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Assessing progress towards Aichi Biodiversity Targets: Contributions and limitations of Essential Biodiversity Variables

GEO 511 Master's Thesis

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Summary

The Strategic Plan for Biodiversity 2011-2020 of the Convention on Biological Diversity, aiming at conserving biological diversity by effective implementation of the 20 Aichi Biodiversity Targets, has reached its temporal mid-point. As a harmonized measurement basis for assessing biodiversity change, Essential Biodiversity Variables are currently identified. Essential Biodiversity Variables (EBVs) are seen as useful link between primary observations of change in the state of biodiversity and high-level indicators of biodiversity and ecosystem services. A subset of EBVs, measurable from space (RS-EBVs), have been proposed in a recent study.

This thesis aimed at developing a validation method for three Aichi Biodiversity Targets (5, 14 and 15) and linking these abstract targets to the proposed RS-EBVs. For a heterogeneous study area around Zurich, Switzerland, priority aspects of the three Aichi Biodiversity Targets were assessed. Candidate RS-EBVs relevant for monitoring those aspects were computed using a simulated Sentinel-2 image of 26 June 2011.

For Aichi Biodiversity Target 5, natural habitat was investigated regarding extent, quality characteristics and fragmentation. For Target 14, conservation status of forest, the lake and urban vegetation was reviewed. Additionally, for each priority ecosystem, one important ecosystem service was approximated by combining RS-EBVs and GIS data. For Target 15, conservation status of forest and raised bogs was reviewed. To relate the conservation status of forest to its resilience and contributions of biodiversity to carbon stocks, spatial heterogeneity of plant traits was measured for total forest area and for the forest protection zone.

Natural habitat in the study area consists mainly of forest and to a small extent of rare habitats like mires, dry grassland, alluvial zones. Most important pressure on natural habitats is high nitrogen dioxide immission from the neighboring settlement areas and agricultural areas. RS-EBVs *primary productivity, leaf area index, plant traits* and *heterogeneity* were successfully computed and show high spatial variability throughout the study area's forests. Fragmentation of natural habitat into separate patches, as well as fragmentation through traffic barriers is very high. Conservation efforts of forests, the lake and urban vegetation happen on multiple levels of different binding character, and are thus hard to quantify. Conservation status of ecosystems in the study area do not necessarily relate to protection and restoration efforts. RS-EBVs were found useful for providing input in assessment of ecosystem services (particularly the leaf area index). Quality estimators for aquatic ecosystems, despite not listed as candidate EBVs, were successfully computed. Regarding Target 15, RS-EBV *heterogeneity* of $CI_{red\text{-}edge}$ and LAI was found lower in protected forest than in unprotected forest.

While RS-EBVs show great potential for monitoring important ecosystem properties, GIS-based data showed more useful in terms of characterizing ecosystem fragmentation. RS-EBVs are also considered pivotal in comparing ecosystems of different conservation status. Summarized, RS-EBVs prove to be a promising input for certain biodiversity indicators needed for assessing progress towards ABTs 5, 14 and 15.

Zusammenfassung

Der Strategische Plan für Biodiversität 2011-2020 der Konvention über die biologische Vielfalt, welcher darauf abzielt, die Biodiversität durch die erfolgreiche Realisierung der 20 Aichi Biodiversitätsziele zu erhalten, ist zur Hälfte vorbei. Es zeigte sich, dass die verwendeten Indikatoren zu weich definiert waren. Als eine harmonisierte Messbasis zur Einschätzung von Veränderung in der Biodiversität werden deshalb im Moment *Essential Biodiversity Variables* festgelegt. *Essential Biodiversity Variables* (EBVs) sind ein hilfreiches Bindeglied zwischen primären Beobachtungsgrössen von Biodiversität und weiter entwickelten Biodiversitätsindikatoren. Eine ausgewählte Teilmenge an EBVs, welche mithilfe von Satellitentechnologie messbar sind (RS-EBVs), wurde kürzlich vorgeschlagen.

Ziel dieser Masterarbeit war die Entwicklung einer Überprüfungsmethode für die drei Aichi Biodiversitätsziele 5, 14 und 15 für ein heterogenes Untersuchungsgebiet in Zürich in der Schweiz mithilfe von RS-EBVs.

Dabei wurden von den vorgeschlagenen RS-EBVs die relevantesten ausgewählt und mithilfe eines simulierten Sentinel-2 Bildes vom 26. Juni 2011 berechnet. Für Ziel 5 wurden natürliche Habitate auf Grösse, Degradation und Fragmentierung untersucht. Für Ziel 14 wurde der Schutzstatus von Wald, dem Zürichsee und Stadtvegetation analysiert. Zusätzlich wurde für jedes dieser Ökosysteme je ein wichtiger *service* mithilfe von RS-EBVs und GIS Daten abgeschätzt. Für Ziel 15 wurde einerseits der Schutzstatus von Wald und Hochmooren überprüft, andererseits wurde der Schutzstatus von Wald mit dessen Anpassungsfähigkeit (*resilience*) und Produktivität in Verbindung gesetzt. Dazu wurde die räumliche Heterogenität von Pflanzenmerkmalen in ungeschütztem und geschütztem Wald gemessen und verglichen.

Natürliche Habitate im Untersuchungsgebiet bestehen hauptsächlich aus Wald und zu einem kleinen Teil aus seltenen Habitaten wie Mooren, Wiesen, Weiden und Auen. Die grösste Belastung erleiden diese Habitate durch erhöhten Nährstoffeintrag aus den umliegenden Siedlungsgebieten und Landwirtschaftsflächen. Die RS-EBVs *primary productivity, leaf area index, plant traits* und *heterogeneity* wurden erfolgreich für die Waldfläche berechnet und weisen eine hohe räumliche Variabilität auf. Fragmentierung der natürlichen Habitate in separate ‘Flecken’, sowie die weitere Fragmentierung dieser durch Verkehrsinfrastruktur ist hoch. Schutzstatus von Wald, dem Zürichsee und urbaner Vegetation sind auf verschiedenen politischen Ebenen festgesetzt und sind nicht unbedingt an die tatsächlichen Restaurierungsmassnahmen gekoppelt. RS-EBVs (vor allem der *Leaf area index*) waren in diesem Zusammenhang vor allem in der Annäherung der *ecosystem services* nützlich. Zusätzlich konnten erfolgreich Wasserqualitätsindikatoren berechnet werden. Im Zusammenhang mit Ziel 15 wurde die Heterogenität der Chlorophyll-Konzentration und des *Leaf area index* gemessen: beide Merkmale sind in geschütztem Wald homogener als in ungeschütztem Wald.

RS-EBVs sind praktisch, um Ökosysteme mit verschiedenem Schutzstatus miteinander zu vergleichen. Während sie ausserdem ein grosses Potential zur Überwachung gewisser Eigenschaften eines Ökosystems zeigen, zeigt sich allerdings, dass zur validen Charakterisierung von Fragmentierung zusätzliche GIS-Daten nötig sind. Zusammengefasst sind die in dieser Arbeit ausgewählten RS-EBVs sehr erfolgsversprechend, um die wichtigsten Biodiversitätsindikatoren für die Aichi Ziele 5, 14 und 15 zu quantifizieren.

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LIST OF ABBREVIATIONS

ABT	Aichi Biodiversity Target
Anth	Anthocyanin
APAR	Absorbed photosynthetically active radiation
APEX	Airborne Prism Experiment
BDM	Biodiversity Monitoring Switzerland
BIP	Biodiversity Indicator Partnership
Car	Carotenoid
CBD	Convention on Biological Diversity
Chl-*a*	Phytoplankton chlorophyll-*a*
COP	Conference of the Parties
EBV	Essential Biodiversity Variable
ECV	Essential Climate Variable
EO	Earth observation
ES	Ecosystem service
ESA	European Space Agency
FOEN	Federal Office for the Environment
fPAR	Fractional absorbed photosynthetically active radiation
GBIF	Global Biodiversity Information Facility
GBO	Global Biodiversity Outlook
GCOS	Global Climate Observing System
GEO BON	Group on Earth Observations Biodiversity Observation Network
GEOSS	Global Earth Observation System of Systems
GIS	Geographic Information System
GPP	Gross primary productivity
IUCN	International Union for the Conservation of Nature
LAI	Leaf area index
LSU	Linear Spectral Unmixing
LUE	Light use efficiency
MEA	Millennium Ecosystem Assessment
MESH	Effective mesh size
MLC	Maximum Likelihood Classification
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multispectral Instrument
NDVI	Normalized Difference Vegetation Index
NP	Number of patches
NPP	Net primary productivity
OSM	Open Street Map
PAR	Photosynthetically active radiation
PD	Patch density

PM10	Particulate matter with an aerodynamic diameter of less than 10 µm
RS	Remote Sensing
RS-EBV	Remote Sensing Essential Biodiversity Variable
SAM	Spectral Angle Mapper
SBS	Swiss Biodiversity Strategy
SHDI	Shannon's diversity index
SHEI	Shannon's evenness index
SIDI	Simpson's diversity index
SIEI	Simpson's evenness index
SIB	Swiss Information-system Biodiversity
SPOT	Satellite Pour l'Observation de la Terre
S-2	Sentinel-2
SVP	Saturated vapor pressure
TSS	Total suspended solids
URPP	University Research Priority Programme
VPD	Vapor pressure density
WCMC	World Conservation Monitoring Center
WSL	Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft
WWEA	Office of Waster, Water, Energy and Air

1 Introduction

This thesis aims at developing a method for monitoring the progress towards a selection of Aichi Biodiversity Targets in an area of 312 km^2 around Zurich, Switzerland, using Essential Biodiversity Variables. Assessment of progress towards the Aichi Targets to be achieved by 2020 is usually conducted on a global or national level. However, regional scale studies may offer a more detailed assessment of ecosystem and biodiversity changes, and hence be helpful for systematic development and implementation of conservation policies. Local, regional or national stakeholders profit more from monitoring and identifying ecosystem change in their spatial proximity, simplifying decision-making processes or reasoning for policy changes related to biodiversity and important habitats. Additionally, this thesis aims at evaluating the potential contribution of the Sentinel-2 satellite mission to monitoring related aspects of biodiversity and progress towards the Aichi Targets.

1.1 Biodiversity change and loss

Biodiversity has been an important and widely discussed issue for many years. As the human influence on the planet increases, biodiversity loss and alteration at all levels, from genes through species, populations, habitats and ecosystems, have become a priority issue for scientists, politicians and stakeholders worldwide (Janetos et al. 2004). Current ecosystem and biodiversity changes are primarily a result of human activities (MEA 2005a). Biodiversity impacts humanity by directly and indirectly affecting a variety of provisioning, regulating and cultural ecosystem services (Cardinale et al. 2012). Ecosystem services are the benefits people obtain from ecosystems (MEA 2005a). And yet, despite biodiversity being fundamental to ecosystem functioning and human wellbeing (e.g. MEA 2005a; Bennett et al. 2015; Jax & Heink 2015), global biodiversity loss is intensifying. Major pressures on global biodiversity are habitat change, pollution, climate change or overexploitation (Pereira et al. 2012). Loss of habitat is the most important cause of species declines, primarily caused by anthropogenic land use change and fragmentation (MEA 2005a). Consequently, biodiversity loss can influence ecosystem functioning negatively by leaving ecological niches underused or even vacant (Hector 2011). Biodiversity change and alterations can be manifested in different ways, e.g. loss of genetic diversity, extinctions, changes in abundance and community structure or range shifts (Pereira et al 2012). The frequently used term biodiversity can hardly be defined in one sentence, as it includes not only the diversity of species (commonly used by the broad public), but also functional types of organisms, genetic variability, habitat and ecosystem diversity. The complexity and heterogeneity of the term make it difficult to grasp and lead to a general uncertainty on how to deal with biodiversity, its assessment and conservation (Jax & Heink 2015; Jürgens 2007). The Convention on Biological Diversity (CBD) defines biological diversity as "*the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems"* (CBD, Art. 2). Dirzo & Raven also group organisms according to their species and define biodiversity as *"the sum total of all of the plants, animals, fungi, and microorganisms on Earth; their genetic and phenotypic variation; and the communities and ecosystems of which they are a part (…)"* (2003:138). Classification of species may be based on morphology, genetics or their functional properties. The traditional approach of using species diversity may underestimate other aspects of ecological functioning and biological diversity (Cornelissen 2003, Li et al. 2015). When talking about functional diversity, Tilman (2001) refers to the components of biodiversity, or the value and range of species traits, that influence one or more aspects of the functioning of an ecosystem, e.g. ecosystem dynamics, productivity, nutrient balance. Each species has different biochemical, structural, phenological, physiological, morphological and behavioral traits or characteristics that influence ecosystems and their functioning differently (Díaz et al. 2013). Those traits are used to generate a classification of organisms into functional groups (Tilman 2001), depending on how they respond to or effect on environmental factors and ecosystem properties (response or effect traits) (Suding & Goldstein 2008). There is growing evidence that functional diversity is directly linked with a number of ecosystem processes (Li et al. 2015; Flynn et al. 2009).

1.2 Strategic Plan for Biodiversity 2011-2020

Upon the growing awareness and desire of the world community to conserve the planet's natural habitats and biological diversity, world leaders agreed on a set of commitments to follow a strategy of sustainable development in order to ensure future generations a healthy planet and biological resources: The Convention on Biological Diversity (CBD). It was opened for signature at the United Nations Conference on Environment and Development (the "Earth Summit") in Rio de Janeiro on 5 June 1992 and entered into force on 29 December 1993 (CBD 2015a). The CBD is one of the three Rio Conventions, alongside with the Convention to Combat Desertification and the Convention on Climate Change. It's three main goals are a) *the conservation of biological diversity,* b) *the sustainable use of the components of biological diversity,* and c) *the fair and equitable sharing of the benefits arising out of the utilization of genetic resources* (CBD 2015b). After a failed first attempt on significantly reducing the *"rate of biodiversity loss at the global, regional and national levels as a contribution to poverty alleviation and to the benefit of all life on earth"* by 2010 (CBD 2002, COP 6, Decision VI/26: 305), a new attempt was made: The new 'Strategic Plan for Biodiversity 2011-2020' is a result of the tenth meeting of the Conference of the Parties (COP) of the CBD, held in October 2010 in Nagoya, Aichi Prefecture, Japan (CBD 2010, COP 10, Decision X/2). Main purpose of this plan is the effective implementation of a set of 20 targets, known as the Aichi Biodiversity Targets (henceforth ABTs). The set serves as basis for mainstreaming communication about biodiversity information, therefore helping to achieve the targets on a global level, but also provides a flexible framework for establishing regional and national targets (ibid.). The plan calls for "*effective and urgent action to halt the loss of biodiversity in order to ensure that by 2020 ecosystems are resilient and continue to provide essential services, thereby securing the planet's variety of life, and contributing to human well-being, and poverty eradication*" (CBD 2010, COP 10, Decision X/2: 8). To achieve the ABTs, various measures, demanding great commitment have to be implemented by all attending parties. The ABTs are organized under 5 goals, addressing "*causes of*", "*pressures on*", the "*status of*", "*benefits from*", and "*responses to*" biodiversity and habitat loss (CBD 2010, COP 10, Decision X/2: 8f.). As monitoring biodiversity proves to be a complex and laborious task, the CBD parties developed an indicator framework for assessing progress in implementation of the Strategic Plan and the ABTs (CBD 2012a, COP 11, Decision XI/3: 97). For each ABT, headline indicators and relevant operational indicators have been formulated; some of them have been used in the Global Biodiversity Outlook 4 (GBO-4) Technical Report, a detailed assessment of target by target status, trends and projections (Leadley et al. 2014). Many of the indicators used in the GBO-4 however are problematic due to low spatial resolution, lack of long-time series of measurements and lack of data standardization (O'Connor et al. 2015). In addition, as the ABTs are seen as flexible framework, specified national targets and indicators have been developed. Different measurement and monitoring approaches are being used by a variety of actors, e.g. national governments, non-governmental organizations, research communities etc. (Scholes et al. 2012; Skidmore et al. 2015).

1.3 Assessing biodiversity (change)

As biodiversity is an enormously complex concept, so is its measurement (MEA 2005c); just as it is impossible to describe as a whole, its assessment has to be adapted to a specific context. Various studies have been working on quantifying the state, trends and conditions of biodiversity in specific habitats (e.g. Magurran 2004; Butchart et al. 2010; Barnosky et al. 2011). One way to assess aspects of biodiversity and related processes is the use of indicators: indicators may be qualitative or quantitative, direct or indirect, measurable on different scales from genetic to ecosystem diversity (FOEN 2012). Biodiversity indicators are defined as statistical measures that help managers, politicians and scientists understand the condition of biodiversity and the factors that affect it (International Union for the Conservation of Nature 2016). Unfortunately, the huge amount of biodiversity-related data that has been collected over time is uncoordinated, unconnected and differs in observation approaches and taxonomy (MEA 2005c; Pereira 2012; Geijzendorffer et al. 2015; Wetzel et al. 2015). Important gaps in knowledge, understanding and data have to be filled to improve indicators and the overall quality of datasets. In an attempt to do so, many international organizations established a variety of regularly updated electronic databases, e.g. the 'Global Biodiversity Information Facility' (GBIF), the Red List of Threatened Species by the International Union for the Conservation of Nature (IUCN), maps of protected areas maintained by UNEP's World Conservation Monitoring Centre (WCMC)) (ibid.), and create indicators according to their respective focus. In addition to these large-scale projects, there are numerous biodiversity monitoring programmes that are run on national level and adapted to the specific situation of the country or region. Switzerland for example has adopted the Swiss Biodiversity Strategy (SBS) in 2012, including ten strategic goals. The Swiss Information-system Biodiversity (SIB) provides an overview on the national implementation of the CBD. Additional to the national targets, the Federal Office for the Environment (FOEN) has launched the program Biodiversity Monitoring Switzerland (BDM) and has developed a set of 34 indicators. The lack of consistent monitoring approaches, little or no sharing of biodiversity information, measurement gaps, missing identification of priorities and no consensus about what exactly to measure are key obstacles when it comes to harmonizing biodiversity monitoring (e.g. Wetzel et al. 2015, Skidmore et al. 2015; Pereira et al. 2013a, Pettorelli et al. 2016a). Wetzel et al. see the key problem in existing data not being "*discoverable, accessible and digestible (interoperable)"* (2015: 1). The 'Group on Earth Observations Biodiversity Observation Network' (GEO BON) links together different existing biodiversity-related networks and helps coordinate and harmonize them and their data (Scholes et al. 2012), "*to improve the acquisition, coordination and delivery of biodiversity observations and related services to users including decision makers and the scientific community*" (GEO BON 2015, last access: 10 August 2016). Linking biodiversity data to the Global Earth Observation System of Systems (GEOSS), decision makers will be provided with access to a wide range of necessary data.

Inspired by the Essential Climate Variables (ECVs) used for the implementation of the Global Climate Observing System (GCOS), a set of candidate 'Essential Biodiversity Variables' (EBVs) has been proposed by GEO-BON (Pereira et al. 2013a). EBVs are measurements "*required for study, reporting, and management of biodiversity change"* (Pereira et al. 2013a: 277). Aiming to harmonize and guide biodiversity monitoring on a global level, EBVs represent a minimum set of measurements and help focus on priorities and facilitating data integration: primary observations (in-situ or remote sensing) are preprocessed and combined into EBVs (Pereira et al. 2013b); they serve as an intermediate conceptual level between primary measurements and indicators like those needed to assess progress towards the ABTs (Pereira et al. 2013a; O'Connor et al. 2015). A review was recently published, discussing in detail the difference between indicators and EBVs (Pettorelli et al. (2016b).

After being tested on relevance, scalability, temporal sensitivity, feasibility and redundancy, the variables were then organized into six classes (genetic composition, species population, species traits, community composition, ecosystem function and ecosystem structure) (ibid), spanning a range of scales from genes to ecosystems (O'Connor et al. 2015). Examples of current EBV candidates (the identification of EBVs is an ongoing process) are species distribution, phenology, physiological traits, and species interactions. However, direct measurement of EBVs on the ground, although very accurate, is laborious, time-consuming, costly and not possible on a global level (Secades et al. 2014; Skidmore et al. 2015). The EBV concept is not an alternative to the biodiversity indicator concept, but rather a complementary tool (ibid.).

1.4 Earth Observation for monitoring ABTs

Remote sensing (RS) opens new pathways for biodiversity monitoring. Earth observation (EO) products from active or passive satellite sensors currently offer the greatest potential when it comes to monitoring progress towards the ABTs, although much of the information are not direct measurements of biodiversity, but rather surrogates of the same (Secades et al. 2014). Satellite derived RS data is cost effective, repeatable, continuous, and can access remote areas (Lillesand et al. 2008; Secades et al. 2014). For example, spectral heterogeneity may serve as spatially continuous and inexpensive proxy for environmental diversity (Rocchini et al. 2010), and despite some pitfalls (see e.g. Rocchini et al. 2015), spectral heterogeneity can provide a valuable first filter estimate for spatial pattern estimation (Rocchini et al. 2010).

Of the 20 ABTs, the status of 11 can currently be totally or partially derived from existing RS-based information (ibid). The before mentioned EBV concept was further developed, defining a subset of the candidate EBVs proposed by Pereira et al. (2013a), existing of those EBVs that are measurable by RS (referred to as RS-EBVs) (Skidmore et al. 2015; O'Connor et al. 2015). Partly measured RS-EBVs depend on supplementary data or modelling. The ten variables proposed by Skidmore et al. (2015) are: species occurrence, plant traits, ecosystem distribution, fragmentation and heterogeneity, land cover, vegetation height, fire occurrence, vegetation phenology, primary productivity and leaf area index (LAI), and inundation. Key functional plant traits which are remotely observable include leaf chlorophyll, leaf phenology, LAI and more. Not all remote sensors are able to assess all RS-EBVs in an equal manner, as their computation depend on certain spectral bands. Therefore, a combination of traditional ground measurements, modelling and RS technologies is seen as the probably most comprehensive and accurate approach towards a representation of ecological processes and changes in biodiversity, even though as with any other biodiversity monitoring approach, access and affordability of satellite data is not always given (Secades et al. 2014). International coordination in data collection and sharing is still of greatest importance for an integrated and robust record (Turner et al. 2015). RS data can be used as model inputs (e.g. climate data), indirect proxies of biodiversity (e.g. availability of long-term global normalized difference vegetation index (NDVI) time series and detailed studies of its relationship with net primary productivity (NPP) for example resulted in its use as a proxy for land degradation (Bai et al. 2008; de Jong et al. 2011)) or even direct measurements of populations or individuals (e.g.

megafauna) (Secades et al. 2014). RS products are used to monitor status and trends of habitat extent, but other variables like vegetation indices are improving in quality and can be used to describe the condition of a land surface (ibid).

To enable the continuity of earth observation and ecosystem monitoring, the Multi-Spectral Instrument (MSI) aboard the Sentinel-2 (S-2) satellite has been designed, particularly as follow up of *Satellite Pour l'Observation de la Terre* (SPOT) and Landsat data into the future (Frampton et al. 2013). S-2 belongs to the 5 Sentinel satellite missions developed by the European Commission's Copernicus programme (ESA n.d.). The polar-orbiting high-swath and high-resolution sensor of the S-2 mission monitors land surface conditions with a revisit time of 10 days at the equator. With the additional twin satellite (launch planned 2017) phased at 180° in the same sun-synchronous orbit, the revisit time will be 5 days (ESA 2015). The first satellite was launched on 23 June 2015. The S-2 mission will make contributions to land cover monitoring and particularly to the assessment of various biogeophysical parameters (e.g. leaf area index, leaf cover, leaf chlorophyll content), emergency management (e.g. natural disasters) and security (e.g. infrastructure surveillance, sea border surveillance) (ESA 2015).

1.5 Objectives and research questions

The above sections discussed the present legal situation with regards to international biodiversity conservation efforts, advancements and prevailing challenges that are faced in current biodiversity research and potential contributions of RS missions to assess biodiversity change. Five years into the 'Strategic Plan for Biodiversity 2011-2020' it is still unclear how to monitor progress towards the ABTs. Available indicators are often not informative for local or regional case studies or are unable to grasp all aspects of an ABT. The main goal of this thesis is the development of a most accurate validation method for selected ABTs, using preferably EBVs measurable from space with S-2 data for a heterogeneous study area in Switzerland.

Of the total 20 ABTs, only ABTs 5, 14 and 15 will be considered in this case study. The selection was based on (i) relevance for the study area, (ii) the possibility to relate their content (at least partially) to EO data (Secades et al. 2014), and (iii) availability of data (e.g. GIS data of protected areas). The selected ABTs are defined as:

ABT 5*: By 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced.*

ABT 14: *By 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well-being, are restored and safeguarded, taking into account the needs of women, indigenous and local communities, and the poor and vulnerable.*

ABT 15: *By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration, including restoration of at least 15 per cent of degraded ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification.*

As can be seen when reading through the ABTs, most of them lack "*explicitly quantifiable definitions of success for 2020*" (Tittensor et al. 2014: 241), and the assessment of the absolute progress towards a certain goal proofs to be difficult (ibid.). In the remainder of this thesis, the aim is to (i) analyze ABTs 5, 14 and 15 in detail and set foci where necessary, (ii) review previous approaches of validating aspects of ABTs and related aspects found in literature, (iii) evaluate potential products of the Sentinel-2 satellite mission to contribute to progress assessment and (iv), give concluding remarks about quantifying state of habitats, biodiversity and conservation situation in the study area, where possible. Following general research questions were developed:

1. *What data is needed to accurately measure progress towards ABTs 5, 14 and 15?*
2. *What can RS-EBVs and the Sentinel-2 mission contribute to this analysis? Where are its limitations?*
3. *Are we on track to achieve ABTs 5, 14 and 15 in the study area?*

As the three selected ABTs differ substantially in content, specific research questions were developed for each ABT. Considering ABT 5, following questions are important: (i) what is the total area of natural habitat in the study area and how can its extent be assessed most accurately? (ii) how can forest degradation be monitored? (iii) how are natural habitats distributed in the study area and how can habitat fragmentation be monitored?
For ABT 14, following research questions were developed: (iv) are ecosystems that provide essential services in the study area legally safeguarded and protected on national and cantonal level? (v) are there specific restoration activities? (vi) can the essential services of the respective ecosystems be mapped and monitored using EO?
For ABT 15, following questions were developed: (vii) what is the conservation status of forests and raised bogs? (viii) how can the relationship between forest conservation and ecosystem resilience be assessed? (ix) what is the relationship between forest diversity and productivity?

2 Materials and methods

2.1 Study area

The study area covers the city of Zurich and its heterogeneous surrounding areas in the northern part of Switzerland, comprising a total area of 336 km^2 (14.6 x 23 km^2). It includes a variety of different land cover types, including urban, forest, and agricultural areas as well as the northern part of Lake Zurich (Fig. 1). The large pre-alpine lake has a total area of 59.85 km^2 and at its deepest location has a depth of 136 m (WWEA 2016a). Two mountain ridges frame the lake. They are partly covered with both deciduous and coniferous temperate forest and partly used as settlement area and agricultural land. In between these ridges, the city of Zurich is located at the northern tip of the lake. In the northeast of Zurich, the Kloten Airport is visible. Around 1.3 Million people live in Zurich and its agglomeration, approximately one third in the city itself (as of 28 December 2015; www.stadt-zuerich.ch).

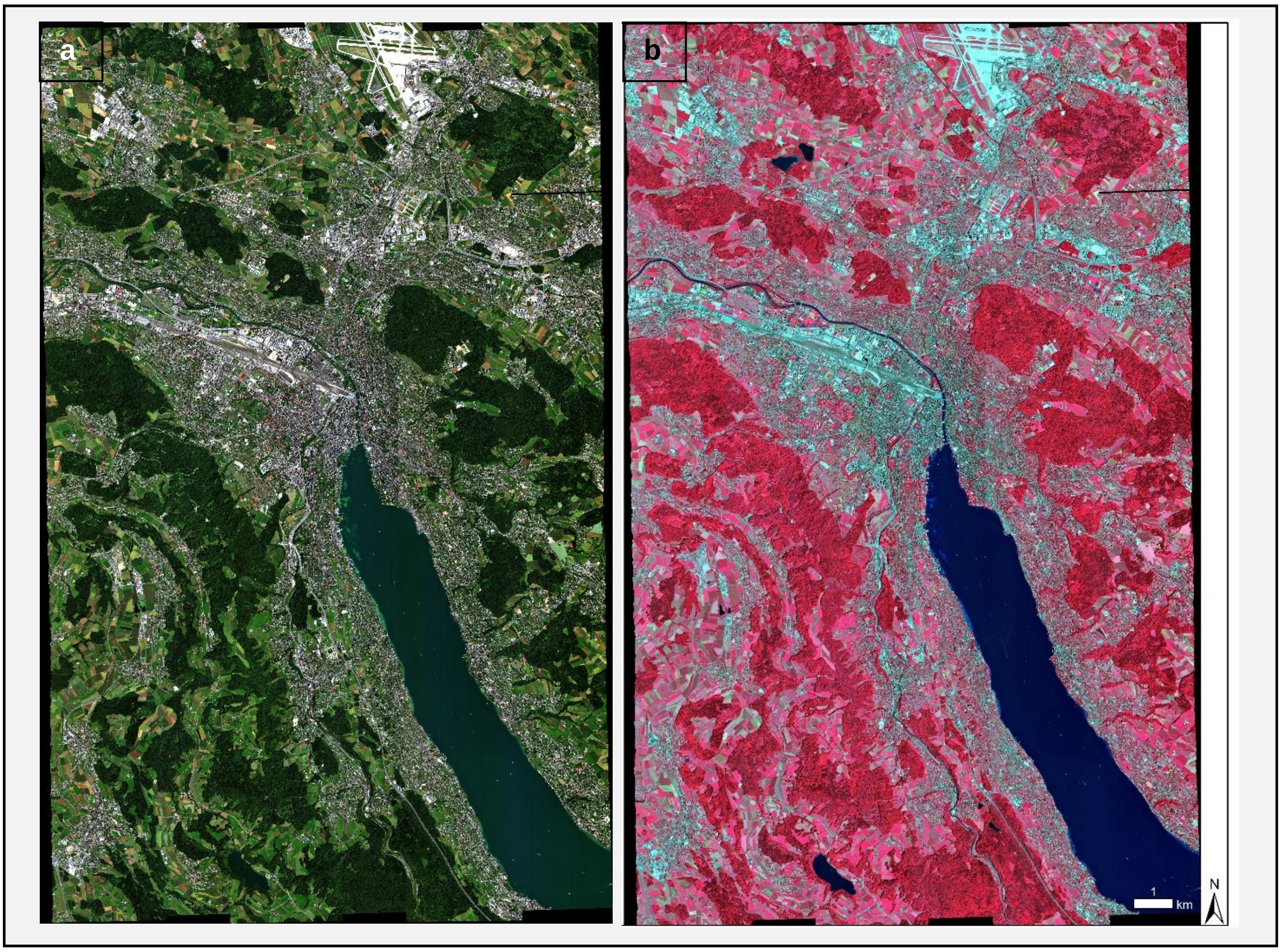

Figure 1: Study area: a) True color composite and b) false color infrared of the simulated Sentinel-2 image showing the study area, Zurich and its surrounding with heterogeneous land cover.

