –which EBV subclasses are not covered by the existing national indicators? As stated above, the Finnish national biodiversity indicators were originally developed in a pragmatic fashion by collecting and using all available relevant data. EBVs provide the first robust framework for analysing the national indicator set from the point of view thematic coverage.

Third, we look for opportunities to fill in some of the gaps in Finnish biodiversity monitoring by using remote sensing and the rapidly developing Earth observation techniques. What are the most feasible next steps in developing the monitoring scheme? At the same time, we also look at how the existing indicators could benefit from RS in terms of data collection and analysis.

We use Finland as an example: a country with rather advanced biodiversity monitoring and indicator schemes, but also with considerable challenges due to large geographical area coupled with low population density, uneven monitoring among main habitat types and dwindling monitoring resources. Many of these limitations and circumstances apply to other countries and therefore we hope that our analysis may provide ideas for developing national monitoring schemes elsewhere. Although the development of EBVs has so far been mainly an international undertaking, we believe it is important to use and test the concept on national scale not only for the benefit national and finer scale biodiversity monitoring but also EBVs themselves.

3. Material and methods

3.1. Current biodiversity indicators and Essential Biodiversity Variables

National biodiversity monitoring in Finland covers species of conservation interest (e.g. endangered species and habitats directive species), common species (e.g. forest birds, mire and farmland butterflies, marine benthic species and weeds on arable fields), entire taxa (e.g. bird and vascular plant atlas) as well as species of commercial interest (e.g. game and fish). On the level of ecosystems, existing monitoring focuses on the Baltic Sea (HELCOM) and on general land cover (e.g. Corine Land Cover, MS-NFI Finland). There is also a long tradition of repeated National Forest Inventories that yield data that can be used for several biodiversity monitoring purposes (Reinikainen et al., 2000). Reporting obligations vary between national scale (e.g. ministries), EU (obligatory in the case of Habitats and Birds Directives and voluntary in the case of Mapping and Assessment of Ecosystems and their Services in relation to the EU Biodiversity Strategy for 2020 (Maes et al., 2012)) and international agreements and initiatives (obligatory to CDB, voluntary to Intergovernmental Platform on Biodiversity and Ecosystem Services).

The current set of Finland's biodiversity indicators can be found at the National Clearing-House platform www.biodiversity.fi. These indicators have been used for reporting to the CBD since the fourth national report (Auvinen et al., 2010) making Finland one of the most advanced countries in this respect (cf. Bubb et al., 2011) . The indicator set follows the drivers, pressures, state, impact, responses (DPSIR) framework advocated by the European Environment Agency, among others (Delbaere, 2003).

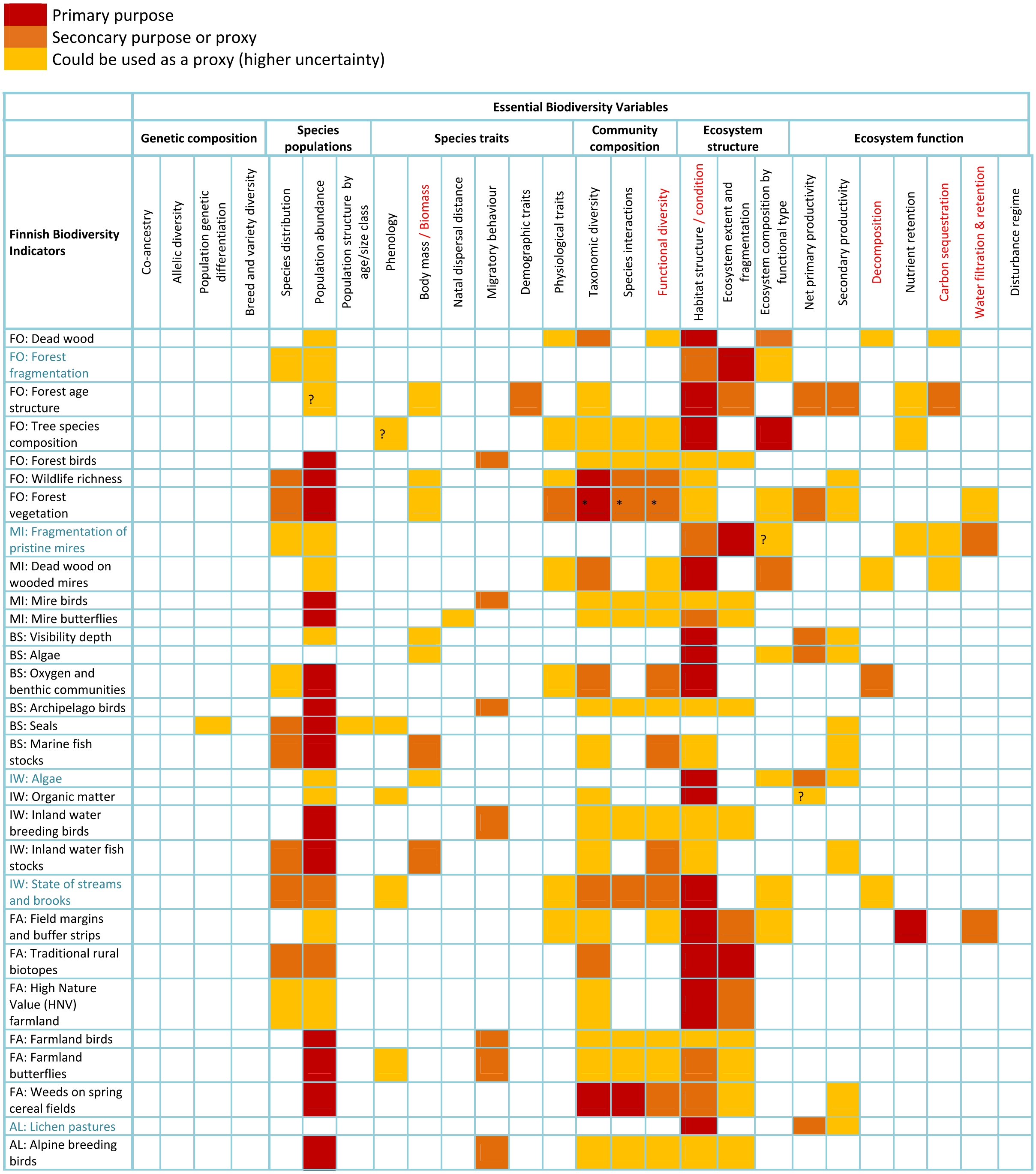
Following the example given by Geijzendorffer et al. (2015), we used the 44 existing or planned national state of biodiversity indicators as a starting point of our analysis to see which EBV classes and subclasses they cover (Table 1). The ultimate target of the indicators is to monitor state of the nine primary habitat types found in Finland. Each indicator was assigned at least one primary EBV subclass (marked with red in Table 1) — meaning an aspect of biodiversity that was originally thought of as the central focus of that particular indicator. Indicators were also assigned 0–5 secondary EBV subclasses (orange) and 0–5 such EBVs (yellow) for which the indicator/monitoring scheme could potentially be used as a supplementary or proxy indicator. Experts involved in the development and updating of biodiversity indicators evaluated the coherence of intersection points of state indicators and EBVs regarding their relevant field of expertise (forests, mires, Baltic Sea etc.)