2.2 APEX Data

The simulated Sentinel-2 image is composed of seven individual flight lines, acquired on June 26, 2011 by the Airborne Prism Experiment (APEX) (Laurent et al. 2014). The APEX instrument is an airborne dispersive pushbroom imaging spectrometer covering the spectral range between 380.5 and 2501.5 nm. The data used for this study were acquired at an altitude of approximately 6.4 km a.s.l. with an average solar zenith angle of

38.6° (Laurent et al. 2014). With a field of view (FOV) of 28°, it records 1000 pixels per scan line, resulting in a ground pixel size of 2 m x 2 m. To obtain at-sensor radiance, the images were radiometrically calibrated (ibid.). APEX data allows to simulate, validate and calibrate satellite sensor data of current or future spaceborne missions (D'Odorico et al. 2013).

2.3 Simulated Sentinel-2 data

Before producing the image mosaic (Fig. 1), the APEX radiance images were pre-processed individually (Laurent et al. 2014): they were normalized to nadir viewing using a Li-Ross bidirectional reflectance distribution function (BRDF, Weyermann et al. 2013), which was spectrally convolved to Sentinel-2 sensor response functions and both geo-corrected and ortho-rectified to the Swiss National Grid (CH1903, Laurent et al. 2014). In the context of this study, the original spatial resolution of the APEX sensor was used for index calculations, but upon deciding whether S-2 is useful for a specific task, its actual spatial resolution was considered. The actual spatial resolution of the S-2 sensor is 10 m for four bands, 20 m for six bands and 60 m for three bands (ESA 2015) (Tab.1). Small differences in central wavelength exist between the original and the simulated MSI sensor (Tab. 1). Band numbers in this study refer to the simulated S-2 image. The band width of the original S-2 bands varies between 15 and 180 nm.

Table 1: Comparison of spectral bands of S-2 MSI and the simulated S-2 spectral bands. The simulated S-2 image only contains 10 bands. The simulated S-2 bands do not always correspond exactly the original band configuration, impacting the decision of what RS-EBVs were selected for monitoring progress towards ABTs.

S-2 band	1	2	3	4	5	6	7	8	8b	9	10	11	12
Central wvl [nm]	443	490	560	665	705	740	783	842	865	940	1375	1610	2190
Bandwidth [nm]	20	65	35	30	15	15	20	115	20	20	30	90	180
Spatial resolution [m]	60	10	10	10	20	20	20	10	20	60	60	20	20
Simulated S-2	1	2	3	4	5	6	7	8	9	10			
Central wvl [nm]	450	461	470	532	551	572	645	702	800	862			
Corresp. S-2 band	1	2	2	(2/3)	3	3	(4)	5	8	8b			

2.4 GIS data

In addition to the simulated S-2 data as primary data source, a variety of GIS data from different sources was used to form the secondary data body of this study (Tab. 2). Depending on the ABT, different key areas are of interest, requiring a preparation of mask layers. Masks have been generated using clipping and merging of shapefiles (Tab. 2). Following mask layers were used for this study: Natural habitat (ABT 5), forest (ABT 5, 14 and 15), protected forest (ABT 14 and 15, including forest area overlapping with the cantonal protection enactment), water bodies (ABT 14), protected areas within settlement area (ABT 14, including settlement area as designated in the cantonal structure plan overlapping with biotopes of national importance, the cantonal protection enactment, hedge slopes listed in the inventory of regional and cantonal importance and nature protection objects listed in the same inventory).

Table 2: GIS data used in this study for natural habitat (ABT 5), protected areas (ABT 14 and 15), settlement area (ABT 14), water bodies (ABT 14), and fragmentation (ABT 5) analyses. The data of each category is divided by authoritative level.

	Name	**Copyrights of GIS data**
Natural habitat (ABT 5)		
National	Federal inventories: - Alluvial zones - Fens - Raised bogs - Dry meadows and pastures	© FOEN, 3003 Bern, Switzerland: Species, Ecosystems, Landscapes Division; Species and habitat section. Available online: FOEN topic biodiversity – geodata: http://www.bafu.admin.ch/biodiversitaet/ (Last access: 8 July 2016)
Cantonal	Cantonal structure plan: layer *Forest*	© GIS-Zentrum des Kantons Zürich GIS-ZH Nr. 173: Geolion: http://geolion.zh.ch/geodatensatz/show?nbid=284 (Last access: 23 August 2016) (Kantonaler Richtplan 'Siedlung und Landschaft')
Protected areas (ABT 14 and 15)		
National	Federal inventories: - Amphibian spawning areas - Alluvial zones - Fens - Raised bogs - Dry meadows and pastures Parks of national importance Bundesinventar der Landschaften und Naturdenkmäler von nationaler Bedeutung	© FOEN, 3003 Bern, Switzerland: see above
Cantonal	- Protected areas in cant. structure plan - Protection enactment (Schutzverordnungen über Natur- und Landschaftsschutzgebiete von überkommunaler (kt./reg.) Bedeutung, SVO) - Protection enactment (old, but legally binding; altrechtliche Verordnungen über den Schutz von Natur- und Landschaftsschutzgebieten)	© GIS Zentrum des Kantons Zürich GIS-ZH Nr. 165: Geolion: http://geolion.zh.ch/geodatensatz/show?nbid=323 (Last access: 23 August 2016) © GIS-ZH Nr. 159: Geolion: http://geolion.zh.ch/geodatensatz/show?nbid=324 (Last access: 23 August 2016)
Communal	Inventory of nature and landscape protection areas of regional importance: - Hedge slopes - Nature protection objects - Nature protection objects (amended)	© GIS Zentrum des Kantons Zürich GIS-ZH Nr. 127 Geolion: http://geolion.zh.ch/geodatensatz/show?nbid=345 (Last access: 23 August 2016)
Settlement area (ABT 14)		
Cantonal	Cantonal structure plan: layer *Settlement area*	© GIS-Zentrum des Kantons Zürich GIS-ZH Nr. 173. Geolion: http://geolion.zh.ch/geodatensatz/show?nbid=284 (Last access: 23 August 2016) Kantonaler Richtplan 'Siedlung und Landschaft'
	Road network canton Zurich	© GIS-Zentrum des Kantons Zürich GIS-ZH Nr. 102. Geolion: http://geolion.zh.ch/geodatensatz/show?nbid=804 (Last access: 23 August 2016)
Water (ABT 14)		
National	Nationales ökologisches Netzwerk (REN, Réseau écologique national): Lebensraum Fliessgewässer/Seen	© FOEN, 3003 Bern, Switzerland: Available online: FOEN topic biodiversity – geodata: http://www.bafu.admin.ch/biodiversitaet/ (Last access: 8 July 2016)
Cantonal	Public open water bodies	© GIS-Zentrum des Kantons Zürich GIS-ZH Nr.: 45: Geolion: http://geolion.zh.ch/geodatensatz/show?nbid=743 Office of Waste, Water, Energy and Air (Last access: 23 August 2016)
Fragmentation data (ABT 5)		
Global	OpenStreetMap data: - Roads - Railways	© OpenStreetMap contributers (*https://www.openstreetmap.org/copyright/en*) Shape files extracted from © BBBike.org; Wolfram Schneider (2011-2016) (Last access: 23 August 2016)

2.5. EBV selection

In this section, ABTs 5, 14 and 15 will be presented and a selection of methods for assessing progress towards all three ABTs, will be made. A statement that is valid for all of the three targets is that the CBD does neither provide concrete guidelines on how the progress towards the ABTs shall be measured nor a specific point of success. There exists an interdependency of statements about the progress towards achieving ABTs on region, habitat type, data availability, element of the ABT itself, which underlines the necessity for a more detailed approach to get a representative conclusion about ecosystems in a certain area. For ABTs 5, 14 and 15 this means that following aspects determine the assessment of the somewhat vaguely formulated targets: the present types of ecosystems, the current conditions and ecological importance of those ecosystems, the availability of financial, human and technological resources, the current rate of loss of habitats and its main causes, ecological, economic and financial cost and benefit arising of reducing habitat loss. An adaption to regional circumstances is necessary.

2.5.1 Target 5

ABT 5*: By 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced.*

ABT 5 approaches the issue of natural habitat and its rate of change, as well as its degradation and fragmentation. The CBD does not specify which habitats are defined as ‘natural’ and should therefore be included, and only recommend setting a focus on forest and a few key habitats. Neither does the CBD specify how degradation shall be assessed or described. Globally, only about 2% of ice-free land are considered highly degraded, but up to 78% are somehow impacted by humans through habitat conversion (Leadley et al. 2014). A broadly accepted definition of degradation is difficult to find and depends on the ecosystem type, as well as the specific interest of involved parties (de Jong et al. 2011). An agricultural expert for example may describe an ecosystem as degraded if it is not able to supply provisioning services anymore, while others see agriculture as a source of land degradation (Leadley et al. 2014). This controversy in finding a definition is one of the most important sources of uncertainty when qualitatively or quantitatively assessing degradation (Leadley et al. 2014). The Millennium Ecosystem Assessment (MEA) defines degradation as “[…] *persistent net loss of capacity to yield* […] *ecosystem services*” (MEA 2005c: 16). In most definitions, the common denominator is the (temporary or long-term, sometimes irreversible) reduction in productivity and in the ability of an ecosystem to provide benefits or (provisioning, regulating, supporting and cultural) services, often a result of various and interlinked natural and anthropogenic factors and processes (Zika & Erb 2009; Bai et al. 2008). Accordingly, if measuring and monitoring land degradation, a certain change in time and an aberration of the ‘normal’ state have to be considered. Main drivers of degradation are erosion, nutrient depletion, inappropriate agricultural practices, unsustainable cultivation, overgrazing, tree-logging etc. (Leadley et al. 2014; Rey Benayas et al. 2009). In this study, the definition of degradation varies with the ecosystem type: loss of area and increase of fragmentation is seen as degradation in all cases. A more specific definition depends on the main stresses of the ecosystem type and are discussed later in the chapter.

Landscape fragmentation is defined as the "*destruction of established ecological connections between adjoining areas of the landscape, for example by dividing up habitats"* (Jaeger 2007: 10). The CBD lists 8 indicators (Tab. 3) as operationally most relevant for ABT 5 (*https://www.cbd.int/sp/indicators/*; last access: 8 July 2016). The Biodiversity Indicator Partnership (BIP) proposes 9 indicators for analyzing ABT 5. It is important to note that some of these indicators are still in development, and measurement guidelines or scales are not yet specified. Besides the global indicators, complementing indicators have been developed on national level (Tab. 3).

Table 3: Potential indicators for assessing progress towards ABT 5: Global indicators, proposed by the Convention on biological diversity (CBD) and the Biodiversity Indicator Partnership (BIP), and national indicators, proposed by the Federal Office of the Environment (FOEN) and Biodiversity Monitoring Switzerland (BDM). Additionally, potential RS-EBVs (proposed by GEO-BON) are listed.

Indicator	Organisation
Extinction risk trends of habitat dependent species in each major habitat type	CBD
Trends in condition and vulnerability of ecosystems	
Trends in extent of selected biomes, ecosystems and habitats	
Trends in fragmentation of natural habitats	
Trends in proportion of degraded/threatened habitats	
Trends in the proportion of natural habitats converted	
Population trends of habitat dependent species in each major habitat type	
Trends in primary productivity and trends in proportion of land affected by desertification	
Red List Index	BIP
Extent of forests and forest types	
Extent of marine habitats	
The Living Planet Index	
The Wild Bird Index for habitat specialists	
Area of forest under sustainable management: degradation & deforestation	
Forest fragmentation	
River fragmentation & flow regulation	
The Wildlife Picture Index	
Size of Valuable Habitats	BDM
Quality of Valuable Habitats	
Landscape Fragmentation	
Swiss Bird Index ®	FOEN
Forest area	
Sites left to natural succession	
RS-EBV	
Ecosystem distribution	GEOBON
Fragmentation and heterogeneity	
Land cover	
Vegetation height	
Plant traits	
Vegetation phenology	
Primary productivity	

Size of Valuable Habitats and *Quality of Valuable Habitats,* both indicators developed by Biodiversity Monitoring Switzerland (BDM), include raised bogs and fens, alluvial zones and dry grassland, which are rare habitat types in Switzerland. The national indicator *Landscape Fragmentation* (BDM 2010; Jaeger 2000) is measured by the *effective mesh size* (MESH). The indicator assesses how Switzerland's landscape (below 2'100 m a.s.l. and excluding water bodies) is cut up by artificial barriers (roads, settlements), based on national maps (BDM 2010). Considering the up to now proposed RS-EBVs (Skidmore et al. 2015), a selection of eight is suitable for monitoring progress towards ABT 5. However, by the time of writing this thesis, no definitive metric was decided on for the individual EBVs: at this stage, it is yet unclear what methodology for generation of an EBV is decided upon and who will take responsibility for this (Pettorelli et al. 2016b). Hence, in this study, methodologies for measuring RS-EBVs have to be selected as well. Following RS-EBVs were selected to assess progress towards ABT 5:

- *Land cover* for the general assessment of natural habitat;
- *Primary productivity, Plant traits and Heterogeneity* for monitoring habitat quality;
- *Ecosystem distribution* and *fragmentation* of natural habitat.

Extent of natural habitat

An emphasis was set on two key terrestrial habitat types: forest and rare habitat types, as proposed by the CBD. Additionally, forest is specifically mentioned in the ABT and it covers a large part of the study area. National forest area has grown continuously since the passing of the Police Act of forests in 1876, leading to a total coverage of 1.31 million hectares in Switzerland in 2015 (Forest Report 2015). Forest extent in Switzerland's Central Plateau has been relatively stable during the past years, thanks to intensive conservation measures. Hardly any changes have been observed in the canton of Zurich since 1985 (Baudirektion Kanton Zürich 2010), which leads to the assumption, that within the study area, also no significant changes have appeared. Two approaches for assessing forest area are considered suitable.

Forest area, as defined by the cantonal structure plan was assessed using the available GIS data (Tab. 2). Additionally, the simulated S-2 image has been used to test assessment methods for forest extent and functional composition (EBVs *Land cover* and *Ecosystem distribution*). Following options were tested to extract forest area: (i) linear spectral unmixing (LSU) using a collection of endmembers; (ii) a Spectral Angle Mapper (SAM), a supervised maximum likelihood classification (MLC), and (iv) a classification based on the sum of bands 7 (red), 5 (green) and 2 (blue), with forest classified as pixels with values between 1 and 800 (Tab. 5). A median filter (kernel size 21) and a vegetation mask based on greenness (NDVI > 0.4) was applied on all results. NDVI is defined as normalized ratio between NIR and red reflectance (Tucker 1979):

$$\mathrm{NDVI} = (R_{862} - R_{645}) / (R_{862} + R_{645}) \qquad (1)$$

with R_{862} and R_{645} being reflectance at 862 and 645 nm wavelength.

Training areas used for LSU, SAM and MLC distributed over the image were selected for following land cover types: Deciduous and coniferous forest, three classes of agricultural fields and grassland based on brightness, bare soil, two types of urban cover (roads and buildings), two types of water (turbid and clear) and shadow. A second focus was set on very rare habitats, high-biodiversity areas, and any kind of habitat that is not influenced heavily by humans. For this thesis, the selection of rare habitats is based on inventories of biotopes of national importance and includes alluvial zones, bogs and fens, and dry meadows and pastures. All of these are present in the study area and are protected by federal law (FOEN 2014a). The inclusion of raised bogs and fens is justified insofar as even though they are not particularly rich in species, there are many species that rely on those habitats as their sole habitat (Cordillot & Klaus 2011). This selection corresponds to the BDM indicators *Size and quality of valuable habitats*. Area of habitats were measured using available GIS data. The simulated S-2 image was also tested on applicability to assess those habitats, using LSU and SAM.

Quality of natural habitat

Condition of forests and rare habitats in Switzerland have been monitored over the past years, however, using diverse methodologies and approaches. Area loss and fragmentation is seen as degradation for all habitat types as well, but handled separately as they are listed separately in the ABT. Additional degradation depends on habitat specific main stresses in the study area. Degradation of rare habitats in the study area is not investigated in detail and considered beyond the scope of this thesis.

The emphasis of this study lies on forest area, because greater potential for RS is seen. The main current and future threats to forest in Switzerland are summarized in this section. Firstly, despite nitrogen emissions being reduced, there are still forest areas exceeding the critical value of nitrogen deposition (Forest Report 2015). In 2014, 95% of national forest area show values exceeding critical loads (input that an ecosystem can deal with, without suffering damage in structure or function) (FOEN 2014b). Reactive nitrogen impacts the environment through chemical, physical and biological processes (Leadley et al. 2014). As the forest patches in the study area are located within a highly urban environment, nitrogen dioxide pollution from traffic, agriculture, industry etc. is high and seen as the major pressure in the study area's forests: while concentrations are usually below limits in rural areas, ambient limit values in urban areas are consistently exceeded (FOEN indicator Nitrogen dioxide immissions), leading to problematic concentration in habitats close to urban areas. Increased nitrogen deposition has various effects on forest ecosystems: while it may cause growth inhibition in beeches and spruces, it can also lead to eutrophication of forests, soil acidification, and reduced resistance ability of trees against drought and parasite infestation (Flückiger et al. 2011). Observed nutrient imbalance in forest trees is related to increased N deposition and evidence for raised instability (Braun et al. 2012). In areas with priority function 'timber use', the main current pressure is the outweighing of timber use in comparison to growth. Main reasons for this are previous storm damages, beetle damages, drought and soil acidification ('*Zwangsnutzung*') (Baudirektion Kanton Zürich 2010). With changing climate, extreme disturbance events (e.g. storms) are likely to become more frequent in future (ibid.). The threat of introduced pests is another increasing pressure on Swiss forest, with unpredictable and quick ways of ecosystem alteration. Inter- and intra-annual variation of crown defoliation (e.g. caused by fungal infestation) is high and not enough data is available for any trend statement (FOEN 2014b).

Forest degradation due to increased nitrogen deposition and climate change is considered a priority in this study. RS-EBVs *primary productivity, plant traits* and *heterogeneity* were selected as most important in connection with monitoring forest degradation.

As nitrogen deposition, timber use activities and climate change often relate to changes in vegetation cover, RS-EBV *primary productivity* is seen as useful for assessing forest degradation. Gross Primary Productivity (GPP) of forest area was approximated using the light use efficiency concept first proposed by Monteith (1972) and since a widely used approach (Hilker et al. 2008). In this approach, GPP [kg C day^{-1}] is calculated as the product of the absorbed photosynthetically active radiation (APAR) ranging from 400 to 700 nm wavelength, and the light use efficiency (LUE) of the plant to convert APAR into biomass (Hilker et al. 2008, Homolová et al. 2013). In this sense, photosynthesis or plant growth is a product of resource times the conversion efficiency (Running et al. 2004). APAR is provided by the combination of the daily incident photosynthetically active radiation (PAR) and the fractional PAR absorption by the vegetation (fPAR) [%] (Running et al. 2004).

So GPP can be estimated as:

$$\text{GPP} = \text{PAR} \times \text{fPAR} \times \text{LUE} \tag{2}$$

PAR was estimated using hourly measurements of global solar irradiance of 3 meteorological stations located within the study area (Zurich, Affoltern and Kloten). The flight acquiring the APEX data was performed between 10:00 and 12:00 UTC, hence, hourly values for 10:00 – 12:00 UTC were downloaded from the data portal CLIMAP (MeteoSwiss). The average shortwave radiation for the time window and all three weather stations amounts to 925.5 Wm^{-2}. However, those measurements include the wavelength range of 305-2800 nm, while PAR is the radiation between 400 and 700 nm, as plants do not use photons outside of that range for photosynthesis. A conversion factor of 0.45 was applied (Running & Zhao 2015), which results in a final value of 416.45 Wm^{-2} or 416.45 $\text{Js}^{-1}\ \text{m}^{-2}$. For calculations, this value was converted to mega joules per hour and multiplied by 4, as the simulated SI-2 image has a pixel size of 2 m x 2 m. Hence, the final PAR value applied in the formula is 5.997 MJ $\text{m}^{-4}\ \text{h}^{-1}$. The value of fPAR was estimated using the near-linear relationship with the greenness index NDVI (Running et al. 2004; Grace et al. 2007). To calibrate the relationship between NDVI and fPAR, a linear regression was performed for MODIS NDVI and fPAR for the day of year of the APEX flight (composite of 26 June to 11 July 2011). Two MODIS products were downloaded for the extent of the study area from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/; Access: 24 February 2016): layer 1 of the MOD15A2 product (8 day composite Fpar, 1 km tile) and layer 1 of the MOD13A2 product (16 day composite NDVI, 1 km tile). The linear regression resulted in following relationship (multiple $R^2 = 0.67$ and $R^2(\text{adj}) = 0.66$):

$$\text{fPAR} = 1.505 \times \text{NDVI} - 0.364 \tag{3}$$

Light use efficiency (LUE) depends on vegetation type and environmental stresses (Hilker et al. 2008). LUE was modeled using the MOD17 algorithm and the Biome-Property-Look-Up-Table for MODIS GPP (Running & Zhao 2015:12). The two parameters temperature (T) and vapor pressure density (VPD) are used to calculate simple ramp functions, which are then multiplied by the class specific LUE_{max}. VPD is computed using the relative humidity (RH) and saturated vapor pressure (SVP):

$$\text{LUE} = \text{LUE}_{\text{max}} \times \text{T}_{\text{min\_scalar}} \times \text{VPD}_{\text{scalar}} \tag{4}$$

$$\text{VPD} = ((100 - \text{RH}) / 100) \times \text{SVP} \tag{5}$$

$$\text{SVP (Pascals)} = 610.7 \times 10^{7.5\text{T}/(237.3+\text{T})} \tag{6}$$

with RH being relative humidity and SVP being the saturated vapor pressure. Hourly mean temperature and RH were obtained for the 3 meteorological stations in the study area. No data was available for the Uetliberg station. The values were averaged (24.9 °C) and VPD was calculated. Based on a vegetation classification (Spectral angle mapper; four vegetation classes: deciduous forest, coniferous forest, grassland and crops), each pixel was assigned the respective LUE value.

Pigment composition is related to the physiological status of plants (Gitelson et al. 2006) and many ecosystem processes are interlinked with chemical, physiological and structural properties of plants (Jetz et al. 2016). Thus, RS-EBV *plant traits* was selected as suitable RS-EBV for monitoring progress towards ABT 5. Leaf chlorophyll, anthocyanin (Anth) and carotenoid (Car) are pigments that absorb light at particular wavelengths and can be assessed with spectral reflectance (Gamon & Surfus 1999), and were selected for monitoring degradation of forest. Chlorophyll absorbs solar light energy in the red and blue spectral range and converts it to chemical energy: chlorophyll therefore relates to photosynthetic activity, primary production, nutrient status, plant stress and senescence (Hendry et al. 1987). Clevers & Gitelson (2013) and Damm et al. (2013) propose the use of a spectral band in the range of 705-740 nm in the denominator, and a spectral band of 800 nm in the numerator as optimal, following the guidance of Gitelson et al. (2006). Clevers & Kooistra (2012, based on Gitelson et al. 2003) propose following equation as best N estimation for S-2:

$$CI_{red\text{-}edge} = (R_{780} / R_{710}) – 1 \tag{7}$$

Adapted to the simulated S-2 image of this study, the equation is:

$$CI_{red\text{-}edge} = R_{800} / R_{702} - 1 \tag{8}$$

Anth is a red pigment protecting the leaves from harmful excess light by their ability to attenuate UV radiation (Chalker-Scott 1999; Merzlyak & Chivkunova 2000). Gitelson et al. (2006) proposed and index based on three spectral bands for the non-destructive assessment of Anth:

$$Anth = R_{800} / (R_{551} – R_{702}) \tag{9}$$

The third main type of leaf pigments are carotenoids, contributing to light harvesting and also protecting the plant from photodamage. Three spectral regions are recommended for Car retrieval (Gitelson et al. 2006): reflectance at 800 nm, 510-520 nm and 690-710 nm. Neither the simulated nor the real S-2 image provides a band in the spectral region of 510-520 nm. The absorption peak of Car at 490 might be used as well, but results are expected to suffer from the overlapping absorption of chlorophyll. Despite these drawbacks, Car was estimated using this adapted formula:

$$Car = R_{800} / (R_{470} – R_{702}) \tag{10}$$

As only 10 bands were available (Tab. 1), the band configurations for calculating indices found in literature were slightly adapted to the available bands of the simulated S-2 image. However, it was checked that the reflectance range was within absorption spectra when calculating the leaf pigments.

An important effect of N accumulation is changing vegetation composition (Leadley et al. 2014) and hence, on RS-EBV *heterogeneity*. Spatial environmental heterogeneity describes the spatial complexity, diversity, heterogeneity or structure of the environment and can be divided into biotic (land cover and vegetation heterogeneity) and abiotic (climatic, soil and topographic heterogeneity) heterogeneity (Stein et al. 2014). Forest composition in the study area may change in the next few decades and plant traits assessed by S-2 may potentially be used for monitoring spatial heterogeneity. The spatial variation of reflectance is proposed to be correlated to spatial variation in the environment, a phenomenon known as spectral variation hypothesis (Palmer et al. 2002). This relationship has been tested and found to improve with increasing spatial scale (Rocchini et al. 2004) and provides a promising tool to analyze environmental heterogeneity. Spatial patterns of the continuous (unclassified) reflectance signal is favored over discrete classification of satellite data, where much of the information gets lost in the process (Palmers et al. 2002). However, there exists no single index that captures all aspects of landscape heterogeneity or diversity (Gorelick 2006). To date, we lack a standardized set of landscape heterogeneity metrics. There has been a proliferation of landscape heterogeneity metrics (McGarigal 2015; Schindler et al. 2015; Cushman et al. 2008) and the quantification has been very divers in past studies (Stein et al. 2014; Tuanmu et al. 2015; Schindler et al. 2015). Most of the popular metrics related to landscape diversity or heterogeneity are based on information theory, e.g. the Shannon's diversity index (SHDI, Shannon & Weaver 1949, McGarigal 2015). SHDI can be used to compare different landscapes or same landscapes at different times, but its absolute value is not particularly meaningful (McGarigal 2015). Another popular metric of landscape heterogeneity is the Simpson's diversity index (SIDI, Simpson 1949, McGarigal 2015), indicating the likelihood that 2 randomly drawn cells are different patch types (McGarigal 2015). SHDI and SIDI were derived from the simulated S-2 for one biochemical parameter, $CI_{red\text{-}edge}$, and one structural parameter, the leaf area index (LAI), after being aggregated to a spatial resolution of 20 m (which would be the resolution of the S-2 products). Both $CI_{red\text{-}edge}$ and LAI are related to nutrient input and therefore likely to change due to increased N input.

Another aspect of landscape heterogeneity is evenness, referring to the distribution of area among different patch types. Corresponding to SHDI and SIDI, Shannon's evenness index (SHEI) and Simpson's evenness index (SIEI) were computed from $CI_{red\text{-}edge}$ and LAI. There exist different ways to estimate LAI from remote sensors (e.g. Haboudane et al. 2004). One possibility to estimate LAI is based on the assumption that there exists a linear relationship between LAI and a Normalized Difference Index (NDI) (Delegido et al. 2011). Delegido et al. (2011) plotted reference LAI measurements against a generic NDI calculated using CHRIS (Compact High Resolution Imaging Spectroscopy) data:

$$LAI = 8.452 \text{ x } (R_{706} – R_{664}) / R_{706} + R_{664}) \qquad r^2 = 0.815 \qquad (11)$$

Adapted to the simulated S-2 image of this study, the formula is following:

$$LAI = 8.452 \text{ x } (R_{702} – R_{645}) / R_{702} + R_{645}) \qquad (12)$$

Fragmentation of natural habitat

The major cause for fragmentation of natural habitats in Switzerland is traffic infrastructure (FOEN 2010). Correspondingly, fragmentation is highest in the densely populated central plateau (FOEN 2014a), endangering species with already small population size (FOEN 2012). To assess fragmentation of natural habitat, *ecosystem distribution* and *fragmentation* were selected as suitable EBVs. The fragmentation of natural habitat can be described using aggregation metrics. They describe how patch types are subdivided into separate patches or fragments. A variety of fragmentation metrics has been developed in the past few years, as well as software packages to calculate them (e.g. Fragstats, Patch Analyst, GRASS etc.) (Llausàs & Nogué 2012), applicable on RS data. The simplest approach is counting the Number of Patches (NP) in the landscape or calculating the Patch Density (PD), where the NP is divided by the total landscape area. Over time, these measures have become more sophisticated (ibid.) and have been applied on RS data (e.g. Southworth et al. 2004). Based on the remarks of Jaeger (2000), 5 aggregation metrics are considered suitable for assessing EBV *fragmentation* (Tab. 4).

Table 4: Landscape aggregation metrics commonly used for subdivision analysis of landscapes: Number of Patches (NP), Patch Density (PD), Landscape Division Index (DIVISION), Effective Mesh Size (MESH) and Splitting Index (SPLIT). Sources: McGarigal (2015), Jaeger (2000).

	Name	Formula	Description
NP	Number of Patches	$\mathrm{NP} = n_i$	NP equals the number of patches of the corresponding patch type (or class). No unit.
PD	Patch Density	$\mathrm{PD} = \frac{n_i}{A}(10{,}000)(100)$	PD equals the number of patches of the corresponding patch type (n_i) divided by total landscape area (m^2), multiplied by 10,000 and 100 (to convert to 100 hectares). Note, total landscape area (A) includes any internal background present. Unit: Number per 100 hectares.
DIVISION	Landscape Division Index	$\mathrm{DIVISION} = \left[1 - \sum_{j=1}^{n}\left(\frac{a_{ij}}{A}\right)^2\right]$	DIVISION equals 1 minus the sum of patch area (m^2) divided by total landscape area (m^2), quantity squared, summed across all patches of the corresponding patch type. Note, total landscape area (A) includes any internal background present. Unit: Proportion.
MESH	Effective Mesh Size	$\mathrm{MESH} = \frac{\sum_{j=1}^{n} a_{ij}^2}{A}\left(\frac{1}{10{,}000}\right)$	MESH equals the sum of patch area squared, summed across all patches of the corresponding patch type, divided by the total landscape area (m^2), divided by 2 10,000 (to convert to hectares). Note, total landscape area (A) includes any internal background present. Unit: hectares.
SPLIT	Splitting Index	$\mathrm{SPLIT} = \frac{A^2}{\sum_{j=1}^{n} a_{ij}^2}$	SPLIT equals the total landscape area (m^2) squared divided by the sum of patch 2 area (m^2) squared, summed across all patches of the corresponding patch type (a_{ij}). 2 Note, total landscape area (A) includes any internal background present. No unit.

Both NP and PD are fundamental as basis for computing other metrics. MESH describes the size of the patches when the landscape is divided into x areas of the same sizes. DIVISION and MESH are perfectly, but inversely related, and therefore redundant. SPLIT is interpreted as the number of patches after dividing the total landscape into patches of equal size so as the new configuration leads to the same degree of landscape division as obtained for the observed cumulative area distribution (McGarigal 2015). MESH is used by the FOEN and BDM Switzerland as national indicator of landscape fragmentation, and thus used in this study.

$$\mathrm{MESH} = \frac{\sum_{j=1}^{n} a_{ij}^2}{A}\left(\frac{1}{10{,}000}\right) \tag{12}$$

MESH gives an area [ha] that corresponds to a regular grid pattern. Different fragmentation geometrics exist, handling anthropogenic and natural elements in a different way (BDM 2010). The official indicator includes highways, 1st and 2nd class roads, railroads, tracks, dams and pressure lines, settlement and industrial areas as fragmentation barriers. In the context of fragmentation of natural habitat, it was decided most reasonable to calculate MESH for the GIS based forest and rare habitat layer, fragmented by roads and railways from *OpenStreetMap* (OSM, map data: © OpenStreetMap contributors). It is the most complete dataset available, including forest paths and roads, and is updated weekly. Compared to national maps, which are only updated every 6 years, this dataset is more convenient for assessing progress towards ABT 5 (to be achieved in 2020). MESH was computed using extracts from January 2016. Subways and tunnels were excluded from all datasets, as they do not impact surface habitat fragmentation.

A further approach for analyzing fragmentation of natural habitat was made, to visualize the phenomenon. OSM data of Zurich and its surroundings were used to analyze fragmentation by traffic barriers within natural habitat. In total, four OSM data sets from different dates were used for this analysis, the earliest from November 2014 and the latest from April 2016. The shapefiles of roads and railways were clipped, merged and the total distance of road and railway sections within the area of natural habitat was measured. Being aware of the difference between highways and small forest roads or even small paths, it was not considered in this part of the analysis. Although small paths through a forest do not hinder animals crossing it, the frequent use of pedestrians and cyclists still disturbs the otherwise untroubled quietness.

Assessing progress towards ABT 5 thus relies on data of extent, quality and fragmentation of natural habitat. (RS-)EBVs that were selected as appropriate contribution, are summarized below (Tab. 5). Each (RS-)EBV is considered adequate and was tested for feasibility regarding both the study area and the S-2 sensor.

Table 5: Overview of selected (RS-)EBVs and the respective metrics for ABT 5: adapted equations applied on the simulated S-2 mosaic.

	(RS-)EBV	Measurement parameter	(Adapted) Equation	Source
Extent of natural habitat	**Land Cover**	Classification based on spectral signal of red, green and blue band GIS data	$1 < R_{645} + R_{550} + R_{461} > 800$	Adapted from Laurent et al. (2014)
Habitat quality assessment	**Primary productivity**	Gross primary productivity	GPP = PAR x fPAR x LUE	Monteith (1972)
		Normalized Difference Vegetation Index	$NDVI = (R_{862} - R_{645}) / (R_{862} + R_{645})$	Tucker (1979)
	Plant traits	Chlorophyll	$CI_{red\text{-}edge} = (R_{800} / R_{702}) - 1$	Gitelson et al. (2003) Clevers & Kooistra (2012)
		Anthocyanin	$Anth = R_{800} / (R_{551} - R_{702})$	Gitelson et al. (2006) Damm et al. (2013)
		Carotenoid	$Car = R_{800} / (R_{470} - R_{702})$	Gitelson et al. (2006)
	Leaf area index	Leaf area index	$LAI = 8.452 \times (R_{702} - R_{645}) / (R_{702} + R_{645})$	Delegido et al. (2011)
	Heterogeneity	Shannon's diversity index, Simpson's diversity index, Shannon's evenness index and Simpson's evenness index	SHDI = $-\sum_{i=1}^{m} (P_i * \ln P_i)$ SIDI = $1 - \sum_{i=1}^{m} P_i^2$ SHEI = $\frac{-\sum_{i=1}^{m} (P_i * \ln P_i)}{\ln m}$ SIEI = $\frac{1 - \sum_{i=1}^{m} P_i^2}{1 - \left(\frac{1}{m}\right)}$	Shannon & Weaver (1949) Simpson (1949) McGarigal (2015)
Fragmentation	**(Fragmentation/ Ecosystem distribution)**	Effective mesh size	MESH = $\frac{\sum_{j=1}^{n} a_{ij}^2}{A} \left(\frac{1}{10{,}000}\right)$	Jaeger (2000) McGarigal (2015)

2.5.2 Target 14

ABT 14: By 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well-being, are restored and safeguarded, taking into account the needs of women, indigenous and local communities, and the poor and vulnerable.

ABT 14 focuses on the restoration and safeguarding of ecosystems that provide essential services. As mentioned in the introductory chapter of this thesis, ecosystem services (ES) are the benefits people obtain from ecosystems (MEA 2005a). Even though all ecosystems provide goods and services, some are particularly important for human wellbeing. The target to be met by 2020 is the restoration and safeguarding of those ecosystems, although it is not specified by the CBD of how those restoration or conservation measures should look like. Indicators for ABT 14 may be grouped into two sections: one type of indicator measures how much of a certain ecosystem is actually protected, safeguarded or restored (e.g. *Trends in protected area* or *Trends in protected forest*), while the second type of indicator may be used to measure the actual service provided for humans by that ecosystem (e.g. *Trends in benefits that humans derive from selected ecosystem services*) (Tab.6). If simply asking the question, if ABT 14 will be achieved by 2020, it would suffice to monitor how ecosystems are protected and restored. However, for both monitoring ES themselves or the success of mentioned protection and safeguarding efforts, additional data is needed.

Table 6: Potential indicators for assessing progress towards ABT 14: Selection of global and national indicators.

Indicator	**Organisation**
Trends in area of degraded ecosystems restored or being restored Population trends and extinction risk trends of species that provide essential services Trends in benefits that humans derive from selected ecosystem services Trends in biocapacity Trends in delivery of multiple ecosystem services Trends in natural resource conflicts Trends in economic and non-economic values of selected ecosystem services Trends in the condition and vulnerability of selected ecosystems used Trends in inclusive wealth Trends in nutritional contribution of biodiversity: food consumption	CBD
Red List Index Ocean Health Index Biodiversity for food and medicine	BIP
Protected area Biotopes of national importance Sustainable wood harvesting	FOEN
Size of protected areas Size of secure protected areas	BDM

As in the case of ABT 5, some indicators are not yet ready for use and it is unclear about data to use or on what scale to measure, or what to measure at all. None of the mentioned indicators are suitable to analyze the priority ecosystems selected for further investigation (see below), despite the *protected area* indicators. RS-EBVs are highly useful to assess efficiency of safeguarding or conservation measures by monitoring if ecosystem quality has improved, remained, or decreased in protected areas. Depending on what ecosystem and ES are investigated, almost all RS-EBVs may be used. Given the favorable conditions of Switzerland's general economic circumstances, the needs of women, indigenous, poor and vulnerable communities can be ignored in this study, as they do not play a major role in the accessibility of ES in the study area. Hence, the selection of ecosystems of particular importance were based on the needs of the local population, their contribution to health, livelihoods and wellbeing and the relation to water. Following three ecosystems in the study area were selected for further analysis:

1. the forest surrounding the city and small towns;
2. Lake Zurich; and
3. urban vegetation

Forest

Forests provide a wide range of ecological, economic and social services and functions, and an irreplaceable landscape for the population of Zurich. The same area has multiple functions and hence provides multiple services: forests are *multifunctional* ecosystems. In the Cantonal Forest Development Plan (Baudirektion Kanton Zürich 2010), the four priority functions of the Canton's forest are *protection* (against erosion, landslides, floods, water pollution, and traffic noise), *timber production, biological diversity* and *recreation*, and depending on its priority function, different safeguarding strategies exist. ES provided by forest also include climate regulation (e.g. C-sequestration) and wildlife habitat. The legal basis of forest protection on federal and cantonal level was reviewed, considering the Federal Constitution, the Federal Act on Forest, the Swiss Forest Policy 2020, the Cantonal Forest Act and the Cantonal Forest Development Plan. Safeguarding and restoration strategies and the designated specific function of the forest area within the study area were reviewed, using the Forest Development Plan. Finally, the forest area within the range of validity of the cantonal protection enactment was reviewed. Thus, the indicator *Protected forest area* was assessed using different strictness levels.

RS-EBVs may contribute to monitoring ES provided by forests in various ways. One specific service was selected in this thesis, namely the recreational value of a forest, and visualized using RS-EBVs and additional data. Recreational value of forests depends primarily on the forest area and the accessibility by roads. According to a survey about the Swiss population and forest by the FOEN and the WSL (Swiss Federal Institute for Forest, Snow and Landscape Research), the most valued forest characteristics are its scent and sounds (BAFU & WSL 2013), but those were not integrated in the product because of the difficulty to relate them to RS-EBVs. The general health of the forest and the presence of streams and ponds are also highly appreciated, while very dense and dark forests tend to be rated rather negatively (ibid.). Thus, to estimate the recreational services of the forests in the study area, a composite of LAI (to approximate the denseness and light availability of the forest, eq. 10) and GIS data of water bodies, streams and the road network was produced (Tab. 7). Buffer zones of 50 m around water bodies and 20 m around roads were added. The resulting shapefiles were subtracted from the LAI image with roads (pixel value 0.2) being more important than water bodies and streams (pixel value 0.1). The resulting map shows areas of high recreational value as low pixel values and areas of low recreational value as high pixel value.

Lake Zurich

Lake Zurich is of great economical, ecological and cultural importance for the surrounding areas. 70% of Zurich's drinking water is lake water, while groundwater and spring water account to 15% respectively (Stadt Zürich 2016; online: https://www.stadt-zuerich.ch/dib/de/index/wasserversorgung/trinkwasser.html, last access: 13 Sept 2016). Thanks to water pollution control and careful lake water treatment, usually no chlorine dioxide needs to be added to the water, which is highly appreciated by the consumers (ibid.). Condition of lakes may be judged regarding water levels, water quality and structure or morphology of the shores. Most of the ES provided by a lake depend in some way on the water quality; the better the water quality, the higher the quality of provided services.

The legal basis of protection of lakes on federal and cantonal level was investigated, reviewing the Federal Act on the Protection of Waters, the Cantonal introductory law for the water protection law and the Cantonal Panning and Building Act, thus collecting the necessary data for the indicator *Protected water bodies*. Additionally, addressing the restoration aspect of ABT 14, changes in water quality indicators over the last decades were reviewed, using data published by the FOEN and the Office of Waste, Water, Energy and Air (WWEA).

No RS-EBVs are yet proposed for freshwater ecosystems, despite being of great importance. However, there exists a variety of empirical procedures of remote sensing of inland waters (Matthews 2011). These include the Secchi disk transparency, total suspended solids, phytoplankton pigment algorithms, coloured dissolved organic matter algorithms (yellow substance), total phosphorus and more (Matthews 2011, Kloiber et al. 2002). In this study, two indices were selected and were tested on applicability using the simulated S-2 image (Tab. 7). Both phytoplankton chlorophyll-*a* and total suspended matter concentrations can be used to trace water pollutants from space using passive sensors (Gitelson et al. 1993). The total suspended solids (TSS) algorithm describes the amount of organic (detritus and phytoplankton) and inorganic (minerals) suspended particles per water volume (Matthews 2011). TSS is related to primary production, micropollutants and fluxes of heavy metals (Dekker et al. 2002). Gitelson et al. (1993) found, that the spectral region from 560-590 nm is most sensitive to variations in suspended matter and detected a close relationship of TSS to a difference ratio using wavelengths 560 and 520 nm. Using the simulated S-2 image, this difference ratio was slightly adapted:

$$\mathrm{TSS} = (R_{572}-R_{532}) / (R_{572}+R_{532}) \tag{12}$$

The second indicator selected is phytoplankton chlorophyll-*a* concentration (Chl-*a*), a key indicator of the biophysical status of inland water bodies (Moses et al. 2009). Lake Zurich still shows increased phytoplankton concentrations, despite decreasing phosphorus concentrations (WWEA 2016c), and is therefore considered worth monitoring on a regular basis. There exist various models to approximate Chl-*a*, using different spectral ranges. The spectral region most sensitive to Chl-*a* variations is 690-710 nm (Gitelson et al. 1993). A three-band model, initially developed to estimate pigment content in terrestrial vegetation (Dall'Olmo et al. 2003, Dall'Olmo & Gitelson 2005) was considered a good estimate for Chl-*a* concentrations in turbid productive waters using MODIS and MERIS data (Gitelson et al. 2009). Wavelengths around 670 nm, 710 nm and 750 nm were used in this model. Since the simulated S-2 image used in this study lacks a band in the region around 750 nm, the two-band model proposed by Moses et al. (2009) was computed (Tab. 7):

$$\mathrm{Chl}\text{-}a = R^{-1}_{645} * R_{702} \tag{13}$$

For reasons of comparison, the water mask applied also contains the main rivers of the study area and small lakes.

Urban vegetation

Urban ecosystems include a multitude of different green spaces. Parks, hedges, single trees, alleys, privately owned gardens, roof greening, allotment gardens and graveyards are examples of green spaces within urban settlements, all of them providing a multitude of different services to humans and the environment; besides habitat for numerous species or recreational value (e.g. parks and gardens) they provide temperature regulation (Loughner et al. 2012), noise moderation, have esthetic quality (Brantley et al. 2014) and improve air quality through filtration, decomposition and dispersion of polluted air (Janhäll 2015; Elmqvist et al. 2015). Accordingly, human health and well-being can be highly improved by maintaining functioning urban ecosystems (CBD 2012b). Being highly modified and under constant pressure from external disturbances, urban vegetation should be taken care of and if necessary, restored (Leadley et al. 2014). Flora and fauna in urban settlements face hard conditions, including soil sealing and compaction, habitat fragmentation and air pollution, but on the other hand, urban environments provide refuges for species that have lost their natural habitat, underlining the importance to safeguard those ecosystems (FOEN 2014a). Federal and cantonal laws and ordinances were reviewed and responsibilities of safeguarding were clarified. Within settlement area, total area of official protection was measured using GIS data of federal and cantonal protection enactments and settlement area as designated in the cantonal structure plan.

RS-EBVs, despite not helpful in measuring the protection status of ecosystems, may contribute in various ways in monitoring urban vegetation, its condition or the service it provides. In this study, a focus was set on mapping of filtration capacity of urban trees and their ability to capture pollutant particles, leading to improved air quality. Vegetation density affects both deposition and dispersion of pollutants (Janhäll 2015). Despite steady improvement of air quality in Switzerland since the 1980's, limit values of ozone, nitrogen dioxide and particulate matter with an aerodynamic diameter of less than 10µm (PM10) are regularly exceeded (Felber Dietrich 2014). PM10 consist of various chemical compounds of various particle sizes, being emitted directly (e.g. from combustion processes) or formed secondarily in the atmosphere (FOEN 2013b). Studies have shown that PM10 can have effects on human health due to the toxicity of sulphates, acids and metals and the additional problem that very small particles are able to intrude the pulmonary alveoli and even translocate from the lung to the blood, leading to respiratory and cardiovascular diseases, asthma attacks, bronchitis and lung cancer (FOEN 2013b; ERS 2010; EKL 2013). Increasing green areas and correct planting of 'green barriers' can significantly improve local air quality (e.g. Baik et al. 2012; Buccolieri et al. 2011). In this context, RS-EBV *Leaf area index* is of greatest use. Ren et al. (2013) found that LAI also had a significant impact on cooling effects of urban parks. Increasing LAI increases the filtration capacity of the vegetation, meaning that trees are more effective than grass or shrubs (Givoni 1991). Coniferous trees are more effective than deciduous trees because their needles do not shed during the winter and because of the higher LAI, suggesting a mix of species, as deciduous trees also show good qualities in absorbing gases (Bolund & Hunhammar 1999). High LAI can therefore be related to both increased pollutant deposition efficiency and cooling effects. As the filtration service is particularly important nearby highly used traffic lines, a useful tool to detect the potential of improvement along these roads was developed, by highlighting areas with low or high filtration capacity (approximated with LAI). LAI was calculated using the adapted formula based on Delegido et al. (2011) (Tab. 7). Buffer polygons around 3 main road types were combined with the LAI image: high performance highways (*Hochleistungsstrassen und Hauptverkehrsstrassen*; buffer: 50 m and 30 m, pixel values 2 and 1) and municipal roads (*Gemeindestrassen*; buffer: 10m, pixel value 0.5) were added to the LAI pixel values. The higher the value within these buffer zones, the higher is the filtration service. If the values are similar to values outside the buffer, smaller or even zero, there exists room for improvement and it is recommended to add some vegetation to this area.

Table 7: Overview of selected RS-EBVs and additional data for assessing progress towards ABT 14: Recreational value of forest was estimated using RS-EBV LAI and GIS data of the road and water network. Lake water quality was estimated using total suspended solids and the chlorophyll concentration algorithm Chl-*a*. Areas of (desirably) high filtering capacity of urban vegetation was estimated using a combination of LAI and buffer areas around intensively used roads.

	Ecosystem service or quality	**RS-EBV**	**Measurement parameter**	**Adapted Formula**	**Source**
Forest	Recreational value	**Leaf area index**	Leaf area index Combined with road network (OSM) and water bodies (GIS)	LAI = 8.452 x $(R_{702} – R_{645})$ / $R_{702} + R_{645})$ Recreational value = LAI – OSM – water Buffer zone around roads = 0.2 Buffer zone around water = 0.1	Delegido et al. (2011) © OpenStreetMap contributors
Lake	Water quality	**-**	Total suspended solids	TSS = $(R_{572}-R_{532})$ / $(R_{572}+R_{532})$	Gitelson et al. (1993)
			Chlorophyll-a	Chl-*a* = R^{-1}_{645} x R_{702}	Moses et al. (2009)
Urban vegetation	Air quality regulation	**Leaf area index**	Leaf area index Combined with intensively used roads Layers form Swiss road network: Hauptverkehrsstrassen (*HVS), Hochleistungsstrassen (HLS), Verbindungsstrassen (VS)* and *Gemeindestrassen (GS)*	LAI = 8.452 x $(R_{702} – R_{645})$ / $(R_{702} + R_{645})$ Area of high filtration capacity = LAI + (HVS & HLS) + VS + GS HVS & HLS = 2 VS = 1 GS = 0.5	Delegido et al. (2011)

2.5.3 Target 15

By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration, including restoration of at least 15 per cent of degraded ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification.

The last ABT considered in this thesis is ABT 15, which sets a focus on ecosystems that store considerable amounts of carbon and their conservation and restoration, thereby improving resilience and contribution of biodiversity to carbon stocks. In the terrestrial biosphere, organic carbon is stored either in living vegetation biomass, or as dead organic matter in litter and soil, or as old soil carbon in permafrost and wetland soils (Ciais et al. 2013). The majority of carbon is stored in soils (Jobbágy & Jackson 2000). In the context of ABT 15, carbon stocks refer to the carbon stores found in both soils and biomass (CBD Quick guide to Aichi Biodiversity Target 15, n.d.). When planning the implementation of this target, the CBD recommends to set the focus on forests, wetlands, peat lands and other ecosystems storing great amounts of carbon. Thus, forests and raised (peat) bogs were selected as priority ecosystems. Global indicators for assessing progress towards ABT 15 are proposed by the CBD (Tab. 8). The BIP does not mention any indicators for ABT 15. RS-EBVs most suitable for assessing progress towards ABT 15 are considered *primary productivity, vegetation phenology, plant traits* and *heterogeneity*.

Table 8: Potential indicators for assessing progress towards ABT 15: Selection of global and national indicators available.

Indicator	**Organisation**
Population trends of forest-dependent species in forest under restoration Status and trends in extent and condition of habitats that provide carbon storage Trends in area of degraded ecosystems restored or being restored Trends in delivery of multiple ecosystem services Trends in biocapacity Trends in economic and non-economic values of selected ecosystem services	CBD
Carbon stocks in forest	FOEN
RS-EBV	
Primary productivity Vegetation phenology Plat traits Heterogeneity	GEOBON

In general, the CBD does not specify restoration measures, which makes sense given that choosing those measures depends on the degree of degradation an ecosystem may suffer. Policy options, soil restoration, reforestation and structural alteration of vegetation are examples for restoration activities (Leadley et al. 2014). With regards to the specific area targeted in this study, restoration options for degraded ecosystem was not further pursued for following reasons: The phrasing of the target implies that there is a distinctive criterion defining an ecosystem as being degraded or not, e.g. some ecosystem property exceeding a certain value (one example would be moisture content or humus content of mires). However, the CBD does not specify whether the *15%* that should be restored refer to the whole degraded area at the time of inspection, the ecosystem area before degradation started, or the manifestation of some degradation symptom as a value on a scale. No definition is provided of what 15% of restoration would look like in practice as there is no reference value with regards to condition or time, meaning that there is no clearly defined value that defines 15% (or 1% or 100%) on a clearly defined time scale. The lack of clarity in the formulation of the target leaves no feasible option to assess progress towards achieving 15% of restoration of degraded ecosystems in the study area, as there are too many unknown and immeasurable variables to consider. In the context of this study, conservation status of both forest and raised bogs were investigated using GIS data and legislative publications.

Forest conservation and contribution of biodiversity to carbon stocks, respectively, were investigated using RS-EBVs as they are useful for monitoring changes within and outside forest conservation areas. Potential contributions of RS-EBVs for finding a link between forest conservation and resilience, and forest conservation and contribution of biodiversity to carbon stocks, respectively, was investigated. The following RS-EBVs were selected as important contribution to assess this relationship:

- *Heterogeneity* of *plant traits* to assess ecosystem resilience
- *Primary productivity* and its relationship to *heterogeneity* of *plant traits* to investigate the contributions of biodiversity to carbon stocks.

Ecosystem resilience

Walker et al. (2004: 2) define resilience as the "*capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks*". The CBD uses more or less the same definition based on Carpenter et al. (2001) in its reports, stating that ecosystem resilience is "*the capacity of ecosystems to absorb and adapt to disturbances while preserving their ecological functions and without moving to a new state governed by different processes and controls*" (Leadley et al. 2014: 361). The CBD strives to enhance ecosystem resilience by restoration and conservation. On landscape level, resilience of ecosystems can be enhanced by increasing spatial heterogeneity, connectivity and the habitat size (Oliver et al. 2015). To assess the status of ABT 15 it was therefore investigated if the heterogeneity of plant traits in the study area was higher in protected areas than in the surrounding ones.

A variety of mechanisms are involved in the relationship between environmental heterogeneity and ecosystem stability, e.g. the asynchrony of species responses to environmental fluctuations, differences in the response speed to perturbations, and a reduction in the strength of competition (Loreau & de Mazancourt 2013). While there is a general acceptance of the need for fostering a positive relationship between heterogeneity, biodiversity and resilience, tracking methods to gather empirical data on a regular basis are yet to be developed, especially in the study area. An alternative tracking method is to monitor recovery of forests after a disturbance, and relate the recovery rate to forest heterogeneity and the conservation status of forest. The first step in this process is mapping heterogeneity of the forest area. The possibilities of heterogeneity assessment via RS was discussed in chapter 2.5.1. Due to missing consensus on landscape heterogeneity metrics, two common simple landscape diversity indices and their respective evenness indices were computed for two plant traits. SHDI, SIDI, and their respective evenness indices of one chemical ($CI_{red\text{-}edge}$) and one structural (LAI) plant trait were calculated for forest areas and compared to SHDI and SIDI of the same plant traits only considering the forest protection zone of the cantonal protection enactment of Canton of Zurich (Tab. 9).

Additionally, the SHDI of both LAI and $CI_{red\text{-}edge}$ was visualized, based on a neighborhood of 1 ha (moving window). To avoid data errors due to proximity to forest edges, SHDI of LAI and $CI_{red\text{-}edge}$ was plotted for two areas of 1 km^2, one within the perimeter of the forest protection zone and one in an unprotected forest.

Contribution of biodiversity to carbon stocks

Significant positive effects of biodiversity on forest productivity have been reported (Paquette & Messier 2011). Finding a relationship between heterogeneity and productivity would approximate the prominent question, whether *biodiversity contributes to carbon stocks*, which is aimed at in ABT 15, but adapted to RS-EBVs. As both forest productivity and forest diversity depend on ecological context (Belote et al. 2011), it is essential to investigate any such relationship in the study area, rather than rely on other studies. Experiments are usually time- and labour-intensive, as well as limited on small areas. In previous studies, a variety of methodologies was used to measure heterogeneity, diversity, and productivity, tested in different ecosystem types (mainly grassland) for different duration and using different scales. Consequently, current research does not agree on the nature of the relationship between heterogeneity or diversity, productivity, and the underlying mechanisms (Adler et al. 2011; Katayama et al. 2014; Fahrig et al. 2011; Lange et al. 2015).

A method to monitor the relationship between heterogeneity of plant traits and productivity of a forest using RS-EBVs measured by S-2 and a selection of heterogeneity metrics was developed. Following methodology was selected to investigate the heterogeneity-productivity relationship of forest in the study area: Forest heterogeneity was measured with the heterogeneity of plant traits chlorophyll content and LAI, using the SHDI. As only one observation is possible within the framework of this thesis, the resulting values were plotted against productivity values, using a simplified version of the GPP Monteith approach (chapter 2.5.1.) with an average LUE of 0.48 g C/MJ for all vegetation types (Tab. 9). To avoid distortion of heterogeneity values due to the forest edges, two squares of the size of 1 km^2 were compared. Both squares are located completely inside forest area, one of them within the forest protection zone of the cantonal protection enactment.

Table 9: Overview of selected RS-EBVs used in the context of ABT 15.

Aspect of ABT 15	RS-EBV	Measurement parameter	Adapted Formula	Source
Resilience	**Plant traits and Leaf area index**	Leaf area index	$LAI = 8.452 \times (R_{702} - R_{645}) / (R_{702} + R_{645})$	Delegido et al. (2011)
		Leaf chlorophyll	$CI_{red\text{-}edge} = (R_{800} / R_{702}) - 1$	Gitelson et al. (2003) Clevers & Kooistra (2012)
	Heterogeneity	SHDI	$SHDI = -\sum_{i=1}^{m} (P_i * \ln P_i)$	Shannon & Weaver (1949) McGarigal (2015)
Contribution to carbon stocks	**Primary productivity**	Gross primary productivity	$GPP = PAR \times fPAR \times LUE$	Monteith (1972)

3 Results

3.1 Target 5

Methods for monitoring extent, degradation and fragmentation of forest and rare habitats were assessed using GIS data and the simulated S-2 image.

3.1.1 Extent of natural habitat

Total area of natural habitat, including forest and rare habitat types, is 84.24 km^2. Forest extent was measured using available GIS data and the simulated S-2 image. There are major differences, depending on what method was used (Tab. 10). Using the forest layer of the cantonal structure plan, forest area amounts to 82.35 km^2 (Fig. 2a). This corresponds to approximately 24.5 % of the study area and 97.5% of total natural habitat. Forest could be extracted from the image using a SAM (98.18 km^2) and a MLC (93.82 km^2). LSU failed to produce reasonable results, while the classification based on the sum of the red, green and blue bands, masking out pixel values higher than 800 resulted in a total forest area of 93.78 km^2 (Fig. 2b). Logically, S-2 extracted forest areas include vegetation outside the area that is defined as forest by law (i.e. the forest of the GIS data), while they omit vegetation inside those boundaries, e.g. in very light forest and clearings.