As an example of the cross-tabulation of national indicators and EBVs, *Population abundance* was deemed as the primary EBV subclass that the indicator *Farmland butterflies* corresponds to. One of the secondary correspondences is *Migration behaviour* since several of the butterfly species monitored migrate to Finland annually. Finally, because of repeated counts during summer, the farmland butterfly census could also be used for monitoring *Phenology*, although such analyses are not done at the moment (i.e. potential indication). Other examples of the evaluation process are illustrated under Results.

3.2. Remote sensing data sources

Remote sensing (RS) techniques have developed rapidly after RS became available for public use and, eventually, when satellite images became openly available (Fig. 1). The potential of EO for biodiversity monitoring has been acknowledged (e.g. He et al., 2015), and detailed reviews on the use of satellite images for monitoring biodiversity have been carried out, for instance, by Turner et al. (2003), Kuenzer et al. (2014), Secades et al. (2014) and O'Connor et al. (2015). Here we focus on the data needs for biodiversity monitoring in Finland. Most of the national biodiversity indicators are not currently spatially

Table 1
Links between Finnish Biodiversity indicators and Essential Biodiversity Variables. Abbreviations: Forests (FO), Mires (MI), Baltic Sea (BS), Inland waters (IW), Farmlands (FA), Alpine habitats (AL), Urban habitats (UA), Shores (SH), Rocky and esker habitats (RE), and Climate change (CC). Indicators with names in blue on the left column are under preparation. EBV sub-classes marked in red are additions suggested by the authors. An asterisk (*) refers to a monitoring scheme at risk of being discontinued. Question mark (?) relates to some uncertainty in the correspondence of the biodiversity indicator and EBV.



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explicit. Therefore the application of RS alone or combined with other GIS or statistical data sources may significantly enhance them. At the same time, it is important to note that *in situ* data is often needed in addition to the RS data for calibration and validation (O'Connor et al., 2015).

Table 1 (*continued*)

AL: Alpine butterflies																										
AL: Extent of palsa mires																								?		
UA: Soil sealing																										
UA: Urban biotopes																										
UA: Urban birds																										
SH: Shoreline vegetation																										
SH: Shore birds																										
RE: Rocky habitat and esker species																										
RE: Exposed rocky and esker habitats																										
CC: Pollen season																										
CC: Butterfly range shifts																										
CC: Bird range shifts																										
CC: Bird phenology																										
CC: Treeline																										

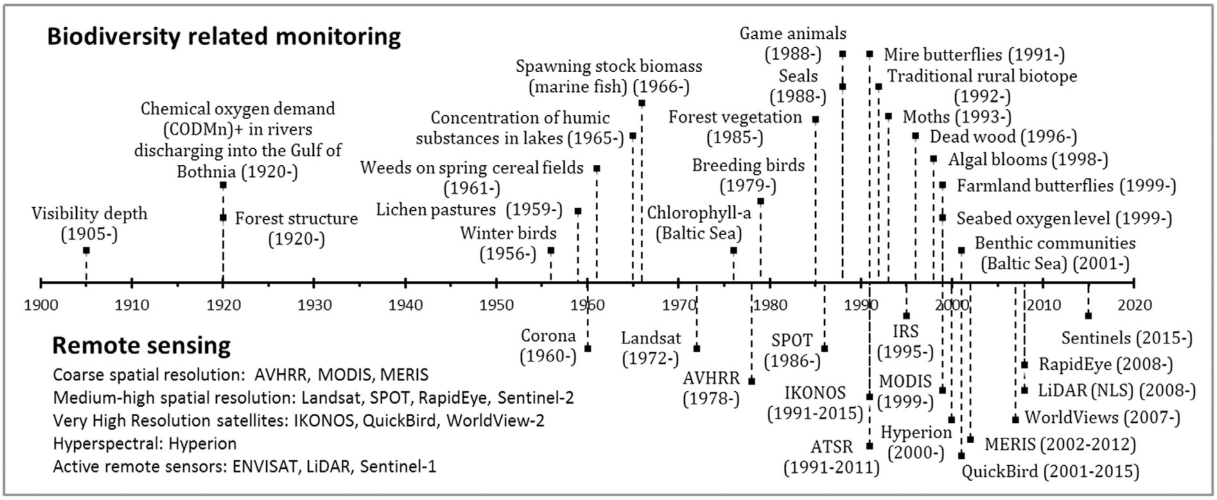

Fig. 1. The timeline of the biodiversity related monitoring in Finland (above the axis) and development of remote sensing (below).

At the Finnish national scale, operational satellite products are available that can be used for selected EBVs. The Multi-Source National Forest Inventory (MS-NFI) dataset in Finland is a combination of high resolution satellite images (Landsat and SPOT) and NFI field plot measurements that are further refined with other digital maps (Tomppo et al., 2011). Multiple measures such as biomass and volume of different tree types and tree parts, site fertility, stand age, and canopy cover are estimated and the data cover the entire Finland at a spatial resolution of 16 m. The MS-NFI data is available for the years 2006 (with less thematic detail), 2009, 2011 and 2013 (File service: http://kartta.luke.fi/index-en.html).

CORINE Land Cover (CLC) is another potential dataset for gaining an overall view of habitat structure. The Finnish High Resolution CLC (raster 20/25 m) has been produced in 2000, 2006 and 2012 based on classification of Landsat ETM and IRS/Spot images and with the aid of auxiliary digital maps at a spatial resolution of 25 m by 25 m (Törmä et al., 2004; Härmä et al., 2005). Land cover change maps are available for 2006 and 2012 with a minimum mapping unit of 1 ha (0.5 ha for urban areas) (Törmä et al., 2011). Both of these datasets are suitable for evaluating ecosystem structure EBVs.

Spatial and spectral resolutions define which RS products are useful for different EBV categories. O'Connor et al. (2015) show that at least 14 of the 22 candidate EBVs have a fully or partly remotely-sensed component. Coarse spatial resolution satellite imagery is useful for detecting general structures of ecosystems and often enables to span the perspective to history (Wulder et al., 2008). For example, Landsat images have been collected since the 1970s. However, it is important to solve how compatible the data are from different sensors within same monitoring programme (Appendix).