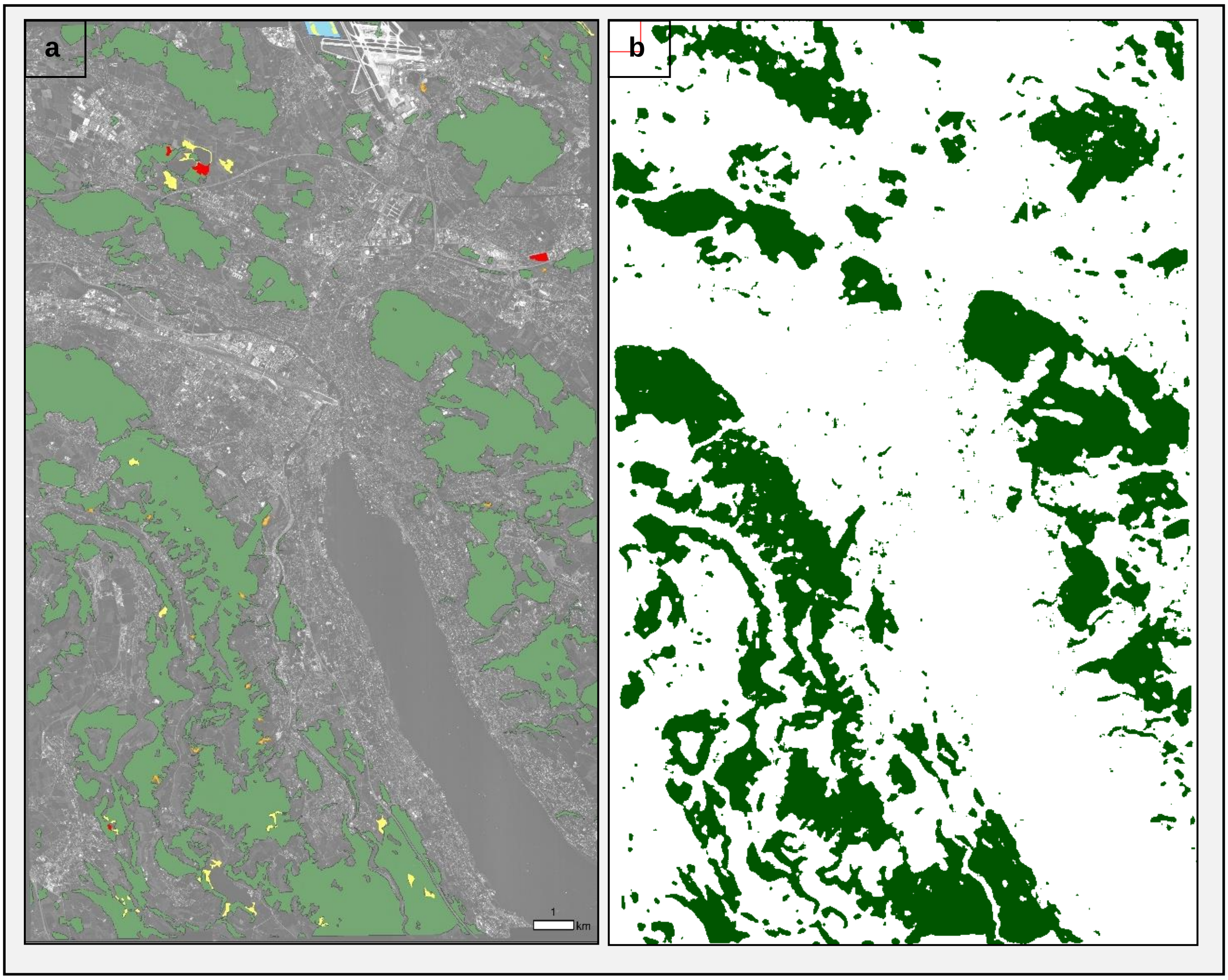

Figure 2: Natural habitat in the study area: a) using available GIS data: Forest (green), alluvial zones (blue), raised bogs (red) and fens (yellow), dry meadows and pastures (orange). b) Forest area extracted from the simulated S-2 image using the sum of bands with reflectance at 645, 550 and 461 nm and masking out values over 800.

Table 10: Total forest area assessed using different methods: Forest area as designated by the cantonal structure plan is over 10 km^2 smaller than forest area extracted forest from the simulated S-2 image.

Assessment method	**Forest area [km^2]**
Cantonal structure plan (GIS)	82.35
SAM	98.18
MLC	93.82
1 < R+G+B < 800	93.78

Based on available GIS data, the indicator *Size of valuable habitats* was assessed. The areas of alluvial zones (blue in Fig. 2a), raised bogs (red) and fens (yellow), dry meadows and pastures (orange) were measured individually (Tab. 11). All rare habitats together cover an area of 1.23 km^2 (123.67 ha), corresponding to approximately 0.36% of the total study area.

Table 11: Sizes of valuable habitats in the study area and in the total area of Switzerland.

	Alluvial zones	**Raised bogs**	**Fens**	**Dry grasslands**
Area [km^2]	1.17	0.15	0.91	0.10
Area [ha]	117.2	15.8	91.4	10.3
Percent of study area	0.35	0.05	0.28	0.03
Switzerland [ha]	22'639	1'524	19'218	21'558
Switzerland [%]	0.55	0.04	0.47	0.52

In the study area, four raised bogs are present (*Chräenriet, Chatzensee, Moos Schönenhof bei Wallisellen* and *Moor Rinderweiderhau*), accounting to a total area of 15.8 ha. Additionally, there are 20 fens present in the study area, most of them very fragmented and small. Their total area amounts to 91.4 ha. Bogs and fens in the study area are all very close to either agricultural area (e.g. *Chatzensee*) or within very urban settlement areas (*Moos Schönenhof bei Wallisellen*). A buffer zone seems to be missing around most bogs and fens and only the ones in the southern part of the study area located in forests and are more or less untroubled by anthropogenic influences. In the intensively used landscape of the study area, dry meadows and pastures are the rarest of natural habitats, amounting to only 10 ha. LSU and SAM were applied on the simulated S-2 image to extract rare habitats, but did not yield satisfying results.

3.1.2 Quality of forest

RS-EBVs *primary productivity*, *plant traits* and *heterogeneity* were assessed for forest area. As estimation for *primary productivity*, GPP was calculated (Fig. 3). GPP values in forest area range from 0 to 7.97 kg C day^{-1}, with a mean value of 1.2 and standard deviation of 2.56. Some artifacts are visible where the flight lines were mosaicked, and also effects of reflectance anisotropy are visible at the western edge of the study area. The GPP product is shown in original APEX spatial resolution, while the potential S-2-product would yield a spatial resolution of 20m. High productivity is often found at forest edges, while areas of low productivity include the mountain ridge west of the lake and the forest area in the northeastern corner of the study area.

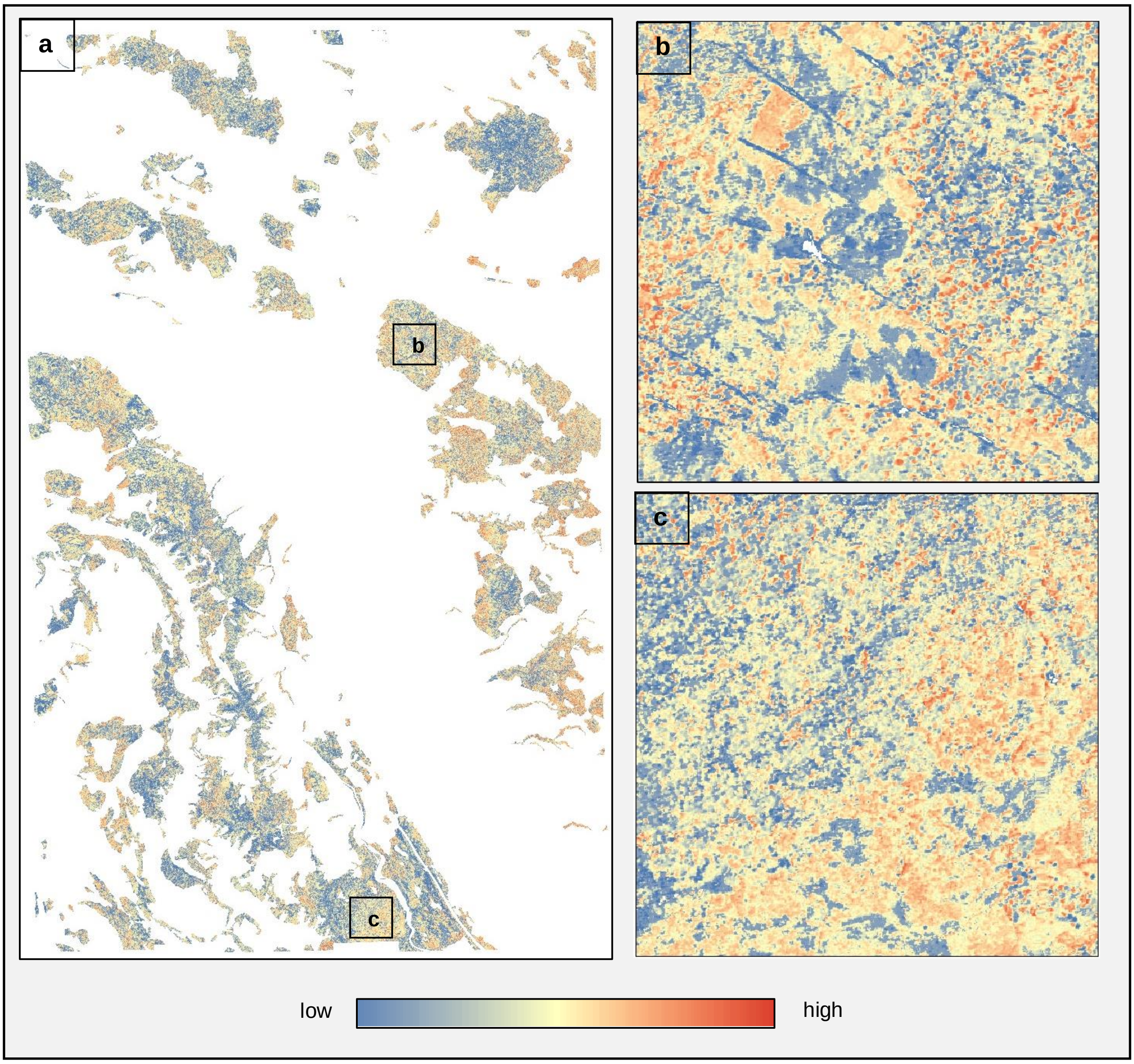

Figure 3: Gross primary productivity (GPP) of forest in the study area. GPP is shown for total forest (a), and two enlarged areas of 1km^2 (b and c). Depending on vegetation type (coniferous or deciduous forest, crop or grassland) different LUE was used. Artifacts of the flight lines and directional effects are clearly visible on the western edge of the study area.

Spatial variability of plant pigments Chl, Anth and Car was assessed (Fig. 4 a-c). $CI_{red\text{-}edge}$ was calculated for forest area using the ratio of simulated S-2 bands with reflectance at 800 nm and 702 nm (Fig. 4a). The index results in positive values, with clearly visible variations. The spatial pattern of $CI_{red\text{-}edge}$ corresponds to variations in GPP. Along the north-south mountain ridge west of the lake, $CI_{red\text{-}edge}$ yields higher values at the west slope than at the east slope. Anthocyanin and Carotenoid concentration was estimated as well, using adapted equations from Gitelson et al. (2006). Both Anth and Car indices result in negative values, with values approximating zero indicating higher pigment concentration. Spatial variations in Anth are very high and Car is impacted by mosaicking artifacts. Car concentration is inversely distributed to $CI_{red\text{-}edge}$. While the $CI_{red\text{-}edge}$ index is able to mask out roads and soil within the forest area, this is not the case for Anth and Car. As the indices differ strongly, the given results are not suitable to compare pigment concentrations to each other, but are only valid for interpretation within one image. The images are shown in the original APEX spatial resolution of 2 m, while the end product of S-2 would have a spatial resolution of 20 m.

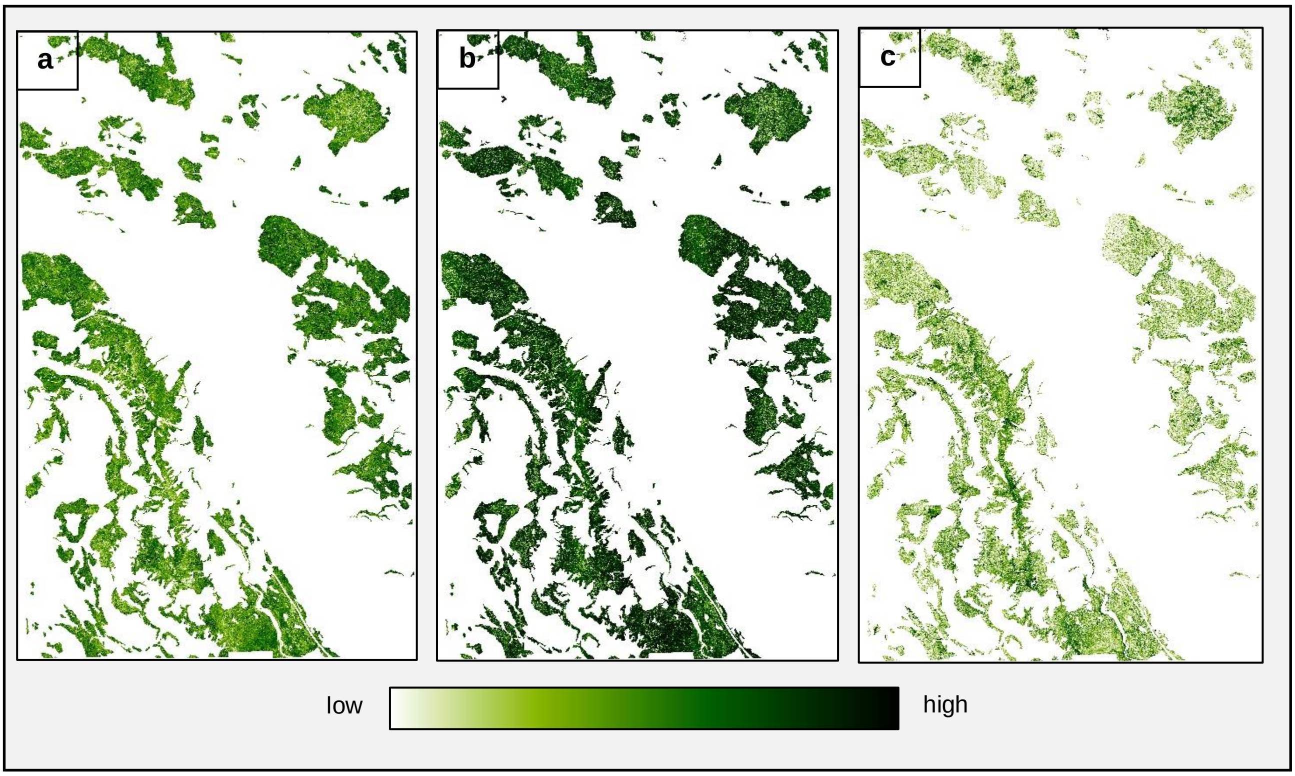

Figure 4: Variation in pigment concentration in the study area's forest. a) Chlorophyll, b) Anthocyanin and c) Carotenoid. The indices have been scaled individually for their respective value range, and are thus not comparable between each other.

To determine plant trait heterogeneity, SHDI, SIDI, SHEI and SIEI were computed for $CI_{red\text{-}edge}$ and LAI for forest area (Tab. 12).

Table 12: Heterogeneity metrics computed for $CI_{red\text{-}edge}$ and LAI using a spatial resolution of 20 m: Shannon's diversity index (SHDI), Simpson's diversity index (SIDI), Shannon's evenness index (SHEI) and Simpson's evenness index (SIEI).

	SHDI	**SIDI**	**SHEI**	**SIEI**
$CI_{red\text{-}edge}$	4.57	0.99	0.76	0.99
LAI	2.11	0.46	0.32	0.99

Heterogeneity values depend on the spatial resolution and the results here refer to a spatial resolution of 20 m. As mentioned, the absolute value of SHDI is not relevant, but it is useful as relative index (e.g. for monitoring the same trait over time). SIDI increases with the probability that two randomly chosen pixels would be different patch types. With SIDI and SIEI values of 0.99, heterogeneity and evenness of $CI_{red\text{-}edge}$ is very high. According to the SIDI, heterogeneity of LAI is smaller than heterogeneity of $CI_{red\text{-}edge}$.

3.1.3 Quality of rare habitats

The most promising approach to assess progress towards ABT 5 in terms of degradation of rare habitats is the BDM indicator *Quality of valuable habitats*. Combining aerial photos and ground assessment of quality features, detailed maps are produced (BDM 2015a). Values of moisture, nutrient, humus, light and share of woody plants are determined for sampling areas of 1 km^2 (Klaus 2007, BDM 2015a). Conducting a total assessment for the total study area goes beyond the scope of this thesis, but is considered necessary for assessing progress towards ABT 5, regarding of rare habitat types.

Considering the mean patch area of rare habitat types (mean area of individual patches of raised bogs, fens, alluvial zones and dry meadows and pastures are 3.95, 2.53, 28.67 and 0.73 ha, respectively) and the spatial resolution of S-2 being 10 and 20 m, RS-EBVs assessed for forest can also contribute information for rare habitat types, if using a GIS based mask: even though rare habitats cannot be distinguished by the MSI instrument aboard S-2, GPP and pigment content may still be monitored.

3.1.4 Fragmentation of natural habitat

The general distribution and size of habitat patches was analyzed using GIS data of forest and rare habitats. A total of 155 individual patches of natural habitat are present in the study area, some of them including more than one habitat type. Mean patch size is 54.34 ha. Most patches are smaller than 5 ha (92 of 155), 20 patches are larger than 50 hectares (Fig. 5). Most forests are located in higher altitudes in the study area, while raised bogs and fens are found in small patches close to water bodies. Dry meadows and pastures are usually located close to forests.

The effective mesh size (MESH) was computed for natural habitat, fragmented by roads and railways, resulting in 2.44 ha.

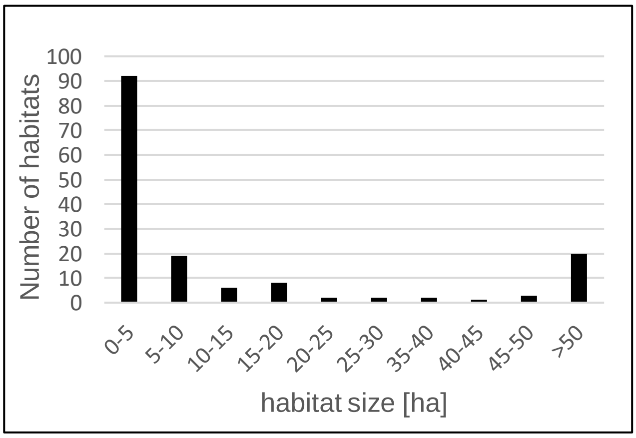

Figure 5: Size distribution of individual patches of natural habitats. Most individual habitat patches are smaller than 5 ha. 20 habitat patches spread over more than 50 ha.

A visual analysis was conducted using again OSM data extracts (Fig. 6). Between 20 November 2014 (blue lines) and 1 April 2016 (red lines) approx. 50 km of road network has been added to the OSM dataset within natural habitat of the study area. Roads and railroads in 2014 sum up to 945 km, and the updated dataset of January 2016 to 993 km. It was also analyzed, if road sections have disappeared from the dataset. A very small amount did actually disappear, however, mainly very short sections of dead-end tracks. One path section of about 700 m along a ridge in the Sihlwald was not found anymore (neither in the Swiss national maps nor in Google maps). Other changes in the data are small adaptions of the exact pathways.

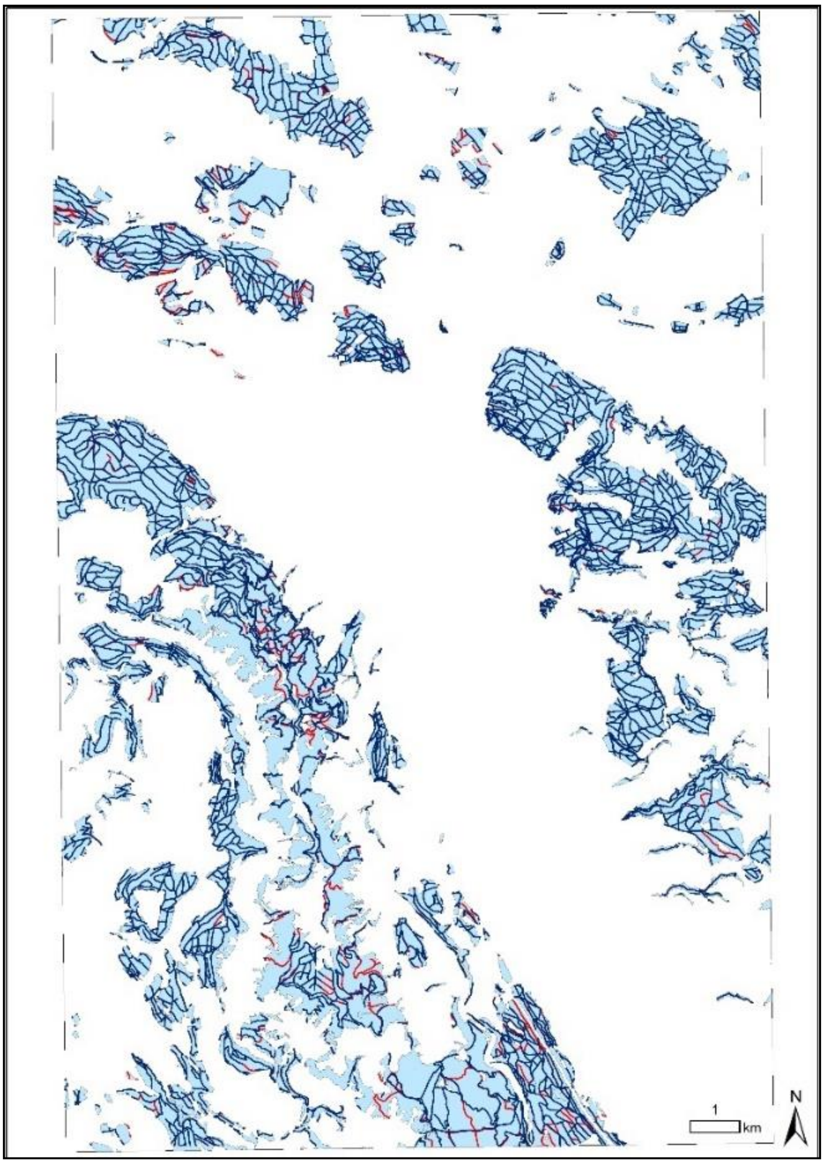

Figure 6: Traffic infrastructure within natural habitat (blue shaded area): roads and railways of the 2014 dataset (blue lines) and those added up to January 2016 (red lines). Note: this map contains information from *OpenStreetMap*, which is made available here under the Open Database License (http://opendatacommons.org/licenses/ odbl/1.0/).

3.2 Target 14

Three ecosystems (forests, lake and urban vegetation) were analyzed on safeguarding approaches, reviewing the legal framework and reports published on the subject. Generally speaking, following three indicators would suffice for monitoring progress towards ABT 14: *Protected forest, protected water bodies* and *protected areas in urban environments*. These areas were assessed on grounds of available GIS data. Additionally, potential contributions of RS for monitoring ES were tested. For better overview, restoration and safeguarding of forest, the lake and urban vegetation will be presented first, while potential contributions of S-2 for monitoring ES will be presented in chapter 3.2.2.

3.2.1 Restoration and safeguarding approaches

Forest

Safeguarding, conservation and restoration of forests in Switzerland is handled on different levels. Legal foundation at federal level is provided by the Federal Constitution. The Federal Act on Forest is intended to conserve the forest in its area and spatial distribution and ensure its functions (Art. 1). Accordingly, deforestation is prohibited, but a permit may be granted for exceptional reasons (Art. 5) and in this case, has to be compensated for (Art.7). Forest area should not be reduced (Art.3). The Federal Act on Forest also provides guidelines for the maintenance and use of the forest:

SR 921.0

Art. 20 Forest management principles

[1] The forest shall be managed in such a way that it can fulfil its functions without interruption or restriction (sustainability).

[2] The cantons shall enact planning and management regulations; in doing this, they shall take into account the requirements of wood supply, near-natural silviculture and the protection of nature and cultural heritage.

[3] Should the state of the forest and forest conservation allow it, the maintenance and use of the forest may be dispensed with entirely or in part for ecological and landscape reasons.

[4] The cantons may delimit suitable areas as forest reserves for the conservation of the species diversity of flora and fauna.

[5] Where required by the protective function of the forest, the cantons ensure a minimum level of maintenance.

For an optimal coordination of economical, ecological and social demands on forest and guarantee of its sustainability, the Swiss Confederation’s Forest Policy 2020 defines long-term policy objectives, strategic guidelines and measures (to 2030) (FOEN 2013a; FOEN 2012). Wood harvest potential, climate change mitigation, ecosystem services, species conservation, forest area conservation, forestry efficiency, soil protection, protection against invasive species, forest as wildlife habitat, leisure and recreation, and education are key aspects of the Forest Policy 2020 (FOEN 2013a). The cantonal forest is managed according to the guidance of the Forest Development Plan (*Waldentwicklungsplan*, WEP, Baudirektion Kanton Zürich 2010). Its declarations are mandatory for cantonal and communal public authorities and private forest owners. Depending on priority function (Fig. 7), safeguarding strategies can differ substantially. The maintenance of *protection forest* demands mixed, semi-natural forest stands and care of forests along ravines, roads, railways and pipelines, without clearings and requires replacement planting if necessary (Baudirektion Kanton Zürich 2010). If the priority function of the forest is *timber production* (dark green in Fig. 7), specifically high quality woods have to be fostered, while soil, flora and fauna need to be treated with care (ibid.). Forests with priority function *biological diversity* (yellow) require professional care to ensure the conservation of structural and species diversity and wildlife habitat; deadwood and old forest shall be conserved and require safeguarding strategies according to location-specific protection targets (e.g. fostering of oaks or yews) (ibid.). Forest with priority function *recreational* use (dashed orange, not present in the study area) requires certain guidance measurements to prevent conflicting use. It needs maintenance taking into account the populations multifaceted requirements. Almost the entire forest area in the study area has a specific priority function, while only small patches have none specified (areas colored bright green). Even though there is no area present in the study area with priority function *recreation*, areas with priority function *timber production* are often as well highly used as recreation area by the population.

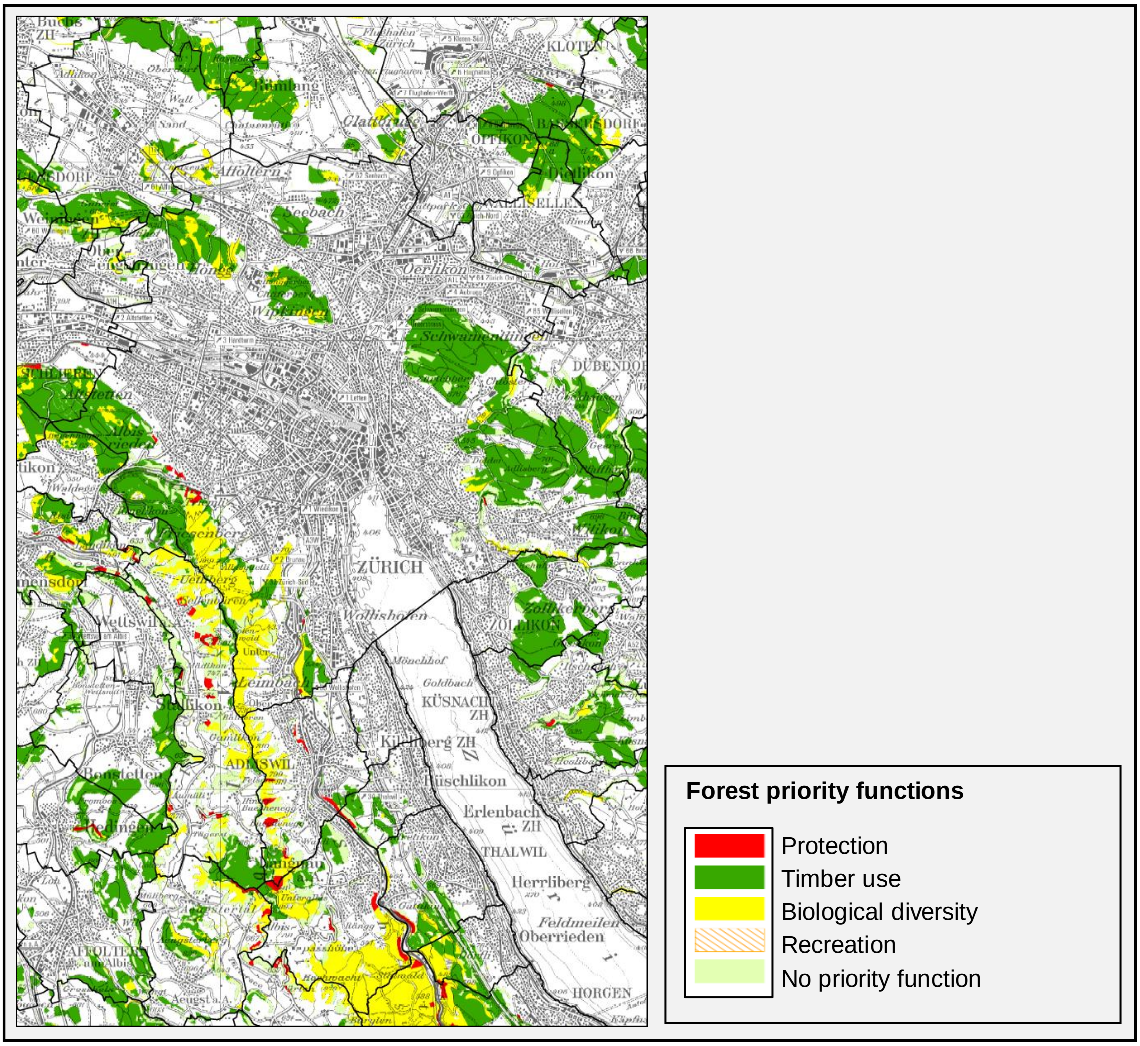

Figure 7: Forest priority functions protection (red), timber use (dark green), biological diversity (yellow) or no priority function (light green). No area of priority function recreation is present in the study area. Source: Baudirektion Kanton Zürich: Waldentwicklungsplan Kanton Zürich 2010 - Waldfunktionen.

Forest accounts for 24.5% of the study area (82.35 km^2), of which 17.48 km^2 (21.22% of forest area) is included in the cantonal protection enactment (*Kantonale Schutzverordnung SVO*) (Fig. 8) or in the cantonal structure plan, which are usually overlapping. Protection enactments are applied by the cantonal authorities where landscapes or ecosystems are of particular importance and are suitable for large-scale protection (Meier 2003). The corresponding care and protection measures vary within the area of the protection enactment, depending on the value and the endangerment of an ecosystem and the duration of recovery in case of degeneration (ibid.). While the protection enactment *by old law* (bright green in Fig. 8) mainly handles the regulation of construction activity, the new enactment also considers other environmental pressures (e.g. nutrient input from agricultural activities) and replaces many of the old enactments with detailed planning strategies (ibid.). The new protection enactment and the inherent ordinance determine the use and restriction of the different zones and set maintenance measures. 7.73 km^2 are explicitly considered as forest protection zone (dark green in Fig. 11). The main goal in forest protection zones is the long-term conservation of site-specific forest communities, forest types worthy of protection, staged forest edges, biologically and scenically valuable elements. The forest is to be fostered and used according to the maintenance plan of the respective municipality. The remaining forest area included in the cantonal protection enactment distinguishes between landscape protection zones (0.3 km^2 or 30 ha), nature protection zones (37 ha), nature proximity zones (0.93 ha), lake and shore protection zones (0.52 ha), and recreation area (1 ha). Each of these zones requires specific maintenance and protection measures that are considered beyond the scope of this thesis.

Depending on how ‘protected’ or ‘safeguarded’ area is defined, the before mentioned suitable indicator *Protected forest area* results in either 100% of forest area (given the remarks in the Federal Act on forest), 21.22% of forest area (regarding the cantonal protection enactment) or 9.3% if only including the forest protection zone.

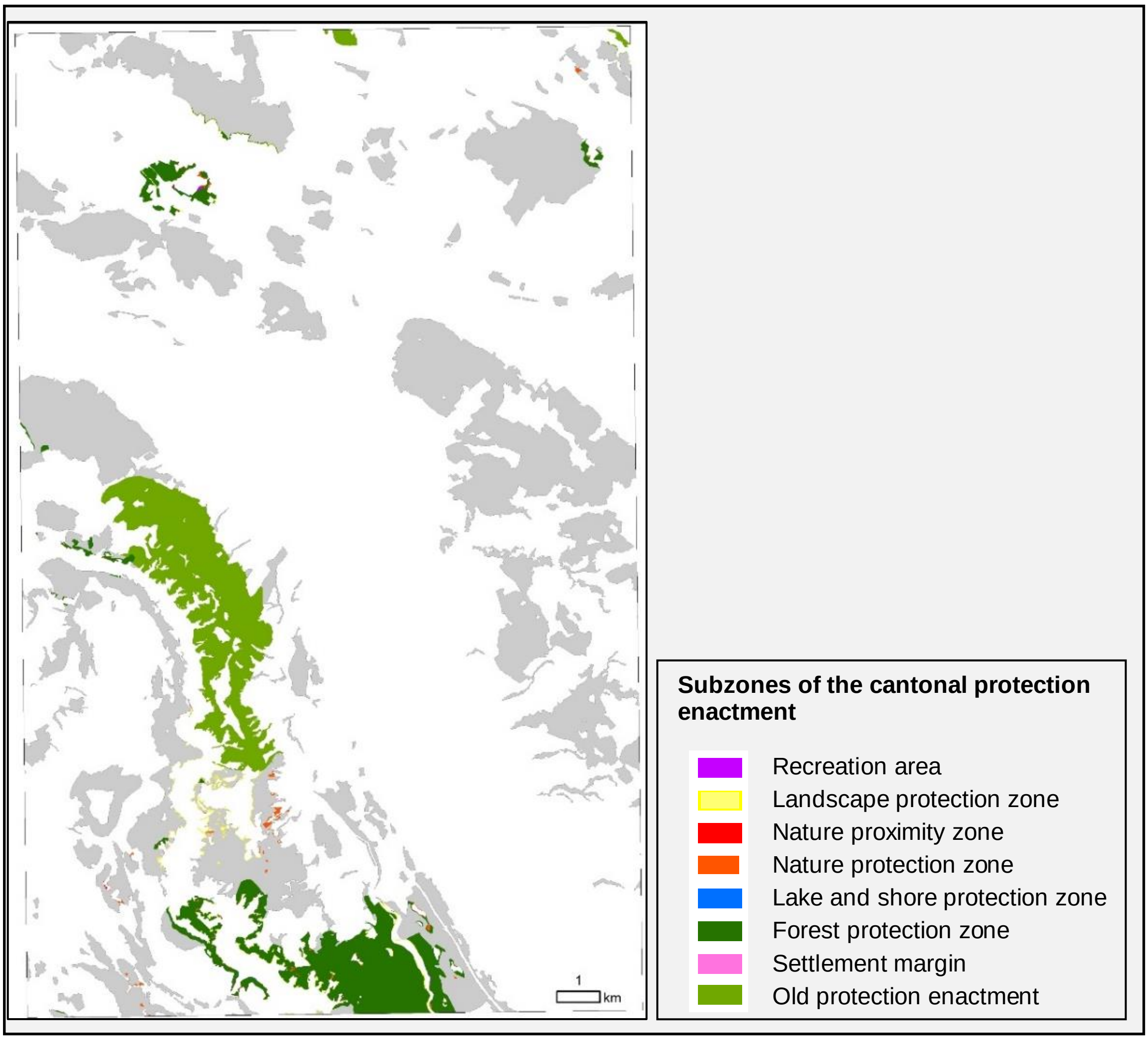

Figure 8: Forest areas (grey) covered by the cantonal protection enactment: the old but still legally binding enactment (bright green), the new enactment, including forest protection zone (dark green), landscape protection zone (yellow), nature proximity zone (red), nature protection zone (orange), lake and shore protection zone (blue), recreation area (purple).

Lake Zurich

The Federal Act on the Protection of Waters aims at, inter alia, *"preserving the health of people, animals and plants, guaranteeing the supply and economic use of drinking water and water required for other purposes, preserving natural habitats of indigenous flora and fauna and ensuring the natural functioning of the hydrological cycle"* (Waters Protection Act, WPA, 814.20, Art. 1). The Waters Protection Act and its associated Ordinance set the legislative basis for water protection in Switzerland. They describe how the quality of water is to be maintained, determine the required measures if the water quality is insufficient, and define responsibilities of the different levels of authority. The restoration and renaturation of watercourses play a major role in future strategic planning, while waste water treatment and selective restrictions of substances are required to improve water quality (FOEN 2014a). The Confederation grants compensatory payments to the cantons for the necessary installations in waste water treatment plants. Additional requirements of standing water bodies are determined: first, changes in terrain (e.g. digging, shore embankment) shall not sustainably change or endanger the morphology nor the functions of the lake bottom, that are essential for the conservation of water quality necessary for the survival of flora, fauna or microorganisms. Second, nutrient concentration shall not exceed mean production of biomass. Third, natural temperature and nutrient conditions shall not be changed (e.g. by water regulation or use). Oxygen concentration shall under no circumstances and in no water depth fall below 4 mg/l (SR 814.201 Waters Protection Ordinance). The cantonal introductory law for the water protection law (711.1) and the respective Ordinance (711.11) additionally issue fields of responsibilities but do not mention Lake Zurich in particular. However, *"essentially unspoiled natural and cultural landscapes, as well as water bodies, including shore and vegetation cover"* (Cantonal Planning and Building Act, LS 700.1, Art. 203), are considered protection objects. Thus, the indicator *Protected water bodies* in the study area can be stated as 100%. Protected Water bodies only including the strict definition of protection by the FOEN, 0% of lake Zurich's area is protected.

Restoration activities of the last decades seem to grasp in Swiss water bodies: Pollutant and nutrient inputs into lakes have declined considerably as the result of a combination of water protection measures, improved waste water treatment, the ban of phosphates in laundry detergents in 1986 and other processes lead to a reduced phosphorus pollution of Switzerland's lakes (FOEN Indicator Phosphorus content in lakes, FOEN 2015). The WWEA publishes assessments of all of the canton's lakes regarding their water quality, development of phyto- and zooplankton and if present, its circulation assistance. Data for Lake Zurich include phosphorus and inorganic nitrate development, oxygen concentration and fresh weight of algae since 1982. As quantitative measure of algae amount, only chlorophyll concentration is measured since 2003. There is no generally valid target value for phosphorus concentration in Swiss lakes, as they react differently to phosphorus pollution, depending on depth, wind conditions or replacement rate. However, for values lower than 0.15 to 02 mg P_{tot}/l, the legal guideline of maximum average production of algae biomass is usually fulfilled (FOEN 2015). During the last four decades, the total phosphorus concentration of Lake Zurich has decreased from ca. 0.1 mg P_{tot}/l to just over 0.02 mg P_{tot}/l (WWEA 2016a). The nitrogen concentration of Lake Zurich has declined since the 1990s (WWEA 2016b). Algae density, despite being regulated by phosphorus, did not decrease, but expanded into deeper water. Since 1985, yearly maximum values of algae biomass production are lower than in the previous investigation period (1972-1984) and mass blooming appeared less often (WWEA 2016c). The fraction of nutrient loving algae decreased, while diatoms and the harmful cyanobakterium *Planktothrix rubescens* increased strongly (ibid.). In Lake Zurich, *P. rubescens* is the dominant primary producer, accounting to half of the total phytoplankton biomass (van den Wyngaert et al. 2011). It profits enormously from longer stratification periods and increased thermal stability due to changing climate (Stadt Zürich 2016). The FOEN's core indicator *Organic trace materials in surface waters* shows negative state and trend. Efforts to improve above mentioned variables include an optimized waste water treatment (Stadt Zürich 2016), change of focus to organic agricultural production (WWEA 2016d) and decreasing atmospheric pollution (2016b).

Urban vegetation

The municipalities of Canton of Zurich are compelled to fulfill certain demands set by laws and provisions to maintain a sustainable land use. The Federal Act on the Protection of Nature and Cultural Heritage (NCHA) sets the framework with regards to the protection of animals and plants (Art. 18). According to the cantonal Planning and Building Act, municipalities are responsible for the protection of objects of communal importance and their maintenance (PBG 700.1, Art. 211). For this purpose, they are obliged to develop an inventory of protection objects of communal importance, which is legally binding for authorities and are to be maintained if public interest is prevailing. Protection objects are, inter alia, *precious parks and gardens, trees, tree populations, thickets and hedgerows* (Art. 203, f.) and *rare or threatened animal or plant species and for their survival necessary habitats* (Art. 203, g.). Protection measures are carried out through provisions of planning acts, protection enactments, provisions or contracts (LS 700.1 Art. 205). Details about implementation of protection measures are listed in Art. 206-217. Any building project requires an inspection, if valuable habitats or species are threatened. If this is the case, controversial interests need to be clarified and carefully balanced (Office of Landscape, Agriculture and Environment, OALE 2016).

Settlement area (as defined in the cantonal structure plan; 121.03 km^2 in the study area) was investigated regarding protection areas. 2.06% of total settlement area (2.5 km^2) are covered by federal or cantonal protection areas (including biotopes of national importance, the cantonal protection enactment and partly the inventory of regional and cantonal importance), in some cases overlapping (Tab. 13). Federal inventories cover 0.25% of the settlement area. These areas are biotopes of national importance or landscapes and natural monuments of national importance, including unique landscapes, typical Swiss landscapes, recreational landscapes and natural monuments. In the study area, two spacious areas are listed as landscapes and natural monuments of national importance: The *Albiskette-Reppischtal*, covering the ridge to the west of the lake, and the area around the *Chatzenseen*. Legal provisions about the use or protection of those landscapes are determined by the cantonal structure plan or the cantonal protection enactment. Along the Albis ridge, those areas fall under an old, but still legally binding protection enactment, the plant protection area Uetliberg (passed 16 April 1959). Rights of private landowners are not restricted. Parts of the landscape of national importance around the *Chatzenseen* is considered landscape protection zone and all changes of the landscape need authoritative approval. The inventory of nature and landscape protection of regional and cantonal importance includes, inter alia, nature protection objects of regional or communal importance (covering 0.45% of settlement area) and hedge slopes of regional or communal importance (covering 0.68% of settlement area). Not included in this study are erratic blocks and geomorphological important objects. No hedges of regional or communal importance are present in the study area.

Table 13: Protected settlement area: Conservation area is split up into national, cantonal, and regional protection inventories, some areas overlapping. Total of officially protected area is stated after removing overlapping areas.

Type of conservation	Area [km^2]	Area [ha]	Fraction of settlement area [%]
Federal inventories	0.299	29.9	0.25
Cantonal protection enactment	1.32	132.345	1.09
Cant./ reg. inventory of protection objects	0.54	54.56	0.45
Cant./ reg. Inventory of hedge slopes	0.82	81.88	0.68
Total (overlapping areas removed)	**2.5**	**250**	**2.06**

After presenting conservation status of forest, lake and urban vegetation, the following chapter presents possibilities to map ES or assessing the quality of an ecosystem with RS-EBVs and GIS data. For forest and urban vegetation, ES regarded as highly important for the population were mapped. In the case of lake Zurich, two water quality indicators were calculated. Consequently, one provisioning, one regulating and one cultural service was estimated.

3.2.2. Recreational value of forest area

Mapping the ES *recreation* (social/cultural service) was achieved by combining a LAI map with road network (accessibility) and water bodies and streams (Fig. 9). Areas of high recreational value show a netlike pattern, associated with the structure of the road and creek network. Forest accessibility is given throughout the study area's forests, and the density of the road network is high. High recreational value is achieved where a path follows a stream in light forest.

Figure 9: Recreational value of forest: Low LAI, accessibility through roads and proximity to streams and lakes increase the recreational value of forest (yellow and brown), while dense forest, inaccessibility and large distance to water bodies decrease the recreational value (blue and green).

3.2.3. Lake water quality

Potential of S-2 to monitor water quality of Lake Zurich was tested by calculating two water quality indices. Total suspended solids (TSS, Fig. 10a) and Chl-*a* (Fig. 10b) were chosen as most important metrics to monitor water quality of Lake Zurich. TSS values are negative, approaching zero indicating higher concentrations of TSS. Along the coastlines, TSS values are increased. Vertical linear artifacts are visible, as well as some linear lines crossing the lake in other directions. Turbulences are visible where the Küssnacht creek enters the lake and at the north-west coast.

Chl-*a* of Lake Zurich shows less spatial variability than TSS. Areas along the shore show lower index values and are generally low compared to the rivers and shorelines of the smaller lakes. TSS and Chl-*a* seem to be inversely related near the shorelines, which is not the case in rivers and the smaller lakes. Vertical artifacts are visible in the Chl-*a* image as well.

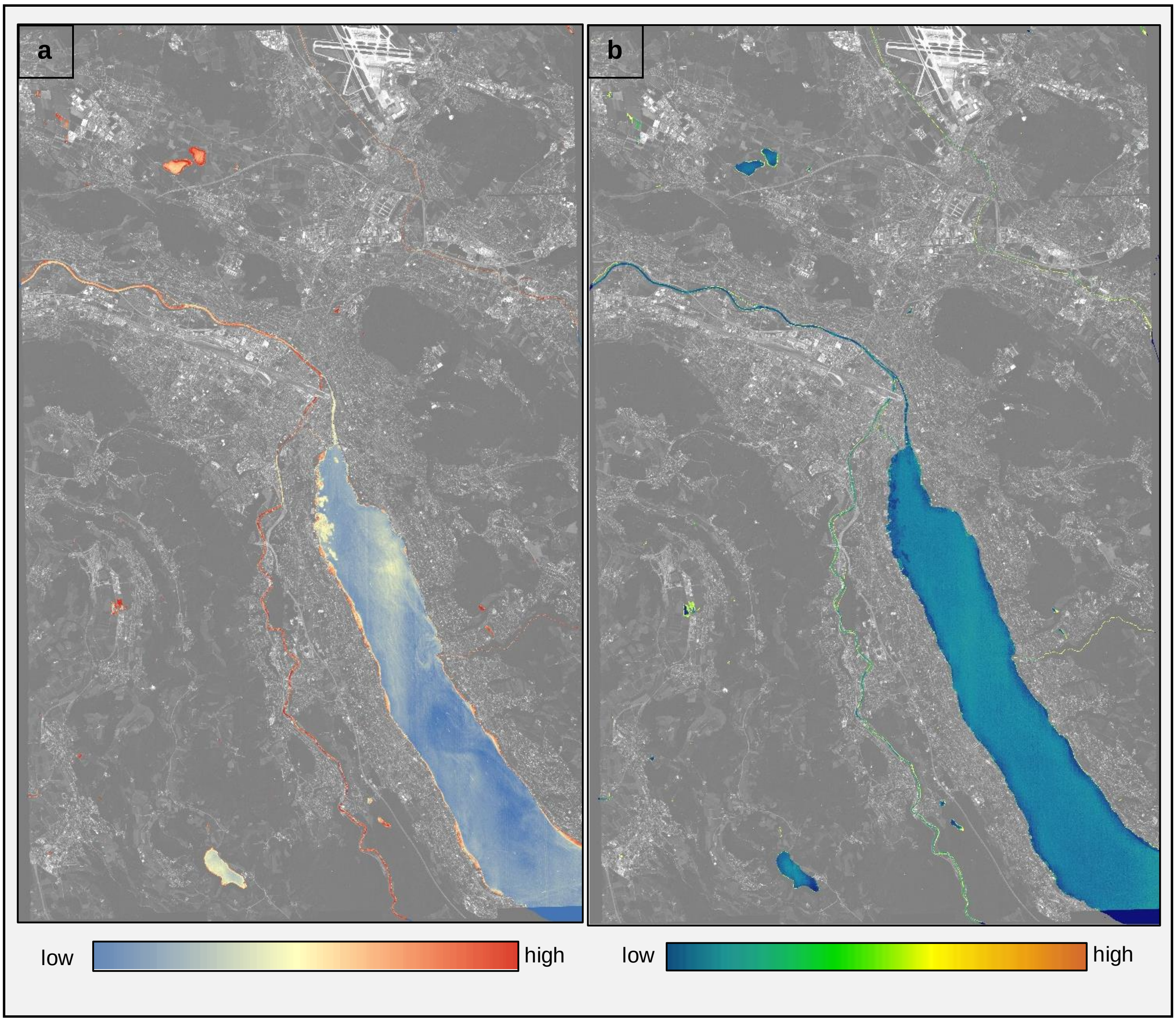

Figure 10: Two water quality indices estimated for Lake Zurich and surrounding water bodies: a) Total suspended solids, indicating the amount of organic and inorganic suspended particles in the water. b) Chl-*a* concentration of the lake and surrounding water bodies. TSS shows high spatial variability in the lake, while Chl-*a* concentration is relatively even.

3.2.4. Air quality regulation of urban vegetation

In the context of urban vegetation, the ES *air quality regulation* by trees was mapped. Filtration capacity was estimated with LAI, using the equation proposed by Delegido et al. (2011). Note that the result is presented in the original APEX spatial resolution of 2 m. Areas of high importance in the context of PM10 capture like buffer zones around highways and other intensively used roads were combined with the LAI image, using different weights and buffer sizes for different road types (Fig. 11). The resulting map highlights areas of high filtering capacity (yellow and brown) or areas where this ES is particularly important (preferably yellow and brown). Green and blue areas indicate low LAI, and within the buffer zones of roads an insufficient filter of PM 10. White areas are not vegetated (in settlement area) or masked out forest area.

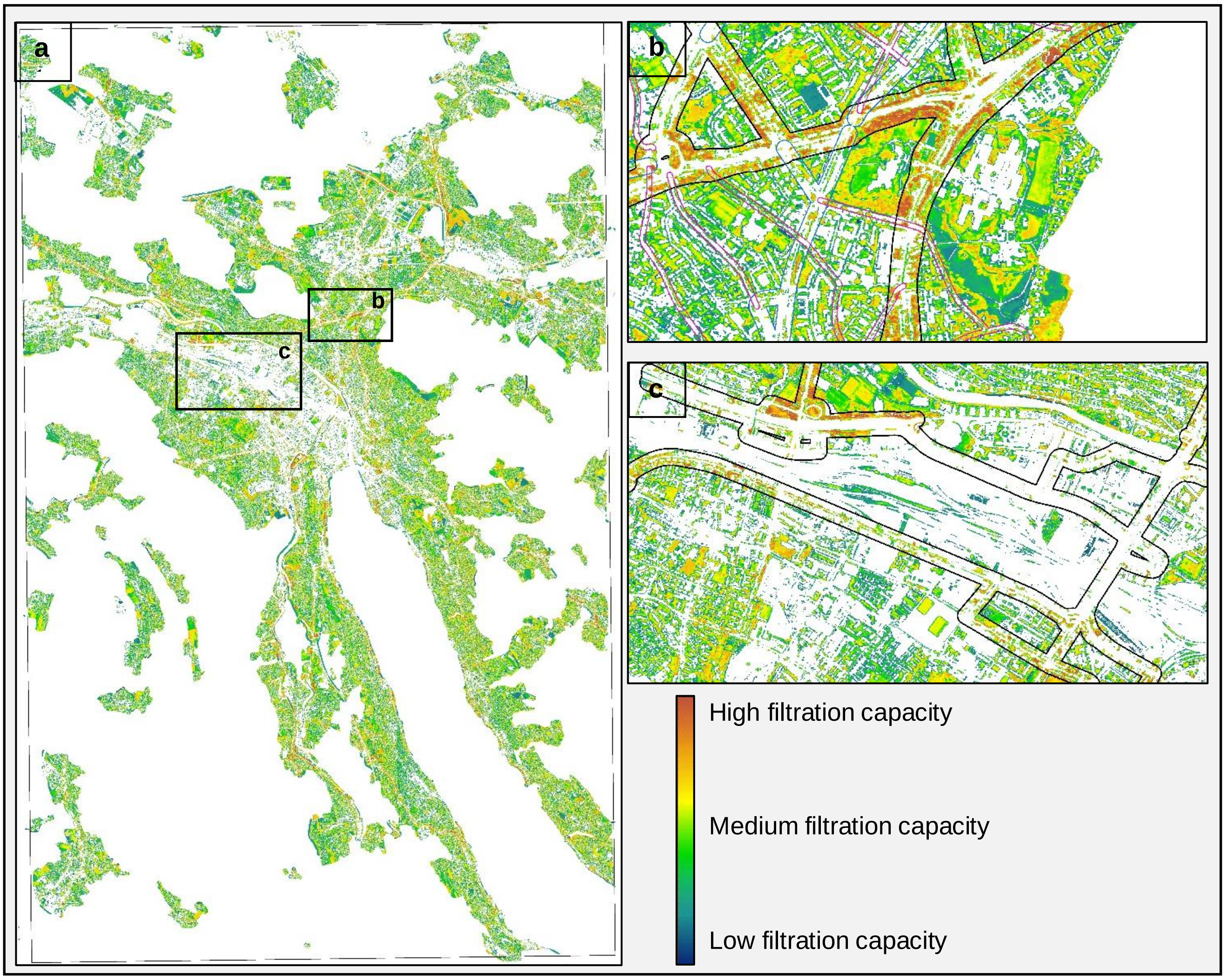

Figure 11: Air quality regulation of urban vegetation a-c: high capacity shown as yellow and brown color, based on LAI and weighted road network. The map can also be used to detect insufficient vegetation cover: within buffer zones of roads, values should be higher, as it is the case near the Irchel campus of the University of Zurich (b); if color is lacking within the buffer zones or blue and green, there exists a lack of vegetation to provide the filtration service. This is e.g. the case near the Hardbrücke and along the Pfingstweidstrasse, north of the railtracks (c).

Generally, settlement areas in the study area provide a lot of green spaces, especially in the outskirts of the city. In the city center of Zurich, around the main station and following the areas along the Limmat river, vegetated areas are rare, while in the residential quarter, there are more vegetated spaces.

3.3. Target 15

3.3.1. Conservation and restoration

Conservation status of forest and raised bogs was investigated. Details about forest conservation was presented in a previous chapter (3.2.1. *Restoration and safeguarding approaches*). All raised bogs in the study area are protected legally binding on national level. Specifically, all raised bogs remaining in Canton of Zurich are listed in the federal inventories of biotopes of national importance. Details on management of raised bogs are declared in the Ordinance on Raised bogs and restoration activities are the responsibility of the canton. Nationwide, raised bogs lost ca. 10% of area between observation periods 1997/2001 and 2002/2006 (Extrapolation of sampling to Switzerland's overall mire area) (BDM 2015a). No data was available for the four individual raised bogs present in the study area. Restoration progress of raised bogs needs monitoring on the ground, and cannot be replaced nor supplemented by satellite remote sensing, an issue mentioned in the context of ABT 5 (3.1.3. *Quality of rare habitats*). RS-EBVs are not considered suitable for assessing small-scale characteristics of raised bogs.

3.3.2. Forest resilience

To assess the relationship between forest heterogeneity and resilience using RS-EBVs, the spatial heterogeneity of two plant traits was measured and compared between total forest area and protected forest. SHDI, SIDI and the respective evenness indices of $CI_{red\text{-}edge}$ and LAI for total forest area and the forest protection zone of the cantonal protection enactment were computed (Tab. 14).

Table 14: Landscape diversity metrics computed for $CI_{red\text{-}edge}$ and LAI: Shannon's diversity index (SHDI), Simpson's diversity index (SIDI), Shannon's evenness index (SHEI) and Simpson's evenness index (SIEI). Heterogeneity metrics were computed for the total forest area and the forest protection zone of the cantonal protection enactment.

		SHDI	**SIDI**	**SHEI**	**SIEI**
Total forest area	$CI_{red\text{-}edge}$	4.57	0.99	0.76	0.99
	LAI	2.11	0.46	0.32	0.46
Forest protection zone	$CI_{red\text{-}edge}$	4.42	0.99	0.81	0.99
	LAI	5.35	0.99	0.84	0.99

Firstly, total forest area yielded a SIDI (indicating the probability that two randomly selected pixels show different trait values) and SIEI of almost 1 for $CI_{red\text{-}edge}$. SIDI of LAI of total forest area is 0.46, indicating medium heterogeneity. Generally, $CI_{red\text{-}edge}$ results in in higher heterogeneity and evenness than LAI for total forest area. On the other hand, when only considering the protected forest, LAI shows higher heterogeneity.

SHDI of $CI_{red\text{-}edge}$ is slightly lower in protected forest than in total forest area, while SHDI of LAI is higher in protected forest. Also, SIDI is higher in protected forest for LAI. Thus, heterogeneity of chlorophyll is lower in protected forest, but heterogeneity of LAI is higher in protected forest.

Both SHEI and SIEI, indicating the evenness of the spatial distribution of trait values, are higher for $CI_{red\text{-}edge}$ than LAI in total forest area, but lower for $CI_{red\text{-}edge}$ in protected forest. Evenness is also higher in protected forest for both $CI_{red\text{-}edge}$ and LAI compared to total forest, except SIEI of $CI_{red\text{-}edge}$, which is the same in total forest and protected forest. Evenness approaching 1 means approaching proportional abundances of trait values (even distribution). SHEI generally shows lower evenness values than SIEI, independent of trait and area of interest.

SHDI was plotted for two squares of exactly 1 km^2, one of it in the forest protection zone, and one in an unprotected forest (Fig. 12).

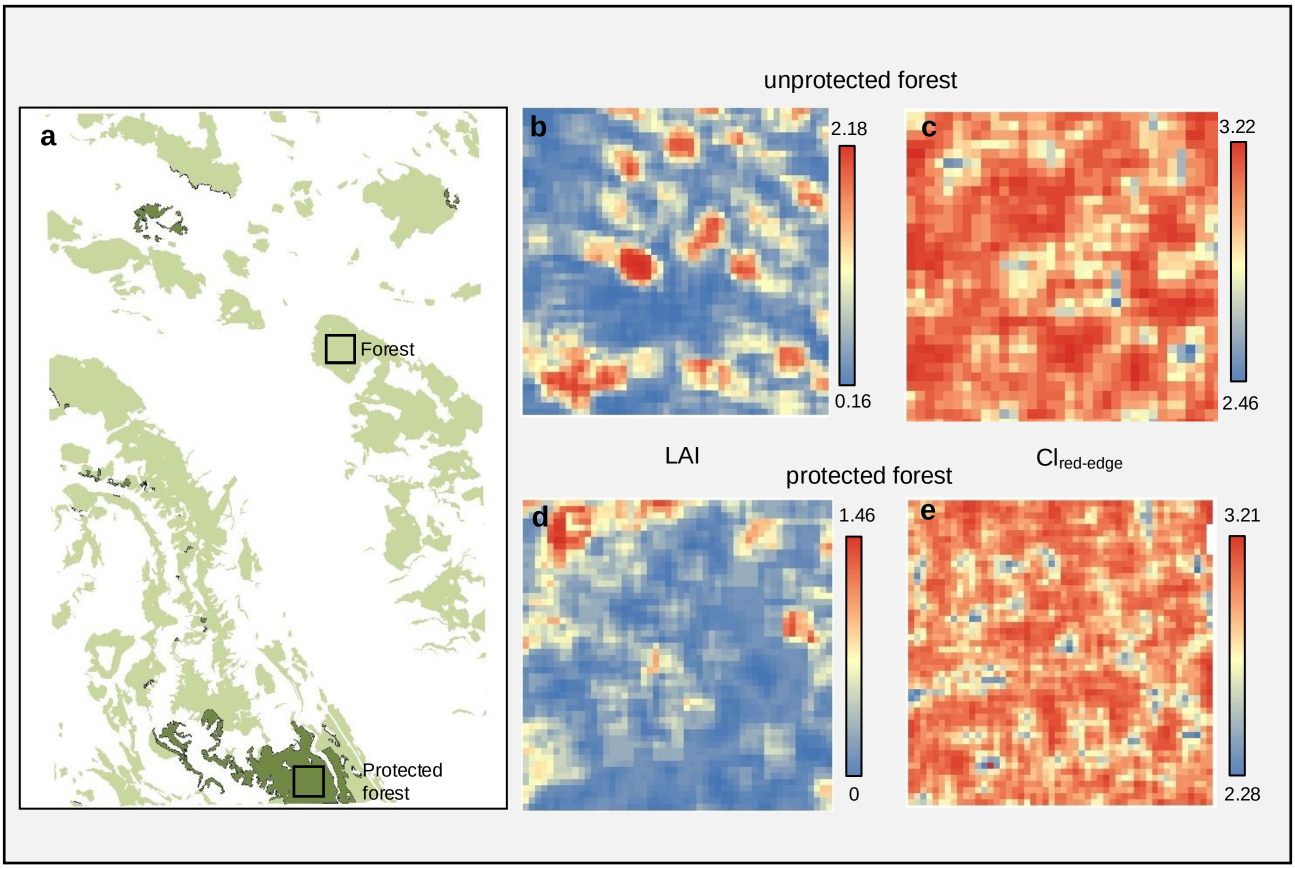

Figure 12: SHDI plots (b-e) of LAI and CI$_{red-edge}$ of a 1 km^2 forest area (b and c), and a 1 km^2 area of the cantonal forest protection zone (d and e). The square of unprotected forest is located east of the Irchel Campus of the University of Zurich, and the square of protected forest is located in the Sihl forest.