The spatial resolution of Very High Resolution (VHR) satellites is typically between 1 and 2 m in the panchromatic channel and 2 and 4 m in multispectral channels. Small spatial resolution data, such as provided by IKONOS, QuickBird or WorldView, can be used for detection of smaller scale elements in the environment. VHR satellite data have been used for detection of heterogeneity (Nagendra et al., 2013; Mairota et al., 2015), for example. Mairota et al. (2015) tested the usefulness of VHR in habitat analysis at different scales: landscape, patch and plot. VHR satellite imagery was found to be useful in estimating habitat quality and in predicting incidence of functional and taxonomic groups (with accuracy differences between groups).

Hyperspectral images have been found useful for differentiating plant communities and even species (e.g. Sadro et al., 2007; He et al., 2011; Somers and Asner, 2012; Aneece and Epstein, 2015) due to higher number of narrow spectral bands (Jafari and Lewis, 2012). Today their use is still expensive and limited mainly to airborne vehicles, but their availability is expected to increase in the future for example with the launch of the hyperspectral satellite Environmental Mapping and Analysis Program (EnMap) planned in 2018.

Apart from passive satellites, active sensors such as radar and laser bring new dimensions to image interpretation. SAR (Synthetic Aperture Radar) satellites are used especially for sea and ice monitoring and can detect surface deformation and help in identifying the composition of forest patches (Schlund et al., 2014). The use of SAR images is expected to increase with Sentinel-1 data becoming accessible particularly in areas such as Finland where weather conditions affect the use of optical imagery. The new instruments on board the Sentinel satellites –the MultiSpectral Instrument (MSI) on board Sentinel-2 and the Ocean and Land Colour Instrument (OLCI) on board Sentinel-3 that were launched very recently by the European Space Agency –are expected to increase the overall performance of satellite based information because of free availability of data, increased spatial resolution, increased temporal resolution due to use of two satellites at the same time and large image size, better spectral resolution in case of Sentinel-2 MSI due to red-edge and atmospheric bands and better usability because same processing algorithms can be used for images from two satellites and instruments have specific bands for atmospheric correction ((Malenovský et al., 2012), see also Box I).

Three-dimensional data can be acquired for landscape scale analyses by airborne laser scanning (ALS) which helps to detect species and species communities (e.g. Hill and Thomson, 2005). ALS data can be combined with field observation data to provide more detailed characteristics for habitat modelling (Melin et al., 2013; Vihervaara et al., 2015). The National Land Survey of Finland (NLS) provides national ALS data for public use. Laser scanning began in 2008 and currently covers over 80% of the land area of Finland. The remaining land area is planned to be scanned by 2019 (NLS Finland, 2016).

In addition to satellite based earth observation of biodiversity, the use of piloted and especially remotely piloted aerial systems (RPAS) have become increasingly popular amongst biologists for the mapping of vegetation (e.g. Husson et al., 2014) and vertebrates (Linchant et al., 2015). The optical sensors in non-satellite based earth observation devices can often produce higher resolution pixels than current civilian satellites. While, at the moment, sensor payload and flight regulations restrict RPAS use (Anderson and Gaston, 2013), it is likely that with the steady miniaturization of sensory equipment RPAS derived data will be used much more frequently alongside satellite data in future biodiversity assessments.

Based on expert judgement and a literature review, we analysed how the multitude of RS instruments and methods could be used to track biodiversity indicators and EBVs in Finland. Data sources were screened and their spatial and temporal resolution and spectral characteristics were taken into consideration (Table 2; Appendix). We also identified existing Finnish cases of environmental monitoring where RS could directly contribute to biodiversity indicators or EBVs.

4. Results

We cross-tabulated the Finnish Biodiversity state indicators with EBVs to find their linkages as well as gaps in current biodiversity monitoring schemes. The results are shown in Table 1. The EBVss along with their definitions were taken from UNEP/CBD/SBSTTA/17/INF/7 (2013). However, we made some additions. Functional diversity was added under Community composition in order to highlight one more important aspect of species communities. Decomposition, Carbon sequestration and Water filtration and retention were added under Ecosystem function. For the latter additions, we refer to a recently developed framework for a national set of ecosystem service indicators (Mononen et al., 2016, www.biodiversity.fi/ecosystemservices) and include those functions that most centrally contribute to nationally important ecosystem services (see Discussion).

We demonstrate the analysis of correspondence points of the current biodiversity indicators and EBVs with two examples: *Dead wood* and *Weeds on spring cereal fields*. *Dead wood* corresponds primarily to the EBV subclass *Habitat structure*. Secondarily, it is linked to *Taxonomic diversity* because 4000–5000 boreal species are dependent on the various successional stages of dead wood (Siitonen, 2001). *Dead wood* also influences *Ecosystem composition by functional type* because species living on dead wood form a particular functional group (decomposers). *Dead wood* can be also seen a possible proxy for *Population abundance* (of certain lichens or beetles, for example), *Physiological traits* (related to decomposition), *Functional diversity* (one pivotal functional group of the boreal ecosystem), *Decomposition*, and *Carbon sequestration* (forest litter constitutes a major carbon stock of the boreal forest; Akujärvi et al., 2016), but these relations are not straightforward to quantify.

Weeds on spring cereal fields corresponds primarily to three EBVs: *Population abundance* and *Taxonomic diversity* of weeds species themselves as well as *Species interactions*. An interaction component has been built into the indicator by assessing how many species of mainly insects and birds feed on the particular weed species in question (Hyvönen et al., 2003). The secondary EBV correspondences of *Weeds on spring cereal fields* were evaluated to be *Functional Diversity* and *Habitat structure/condition*. In terms of the former, the weed indicator relates directly at least to two basic functional groups: primary producers and herbivores; and indirectly to carnivores. In term of the latter the composition and biomass of the weed community constitutes an important habitat quality element for numerous species of agricultural habitats. The most indirect points of correspondence of *Weeds on spring cereal fields* are to EBV two subclasses: *Ecosystem extent and fragmentation* (related to the occurrence of weed communities) and Secondary productivity (see above).

Table 1 reveals quite clearly where national indicators and EBVs do and do not meet. Most of the primary correspondences fall to two EBV subclasses: *Population abundance* and *Habitat structure*. This is understandable since the crude following

Table 2
Which category of EO data can biodiversity indicators benefit from? See further details in Appendix.