Generally, LAI is quite homogeneous in both protected and unprotected forest, showing slightly lower heterogeneity in the protected forest (Fig. 12 d) compared to the unprotected forest (b). There are small areas of high heterogeneity visible in both plots. Mean SHDI computed for the total area of both squares yields lower LAI heterogeneity for protected forest (SHDI=4.81) than unprotected forest (SHDI=4.96). CI$_{red-edge}$ yields lower mean SHDI (4.05) in protected forest (e) compared to unprotected forest (c, SHDI=4.32). The unprotected forest also looks more heterogeneous when visualized, specifically showing larger areas of high heterogeneity.

3.3.3. Heterogeneity – productivity relationship in forests

To investigate the heterogeneity – productivity relationship in forests in the study area, time series of compositional heterogeneity and productivity are needed. GPP, LAI, CI$_{red-edge}$ and heterogeneity indices of both LAI and CI$_{red-edge}$ was computed successfully in this thesis (see Chapter 3.1.2. and 3.3.2.). Thus it is possible to monitor long-term changes in all of them, as well as investigate a potential relationship between changes in productivity and heterogeneity of LAI and CI$_{red-edge}$ and its potential different behavior within and outside conservation areas. In this study, one snapshot for the 26 of June 2011 was computed as an example. SHDI values were plotted against GPP for the 1 km^2 squares used before to visualize heterogeneity (Appendix, Fig. A-2).

Disregarding of the trait (LAI or $CI_{red-edge}$) and the area of interest (total forest or protected forest), the point cloud looks similar: no clear relationship is visible and a linear regression resulted in very low R-squared ($R^2<0.1$) The same procedure was conducted for total forest area, and total area of the forest protection zone. No clear relationship was found either. Areas of low heterogeneity showed similar GPP values, while areas of high heterogeneity showed great variations in productivity. Also, it was tested using a spatial resolution of 2 m instead of 20 m, which neither resulted in a clear relationship (Appendix, Fig. A-3).

Long-term time series of both productivity and traits will enable to relate productivity changes over time to heterogeneity of forest. This was not possible to investigate in the scope of this study.

3.4. Linking RS-EBVs to biodiversity indicators

To assess progress towards ABTs 5, 14 and 15, six (RS-)EBVs were selected as useful and were tested for applicability in this study (Tab. 15). Ecosystem extent (*Land cover*) was assessed using GIS data in the context of this study, as the accuracy of the data is flawless. Forest area can also be assessed using S-2 data, but a regular assessment of change in extent was not considered a priority in the study area. Also, *fragmentation* due to traffic barriers was assessed with GIS data. However, it is also possible to assess fragmentation of individual forest patches with S-2 data only. *Primary productivity, plant traits, leaf area index* and *heterogeneity* are of great use in all three ABTs, enabling monitoring of productivity, leaf pigments and structural changes of forest, once data is available for a few years. Thus, certain long-term changes in forest condition can be detected. Returning to the previously mentioned biodiversity indicators, the selected RS-EBVs are essential state variables needed as their input (Tab. 15).

Looking at priority aspects in the study area, it is possible to validate the most important aspects of the three ABTs and the respective biodiversity indicators with a small set of six (eight, if water quality indices are counted as well) RS-EBVs. Thus, combinations of six (or eight) multi-annual data sets, potentially assessed with the same sensor, will deliver sufficient information to make important statements about progress towards three ABTs. Not all biodiversity indicators proposed for each ABT were considered. Also, only certain aspects, based on the conditions of the study area, are addressed by the proposed (RS-)EBVs, not more and not less. Hence, this compilation of (RS-)EBVs might not be as informative in other regions, where other ecosystem types are considered more important.

Table 15: Linking different aspects of ABTs 5, 14 and 15 to biodiversity indicators (proposed by the CBD), and also to RS-EBVs used in this study that may serve as input for these indicators. ABTs are divided into separate parts that require different indicators and RS-EBVs.

ABT	Aspect of ABT	Indicator (CBD)	RS-EBV
5	Habitat extent	Trends in extent of selected biomes, ecosystems and habitats	Land cover
	Habitat degradation	Trends in condition and vulnerability of ecosystems	Primary productivity, Plant traits, Heterogeneity
	Habitat fragmentation	Trends in fragmentation of natural habitat	Ecosystem distribution/ Fragmentation
14	Restoration and safeguarding	Trends in area of degraded ecosystems restored or being restored	-
	Condition of ecosystems	Trends in condition and vulnerability of ecosystems	Primary productivity, Plant traits, Heterogeneity
	Ecosystem services	Trends in benefits that humans derive from selected ecosystem services Trends in delivery of multiple ecosystem services	Leaf area index, (Water quality, phytoplankton distribution)
15	Conservation and restoration	Trends in area of degraded ecosystems restored or being restored	-
	Ecosystem resilience	-	Plant traits, Heterogeneity
	Contribution of biodiversity to carbon stocks	Status and trends in extent and condition of habitats that provide carbon storage	Primary productivity, Plant traits, Heterogeneity

4 Discussion

4.1 Data selection

The focus of this thesis was the validation of progress towards ABTs 5, 14 and 15 and the contributing value of RS-EBVs. For each of the selected ABTs, the most important aspects were determined and suitable RS-EBVs selected and combined with available GIS data. Following RS-EBVs are suitable for monitoring ABTs 5, 14 and 15: *Land cover, ecosystem distribution and fragmentation, primary productivity, plant traits, heterogeneity* and *leaf area index* (Tab. 15). They were combined with GIS data available for land cover, conservation areas, traffic infrastructure and surface waters. Similar to many of the environmental indicators developed for assessing progress towards ABTs, at the time of writing this thesis it was not decided on a set of metrics for RS-EBVs. Hence, decisions on measurement parameters or metrics were made based on published literature. GIS data has been particularly helpful regarding assessing rare habitats, fragmentation and selecting conservation areas, which do play a great part in ABTs 14 and 15. Both focus on conservation and restoration of ecosystems, based on assumptions about processes that are not yet understood completely. Assessing progress towards those two would be possible by only investigating conservation status and restoration activities. RS-EBVs contribute in investigating ecosystem properties and assessing whether those behave differently within and outside of conserved areas, thus providing information whether the implied safeguarding strategies are actually grasping or helping. Both aspects were considered in this thesis, as they both play a major role in the context of working with ABTs or similar biodiversity targets. As before, the ABTs are discussed separately.

4.2 Target 5

Methods to monitor extent, degradation and fragmentation of forest and rare habitat types were analyzed. Depending on what aspect of the target was concentrated on, advantages and disadvantages of RS-EBVs were detected. Highest potential is seen in inspecting forest conditions by monitoring productivity and pigment composition.

4.2.1 Assessment of habitat extent

Different methods for assessing forest area and rare habitats were tested. Forest area was successfully assessed using both the GIS dataset and the simulated S-2 image, resulting in approximately 82 km^2 and 93 to 98 km^2, respectively. Best RS results were achieved by adding the R, G and B band and selecting only pixels with values between 1 and 800. The main advantage compared to other approaches tested is the independency from selecting training areas and thus, fast and simple computation. A similar approach was also conducted by Laurent et al. (2014). Comparing forest area from GIS and S-2 data still shows some differences. Considering the accurate GIS data set and the small changes in forest extent over the past decades, monitoring forest extent seems redundant in the study area. However, it is possible and may provide valuable insights in future years. There is potential for detecting a rate of change, as soon as a sufficiently long time series of S-2 or other missions are available. It is assumed that forest extent in the study area will not change significantly, thanks to a throughout protection policy ensuring a sustainable use and systematic care (see chapter 3.2.1.). This assumption is supported by the fact that since the mid 1980’s hardly any changes of forest area have been observed in the canton Zurich (Baudirektion Kanton Zürich 2010). The metropolitan area around Zurich was particularly affected by land use change since 1985, but settlement area expanded mainly to the expense of agricultural land (FSO 2013). Thus it is concluded, that even though S-2 is able to assess forest extent and changes of it, there is no need for monitoring its extent on a regular basis in the study area, but rather concentrate on the condition of forest.

Rare habitats were assessed using available GIS data of biotopes of national importance. With a cover of 0.36% of the study area, they are even rarer than the Swiss average. Especially dry grassland is very rarely found. Given the high population of the study area, and the high fraction of urban cover and agricultural use, this situation was expected. Zurich is one of Switzerland metropolitan centers and landscapes are intensively used in different ways. Monitoring rare habitat extent is considered very important, particularly in the study area where environmental pressures are high. The S-2 image did not provide satisfying results for rare habitats, following aspects being important reasons: Firstly, rare habitats are often covered by tree canopies, and are thus not detectable as distinct land cover type. Secondly, the boundaries of rare habitats as designated in the federal inventories are often overlapping and sometimes include a buffer zone that does not necessarily correspond to the same land cover type. Thirdly, the criteria for being included in the federal inventories are not always discernible for a remote sensor, e.g. not all dry meadows and pastures present in the study area are included in the federal inventories, but only the most important 30% of the ones listed in cantonal inventories, based on plant sociological criteria and minimum area. Given the accuracy of GIS data available, it was decided the best option for assessing area of rare habitats, despite update intervals being very long and the necessary ground assessment time consuming.

4.2.2 Assessment of habitat quality

Regarding assessment of habitat condition, three RS-EBVs were selected as most adequate for forest in the study area (*primary productivity, plant traits* and *heterogeneity*) and tested for applicability using the simulated S-2 image. Forest and rare habitats were again considered separately. Assemblage of potential S-2 products for monitoring degradation or ecosystem condition in general focused on the vast area of forest, rather than including rare habitats, as this was considered the more promising contribution of S-2. The set of 3 RS-EBVs enables insights on biochemical and structural changes of the forest when monitored over a sufficient period of time and helps detecting changes caused by increased nitrogen deposition levels, timber use activities, storm and beetle damages, which are the major pressures on forests in the study area.

Monitoring productivity

Primary productivity is considered a suitable variable to monitor forest productivity on a regular basis. Remotely sensed time series of vegetation and productivity dynamics have been used as proxy for land degradation in previous studies (e.g. Bai et al. 2008; de Jong et al. 2011). In the scope of this thesis, only one image was computed, showing the GPP of 26 June 2011. This glimpse in time does not say much about forest degradation, as degradation is always related to a change in time. However, areas of high or low productivity can be detected and selected as focus area in future studies. With multi-annual time series, it is also possible to monitor long term changes and changes in growing season due to climate change (RS-EBV *phenology*). However, changes in productivity, although easy to monitor, still have to be seen in the specific context of the ecosystem and underlying causes of the changes may need to be investigated *in situ.* In this study, GPP was estimated with the Monteith approach, using fPAR calibrated with NDVI and vegetation specific LUE (based on a land cover classification), considering temperature and moisture stress. Meteorological data from three weather stations within the study area were considered. However, the computed product does not take into account small scale climatic and topographic variabilities. Calibration with ground data is necessary to improve the absolute accuracy of the product. There have been developed more sophisticated ways to estimate GPP, e.g. estimating plant LUE with sun-induced chlorophyll fluorescence (FS), based on the Fraunhofer Line Depth (FLD) approach originally proposed by Plascyk et al. (1975) (Damm et al. 2012). However, the spectral resolution of S-2 is not suitable to detect changes in the narrow absorption bands necessary to detect FS. APEX on the other hand is able to retrieve FS from reflected radiances in and outside of the O2-A absorption feature, presenting a potential product to accurately monitor GPP with high spectral and spatial resolution (Damm et al. 2012). Thus, given the spectral resolution of S-2, the Monteith approach is considered a good option and suggested as working method for monitoring changes in forest productivity. In a next step, net primary productivity can be obtained by subtracting autotrophic respiration from GPP.

Monitoring plant traits

The leaf pigments chlorophyll, anthocyanin and carotenoid were estimated. Comparable to the above discussed GPP product, limitations exist due to only having one observation. However, single observations of plant pigments give information about the current health of forests, e.g. light stress.

Spatial variations in all computed pigment images are partly related to different vegetation types (e.g. grass or trees) and to some extent to the mosaicking of the APEX flight lines and anisotropy effects. The proposed indices are only estimations and not showing absolute values. Also, the index equations found in literature had to be adapted to some degree for all three pigments, which likely affects the accuracy of those estimations. Especially the Car equation uses a band that is out of the suggested range. This topic requires further research and calibration with *in situ* data. However, despite not being able to measure concentrations most accurately, the potential of S-2 to approximate pigment concentration on a regular basis is considered of great value and will lead to better understanding potential causes and consequences. Especially the $CI_{red\text{-}edge}$ algorithm is considered important for monitoring forest in the study area, and the algorithm was already recommended for the S-2 mission (Clevers & Kooistra 2012). However, a recently published study comparing chlorophyll estimators found $CI_{red\text{-}edge}$ only to be the fifth best of totally eight tested indices (Vincini et al. 2016). The $CI_{red\text{-}edge}$ index was also selected as suitable metric for estimating N in plants, made possible by the high correlation between leaf pigments and N content (Muñoz-Huerta et al. 2013). A major pressure in forests in the study area is increased N deposition, but no direct monitoring approach from spaceborne sensors was found in literature. Compared to other methods, computation is simple, non-invasive and does not necessarily require additional data. The exact correlation between N and chlorophyll is species specific, and the choice of the exact wavelength for chlorophyll retrieval varies with vegetation type (Clevers & Gitelson 2003, Homolová et al. 2013). Additionally, coniferous canopies show high uncertainties in nitrogen estimation accuracy, due to their complex canopy structure (ibid.). Thus, to acquire more accurate data, ground measurements for calibration are needed. Time series of $CI_{red\text{-}edge}$ will contribute to better understanding of the complex effects of high nutrient input to forest ecosystems.

Wavelength regions around 660 nm and 750 nm were also reported as useful for forest canopy N estimations (Smith et al. 2003). A recent study proposed a continuous nonparametric approach based on Gaussian process techniques, allowing inclusion of all bands, instead of restricting oneself to two-band indices (Verrelst et al. 2012). In this context, the Normalized Area Over the reflectance Curve (NAOC) index was developed to estimate chlorophyll concentrations in crop fields (Delegido et al. 2010). Using the NOAC index for forest canopies may demand additional calibration and certainly holds potential for the future. On the other hand, in the context of assessing progress towards ABT 5 it is not urgently necessary to estimate chlorophyll content as accurately as possible, but rather to monitor compositional variations over a longer period of time. Thus, a simple ratio index as the one used in this study is considered sufficient.

Monitoring heterogeneity

Increased N deposition can also have effects on the heterogeneity of forest. Environmental heterogeneity is providing a range of different resources and microclimatic milieus, thus allowing more species to co-exist through niche partitioning (Tews et al. 2004, Oliver et al. 2010; Oliver et al. 2015), and is generally positively correlated with species richness across regions, scales and taxa (Stein et al. 2014). Negative relationships between N deposition and both plant species richness and community composition were found in Swiss mountain grasslands (Roth et al. 2013). A method to monitor the heterogeneity forest was selected in this analysis, by investigating heterogeneity of $CI_{red\text{-}edge}$ and LAI, as they are likely being impacted by changes in nutrient input. In this study, two common landscape diversity indices and their respective evenness indices were computed for both $CI_{red\text{-}edge}$ and LAI. SIDI yielded medium heterogeneity of LAI and high heterogeneity of $CI_{red\text{-}edge}$ when calculated for the total forest area. Higher values were computed for all heterogeneity metrics when using $CI_{red\text{-}edge}$, compared to the same metrics based on the LAI image, suggesting that structural heterogeneity is lower than biochemical heterogeneity. However, heterogeneity of plant traits can be assessed in various ways, potentially leading to different results.

The classic indices of Shannon's and Simpson's diversity and evenness have been used to describe the compositional heterogeneity of landscapes (e.g. Rocchini et al. 2013; Debouk et al. 2015, Katayama et al. 2014). They tend to be less sensitive to increased spectral variability due to shadow, water or soil pixels than other indices (Rocchini et al. 2015). They have been applied on RS data before (e.g. Rocchini et al. 2013; Schindler et al. 2015), are easily computable and intuitive to interpret. General comprehensibility of methods used to monitor progress towards ABTs is aimed for throughout this thesis, as results regarding forest condition are not only thought to interest scientists, but also politicians, managers, decision makers, conservationists or the wider public. However, one has to keep in mind that landscape heterogeneity approximated using the spectral signal also has its limitations and does not take into account every aspect of ecological importance (Rocchini et al. 2015). Heterogeneity effects can operate from very fine scale up to landscape scale (Oliver et al. 2015). Also, heterogeneity metric behavior is impacted by spatial resolution of input data as well as the moving window size. This was also reported in other studies (e.g. Schindler et al. 2015). When calculated with the original APEX resolution of 2 m, heterogeneity of both LAI and $CI_{red\text{-}edge}$ was lower than with 20 m resolution. In the study area, heterogeneity of LAI is higher at forest edges, as neighboring grassland or agricultural fields are slightly included in the forest data used. Heterogeneity is also higher in areas where the forest is light, because of grass and shrubs being visible and roads shining through. Here, two conflicting aspects meet each other. Fragmentation, which is negatively affecting forest ecosystems, increases heterogeneity as seen by the remote sensor, when using the proposed method. In an attempt to deal with this issue, roads could be masked out by applying a vegetation mask (e.g. NDVI > 0.4). Some of the variability in heterogeneity may also come from mosaicking the seven APEX flight lines and, potentially, from directional effects caused by surface reflectance anisotropy, despite a correction applied on the used dataset (Weyermann et al. 2013). All the above mentioned aspects might impact the heterogeneity values to an extent, that changes due to increased N input may remain undetected. Keeping the above limitations in mind, it is still considered worthy to investigate heterogeneity of chlorophyll and LAI over a longer period of time. Given the effects of N inputs on different parts of the forest ecosystem (soil eutrophication, plant growth, resistance, etc.), changes need to be monitored over decades. Jones & Schmitz (2009) mention the problem that many ecosystems across the planet have been in a degraded state for such a long time that it is not possible to know the *success point* of a restoration activity.

Despite providing information on changes productivity, plant traits or heterogeneity of the forest, those RS-EBVs are not able to distinguish the underlying *causes* of this change, which is why ground based studies and other (pressure) indicators are necessary for further information (Leadley et al. 2014). In the case of forest in the study area, main pressures are known and their expected impact partly understood. However, different stresses may have contradictory effects on ecosystems, e.g. the effect of increased N on plants: on the one hand it can act like a fertilizer if overly available, but on the other hand it can also change the nutrient balance of a tree and lead to acidification of forest soil, or N leaching into the groundwater, leading to nutrient depletion in the soil (Forest Report 2015). High N deposition also leads to decreasing resistance against frost, drought and parasites (Flückiger et al. 2011). The relationship between N and other nutrients, e.g. phosphorus, or the C/N-ratio all determine if growth is stimulated or not (Braun et al. 2010, Braun et al. 2012). Increased N deposition has also been responsible for nutrient imbalances detected in Swiss forests, inhibited nutrient absorption capacity of roots, leading to decreasing growth (ibid.). Hence, depending on species, location, nutrient availability and general environment, increased N input may lead to different reactions of forests, including changes in GPP or $CI_{red\text{-}edge}$, LAI and heterogeneity. The consequence is, that we can collect data of productivity, pigments, and other plant traits and their spatial distribution and heterogeneity on a regular basis with S-2 or other remote sensors, but are still not able to grasp the complexity of the forest ecosystem and predict its responses to the underlying cause of degradation in the study area.

To highlight the expressiveness of the above set of RS-EBVs to give evidence for habitat degradation, it is compared to a recent global mid-term analysis of the progress towards ABTs (Tittensor et al. 2014). In their study, the *Wild Bird Index for habitat specialists* is used as only indicator for global land degradation. According to the authors, bird species characteristic for a certain habitat type are seen as useful indicators for habitat health. A decline in habitat specialist species might therefore suggest degradation of habitats. Even though all taxonomic groups are impacted by habitat degradation, birds seem to be exceedingly sensitive to disturbances, especially to forest conversion into agriculture (Gibson et al. 2011). Compared to this indicator, RS-EBVs give information that is less abstract and more easily to interpret, by effectively describing properties important for the functioning of the ecosystem.

Rare habitat degradation

Pressure on rare habitats remains high and degradation takes place in a subtle way (Klaus 2007; Martin et al. 2012). All of the above proposed RS-EBVs can be assessed for rare habitats as well. However, productivity and pigment composition are not necessarily displaying degradation characteristics of alluvial zones, bogs and fens. Also, much of the fine grained heterogeneity crucial for the functioning of those small-scale ecosystem is not captured by S-2 and the subpixel variability remains hidden (Rocchini et al. 2015). Fieldwork-based data collection is inevitable for a throughout assessment of habitat condition. The fine-scale variability in the characteristics of remaining rare habitats requires a throughout qualitative assessment of the total area and its full character, as well as a buffer zone around the habitat: such assessment may include changes in moisture, nutrient content, humus layer, vegetation cover and fraction of fen type, similar to the quality assessment by Klaus (2007). This level of qualitative precision is being met with the BDM indicator *Quality of valuable habitats*, monitoring exactly these characteristics. Despite an extraordinary effort being necessary, it is the only way to meet the requirements posed by the mere rarity of e.g. mires and its ongoing degradation over the last century. This complexity can be transferred to other rare habitat types. Without a throughout assessment of each individual habitat type, its condition and the monitoring of its development (considering every important aspect of the ecosystem) over a sufficient amount of time in regular time intervals, no statement about degradation of those habitats in the study area is possible. Such an assessment goes beyond the scope of this thesis.

This leads to the conclusion that in the case of rare habitats, RS-EBVs are not the most accurate way to assess progress towards ABT 5.

4.2.3 Assessment of habitat fragmentation

Forest and rare habitats are strongly fragmented in the study area. On the one hand, forest and rare habitats are separated into isolated patches, and on the other hand, those patches are again fragmented by traffic infrastructure. Isolation is an important aspect of habitat loss and fragmentation, as it leads to a decrease of remaining individual habitat patches, up to a point where the habitat is too small to sustain a population and makes the probability of crossing over to other separate habitat patches less likely (Fahrig 2003).

Regarding OSM based roads and railways, no changes were observed between January and April 2016 in natural habitat of the study area, leading to the conclusion that it is not necessary to monitor forest fragmentation monthly. Based on this study, it is believed more appropriate to monitor fragmentation on a yearly basis and to calculate MESH of natural habitat fragmented by roads and railroads entailed in *OpenStreetMap*. This would give an arranged and complete product to work with. Instead of only using certain road types, all road types and railroads were included here: it is argued that either all or no roads shall be included when calculating fragmentation, as the selection of certain road types postulates a classification of which organisms are affected by the fragmentation barrier; a forest path is neither an obstacle for snails nor bats, while a highway is an obstacle for snails but not for bats. Thus, to avoid the question of which organisms are actually impaired in their movement, all road types were included. However, MESH can be adjusted to any group or species, making it a flexible tool to measure fragmentation. A drawback of the proposed method is, that it is unclear from the data if additional road sections have been newly built since the last update, or only just added to the OSM dataset. Extracting fragmentation metrics from S-2 data is, considering selected habitats, not regarded as any added value, and thus not recommended. MESH as computed for the official national fragmentation indicator is based on national maps, which are updated only every 6 years. According to a quantitative analysis of changes in landscape fragmentation between 1885 and 2002 using MESH, fragmentation of Swiss landscapes has increased in almost all parts of the country and canton Zurich belongs to the most fragmented cantons (Jaeger et al. 2007). This decreasing connectivity can decrease species and functional diversity in the study areas natural habitat (Loreau et al. 2003). The remaining small patches of habitat suffer not only degradation, but fragmentation can also lead to changes in species composition and have huge effects on the functioning of ecosystems, varying across scales (Olff & Ritchie 2002). Llausàs & Nogué (2012) summarize three negative effects of fragmentation on the functioning of the environment: first, abiotic conditions might be changed when habitat is removed, modified or fragmented; second, increased mortality due to collisions on roads and railways; and third, fragmentation leads to reduced dispersal rates, constraints to gene flow and an overall disturbance of the whole ecosystem (ibid.).

4.3 Target 14

Leadley et al. (2014) point out the challenges of measuring progress towards ABT 14. Depending on thematic and geographic focus, different ecosystems are considered and different trends are notable. In the scope of this thesis, safeguarding and restoration approaches for forests, Lake Zurich and urban vegetation within the study area have been investigated reviewing legal texts and reports on the subject. Additionally, potential products to monitor important services provided by these ecosystems were developed.

4.3.1 Safeguarding of ecosystems

A problematic issue detected while working on this study was the incredible patchiness of conservation areas of all kind (regarding not only the 3 selected ecosystems, but the whole study area), their division into subzones and areas of different protection strictness. There is high potential to enhance the size of protected areas, especially connect the already existing protection areas. This is not only the case in the study area, but also globally (Pouzols et al. 2014). The 2014 United Nations List of Protected Areas contains 209'429 protected areas covering about 32'868'673 km^2 (Deguignet et al. 2014). This corresponds to 3.41% of the marine area and 14% of the terrestrial area (ibid.). All of the selected ecosystems in the study area are directly or indirectly protected or safeguarded. In this thesis, safeguarding of ecosystem was investigated in a general approach, without focusing on a special ES.

Forest protection is highly developed and its use is organized in great detail on the different authoritative levels. The sustainable and intelligent use of forests is essential to keep up quality and productivity of this ecosystem and guarantee the preservation of it for the generations to come. A good balance and an intelligent separation of forest areas for use and production on the one hand, and for wildlife habitat on the other hand would be ideal and is the case in the study area. Area of *Protected forest*, including forest areas that are part of the cantonal protection enactment, is 21%, but if including only the subzone of forest protection area, only 9.3% of total forest area. However, it is arguable, whether the area or fraction of forest being protected does actually meet the needs of safeguarding forest in the study area: certainly it maintains forest in its extent, and dictates certain restoration strategies. But N immissions are not lower in protected forest than in unprotected forest. Emissions and immissions of nitrogen oxides have decreased nationwide since the 1980's. Monitoring and further reducing emissions is thus essential to safeguard forests in in the study area and should thus be a focus in the implementation of ABT 14.

Lake Zurich is not included in any specific protection area, let alone a national biotope. Only the Planning and Building Act of Canton of Zurich states water bodies as generally protected. In the past years, efforts to reduce pressures on lake water have been addressed successfully, and nutrient input has decreased. Subsequently, nutrient loving algae have decreased, while diatoms increased. A future problem will be the increasing appearance of *P. rubescens*. The issue of monitoring lake water quality and providing high quality wastewater treatment is taken seriously and is also constantly updated to contemporary needs, as the recent adding of an article regarding the removal of organic trace substances into the Water Protection Act shows. Water quality of lakes regarding nutrients has improved nationwide (BAFU & BLV 2016).

Safeguarding of Lake Zurich begins on land, as the lake's water quality depends on its tributaries and the whole catchment area. Hence, safeguarding and protection needs to integrate all incoming streams, the surrounding agricultural areas, waste water from settlement areas and generally the total influx, including rain. This poses many problems and increases the task of safeguarding the lake enormously. Pollution events

outside of the study area may impact Lake Zurich's water quality, even though protection may be given within the perimeter of the study area.
Settlement area in the study area is partly included in official protection areas, with only 0.25% listed in federal inventories. There are other protection measures, e.g. the general conservation measures of trees (Grün Stadt Zürich) and detailed instructions on the general handling of trees in the city of Zurich. As the example of safeguarding and restoring vegetation in urban environments shows, vegetation is also taken care of, despite not being strictly protected by law. 20'000 trees are growing in Zurich alone, and all of them receive professional care to guarantee their ability to survive in this hard environment, as well as provide essential services for the city's population. In the densely populated study area, restoration of threatened green areas is essential. Next to ecological and social advantages, investing in protection and restoration of urban vegetation also brings economic benefits (e.g. by cooling effects and hence energy saving), which are, however, hard to quantify (Elmqvist et al. 2015).

This thesis shows that some protection measures do not necessarily meet the most important pressures on ecosystems, nor support the ecosystems ability to provide a specific ES. For example, forest being included in the forest protection zone does neither prevent it from the major pressure of increased N immission, nor does it have much influence in the recreational value of forest. The proper maintenance and the reduction of pressures are needed additionally to protection areas. This does not mean that protection areas are pointless. They do play a regulating role and give relief of some pressures (e.g. additional building activities). Considering the current situation in the study area, reducing pressures like pollution is still an essential safeguarding strategy for the here selected ecosystems.

4.3.2 Contributions of RS-EBVs

Monitoring towards ABT 14 not only includes the safeguarding status of ecosystems, but also monitoring the aspects of the ecosystems that provide the service or, if possible, estimate the service itself. As example products, maps of recreational value of forest, water quality of Lake Zurich and filtering capacity of urban vegetation were computed.