Remote sensing instruments	Spatial Resolution	Biodiversity indicators
Coarse spatial resolution MODIS, AVHRR, MERIS, Sentinel-3	250 - 1200 m	Algae (marine and inland waters) (Box 1), Organic matter (Box 1), Pollen season**) (Hogda et al. 2002)
Medium to high spatial resolution Landsat, SPOT 5&6, IRS LISS, RapidEye, Sentinel-2	5-30 m	Forest fragmentation, Fragmentation of pristine mires, Lichen pastures, Tree line, Tree species composition*), High Nature Value Farmland**) (Hazeu et. al. 2014), Farmland birds**) (Prins et al.2005), Soil sealing*), Lichen pastures (Colpaert et al. 2003, Johansen & Karlsen 2005), Seals (LaRue et al. 2011), Bird and butterfly habitats**), Butterfly range shifts**), Shoreline vegetation
High temporal resolution data DMC, IRS AWIFs, MODIS, AVHRR, Sentinel-2	22-1000m	Tree species composition, Pollen season**)
Very high spatial resolution IKONOS, QuickBird GeoEye, WorldView RPAS	0.5-1 m Pancromatic 2-4 m Multispectral 2-10 cm	Dead wood**), Dead wood on wooded mires**), Forest vegetation, Shoreline vegetation (Box 2), Traditional rural biotopes**), High Nature Value Farmland, Tree species composition, Field margins and buffer strips**), ***), Urban biotopes, Bird and butterfly habitats**), ***), Butterfly range shifts**), Seals
Hyperspectral Airborne instruments like AISA, AVIRIS Hyperion	1-2 m (depending on flight height) 30 m	Field margins and buffer strips**), ***), Forest vegetation*), Shoreline vegetation, Tree species composition*), Weeds on spring cereal weeds***), Urban biotopes
Active remote sensing data SARs: ERS-1 & 2, ASAR, Radarsat 1-2; TerraSAR-X, Cosmo-Skymed, Sentinel-1, LiDAR (not in satellites atm)	1-100m	Forest age structure*), Forest birds **), Wildlife richness**), Exposed rocky and esker habitats*), **), Tree species composition (Korpela et al. 2010, Puttonen et al. 2010), Extent of palsa mires (Bartsch et al. 2007), Visibility depth, Rocky habitat and esker species*), **)

*) Existing GIS datasets that are based on satellite images can be applied (e.g. NFI, CLC)
**) Other existing GIS datasets are needed to provide better information (e.g. in-situ data, statistics)
***) Benefits significantly from the use of RPAS = Remotely piloted aerial systems

of population trends and habitat condition has been the primary goal of the indicator set. The second most common EBVs marked with primary or secondary indication are also rather clear: *Species distribution* and *Ecosystem extent and fragmentation*. Taxonomic and functional diversity are also quite often a point of secondary or potential correspondence. EBVs subclasses listed under *Species traits* and *Ecosystem function* receive less "hits" and there is almost no connection between *Genetic composition* and current biodiversity indicators.

Remote sensing was evaluated to hold potential for providing new and more comprehensive data for several indicators and EBVs (Table 2). For instance the monitoring of *Species traits*, *Community composition*, *Ecosystem structure* and *Ecosystem function* could be improved with remotely sensed data. In Finland, RS data have already been utilized for monitoring the environment and these applications could also contribute to biodiversity indicators. Two potential examples were identified: water quality monitoring where quality parameters have been identified from optical satellite images (Box I) and the mapping of coastal vegetation where high resolution satellite images have been used for identifying the change of shore vegetation with Normalized Difference Vegetation Index (Box II). Additionally, ALS is increasingly being used for species distribution modelling, falling under EBV subclass S *pecies populations* (Melin et al., 2013), and for predicting the occurrence forest bird indicator species, falling under EBV subclasses *Species populations*, *Community composition*, *Ecosystem structure* (Vihervaara et al., 2015).

5. Discussion

5.1. Missing EBVs

We approach the current list of EBVs as an inventory of potential indicators open to modifications based on experiences from real-life applications (cf. Pereira et al., 2013). From this standpoint, we suggest a few additions on the list of EBV subclasses. First, we added *Functional diversity* under *Community composition*. This refers to functional aspects of communities –separated from hierarchical levels of species and ecosystems. Functional traits of species, and their cumulative impact on functioning of communities and ecosystems are receiving more and more attention especially when focusing ecosystem services (processes) such as nutrient, carbon or water cycling as a part ecosystem assessments (Kremen, 2005).

Second, we added the word "condition" in the name of the subclass *Habitat structure* in order to refer to the quality aspects of habitats that are not necessarily conceived as structure. Examples of such quality elements include water turbidity and

Towards operative water quality monitoring by remote sensing

The main water quality parameters accessible by optical remote sensing include chlorophyll *a* (a proxy for phytoplankton biomass); water turbidity and the concentration of total suspended solids; water transparency; coloured dissolved organic matter; as well as algae blooms and their surface accumulations (e.g. Eleveld et al., 2014; Moses et al., 2012; Attila et al., 2013). The satellite based monitoring of water quality in coastal and open sea areas is already a routine practice in many countries. In Finland, operative monitoring of the Baltic Sea has been performed since early 2000's (www.syke.fi/earthobservation). In the optically more complex inland waters, the estimation of water quality from satellite data has so far been primarily a research topic (e.g. Brezonik et al., 2015; Li et al., 2015; Kallio et al., 2015), but operative services delivering this information from lakes are anticipated especially through the Copernicus programme and Sentinel satellites by the European Space Agency (Palmer et al., 2015). In the Table 3, the general applicability of MSI (Sentinel 2) and OLCI (Sentinel 3) instruments in deriving EBV related content from water areas is classified into three classes (D = *direct*, S = *Supportive/likely*, NA = *not applicable)*. The applicability is mainly based on the spectral ability of satellite instruments to detect different water quality parameters (c.f. Malenovský et al., 2012; Palmer et al., 2015).

Box I.

nutrient content (see Box I). The monitoring of ecosystem condition is an important topic for the implementation of the EU Biodiversity strategy (EEA, 2015). Monitoring quality parameters may also be the only way to monitor the state of some aquatic ecosystems using remote sensing applications.

Third, we suggested three new subclasses under *Ecosystem function*: *Decomposition*, *Carbon sequestration*, and *Water filtration and retention*. These are all significant ecosystem processes that depend on biodiversity while, at the same time, they are noted as crucial regulating ecosystem services. Including them in the list of EBVs could improve our understanding of the interactions of abiotic and biotic processes as well as such hidden functional properties of biodiversity as soil biota or meta-ecosystem effects on ecosystem functioning. The links between EBVs and ecosystem services are noted, for example, by UNEP/CBD/SBSTTA/17/INF/7 (2013). We recommend that these missing EBVs should be considered in the list of global EBV candidates by GEO BON, increasing their number from 22 to 26.

5.2. Missing national biodiversity indicators

Contrasting national biodiversity indicators with EBVs revealed some gaps in the current indicator-based monitoring and evaluation scheme. Current indicators focus primarily on the EBV subclasses *Population abundance* or *Habitat structure* (under *Species populations* and *Ecosystem structure*, respectively). There are only few indicators which primary focus is on *Community composition* –at present, *Wildlife richness*, *Forest vegetation* and *Weeds on spring cereal fields* could be considered as such. Even these deal with a rather limited variety of species (hunted mammals and birds or vascular plants, lichens and mosses). The community aspect is mostly missing from the Finnish monitoring system, and the same is also true for functional diversity.

Combining remote sensing of pre-selected areas with multi-taxa surveys could improve the scope of biodiversity assessment considerably. Examples of potential habitats for the monitoring of community composition include biodiversity hotspots such as traditional rural biotopes, old-growth forests and other woodland key habitats, as well as coastal meadows (Rassi et al., 2010; Timonen et al., 2010). Several mires types (including palsa mires) could also be monitored in this way. Having a pre-selected sample of areas to monitor would allow for the use of detailed RS products (cf. Table 2, Appendix) since the total monitoring area would remain reasonably small. This approach comes quite close to the biodiversity monitoring scheme of Switzerland (BDM Coordination Office, 2014) or the Wider Countryside Survey of Great Britain (Firbank et al., 2003).

5.3. Challenging EBVs

We felt some EBVs particularly difficult to understand and, therefore, had problems to locate them in the national monitoring scheme. The most complicated was *Ecosystem composition by functional type* which description reads: "*This is the basis of ecosystem classification. It can be informed by community composition intersected by species traits, or can be measured directly by assessing the degree of coverage by stratum for different plant life forms. The functional composition of ecosystems controls their delivery of ecosystem services, and thus their 'health' or 'degradation'*" (UNEP/CBD/SBSTTA/17/INF/7, 2013). Perhaps our addition of *Functional diversity* comes quite close to this, although it focuses on functional diversity from the point of view of *Community composition* and not of *Ecosystem structure*. Measuring compositional properties of ecosystems is nevertheless missing from Finland's current monitoring scheme.

The EBV class *Genetic composition* received only one potential hit from current biodiversity indicators (genetic differentiation of the seal population). The challenge of monitoring genetic variation has been noted from the beginning of the discussion on EBVs (cf. Geijzendorffer et al., 2015), and our Finnish exercise does not shed any new light on the issue.

Table 3
The main water quality parameters accessible with optical remote sensing in the EBV context and the general classification on the applicability (D = direct, S = Supportive/likely, NA = not applicable) of MSI (Sentinel 2) and OLCI (Sentinel 3) instruments (D = direct, S = Supportive/likely, NA = not applicable) based on the spectral properties of satellite instruments.

Parameter	Information	Habitats	Applicability of the MSI instrument (Sentinel 2)	Applicability of the OLCI instrument (Sentinel 3)	Update frequency of data	Observation scale
Chlorophyll a (a proxy for phytoplankton biomass)	Measure of eutrophication	sea and coastal areas, lakes	S	D	Daily-weekly	Global data
Water turbidity, total suspended matter	River runoff, drainage basin properties, changes in precipitation, phytoplankton biomass	sea and coastal areas, lakes	D	D	Daily-weekly	Global data
Coloured dissolved organic matter (CDOM)	River runoff, drainage basin properties, changes in precipitation	sea and coastal areas, lakes	S	D	Daily-weekly	Global data
Algae blooms, cyanobacteria biomass (through phycocyaning)	Measure of eutrophication, algae bloom characteristics and abundance	sea areas, coastal areas and lakes to some extent	D/S	D	Daily-weekly	Global data
Water transparency	Measure of eutrophication, river runoff, drainage basin properties, changes in precipitation	sea areas, coastal areas and lakes to some extent	S	D	Daily-weekly	Global data

Other EBV sub-classes that had only one or a few linkages to current indicators were *Population structure by age/size class*, *Body mass*, *Natal dispersal distance*, *Demographic traits*, and *Disturbance regime*. While the eco-evolutionary importance of the first four is evident, we thought that their monitoring on a national scale is difficult as information on these phenomena is limited to certain species and individual research projects. Their connection to remote sensing was also seen as vague. The best examples of shifts in population structure and demographic traits come, perhaps, from fish studies where human pressure in the form of over-fishing has caused the population age-structure to truncate and individuals to shrink in size and breed younger (e.g. Shelton et al., 2015; Barot et al., 2004). The EBV subclass *Disturbance regime* under *Ecosystem function* is interesting, but only of limited scope in present-day Finland since large-scale forest fires are rare today due to effective prevention, detection and extinguishing. Disturbance regimes would, nevertheless, be an interesting topic in the case of some special habitat types such as inland flooded forests and coastal habitats subjected to ice erosion.

Identifying Common reed patches from satellite images

The common reed (*Phragmites australis*) is an erect perennial grass species growing both in saline and freshwater coasts. It forms dense and somewhat monospecific patches and modifies the ground by its rhizomes. The reed patches reach their full height and density in the end of the summer in the Northern Baltic Sea when they also have the greatest impact on other wetland species in their vicinity (Güswell and Edwards, 1999). It is commonly suggested that land use changes, disturbance and eutrophication are beneficial to common reed and can affect the plant community composition (Tilman, 1982, 1987). In the Northern Baltic Sea the post-glacial land uplift creates suitable shallow areas for reed belts. In many parts of the world common reed is seen as a nuisance species, but reactions towards reed vegetation in environmental management programs have varied (Chambers et al., 1999). Reed vegetation provides habitats for many invertebrates and shelter for fish fry.

Common reed is easy to identify from the air by remote sensing methods. We used high-resolution satellite images (WorldView-2 and RapidEye) for mapping reed belts in a test area in SW Finland. Used images were taken in 2009 (RE), 2011 (RE), 2012 (WV-2) and 2013 (WV-2). The vegetation was identified by calculating Normalized Difference Vegetation Index (NDVI) by the following formula: NDVI = (infrared band –red band)/(infrared band + red band). After the calculation, the index layer was cropped by a shoreline polygon to cover only water areas and resampled to the same pixel size for easier comparison of the images. The resulting layers were assumed to show the extent of common reed as it is the dominant coastal species in SW Finland but there might be some other wetland plant species among it (Fig. 2).