Forest

Recreational value of forest was estimated, depending on accessibility, forest density and presence of lakes and streams. These inputs were selected on the basis of a survey investigating what the population of Switzerland likes to do in forests and which characteristics they value most. The resulting map highlights areas that are accessible, near to lakes and streams and have low LAI, meaning the forests are not too dense, and therefore not too dark. How forest is perceived differs from person to person, so this map only shows a general picture of recreational value of forest. However, it can be used as approximation, where most forest visitors are. On this basis, this map can help improving other aspects that decrease the potential strain on forest by visitors (e.g. by providing waste bins) or increase the recreational or educating value of this forest area even more (e.g. by setting up an educational nature trail). What the product does not provide, is the information whether ABT 14 is achieved or not. This is associated with the phrasing of the target, that primarily strives to protect or restore forests (or other ecosystems). The conservation status of forest does not necessarily relate to the recreational value. Regarding accessibility, the cantons are obligated to ensure accessibility of forests to the general public, with restrictions if conservation interests are considered important (Federal Act on Forest, Art.14). Thus, safeguarding of forest may in some cases even obstruct the recreational value of forest. Adaption of the product by only including hiking trails or biking trails would offer potential improvement.

Where RS-EBVs can also contribute, as seen in the context of ABT 5, is in the monitoring of certain characteristics that are essential for the functioning of the ecosystem, e.g. *plant traits* and how they change over time. And of course, *primary productivity* can be used as basis for estimating the service of climate regulation. There is great potential in mapping different ES with imaging spectroscopy as shown in recent studies (e.g. Diek et al. 2014; Homolová et al. 2014; Maes et al. 2015).

Lake Zurich

A method to monitor water quality of Lake Zurich was suggested, by monitoring TSS and Chl-*a*. TSS, providing information about inorganic and organic components suspended in the water is a widely used water quality index, related to primary production, micro pollutants and fluxes of heavy metals (Dekker et al. 2002). The simulated S-2 image yielded a very good result for TSS, suggesting further research and calibrating the index with ground data to derive a time and site specific algorithm (Matthews 2011), thus developing a reliable dataset. While RS monitoring of TSS can provide multi-temporal and area-covering information, *in situ* point measurements of suspended matter are not considered representative (Dekker et al. 2002). The example map derived for the study area using the simulated S-2 image does not provide absolute values, but shows relative variations in the lake. High values along the coastlines may result from shallow water and ground shining through, while the turbulences on the northern coast result from Küssnacht creek. High index values at the north-west coast may be caused by ships arriving at and leaving the harbor. Linear patterns across the lake may result from ship traffic. Vertical linear artifacts from the APEX sensor are slightly visible. I conclude that TSS is a valuable algorithm for monitoring the water quality of Lake Zurich, an ecosystem providing essential services to the local population. Despite not listed as RS-EBV yet, it is suggested worth monitoring in the study area. As Lake Zurich is showing increased levels of phytoplankton, it was also considered important to monitor on a regular basis. Traditionally for Lake Zurich, chlorophyll concentration is measured monthly using three samples at different water depth. Monitoring the chlorophyll concentration from space gives the advantage of a more regular dataset over the entire area of the lake. Phytoplankton phenology and its spatial and temporal variability, systematically monitored from space will provide useful time-series will allow useful insights in lake water dynamics (Palmer et al. 2015). The Chl-*a* algorithm is the most commonly used parameter to estimate phytoplankton pigment concentration (Matthews 2011). In this study the two-band based ratio of reflectance at 700 nm and 645 nm (Moses et al. 2009) was calculated, due to the lack of a band at 750 nm in the simulated S-2 mosaic, which would enable the computation of the three-band model (note that the real MSI instrument aboard S-2 does have a band at 740 nm). Compared to the irregular pattern of the TSS algorithm, Chl-*a* yielded a relatively even result. No recognizable pattern is visible. Further research is proposed for both the two-band and three-band model, including calibration with *in situ* measurements to determine the best way of monitoring phytoplankton activities in Lake Zurich. The supplementary value of monitoring water quality indices on a regular basis as given by RS and particularly S-2 compared to the traditional monthly samples conducted by the WWEA is vast, however, there are also drawbacks: considering that algae have moved to deeper waters, it is questionable whether RS data can still contribute to the monitoring progress. *In situ* measurements at different depths are irreplaceable, thus I emphasize the supplementary nature of RS monitoring, rather than seeing it as an alternative for ground measurements. Combination of remotely sensed surface Chl-*a* and depth-resolved Chl-*a* time series of the past 30 years of Lake Zurich are currently subject of research to establish a link to the magnitude of algae bloom events and ecological significance of horizontal variability of primary production in Lake Zurich (University of Zurich, URPP Global Change and Biodiversity, Project 2).

Urban vegetation

The third ecosystem of interest in this study was urban vegetation. Mapping the filtering capacity of urban trees and other green spaces was achieved by combining LAI with buffers of intensively used roads. The map highlights areas within the buffer zones with high LAI (i.e. sufficient filtering capacity), and shows areas of poor filtering capacity as white (no vegetation) or blue/green areas (low LAI). As PM10 concentrations in Switzerland frequently exceed the air quality standard limit values (20µg/m^3 for yearly average, 50µg/m^3 for daily average, Ordinance on Air Pollution Control OAPC), especially in urban areas and along highways (FOEN 2013b), the choice of intensively used traffic lines is considered good. However, the effects of vegetation in urban settings on local air quality are a highly complex issue, being influenced by the level of air pollution, particle size, vegetation geometry, width of the vegetation barrier and its distance to the source (e.g. the road), as well as spacing between plants (Brantley et al. 2014), wind direction and speed, and many other parameters (Janhäll 2015; Litschke & Kuttler 2008). An effective mitigation of PM10 pollution and improvement of the urban population's health is only possible by significantly reducing emissions from transport, industry, households, agriculture and forestry (EKL 2013). Thus, the developed product is only considered useful as general guideline or recommendation to further investigate certain areas, using ground measurements. Beckett et al. (2000) found that coniferous trees or trees with hairy leaves are more efficient in capturing particles due to their finer and more complex foliage structure. Additional advantage of conifers is the year-round presence of needles, while deciduous trees lack foliage during winter months (Litschke & Kuttler 2008). Another study did not detect a significant difference in particle numbers of the size from 0.5 to 2 µm, but reductions in black carbon concentration behind vegetation barriers (Brantley et al. 2014). As dilution of emissions is a crucial part of air quality improvement, vegetation barriers should be close to the surface and porous enough, so air flow is still able to pass through (Jänhall 2015). The developed product is not showing this aspect of the vegetation barrier: from the image it is unclear whether the vegetation element reaches ground level (e.g. a hedge).
Vegetation density can also have a significant impact on cooling effects of parks, caused by shading and evapotranspiration (Ren et al. 2013) and reduce the so called urban heat island effect (e.g. Loughner et al. 2012; Wong & Yu 2005).

The three example products computed using RS-EBV *leaf area index* in combination with GIS data for mapping ES of forest and urban vegetation and assessing two water quality indices show the versatility of S-2. Despite RS-EBVs not being suitable to monitor progress towards ABT 14 alone, they hold potential to monitor ecosystem functioning, quality and services. Research is growing in this area, and a growing number of studies relates remotely sensed plant traits to ecosystem services (e.g. Lavorel et al. 2011, Homolová et al. 2014).

4.4 Target 15

4.4.1 Conservation and restoration

Forest conservation was discussed before in the context of ABT 14 and thus not further mentioned here (see chapter 4.3.1 *Safeguarding ecosystems*). Monitoring restoration activities and their impact on raised bogs in the study area is necessary on ground and includes examination of different mire characteristics (4.2.2 *Assessment of habitat quality*). Active management and proper maintenance is required to fight shrub encroachment caused by drier conditions (Feldmeyer et al. 2010). Drainage systems remain existing in most bogs and fens, promoting further drying (Klaus 2007), while fertilizer of neighboring agricultural areas and atmospheric N immissions potentially change the vegetation composition.

It was decided impossible to assess progress towards achieving the 15% restoration of degraded ecosystems, reasons being lack of definitions and clarifications by the CBD, even when only considering one single type of ecosystem. Firstly, as there is no explicit boundary between a raised bog (or any habitat type) being degraded or not degraded, it is not possible to determine an actual area or fraction of raised bogs being degraded. Secondly, it does make a huge difference whether the current situation of raised bogs is compared to the situation 5 years ago or 100 years ago. Hence, we did not further follow up the aspect of restoring 15% of degraded ecosystems, as it is on the one hand unclear what is actually meant, and on the other hand all remaining raised bogs being federally protected and under active restoration already. However, as mentioned in connection with forest safeguarding: being under national protection and listed in a federal inventory does not hinder climate change or nitrogen oxide emissions and deposition slowly changing the characteristics of a raised bog. RS-EBVs are not considered suitable for assessing progress towards the conservation/ restoration aspect of ABT 15. Hence it was focused on comparing plant trait heterogeneity inside and outside protected area.

4.4.2 Forest heterogeneity and resilience

In the context of ABT 15, a method was proposed to find a link between forest trait heterogeneity and resilience using RS-EBVs. By comparing heterogeneity of plant traits of total forest and protected forest, the relationship between conservation status, heterogeneity and resilience in the study areas forest can be characterized. Two diversity and two evenness metrics were computed for a biochemical ($CI_{red\text{-}edge}$) and a structural (LAI) plant trait to approximate forest heterogeneity. Heterogeneity of LAI is higher in protected forest than in total forest, disregarding spatial scale, when comparing the total forest area within the study area with the total area of the forest protection zone. Heterogeneity of $CI_{red\text{-}edge}$ is more or less the same within and outside protected forest, yielding very high heterogeneity values in both cases and for both spatial resolutions. The method used in this study to compare plant trait heterogeneity of total forest area with protected forest area is considered of medium potential, after considering all impacting aspects (see chapter 4.2.1. *Monitoring heterogeneity*). The heterogeneity values of LAI are being affected by the patchiness of forest in the study area and hence a big number of pixels are close to forest edges, where heterogeneity is high. Also, many forest edges are included in the protection enactment. In an attempt to avoid this problem, two 1 km^2 areas that are located completely within forest area were investigated more closely. This resulted in lower trait heterogeneity in protected forest compared to unprotected forest.

Lower LAI heterogeneity in protected forest are explained by the denser canopy. Forest roads are not shining through the canopy, compared to the unprotected area, where the canopy is not as dense. Canopy denseness might also be affecting $CI_{red\text{-}edge}$ heterogeneity. If so, it is doubtful, whether LAI heterogeneity is suitable to compare unprotected and protected areas with regards to forest resilience, because protected forest is likely to have a denser canopy in many cases, as forest is not as impacted by logging activities. Hence, the proposed method might not be suitable for comparing heterogeneity of plant traits within and outside conservation areas. Diversity measures have been generally criticized as they do not capture the actual species composition (McGarigal 2015), however, they are a practical and efficient way to summarize large multivariate datasets into an interpretable value (Rocchini et al. 2013). Instead of only considering a value based on one single image, it is suggested to compute some kind of composite value (e.g. monthly mean) and monitoring it over a longer period of time to detect other potential drawbacks.
There exist other methods for assessing heterogeneity of plant traits. Based on image texture characterized by MODIS Enhanced Vegetation Index (EVI), a recent study developed 14 new metrics that are able to capture different aspects of global habitat heterogeneity at a resolution of 1 km (Tuanmu & Jetz 2015). According to this study, the new metrics outperform conventional topography- and land-cover-based measures of habitat heterogeneity for modelling fine-grain bird species richness. Instead computing based on EVI, plant traits assessed by S-2 could be used as input, and hence, provide increased spatial resolution. The plant traits used in this thesis are not irreplaceable. Heterogeneity of other plant traits may as well be investigated for a link to resilience, but LAI and $CI_{red\text{-}edge}$ were considered convenient in the context of this thesis, as they are easily assessable by S-2, represent both the biochemical and the structural aspects of forest that are affected by changes in nutrient input. Disregarding the plant traits or heterogeneity metrics used, there will always be certain problems when comparing protected and unprotected forest areas. A reliable comparison would require two identical forest plots (i.e. same species composition, tree age, climatic conditions etc.). This is nearly impossible.

After all, the link between heterogeneity and actual forest resilience can be investigated only, after some impact has disturbed the forest (e.g. a drought, storm or fire) and the recovery towards some equilibrium state can be monitored. Yet, until then, it is not possible to find any correlation, except an impact is forced in the scope of an experiment. The generally positive relationship between habitat heterogeneity and resilience (Loreau & de Mazancourt 2013, Oliver et al. 2015) may be presumed to hold for the study area. Resilience research could also look similar to a recently published study, where remote sensing and functional trait data was compared to recovery of productivity after wildfires (Spasojevic et al. 2016). The study provides some of the first empirical evidence for the positive link between resilience and diversity.

4.4.3 Forest heterogeneity and productivity

Linking trait heterogeneity with productivity, SHDI values were plotted against GPP. To avoid impacts of forest edges, clearings and residues of the flight line mosaicking, two squares of 1 km^2 were compared only. No clear relationship was found. A linear regression was applied, resulting in very low R-squared, which was expected ($R^2 < 0.1$). This was the case for both $CI_{red\text{-}edge}$ and LAI and disregarding scale (2 m or 20 m). Following three explanations are possible: a) there is no relationship between productivity and heterogeneity of LAI and

$CI_{red\text{-}edge}$, b) the selected metrics fail to properly grasp the heterogeneity of the selected traits, or c) the method fails because it only takes into account a snapshot in time, instead of considering productivity over a longer time period. This uncertainty can be addressed by monitoring changes in productivity over *time*, and link it with heterogeneity of plant traits, rather than only relating heterogeneity with productivity variability over *space*. In other words, instead of comparing a value of productivity of a forest pixel to a heterogeneity metric, a more hopeful approach is seen in comparing mentioned heterogeneity of plant traits to long-term changes in productivity.

Given the framework of this study, only one observation was available, but exploring multi-annual time series of forest productivity and relating it to heterogeneity of both $CI_{red\text{-}edge}$ and LAI will be possible with S-2 in the coming years. Its spectral capabilities, especially the presence of bands in the red-edge region, centered at 705, 740 and 783 nm, are highly suitable for the computation of the $CI_{red\text{-}edge}$ index and the LAI. Drawbacks of the proposed heterogeneity metrics and the factors influencing them have been discussed before.

Alternative to only using RS-EBVs to investigate conservation areas, long-term changes in species or functional diversity can be compared to changes in productivity. Many recent experiments have observed an increase in soil carbon storage (e.g. Fornara & Tilman 2008; Steinbeiss et al. 2008, Lange et al. 2015) or aboveground biomass (e.g. Tilman et al. 2001; Loreau et al. 2003; Marquard et al. 2009; Wang et al. 2016; Debouk et al. 2015) when increasing plant diversity or changing composition, or the opposite, when reducing diversity (e.g. Hector et al. 1999). Tilman et al. (2012) suggest that high diversity of species in certain ecosystems may have an as big an impact on productivity as fertilization, while sustaining ES. Regarding estimations of functional diversity, Schleuter et al. (2010) examined the performance of functional richness, evenness and divergence indices. Fontana et al. (2015) tested a selection of multivariate indices for trait richness, evenness and divergence and recommended to use the TOP (trait onion peeling) index, TED (trait even distribution) index for evenness and FDiv index for trait divergence to measure trait diversity. However, in a field experiment where nitrogen and phosphorus fertilization was increased, species diversity sharply decreased, while functional diversity remained stable, suggesting that species diversity may be more important for ecosystem processes (Li et al. 2015). Generally, spatial patterns in species richness don’t necessarily correspond with patterns in functional diversity, raising the dilemma, which diversity component should be focused on in conservation strategies (Devictor et al. 2010).

This should be considered in future studies in the study area. Estimations of species and functional diversity were not further pursued in this study, as the focus was set on RS-EBVs.

4.5 Achieving the targets

Only limited statements are possible about achieving the investigated ABTs in the study area, as in most cases, no time series for trend analysis is available yet. This is particularly an issue for ABT 5, where a reduction of the rate of loss of habitat and a reduction of degradation and fragmentation is strived for. Up to now, no clear trends in area of forest and rare habitats are available for the study area. Assumptions can be made, considering published literature on nationwide trends, the conditions in the study area, and the results of this study, but are abstained from. The main pressure in the study area is (currently) not necessarily the loss of habitat area, but the degradation due to N depositions exceeding critical values. This is a threat for forests, as well as rare habitats. And despite N emissions being reduced in the last few years, the effect on forests and rare habitats are not predictable. Surely, forest and rare habitats are highly fragmented in terms of both separation into individual patches, as well as fragmentation through roads and railways. Considering fragmentation studies from Switzerland (Jaeger et al. 2007, BDM 2010), one could assume, that fragmentation in the study area is increasing. Also, the OSM based analysis showed an increase between 2014 and 2016. The available data fails however to give clear evidence about the magnitude of longer-range fragmentation trends in the study area.

Considering that the phrasing of ABT 14 is again somewhat vague, achieving it by 2020 depends on the strictness of what is seen as safeguarding and each country's framework. In the Zurich area, forests, the lake and urban vegetation are all safeguarded and restoration activities take place where necessary. Specific restoration activities have taken place in the past years. Regarding the ES investigated in this study, all three ecosystems are sufficiently protected: forest is preserved in its extent and made accessible to the wider public, sustaining its recreational value. Lake Zurich provides drinking water of very good quality with stable nutrient concentration since 1996 and good hygienic conditions (Stadt Zürich 2013). To achieve ABT 14 regarding Lake Zurich, most importantly, wastewater treatment infrastructure needs to be maintained and, if necessary, modernized. Urban vegetation in the city of Zurich and neighboring municipalities is being cared of and restored where necessary. *Grün Stadt Zürich* fosters road trees, alleys, parks cemeteries and other green areas faithfully and contributes to planning and development of green spaces in the city region. Regarding the filtering service provided by vegetation along roads, the alley concept (*Alleenkonzept*) is worth mentioning: adopted in 1991, as a long term project for the future, it provides a guideline to plant new alleys throughout the city, maintaining the ecological functioning of urban vegetation. Changes in the forest ecosystem due to high N emissions are hard to predict and need further monitoring. Also, new pressures appear that require adapted strategies: the more frequent appearance of the toxic cyanobacterium *P. rubescens* in Lake Zurich presents a threat that needs to be addressed. Thus, despite forest, the lake and urban vegetation being highly safeguarded and cared of, it is hard to make a statement about achieving ABT 14. There is certainly potential in reducing some of the main pressures, and in some aspects, the existing safeguarding program is flawless.

Achieving ABT 15 in the study area depends on conservation and restoration of forests and raised bogs. Forests are safeguarded very well, with conservation measures in terms of extent and condition. Safeguarding strategies are focusing very much on preservation of forest extent on national level, but also on forest condition, restrictions of use and maintenance measures on the cantonal level. Changes due to climate change and nutrient pressure are not (yet) equally well addressed, but awareness about the problem exists, and emission trends are improving. There is still potential in reducing pressures on forest and other ecosystems. All raised bogs in the study area are under federal protection and therefore fully conserved and actively managed.

Considering the fact that one of the bogs is located very close to settlement area (e.g. *Moos Schönenhof bei Wallisellen*) or agricultural area (e.g. *Chräenriet*), pressures are very high and special maintenance is necessary.

Also, achieving the ABT 15 partly depends on whether there is actually a positive relationship between conservation and restoration on the one hand, and resilience and contribution of biodiversity to carbon stocks on the other hand. This is an aspect, where RS-EBVs show great potential for future studies, but no statement is possible yet for the study area.

4.6 Contributions and limitation of RS-EBVs

Originally proposed to capture major dimensions of biodiversity change (Pereira et al. 2013a), EBVs, and specifically RS-EBVs can be used as link between primary observations and high-level indicators (Pettorelli et al. 2016b), as demonstrated in this thesis. They are not as abstract as biodiversity indicators and deliver transparent information of ecosystem state that can be combined for different purposes. This study was concentrating on the basic data needed to quantify the most important aspects of ABTs 5, 14 and 15, considering major pressures on the ecosystems of the study area. With multi-annual time series of RS-EBVs proposed in this study, necessary information for monitoring progress in implementation of the Strategic Plan for Biodiversity 2011-2020, particularly ABTs 5, 14 and 15 can be gathered. Once calibrated with *in situ* data, they are convenient variables that can be used as regular and repeatable input for biodiversity indicators providing global data. Effective integration of RS data with site-based measurements are the key to accurately monitor ecosystem condition (Lawley et a. 2016). This will also contribute in studying EBVs on different spatial scales.

High-level indicators for ABTs 5, 14 and 15 include trends in extent, condition and fragmentation of certain ecosystems, as well trends in conservation status. In combination with GIS data, RS-EBVs are also useful to map certain aspects of ecosystem services. Measured with S-2 they would also provide a dataset enabling global comparison with relatively good spatial resolution of 20 m for most RS-EBVs.

However, the selection of EBVs and RS-EBVs was adapted to the specific circumstances of the study area. This will likely lead to problems in comparability when applied globally: priority ecosystems are not the same everywhere, and even when looking at the same ecosystem type (e.g. forest), major pressures may differ from the ones found in this study area. In other parts of the world, other biodiversity variables are *essential*. So even if the proposed set of RS-EBVs is monitored regularly and in a harmonized way, they may not be as important as in the study area and thus not the best combination as input for the same biodiversity indicator.

Also, not every aspect significant for mentioned ABTs can be observed with RS-EBVs. Assessing habitat fragmentation through traffic infrastructure proved to be impossible without additional GIS data. Changes in measurable variables may express themselves differently on different scales or may not be detectable at all. Concluding this subject, it should be highlighted that RS-EBVs are not to be seen as alternative to indicators, but as linking variable within the biodiversity research community that simplify assessment of certain dimensions of biodiversity and data integration.

4.7 Contributions and limitations of S-2

The S-2 mission can contribute in many aspects, as shown in this study. Particularly valuable contributions include its ability to monitor forest productivity, leaf pigments and leaf area index. Regularly monitoring plant traits and their relations to other ecosystem properties will deepen our understanding of underlying ecosystem processes as well as help manage their consequences (Jetz et al. 2016). The RS-EBVs proposed to monitor vegetation changes might provide especially valuable insights if combined with ground data and monitored over a sufficient time period. S-2 provides data in better spatial resolution than other satellites (e.g. MODIS/TERRA GPP has a spatial resolution of 500 x 500 m).

Additionally, the S-2 mission allows to successfully calculate two water quality indices for the area of Lake Zurich, with particularly satisfying results for the TSS algorithm. Despite not being listed as RS-EBV, this is considered as an important contribution to assess aquatic ecosystems. Limitations were mainly given by the lack of consensus on how to assess certain RS-EBVs (e.g. *fragmentation* or *heterogeneity*). Insufficient spectral resolution or unsuitable placing of the bands made it difficult to calculate certain plant traits (like carotenoid concentration). Calculating certain EBVs for different spatial resolutions led to inconsistent results. Most RS-EBVs measured by S-2 result in a cell size of 20 m, which had to be kept in mind whenever monitoring ecosystem properties. Ecological processes and its components are often interlinked on different scales in space and time and can interact across those scales (Soranno et al. 2014). In many cases it is not possible to predict the effects of small changes within an ecosystem to other parts of it.

Limitations of data availability and consistency have a direct impact on assessing progress towards targets, which will be discussed in the following section. Since the launch of S-2A in June 2015, data is available with a 10-day revisit time. To this date, the sensor has only been collecting data for one year, so no statement about any long-term trend can be made using S-2 data. Research about best estimator indices for different vegetation characteristics under varying circumstances is currently in progress. As a consequence, indices selected during the beginning stage of this study may not match the latest findings.

5 Conclusion

5.1 Achievements

This thesis aimed at developing a method for monitoring the progress towards ABTs 5, 14 and 15 in an area of 312 km^2 around Zurich, Switzerland, using RS-EBVs. Specifically, data for assessing progress towards ABTs 5, 14 and 15 was gathered, consisting of preferably RS-EBVs, available GIS data and other data.

A first literature research showed that a variety of organizations and databases with different foci, measuring on different scales and dimensions, lead to a vast amount of widely inconsistent environmental and biodiversity-related data. Countless indicators were developed for monitoring specific aspects of the environment. Before existing indicators were further developed, new ones came after, without any measurement basis or specific instructions. Passing 2016, there is still no agreement on how to consistently assess progress towards some of the ABTs and their indicators, and methodologies differ from study to study. The call on agreement on a definitive set of biodiversity variables came late, but it came (Skidmore et al. 2015). EBVs and particularly RS-EBVs measurable from space are the first potential set of measures that can be worked with, and combined with growing open satellite data (e.g. S-2) is providing great potential in harmonized ecosystem monitoring (ibid.) and as input for high-level biodiversity indicators. But despite the process of selecting essential variables being in progress, the decision on what metrics and methods to use for their assessment is yet to happen. This was the largest uncertainty in this thesis, and it shall be pointed out that the methods used in this thesis were adjusted to both the specific environment of the study area and the framework given by the simulated S-2 image. Addressing the first research question of this study, the data that was eventually used and considered beneficial for assessing progress towards ABTs 5, 14 and 15, is summarized below.

For ABT 5, RS-EBVs *land cover, primary productivity, plant traits, heterogeneity* and *fragmentation* were computed and connected to the most important indicators (Tab. 15). Given the specific circumstances of the study area, GIS data was preferred for assessment of habitat extent, as changes in forest extent are not expected and rare habitats are not assessable with the S-2 sensor. Forest extent is, however, assessable and can be monitored regularly. The RS-EBVs suggested in this study are considered of great potential for monitoring forest condition. Particularly with regards to parts of its biochemical and structural aspects, and their potential behavior towards high nutrient input, RS-EBVs *primary productivity, leaf area index, heterogeneity* and *plant traits* can be helpful. Three leaf pigments were estimated: chlorophyll, anthocyanin and carotenoid. Calibration with ground data allows to accurately measure pigment content, especially since the equations were adapted to the available spectral bands. The same accounts for GPP and LAI. As the S-2 mission is relatively young, research on best estimator indices are regularly published (e.g. Vincini et al. 2016). Forest *heterogeneity* was measured with simple landscape heterogeneity metrics. Spatial heterogeneity of $CI_{red\text{-}edge}$ was found higher than heterogeneity of LAI for total forest area. While single observations of mentioned RS-EBVs provide valuable insights in spatial patterns of biochemistry and structure of forest area, changes of those need systematic monitoring over decades to give significant information.

Fragmentation of natural habitat was found more suitable to assess using OSM data, as spreading traffic infrastructure is the major cause for fragmentation in the study area. Between November 2014 and April 2016, 50 km of traffic infrastructure was added to the dataset within the boundaries of natural habitat. The MESH provides a useful metric to quantify separation of forest into individual patches, which can be applied on remotely sensed land cover data or GIS data. In conclusion, progress towards ABT 5 can elaborately be assessed for forest area, by combining RS-EBVs and GIS data. Once assessed on a regular basis, rates of change in extent, quality and fragmentation of natural habitats are eventually quantifiable. Assessment of extent, degradation and fragmentation of rare habitats, as discussed, relies on detailed ground data.

Assessing progress towards ABT 14 and 15 are not necessarily depending on RS-EBVs. Their wording mainly strives to increase restoration and safeguarding activities, including the conservation of a certain selection of ecosystems, enhancing the benefits that are derived from those. All three selected priority ecosystems are under certain restoration and safeguarding activities and are properly safeguarded to maintain ecosystem services. Awareness of their importance is high and their conservation status have improved in the last decades, particularly in the cases of forest and the lake. In the context of this study, a product was developed for monitoring an important service provided by each ecosystem of interest, using both RS-EBVs and GIS data. Targeting at investigating one provisioning, regulating and cultural service each, that relate to water, contribution to health, livelihoods and well-being, following services were approximated: the recreational value of forest, the provision of clean drinking water and the filtration capacity of urban vegetation. Recreational value of forest was estimated using the LAI (expressing denseness of forest), the road network for accessibility and public open water bodies. As most of the populations drinking water originates from the lake, its water quality was estimated by computing total suspended solids and phytoplankton chlorophyll-*a*. Urban vegetation's ability to filter and deposit PM10 was estimated by combining LAI with a buffer zone around intensively used roads. All three products are but approximations of the respective ES. These products are not necessarily needed to assess progress towards ABT 14, however, they highlight the ability and versatility of RS-EBVs for monitoring ecosystem services and important ecosystem properties in general, and provide more meaningful results than the simple assessment of the conservation status of an ecosystem.

ABT 15 strives for the conservation and restoration of (degraded) ecosystems to increase resilience, contributions of biodiversity to carbon stocks and mitigation of climate change. Conservation status of forest and raised bogs was assessed to validate progress towards the target. This thesis showed that the fraction of protected areas varied strongly, depending which levels of strictness are considered. The focus was on investigating the link between conservation and resilience and contribution to carbon stocks, using RS-EBVs *heterogeneity, plant traits* (chlorophyll), *leaf area index* and *primary productivity.* This study was successful in computing the individual RS-EBVs, but investigating the long-term relationship between heterogeneity of plant traits and resilience or productivity, respectively, requires multi-annual research. In the study area, high LAI heterogeneity in unprotected forest is caused by the lower canopy denseness and lower vegetation and traffic being visible for the sensor. This leads to the conclusion that LAI heterogeneity does not necessarily relate positively to conservation status, or if, rather inversely, as protected forest tends to have a denser canopy (no timber use activities, less road network etc.). More research is required for this aspect of the ABT.

This thesis showed that RS-EBVs are a useful concept to relate primary observations of satellite missions to the somewhat abstract biodiversity indicators developed for assessing progress towards ABTs 5, 14 and 15, however, ground measurements are needed to accurately calibrate the indices. Being state indicators, RS-EBVs are a promising tool to describe and quantify consequences of ecosystem pressures. Contributions and limitations of RS-EBVs, as well as of the S-2 mission to assess them, were discussed.

It should be highlighted that RS-EBVs are not to be seen as alternative to indicators, but as linking variable within the biodiversity research community that simplify both the assessment of certain dimensions of biodiversity, and data integration. They measure narrowly defined ecosystem properties, that are to some extent affected by environmental changes caused by human activities. Not all relationships are clear yet, and changes in the EBVs also depend on site-specific circumstances. Hence, assessing progress towards ABTs in other regions of the planet may require other RS-EBVs as input for the same biodiversity indicators. Harmonizing the assessment of ABTs 5, 14 and 15 on a global level is not entirely possible.