Image resolution and the observation time affected the results. The resolution of the Landsat TM-7 satellite images is too coarse (30 m) but the VHR images such as RapidEye (5 m) and WorldView-2 (2 m) images gave more realistic results on the reed belt extent. We also found that the early spring and summer images do not show the maximum reed belt extent, whereas, images from July to early September are more accurate due to the short growing season in high latitudes. The images taken in September underestimate the reed extent by 10%.

Box II.

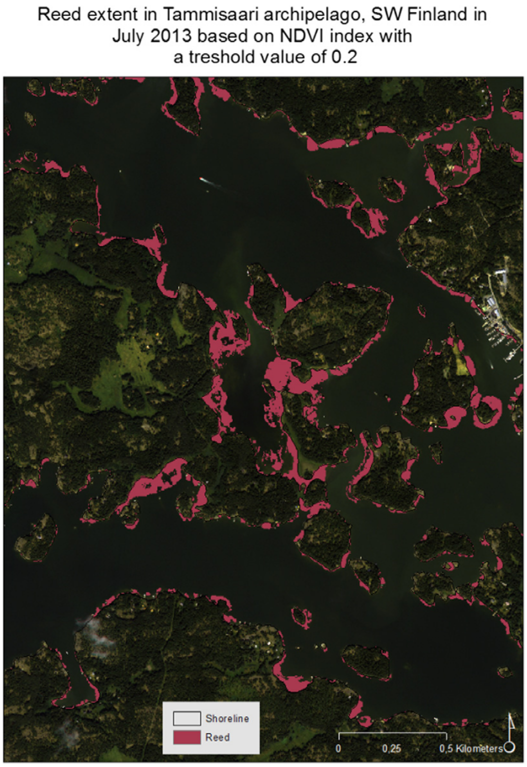

Fig. 2. Common reed extent in Tammisaari archipelago, SW Finland in July 2013 based on NDVI index with a threshold value of 0.2.

Similar to us, Australian experts, in their respective study related to the biodiversity of New South Wales, to did not agree upon the usefulness of EBVs *Ecosystem composition by functional type, Disturbance regime* or *Body mass* (Turak et al., in press). Some of the difficulties in applying EBVs to specific circumstances may due to the varying ecological conditions yet some may also be due to inherent challenges in the suggested EBVs themselves. Therefore we find it important to test the EBV framework in several specific contexts in order to find out which EBVs can realistically advance biodiversity monitoring.

5.4. Remote sensing opportunities on different ecosystems

Our analysis of current national biodiversity indicators and their relation to EBV classes revealed some opportunities where remote sensing applications could significantly improve data production for existing indicators or result in totally new biodiversity parameter to be monitored in the future (Table 2). In particular, many structural and several functional EBVs could be studied by using remote sensing (cf. Skidmore et al., 2015; Pettorelli et al., 2016; O'Connor et al., 2015). Vegetation phenology observations at high spatial and temporal resolution with the Sentinel-2 could also help the mapping of forests, mires and especially farmlands. Most Finland's current biodiversity indicators are based on what Proença et al. (in press) call extensive schemes –for example, butterfly and bird monitoring programmes. With the help of RS results from intensive schemes such as those included in the Finnish LTSER network (http://www.syke.fi/projects/lter) could better be generalized to apply to larger areas and thus to serve biodiversity monitoring on national level.

Forests — Tree species can be related to EBVs such as *Physiological traits* and *Functional diversity* and could be tracked e.g. by hyperspectral satellite data (Jetz et al., 2016). Several remote sensing applications including ALS, aerial images and satellite data, can be used to track *Ecosystem structure*. When analysing forest species indicators, such as forest birds, wildlife richness and forest vegetation, remote sensing data could be used either as a proxy or, preferably, it could be combined with *in situ* observation data and modelled to produce habitat suitability and distribution maps (Goetz et al., 2010; Vihervaara et al., 2015). Opportunities of radar and hyperspectral data should also be tested to detect functional properties of forest vegetation and habitat structure and conditions the particular vegetation types need. An indicator for forest fragmentation has been under development for years. Remote sensing holds key to finalizing the indicator.

Mires — Because of the patch-like distribution of suitable habitat for mire species the fragmentation of pristine mires is a crucial indicator of the state of Finnish mires. The current fragmentation indicator needs revising and would benefit greatly from remote sensing especially use of VHR imagery in order to detect the spatial variability of mire surface materials and microwave SAR to estimate surface moisture. Functional aspects of mires are currently covered neither by national biodiversity indicators nor by EBVs. Their role in landscape scale ecosystem processes is, however, very important in a boreal landscape.

Baltic Sea and inland waters — The structure, or merely condition, of aquatic habitats could be monitored by satellite products for vast areas (see Boxes I and II). Chlorophyll α and algal blooms can be used also as measures of primary production and to indicate, possibly, population abundance of the algal species. Habitat structure and abundance of macroalgae –the extent of bladder wrack (*Fucus vesiculosus*) and eelgrass (*Zostera marina*) habitats, for instance –and vascular plants can be detected from aerial images or VHR satellites, and in some cases from RPASs. Also, LIDAR is being tested for identifying underwater structures, including algal stands. The use of thermal sensors (TIR) is a particularly important source of water temperature data which is a physical proxy for biodiversity distribution, for example. Functional trait hot spots of fish and other aquatic biota are poorly known, but perhaps a very important section of biodiversity to be monitored in the future (Stuart-Smith et al., 2013). However, these are the data which probably do not benefit from remote sensing data so far.

Farmlands — There is relatively good GIS data and statistics available due to the socio-economic importance of agriculture. However, we think that there are important aspects of farmland biodiversity that should be monitored more closely and which scope and accuracy could be improved by remotely sensed data. For instance, the location and extent of traditional rural biotopes is already reasonably well known and stored in GIS, but data are missing on the development of their condition. The over-growing and canopy-closure of these habitats could be tracked based on satellite data and aerial images, or even more accurately by ALS. The use of drones is marginal, because the analysis and data gathering needs quite a lot of resources. However, the quantification of changes in ecosystem condition might become more accurate than by mere eyesight. The mapping of field margins and buffer strips could possibly be done based on remote sensing, and to get these narrow habitats under monitoring might provide link to catchment ecosystem processes, such as nutrient cycling and hydrology. For farmland birds and butterflies, a similar approach as in forest species can be used, whereas habitat preferences of insects are dependent more on small-scale characteristics and the evident metapopulation behaviour.

Alpine habitats — There are currently only few state indicators of which lichen pastures and extent of palsa mires could be obviously monitored by various remote sensing techniques. Alpine areas are distant and their field monitoring expensive and time-consuming, which makes the development of remotely sensed monitoring an especially attractive option. Monitoring of alpine biodiversity is directly linked with the impacts of climate change (see below). Many species are directly dependent on snow cover and remotely sensed products on snow and change of snow from Sentinel-2 may be beneficial for their monitoring.

Urban habitats — High resolution data from VHR satellites, ALS and aerial images have been used, but monitoring of this ecosystem type is difficult to tailor, because it is totally dependent on human influence and management. One example of the use of remote sensing in the monitoring of urban habitats is the soil sealing layer developed for Europe (EEA, 2011). However, the layer is not very accurate for Finland and would need fine tuning-based higher resolution images and national data bases. Taxonomic diversity in urban habitats can be very high at landscape level due to small gardening, parks and green areas, and small-scale conservation areas.

Shores, rocky habitats and eskers — Some micro habitats under these categories can be very dynamic and temporary because they are dependent on extreme weather events; for instance, storms can build shoreline walls from dead organic material in the shallow coastlines of the Baltic sea which have high associated biodiversity while esker habitats are naturally characterized by forest fires that create openings inside the habitat. To monitor such characteristics automated and frequent scanning of VHR satellite data could be used. Shoreline vegetation (e.g. reedbeds of *Phragmatis australis*; see Box II) has a significant influence on species diversity, but it may also have important functional properties.

Climate change — Several climate change indicators, such as those based on vegetation phenology, are directly observed from coarse resolution satellite imagery, such as MODIS, in Finland (Karlsen et al., 2006; Böttcher et al., 2014). Moth phenology is currently studied in Finland by using long-term monitoring datasets of Finnish moths (Leinonen et al., 2016) together with remote sensing variables such as snow melt and the start, maximum and end of the growing season. The recent launch of Sentinel-2A/B opens a new opportunity for monitoring phenology (and plant productivity) at much higher spatial resolution (up to 10 m) in the future. Shifts in tree line in the alpine zone is a slower process, but can be monitored quite well by using satellite data (e.g. Zhang et al., 2009). Radar has shown potential to detect mass migration of insects such as aphids, butterflies, and pollinators which have crucial role in ecosystem functioning and also contribute to many ecosystem services. These kinds of new indicators benefiting from modern remote sensing data illustrate the potential to update biodiversity monitoring schemes on a national scale. Climate change indicators in Finland are still under construction and functional dynamics seems to have a special importance in their building where remote sensing can help a lot.

Ecosystem functions — In addition to the EBVs about traits and functional diversity, the potential and interesting classes based on our analysis, and where also remote sensing could play a role in monitoring, were the ecosystem function sub-classes. The use of hyperspectral satellite data to trace functional traits were recently illustrated by Jetz et al. (2016), but in our case the challenge is how well this might work at high resolution scale. Kalacska et al. (2015) showed that chemical compounds of mire vegetation can be mapped by such techniques. Even though such variables could be monitored using remote sensing it needs to be tested how it might work at larger geographical scales. A general question rising from our analysis is also how *in situ* species information and remote sensing data could be used together via modelling and building up for instance indices to be included in national biodiversity monitoring schemes (see also Vihervaara et al., 2015; GEO BON, 2015a,b)? Use of indices in biodiversity monitoring of inland waters was also recently reviewed by Heino (2015). In general, different indices developed in inland waters tell us different things about biodiversity, ecosystem state and ecosystem services, suggesting that various indices should be used for biodiversity monitoring.

5.5. Applicability, feasibility, scalability and continuity

We think that the observations described in this paper fit with the rationale of robust biodiversity monitoring on a national scale and provide several pathways for improving the current monitoring scheme. However, it is important to remind that while the new remote sensing datasets and adjusted EBV classes can track local (and national) scale biodiversity change more precisely, the data they provide has to be comparable to other countries' assessments to build the big picture of the state of biodiversity on regional and global scales. This kind of data scalability has been one of the starting points of EBV definition (Pereira et al., 2013). The operationalization of RS data in biodiversity monitoring depends also on the costs of acquisition and interpretation of data, which might need a hierarchical approach so that rough parametrization of nationally relevant key EBVs are based on wall-to-wall HR imagery (free Landsat & Sentinel-2), and detailed analysis of hot spots on VHR, airborne hyperspectral and laser scanning.

It is also crucial to develop the monitoring in a synergetic collaboration with science-policy platforms: research and new monitoring is dependent on resources invested in testing and building up these systems. National focal points and decision makers have to be aware of the new possibilities of applying remote sensing in biodiversity monitoring. Highlighting the relationship of biodiversity and ecosystem services is also needed to receive the support of the wider society for biodiversity monitoring and to show the potential risks related to missing knowledge of ecosystem functioning, for instance, under climate change. This makes it important to include EBVs in the ecosystem assessments prepared under IPBES and MAES, as well as to link the biodiversity and ecosystem service monitoring demands to the Copernicus programme and planning of post 2020 biodiversity strategies.

6. Conclusions

We have described how the current state of biodiversity indicators of Finland could be improved by applying the concept of Essential Biodiversity Variables and using remote sensing. Our findings suggest that monitoring EBVs such as *Ecosystem function*, *Ecosystem structure*, *Community composition* and *Species traits* could benefit substantially from the use of remotely sensed data on national scale. While remote sensing data could bring many enhancements to the current situation, such as increased geographical coverage and repeated measures over time, we want to emphasize the importance of long-term surveys and the crucial role of field verification at the same time. Together these two could improve for example model-based evaluations of biodiversity change under various pressures.

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Appendix

See Table A.1.

Table A.1
Steps in remote sensing development. Note: This table represents a sample of important steps of remote sensing development and potential RS products that are considered useful for environmental monitoring.

AVHRR = Advanced Very High Resolution Radiometer; **ATSR** = Along Track Scanning Radiometer; **CAVIS =** Cloud, Aerosol, Vapor, Ice, Snow; **HRC** = High Resolution Camera; MS = Multi-spectral (Red, Green, Blue, Near-Infrared); **NIR** = Near infra red; **OLCI** = Ocean and Land Colour Instrument; **Pan** = Panchromatic (Black & White); **SLSTR =** Sea and Land Surface Temperature Radiometer; **SWIR** = Short-wave infrared; **PS =** Pan sharpened; **VIS**= Visual

	1960-1972	**1972-**				**1978-**			**1986-**				**1995-**	
Programme	Corona (Surveillance satellite)	Landsat programme (NASA)				NOAA Polar orbiting weather satellites AVHRR			SPOT (commercial)				IRS (Indian remote sensing satellites)	
Satellites		Landsat 1: 1972-1978 Landsat 2: 1975-1982 Landsat 3: 1978-1983 Landsat 4: 1982-1993 Landsat 5: 1984-2013 Landsat 7: 1999- Landsat 8: 2013-				TIROS-N: 1978-1980 NOAA-6: 1979-1986 NOAA-7: 1981-1986 NOAA-8: 1983-1985 NOAA-9: 1985- NOAA-10: 1986- NOAA-11: 1988-1994 NOAA-12: 1991- NOAA-14: 1994- NOOA-15: 1998-			SPOT 1: 1986-1990 SPOT 2:1990-2009 SPOT 3: 1993-1997 SPOT 4:1998-2013 SPOT 5:2002-2015 SPOT 6:2012- SPOT 7: 2014-				IRS-1A: 1988-1992 IRS-1B: 1991- IRS-P2: 1994- IRS-1C/1D: 1995-2010 IRS-P3: 1996-2004 IRS-P4: 1999-2010 IRS-P6: 2003- IRS-P5: 2005- Cartosat-2A: 2008- IMS 1: 2008- Oceansat-2: 2009- Cartosat-2B: 2010- Resourcessat-2: 2011- SARAL: 2013- ...	
		L1-3	L4-5 TM	L7 ETM+	L8 OLI/TIRS	TIROS-N AVHRR	NOAA-6-14 AVHRR	NOAA-15 AVHRR	SPOT 1-3	SPOT 4	SPOT 5	SPOT 6 & 7	IRS-1C/1D	IRS-1P6 LISS, AWiFS
Spatial resolution	Initially 8 m, later 2 m	Resampled to 60 m	30 m (VIS, NIR,	15 m Pan; 30 m	30m (VIS, NIR,	1100 m	1100 m	1100 m	10 m Pan; 20 m G,	10 m Pan; 20 m G,	2.5-5 m Pan; 10 m	1.5 m - 2.2 Pan;	5,8 m Pan; LISS-III:	5.8m Pan; LISS-IV: 5.8 m G,
		(VIS-NIR)	SWIR); 120 m thermal IR	(VIS, NIR, SWIR); 60m thermal	SWIR); 15m Pan.; thermal 100 m				R, NIR	R, NIR, SWIR	(MS) 20m (SWIR)	8.8 m (MS)	23m G,R,NIR; 70m SWIR; 188m WIFS R, NIR	R, NIR; LISS-III: 23 m G, R, NIR, SWIR; AWIFS: 60 m G,R, NIR,SWIR
Bands		4	7	8	11	4	5	7	4	5	6	5	4	4
Temporal resolution		18 days	16 days	16 days	16 days	0.5 days	0.5 days	0.5 days	1-3 days	2-3 days	2-3 days	1-5 days	24 days	5 days
Design age		1 year-	3 years-	5 years-	5 years-				3 years	5 years	5-7 years	10 years	3 years	5 years

(*continued on next page*)

Table A.1 (*continued*)

	1991–2011		1999–2015	2000-	2001	2002–2012		1999-	2001-2014
Programme	ERS (ESA)		IKONOS (commercial)	EO-1 (NASA)	PROBA (ESA)	ENVISAT (ESA)		MODIS (NASA)	QuickBird (commercial)
Satellites	ERS-1: 1991-2000 ERS-2: 1995-2011		Ikonos-2: 1999-2015	EO-1: 2000-	PROBA1: 2001 PROBA-2: 2009- PROBA-V: 2013-	ASAR: 2002-2012, MERIS, AATSR, SCIAMACHY, MIPAS, GOMOS, DORIS, RA-2, MWR, LRR		TERRA (EOS AM-1): 1999- Aqua (EOS PM-1): 2000-	QuickBird II: 2001-2014
	ERS-1 ATSR-1 sensor	ERS-2 ATSR-2	Ikonos-2	Hyperion (sensor) (EO-1)	PROBA-V (PROBA)	ASAR	MERIS	MODIS	QuickBird II
Spatial resolution	1000 m	1000 m	1 m Pan; 4 m MS; 1 m PS	30 m	100 m , 300, 1000 m (B, R, NIR, SWIR)	30 m	Ocean: 1040 m x 1200 m (at nadir); Land: 260 x 300 m (at nadir)	250-1000 m	0.61 cm Pan; 2.4 m MS
Bands	4	7	6	220 spectral bands	4	C-Band (5 polarization modes	15 spectral bands	36	5
Temporal resolution	3 days	3 days, 35 days	14 days		2 days		7 days	1-2 days	1-4 days
Design age	2 years	3 years	7 years	1.5 years	2.5 years	2.5-5 years	5 years	6 years	7 years

	2007-			2008-	2008-	2014-		
Programme	Worldview (commercial)			RapidEye (commercial)	GeoEye (commercial)	Copernicus programme (ESA)		
Satellites	WorldView-1: 2007- WorldView-2: 2009- WorldView-3: 2014-			RapidEye 1-5	GeoEye-1: 2008- GeoEye-2: 2013-	Sentinel-1A: 2014- Sentinel 1B: 2016- Sentinel-2A: 2015- Sentinel-2B: 2017- Sentinel-3: 2016- Sentinels 4-6:		
	WV-1	WV-2	WV-3		GeoEye-1	Sentinel 1A & 1B	Sentinel 2A & 2B	Sentinel-3 OLCI, SLSTR
Spatial resolution	0,5 m	0,46 m	0,31 m Pan; 1,24 m MS; 3,7 SWIS, 30m CAVIS	6,5 m resampled to 5 m pixels (RGB, NIR, Red edge)	0,41 m Pan; 1,65m MS	5-40 m	10 VIS; 20, 60m	OCLO: 300 m SLSTR: 500-1000 m
Bands	1	9	29	5	5	C-band SAR	13 VNIR, SWIR	21 (OLCI) 9 (SLSTR)
Temporal resolution	1-6 days	1-4 days	< 1 day	1-5 days	1-3 days	6-12 days	5-10 days	(OLCI) 1-2 days (SLSTR)
Design age	7.25 years	7.25 years	7.25 years	7 years	7 years	7 years	7.25 years	7.5 years

Additional sources:
Earth Observation Portal: https://directory.eoportal.org/.
European Space Agency: http://www.esa.int/ESA.
Landsat: http://pubs.usgs.gov/fs/2015/3081/fs20153081.pdf.
Envisat: https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat.
AVHRR: http://edc2.usgs.gov/1KM/avhrr_sensor.php.
IRS: https://directory.eoportal.org/web/eoportal/satellite-missions/i/irs.
GeoEye: https://www.orbitalatk.com/space-systems/commercial-satellites/imaging-satellites/docs/FS017_10_OA_3695%20GeoEye-1.pdf.
MODIS: http://modis.gsfc.nasa.gov/.

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