An important variable not further investigated in this study is *vegetation phenology*. Phenology describes the seasonal timing of foliage (Cornelissen 2003). The RS proxy of leaf phenology is the length of the vegetation season (Homolová et al. 2013); Vegetation phenology is an essential component of ecosystem functioning and can be monitored using time series of Vegetation Indices NDVI, Leaf Area Index (LAI) or fPAR (Homolová et al. 2013, Secades et al. 2014). Inter-annual variability in trends of vegetation activity (e.g. measuring greening and browning trends approximated by NDVI) can be assessed using consistent and long-term RS data (de Jong et al. 2012). Despite not being part of this thesis, phenology trends can be observed from space and give valuable insights regarding vegetation changes due to climate change.

5.2 Outlook

Since assessment of progress depends on comparable data raised at specific intervals over a long period of time, no trends of selected RS-EBVs were investigated yet. Currently, the framing of the concept of RS-EBVs is taking place and priorities are established (Pettorelli et al. 2016a; Pettorelli et al. 2016b). RS is an ever evolving field, providing information related to ecosystem properties and functioning in a timely manner at different spatial and spectral scales (Rocchini 2015), and RS-EBVs offer an opportunity to track certain aspects of ABTs 5, 14 and 15 in a standardized manner. They contribute to consistently assessing important ecosystem properties related to the achieving of the ABTs. Deciding on a subset of essential variables is a step in the right direction with regards not only to validating the ABTs, but observing ecosystem change in general.

This study concentrated on ABTs 5, 14 and 15, but RS-EBVs are also considered useful for other ABTs. ABT 8 strives to reduce ecosystem pollution, including from excess nutrients, an issue also addressed in the context of this study. Also, potential of RS-EBVs is seen in monitoring conditions of agricultural areas, which is subject of ABT 7. The most important future step in this research area is the definitive agreement on a set of variables, potentially the ones proposed by Skidmore et al. (2015) and additional ones like phytoplankton chl-*a*. Secondly, reaching consensus on assessment methodology for each of the RS-EBVs is necessary, potentially similar to the ones proposed in this study. Thirdly, multi-annual time series need to be collected and stored openly available for scientists, conservationists, and other stakeholders. A guideline for high-level indicators and their relation to RS-EBV time series has to be developed, including specification on spatial and temporal scales. For this whole progress to happen in a time-efficient manner, coordination and conversation between key actors of politics, science and conservation is necessary (O’Connor et al. 2015). The GEO BON is supporting and coordinating the ongoing EBV development process. Despite the fact that the implementation of the Strategic Plan for Biodiversity is focusing on the time window between 2011 and 2020, continuous monitoring of ecosystem change is necessary afterwards, due to delayed changes in vegetation.

6 Literature

Adler, P.B., Seabloom, E.W., Borer, E.T., Hillebrand, H., Hautier, Y., Hector, A., Harpole, W.S., O'Halloran, L.R., Grace, J.B., Anderson, T.M., Bakker, J.D., Biederman, L.A., Brown, C.S., Buckley, Y.M., Calabrese, L.B., Chu, C.-J., Cleland, E.E., Collins, S.L., Cottingham, K.L., Crawley, M.J., Damschen, E.I., Davies, K.F., DeCrappeo, N.M., Fay, P.A., Firn, J., Frater, P., Gasarch, E.I., Gruner, D.S., Hagenah, N., Lambers, J.H., Humphries, H., Jin, V.L., Kay, A.D., Kirkman, K.P., Klein, J.A., Knops, J.M.H., La Pierre, K.J., Lambrinos, J.G., Li, W., MacDougall, A.S., McCulley, L., Melbourne, B.A., Mitchesll, C.E., Moore, J.L., Morgan, J.W., Mortensen, B., Orrock, J.L., Prober, S.M., Pyke, D.A., Risch, A.C., Schuetz, M., Smith, M.D., Stevens, C.J., Sullivan, L.L., Wang, G., Wragg, P.D., Wright, J.P. & Yank, L.H. (2011): Productivity is a poor predictor of plant species richness. In: Science, 333 (2011), 1750-1753.

BAFU und WSL (Hrsg.) (2013): Die Schweizer Bevölkerung und ihr Wald. Bericht zur zweiten Bevölkerungsumfrage Waldmonitoring soziokulturell (WaMos 2). Bundesamt für Umwelt, Bern und Eidg. Forschungsanstalt für Wald, Schnee und Landschaft WSL, Birmensdorf. Umwelt-Wissen Nr. 1307: 92 S.

BAFU & BLV (Hrsg.) (2016): Umsetzung des Protokolls Wasser und Gesundheit in der Schweiz. Bewertung der von 2013 bis 2015 erzielten Fortschritte nach Artikel 7 des Protokolls. Bundesamt für Umwelt; Bundesamt für Lebensmittelsicherheit und Veterinärwesen.

Bai, Z. G., Dent, D. L., Olsson, L. & Schaepman, M. E. (2008): Proxy global assessment of land degradation. In: Soil Use and Management, 24 (2008), 223-234.

Baik, J.-J., Kwak, K.-H., Park, S.-B. & Ryu, Y.-H. (2012): Effects of building roof greening on air quality in street canyons. In: Atmospheric Environment, 61 (2012), 48-55.

Barnosky, A. D., Matzke, N., Tomiya, S., Wogan, G. O. U., Swartz, B., Quental, T. B., Marshall, C., McGuire, J. L., Lindsey, E. L., Maguire, K. C., Mersey, B. & Ferrer, E. A. (2011): Has the Earth's sixth mass extinction already arrived? In: Nature, 471 (2011), 51–57.

Baudirektion Kanton Zürich (Ed.) (2010): Waldentwicklungsplan Kanton Zürich 2010. Amt für Landschaft und Natur, Abteilung Wald.

BDM (2010): Landscape Fragmentation. Basic data from biodiversity monitoring Switzerland. Indicator E 15. http://www.biodiversitymonitoring.ch/ (Access: 10.08.2016). Federal Office for the Environment, Bern.

BDM (2015a): Quality of Valuable Habitats. Basic data from biodiversity monitoring Switzerland. Indicator Z 11. http://www.biodiversitymonitoring.ch/ (Access: 16.08.2016). Federal Office for the Environment, Bern.

BDM (2015b): Biodiversity Monitoring Switzerland. http://www.biodiversitymonitoring.ch/ (Access: 31.12.2015). Federal Office for the Environment, Bern.

Beckett, P., Freer-Smith, P.H. & Taylor, G. (2000): Particulate pollution capture by urban trees: effect of species and windspeed. In: Global Change Biology, 6 (2000), 995-1003.

Belote, R.T., Prisley, S., Jones, R.H., Fitzpatrick, M. & de Beurs, K. (2011): Forest productivity and tree diversity relationships depend on ecological context within mid-Atlantic and Appalachian forests (USA). In: Forest Ecology and Management, 261 (7), 1315-1324.

Bennett, E. M., Cramer, W., Begossi, A., Cundill, G., Díaz, S., Egoh, B. N., Geijzendorffer, I. R., Krug, C. B., Lavorel, S., Lazos, E., Lebel, L., Martín-López, B., Meyfroidt, P., Mooney, H. A., Nel, J. L., Pascual, U., Payet, K., Pérez Harguindeguy, N., Peterson, G. D., Prieur-Richard, A., Reyers, B., Roebeling, P., Seppelt, R., Solan, M., Tschakert, P., Tscharntke, T., Turner II, BL., Verburg, P. H., Viglizzo, E., White, P. C. L. & Woodward, G. (2015): Linking biodiversity, ecosystem services, and human well-being: three challenges for designing research for sustainability. In: Current Opinion in Environmental Sustainability, 14 (2015), 76-85.

Brantley, H.L., Hagler, G.S.W., Deshmukh, P.J. & Baldauf, R.W. (2014): Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. In: Science of the Total Environment, 468–469 (2014), 120–129.

Braun, S., Thomas, V.F.D., Quiring, R. & Flückiger, W. (2010): Does nitrogen deposition increase forest production? The role of phosphorus. In: Environmental Pollution, 158 (2010), 2043-2052.

Braun, S., Rihm, B. & Flückiger, W. (2012): Stichstoffeinträge in den Schweizer Wald: Ausmass und Auswirkungen. In: Schweiz Z Forestwes, 163 (9), 355-362.

Buccolieri, R., Salim, S.M., Leo, L.S., Di Sabatino, S., Chan, A., Ielpo, P., de Gennaro, G. & Gromke, C. (2011): Analysis of local scale tree-atmosphere interaction on pollutant concentration in idealized street canyons and application to a real urban junction. In: Atmospheric Environment, 45 (2011), 1702-1713.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Hernández Morcillo, M., Oldfield, T.E.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vié, J.-C. & Watson, R. (2010): Global biodiversity: indicators of recent declines. In: Science, 328 (5982), 1164–68.

Cardinale, B.J., Duffy, E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S. & Naeem, S. (2012): Biodiversity loss and its impact on humanity. In: Nature, 486 (2012), 59-67.

Carpenter, S., Walker, B., Anderies, J.M. & Abel, N. (2001): From Metaphor to Measurement: Resilience of What to What? In: Ecosystems, 4 (2001), 765-781.

CBD (2002): Report of the sixth meeting of the conference of the parties to the Convention on Biological Diversity. COP 6, The Hague. Annex: Decisions, VI/26. Strategic Plan for the Convention on Biological Diversity. Secretariat of the Convention on Biological Diversity.

CBD (2010): Report of the tenth meeting of the conference of the parties to the Convention on biological diversity. COP 10, Nagoya, Japan. Annex: Decisions, X/2. The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets. Secretariat of the Convention on Biological Diversity. 111-123.

CBD (2012a): Report of the eleventh meeting of the conference of the parties to the Convention on Biological diversity. COP 11, Hyderabad, India. Annex I: Decisions XI/3: Monitoring Progress in implementation of the Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets. 97-99.

CBD (2012b): Cities and Biodiversity Outlook. Secretariat of the Convention on Biological Diversity. Montréal, Canada.

CBD (2015a): History of the Convention. Secretariat of the Convention on Biological Diversity.https://www.cbd.int/history/ (Access: 11.10.2015).

CBD (2015b): Introduction. Secretariat of the Convention on Biological Diversity. https://www.cbd.int/intro/default.shtml (Access: 11.10.2015).

CBD (n.d.): Quick guide to the Aichi Biodiversity Targets – 15: Ecosystems restored and resilience enhanced. www.cbd.int/sp (Access: 02.09.16)

Chalker-Scott, L. (1999): Environmental Significance of Anthocyanins in Plant Stress Responses. In: Photochemistry and Photobiology, 70 (1), 1-9. American Society for Photobiology.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., Defries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R.B., Piao, S. & Thornton, P. (2013): Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 465-570.

Clevers, J.G.P.W. & Gitelson, A. (2013): Remote estimation of crop and grass chlorophyll and nitrogen content using red-edge bands on Sentinel-2 and -3. In: International Journal of Applied Earth Observation and Geoinformation, 23 (2013), 344-351.

Clevers, J.G.P.W. & Kooistra, L. (2012): Using Hyperspectral Remote Sensing Data for Retrieving Canopy Chlorophyll and Nitrogen Content. In: IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 5 (2), 574-583.

Cordillot, F. & Klaus, G. (2011): Threatened Species in Switzerland. Red List Synthesis Report, Status 2010. Federal Office for the Environment, Bern. State of the environment No.1120: 111 pp.

Cushman, S.A., McGarigal, K. & Neel, M.C. (2008): Parsimony in landscape metrics: Strength, universality and consistency. In: Ecological Indicators, 8 (2008), 691-703.

Damm, A., de Jong, R., Braun, D., Garbari, S. & Schaepman, M.E. and SEON partners (2013): APEX Product Table. Document version 01-19.11.2013.

Damm, A., Kneubühler, M., Schaepman, M.E. & Rascher, U. (2012): Evaluation of gross primary production (GPP) variability over several ecosystems in Switzerland using sun-induced chlorophyll fluorescence derived from APEX data. In: IEEE 2012, 7133-7136.

Debouk, H., de Bello, F. & Sebastià, M.-T. (2015): Functional Trait Changes, Productivity Shifts and Vegetation Stability in Mountain Grasslands during a Short-Term Warming. PLoS ONE 10(10): e0141899. doi:10.1371/journal.pone.0141899.

Deguignet M., Juffe-Bignoli D., Harrison J., MacSharry B., Burgess N. & Kingston N. (2014): 2014 United Nations List of Protected Areas. UNEP-WCMC: Cambridge, UK.

de Jong, R., de Bruin, S., Schaepman, M. & Dent, D. (2011): Quantitative mapping of global land degradation using Earth observations. In: International Journal of Remote Sensing, 32 (21), 6823-6853.

de Jong, R., Verbesselt, J., Schaepman, M.E. & de Bruin, S. (2012): Trend changes in global greening and browning: contribution of short-term trends to longer-term change. In: Global Change Biology, 18 (2012), 642-655.

Dekker, A.G., Vos, R.J. & Peters, S.W.M. (2002): Analytical algorithms for lake water TSM estimation for retrospective analyses of TM and SPOT data. In: International Journal of Remote Sensing, 23 (1), 15-35.

Delegido, J., Alonso, L., González, G. & Moreno, J. (2010): Estimating chlorophyll content of crops from hyperspectral data using a normalized area over reflectance curve (NAOC). In: International Journal of Applied Earth Observation and Geoinformation, 12 (2010), 165-174.

Delegido, J., Verrelst, J., Alonso, L. & Moreno, J. (2011): Evaluation of Sentinel-2 Red-Edge Bands for Empirical Estimation of Green LAI and Chlorophyll Content. In: Sensors, 11 (2011), 7063-7081.

Devictor, V., Mouillot, D., Meynard, C., Jiguet, F., Thuiller, W. & Mouquet, N. (2010): Spatial mismatch and congruence between taxonomic, phylogenetic and functional diversity: the need for integrative conservation strategies in a changing world. In: Ecology Letters, 13 (2010), 1030-1040.

Diek, S., de Jong, R., Braun, D., Böhler, J. & Schaepman, M. (2014): Deriving soil function maps to assess related ecosystem services using imaging spectroscopy in the Lyss agricultural area, Switzerland. Geogphysical Research Abstracts, 16, EGU2014-15115, 2014.

Díaz, S., Purvis, A., Cornelissen, J. H. C., Mace, G. M., Donoghue, M. J., Ewers, R. M., Jordano, P. & Pearse, W. D. (2013): Functional traits, the phylogeny of function, and ecosystem service vulnerability. In: Ecology and Evolution, 3 (9), 2958-2975.

Dirzo, R. & Raven, P. H. (2003): Global state of biodiversity and loss. Annu. Rev. Environ. Resour. 28 (2003), 137-167.

D'Odorico, P, Gonsamo, A., Damm, A. & Schaepman, M. E. (2013): Experimental Evaluation of Sentinel-2 Spectral Response Functions for NDVI Time-Series Continuity. In: IEEE Transactions on Geoscience and Remote Sensing, 51(3), 1336–1348.

EKL (2013): Feinstaub in der Schweiz 2013. Eidgenössische Kommission für Lufthygiene, Bern.

Elmqvist, T., Setälä, H., Handel, S.N., van der Ploeg, S., Aronson, J., Blignaut, J.N., Gómez-Baggethun, E., Nowak, D.J., Kronenberg, J. & de Groot, R. (2015): Benefits of restoring ecosystem services in urban areas. In: Current Opinion in Environmental Sustainability, 14 (2015), 101-108.

ERS (2010): Air Quality and Health. European Respiratory Society, Lausanne.

ESA (n.d.): Introducing Sentinel-2. www.esa.int. (Access: 08.07.16).

ESA (2015): Sentinel-2 User Handbook. European Space Agency, Issue 1.2, 1-64.

Fahrig, L. (2003): Effects of Habitat Fragmentation on Biodiversity. In: Annual Rev. Ecol. Evol. Syst, 34 (2003), 487-515.

Fahrig, L., Baudry, J., Brotons, L., Burel, F.G., Crist, T.O., Fuller, R.J., Sirami, C., Siriwardena, G.M. & Martin, J.-L. (2011): Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. In: Ecology Letters, 14 (2011), 101-112.

Felber Dietrich D. (2014): Luftverschmutzung und Gesundheit. Übersicht zu den Auswirkungen. Bundesamt für Umwelt, Bern. Umwelt-Wissen Nr. 1425, 1-15.

Feldmeyer, E., Küchler, M., Graf, U., Ecker, K. & Wildi, O. (2010): Hochmoore regenerieren. Informationsblatt Landschaft, 76 (2010), Eidg. Forschungsanstalt WSL.

Flückiger, W., Braun, S., Mainiero, R., Schütz, K. & Thomas, V. (2011): Auswirkung erhöhter Stickstoffbelastung auf die Stabilität des Waldes. Synthesebericht im Auftrag des BAFU. Bundesamt für Umwelt, Bern.

Flynn, D.F.B., Gogol-Prokurat, M., Nogeire, T., Molinari, N., Trautman Richers, B., Lin, B.B., Simpson, N., Mayfield, M.M. & DeClerck, F. (2009): Loss of functional diversity under land use intensification across multiple taxa. In: Ecology Letters, 12 (2009), 22-33.

FOEN (ed.) (2010): Switzerland's Fourth National Report under the Convention on Biological Diversity, Bern.

FOEN (ed.) (2012): Swiss Biodiversity Strategy. Federal Office for the Environment, Bern.

FOEN (ed.) (2013a): Forest Policy 2020. Visions, objectives and measures for the sustainable management of forests in Switzerland. Federal Office for the Environment, Bern.

FOEN (ed.) (2013b): PM10 and PM2.5 ambient concentrations in Switzerland. Modelling results for 2005, 2010 and 2020. Federal Office for the Environment, Bern.

FOEN (ed.) (2014a): Switzerland’s Fifth National Report under the Convention on Biological Diversity. Federal Office for the Environment, Bern.

FOEN (ed.) (2014b): Jahrbuch Wald und Holz 2014. Bundesamt für Umwelt, Bern. Umwelt-Zustand Nr. 1420.

FOEN (ed.) (2015): Water. Indicator Phosphorus content in lakes. http://www.bafu.admin.ch/umwelt/indikatoren/08605/08608/index.html?lang=en (Access: 22.03.2016).

Forest Report (2015): Rigling, A. & Schaffer, H.P. (Eds.): Forest Report 2015. Condition and Use of Swiss Forests. Federal Office for the Environment, Bern, Swiss Federal Institute WSL, Birmensdorf. 1-144.

Fontana, S., Petchey, O.L. & Pomati, F. (2015): Individual-level trait diversity concepts and indices to comprehensively describe community change in multidimensional trait space. In: Functional Ecology, 2015. British Ecological Society.

Fornara, D.A. & Tilman, D. (2008): Plant functional composition influences rates of soil carbon and nitrogen accumulation. In: Journal of Ecology, 96 (2008), 314-322.

FSO (2013): Land use in Switzerland. Results of the Swiss land use statistics. Swiss Federal Statistical Office.

Gamon, J.A. & Surfus, J.S. (1999): Assessing leaf pigment content and activity with a reflectometer. In: New Phytologist, 143 (1999), 105-117.

GEO BON (Group on Earth Observations – Biodiversity Observation Network). http://geobon.org/ (Access: 10.09.2015).

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E. & Sodhi, N.S. (2011): Primary forests are irreplaceable for sustaining tropical biodiversity. In: Nature, 478 (2011), 378-383.

Gitelson, A.A. Garbuzov, G., Szilagyi, F., Mittenzwey, K.-H., Karnieli, A. & Kaiser, A. (1993): Quantitative remote sensing methods for real-time monitoring of inland waters quality. In: International Journal of Remote Sensing, 14 (7), 1269-1295.

Gitelson, A.A., Gritz, Y. & Merzlyak, M.N. (2003): Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. In: Journal of Plant Physiology, 160 (2003), 271-282.

Gitelson, A.A., Keydan, G.P. & Merzlyak, M.N. (2006): Three-Band Model for Non-invasive Estimation of Chlorophyll Carotenoids and Anthocyanin Contents in Higher Plant Leaves. Papers in Natural Resources. Paper 258. In: Geophysical Research Letters, 33 (2006), 1-5.

Gitelson, A.A., Gurlin, D., Moses, W.J. & Barrow, T. (2009): A bio-optical algorithm for the remote estimation of the chlorophyll-a concentration in case 2 waters. In: Environmental Research Letters, 4 (2009), 1-5.

Givoni, (1991): Impact of planted areas on urban environmental quality: a review. In: Atmospheric Environment, 25B (3), 289-299.

Gorelick, R. (2006): Combining richness and abndance into a single diversity index using matrix analogues of Shannon’s and Simpson’s indices. In: Ecography, 29 (2006), 525-520.

Grace, J., Nichol, C., Disney, M., Lewis, P., Quaife, T. & Bowyer, P. (2007): Can we measure terrestrial photosynthesis from space directly, using spectral reflectance and fluorescence? In: Global Change Biology, 13 (2007), 1484-1497.

Haboudane, D., Miller, J.R., Pattey, E., Zarco-Tejada, P.J. & Strachan I.B. (2004): Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: Modeling and validation in the context of precision agriculture. In: Remote Sensing of Environment, 90 (2004), 337-352.

Hector, A., Schmid, B., Beierkuhnlein, C., Caldeira, M.C., Diemer, M., Dimitrakopoulos, P.G., Finn, J.A., Freitas, H., Giller, P.S., Good, J., Harris, R., Högberg, P., Huss-Danell, K., Joshi, J., Jumpponen, A., Körner, C., Leadley, P.W., Loreau, M., Minns, A., Mulder, C.P.H., O’Donovan, G., Otway, S.J., Pereira, J.S., Prinz, A., Read, D.J., Scherer-Lorenzen, M., Schulze, E.-D., Siamantziouras, A.-S. D., Spehn, E.M., Terry, A.C., Troumbis, A.Y., Woodwards, F.I., Yachi, S. & Lawton, J.H. (1999): Plant Diversity and Productivity Experiments in European Grasslands. In: Science, 286 (1999), 1123-1127.

Hector, A. (2011): Diversity favours productivity. In: Nature, 472 (2011), 45-46.

Hendry, G.A.F., Houghton, J.D. & Brown, S.B. (1987): The degradation of chlorophyll – a biological enigma. In: New Phytologist, 107 (1987), 255-302.

Hilker, T., Coops, N.C., Wulder, M.A., Black, T.A. & Guy, R.D. (2008): The use of remote sensing in light use efficiency based models of gross primary production: A review of current status and future requirements. In: Science of the total environment, 404 (2008), 411-423.

Homolová, L., Malenovský, Z., Clevers, J.G.P.W., García-Santos, G. & Schaepman, M.E. (2013): Review of optical-based remote sensing for plant trait mapping. In: Ecological Complexity, 15 (2013), 1-16.

Homolová, L., Schaepman, M.E., Lamarque, P., Clevers, J.G.P.W., de Bello, F., Thuiller, W. & Lavorel, S. (2014): Comparison of remote sensing and plant trait-based modelling to predict ecosystem services in subalpine grasslands. In: Ecosphere, 5 (8), 1-29.

International Union of for Conservation of Nature (2016): Biodiversity Indicators. www.iucn.org (Access: 26.07.2016).

Jaeger, J. A. G. (2000): Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. In: Landscape Ecology, 15 (2000), 115-130.

Jaeger, J. A. G., Bertiller, R. & Schwick, C. (2007): Degree of Landscape Fragmentation in Switzerland: Quantitative analysis 1885–2002 and implications for traffic planning and regional planning. Condensed version. Federal Statistical Office, Neuchâtel, 1-36.

Janetos, A. C., Kasperson, R., Agardy, T., Alder, J., Ash, N., DeFries, R. & Nelson, G. (2004): Synthesis: Condition and Trends in Systems and Services, Trade-offs for Human Well-being, and Implications for the Future. In: Hassan, R., Scholes, R. & Ash, N. (Ed.) (2004): Ecosystems and Human Well-being: Current State and Trends, Vol. 1, Chapter 28. Millennium Ecosystem Assessment. Island Press, Washington.
Janzen, H.H. (2004): Carbon cycling in earth systems—a soil science perspective. In: Agriculture, Ecosystems and Environment, 104 (2004), 399–417.

Janhäll, S. (2015): Review on urban vegetation and particle air pollution e Deposition and dispersion. In: Atmospheric Environment, 105 (2015), 130-137.

Jax, K. & Heink, U. (2015): Searching for the place of biodiversity in the ecosystem services discourse. In: Biological Conservation, 191 (2015), 198-205.

Jehle, M., Hueni, A., Damm, A., D'Odorico, P., Weyermann, J., Kneubühler, M., Schläpfer, D. & Schaepman, M. E. (2010): APEX - Current Status, Performance and Validation Concept. In: IEEE Sensors 2010 Conference, 533-537.

Jetz, W., Cavender-Bares, J., Pavlick, R., Schimel, D., Davis, F.W., Asner, G.P., Guralnick, R., Kattge, J., Latimer, A.M., Moorcroft, P., Schaepman, M.E., Schildhauer, M.P., Schneider, F.D., Schrodt, F., Stahl, U. & Ustin, S.L. (2016): Monitoring plant functional diversity from space. Comment in: Nature Plants, 2 (2016), 1-5. Macmillan Publishers Limited.

Jobbágy, E.G. & Jackson, R.B. (2000): The vertical distribution of soil organic carbon and its relation to climate and vegetation. In: Ecological Applications, 10(2), 423– 436.

Jones, H.P. & Schmitz, O.J. (2009): Rapid Recovery of Damaged Ecosystems. PLoS ONE, 3 (5): e5653. doi:10.1371/journal.pone.0005653

Jürgens, N. (2007): Biodiversität und Artenverlust. Kapitel 28: Global Change, Syndromkomplexe und globale Ressourcenkonflikte. In: Gebhardt, H., Glaser, R., Radtke, U. & Reuber, P. (Hrsg.) (2007): Geographie. Heidelberg: Spektrum Akademischer Verlag.

Katayama, N., Amano, T., Naoe, S., Yamakita, T., Komatsu, I., Takagawa, S., Ueta, M. & Miyashita, T. (2014): Landscape Heterogeneity-Biodiversity Relationship: Effect of Range Size. PLoS ONE, 9 (3): e93359. doi:10.1371/journal.pone.0093359.

Klaus, G. (Ed.) (2007): Zustand und Entwicklung der Moore. Ergebnisse der Erfolgskontrolle Moorschutz. Umwelt-Zustand Nr. 0730. Bundesamt für Umwelt, Bern.

Lange, M., Eisenhauer, N., Sierra, C.A., Bessler, H., Engels, C., Griffiths, R.I., Mellado-Vázquez, P.G., Malik, A.A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B.C., Trumbore, S.E. & Gleixner, G. (2015): Plant diversity increases soil microbial activity and soil carbon storage. In: Nature Communications, 6:6707 doi: 10.1038/ ncomms7707 (2015).

Laurent, V. C. E., Schaepman, M. E., Verhoef, W., Weyermann, J. & Chávez, R. O. (2014): Bayesian object-based estimation of LAI and chlorophyll from a simulated Sentinel-2 top-of-atmosphere radiance image. In: Remote Sensing of Environment, 140 (2014), 318-329.

Lavorel, S., Grigulis, K., Lamarque, P., Colace, M.-P., Garden, D., Girel, J., Pellet, G. & Douzet, R. (2011): Using plant functional traits to understand the landscape distribution of multiple ecosystem services. Journal of Ecology, 99, 135-147.

Lawley, V., Lewis, M., Clarke, K. & Ostendorf, B. (2016): Site-based and remote sensing methods for monitoring indicators of vegetation condition: An Australian review. In: Ecological Indicators, 60 (2016), 1273-1283.

Leadley, P. W., Krug, C. B., Alkemade, R., Pereira, H. M., Sumaila U. R., Walpole, M., Marques, A., Newbold, T., Teh, L. S. L, van Kolck, J., Bellard, C., Januchowski-Hartley, S. R. and Mumby, P. J. (2014): Progress towards the Aichi Biodiversity Targets: An Assessment of Biodiversity Trends, Policy Scenarios and Key Actions. Technical Series No. 78. Secretariat of the Convention on Biological Diversity, Montréal, Canada.

Li, W., Cheng, J.-M., Yu, K.-L, Epstein, H.E., Guo, L., Jing, G.-H., Zhao, J. & Du, G.-Z. (2015): Plant functional diversity can be indiependent of species diversity: obersvations based on the impact of 4-yrs of nitrogen and phosphorus additions in an alpine meadow. PLoS ONE 10(8): e0136040.doi:10.1371/journal.pone.0136040.

Litschke, T. & Kuttler, W. (2008): On the reduction of urban particle concentration by vegetation – a review. In: Meteorologische Zeitschrift, 17 (3), 229-240.

Llausàs, A. & Nogué, J. (2012): Indicators of landscape fragmentation: The case for combining ecological indices and the perceptive approach. In: Ecological indicators, 15 (2012), 85-91.

Loreau, M., Mouquet, N. & Gonzalez, A. (2003): Biodiversity as spatial insurance in heterogeneous landscapes. In: PNAS, 100 (22), 12765–12770.

Loreau, M. & de Mazancourt, C. (2013): Biodiversity and ecosystem stability: a synthesis of underlying mechanisms. In: Ecology Letters, 16 (2013), 106-115.

Loughner, C.P., Allen, D.J., Zhang, D.-L., Pickering, K.E., Dickerson, R.R. & Landry, L. (2012): Roles of Urban Tree Canopy and Buildings in Urban Heat Island Effects: Parameterization and Preliminary Results. In: Journal of Appllied Meteorology Climatology, 51 (2012), 1775–1793.

Maes, J., Fabrega, N., Zulian, G., Barbosa, A., Vizcaino, P., Ivits, E., Polce, C., Vandecasteele, I., Rivero, I. M., Guerra, C., Castillo, C. P., Vallecillo, S., Baranzelli, C., Barranco, R., e Silva, F.B., Jacobs-Crisoni, C., Trombetti, M. & Lavalle, C. (2015): Mapping and Assessment of Ecosystems and their Services: Trends in ecosystems and ecosystem services in the European Union between 2000 and 2010. JRC Science and Policy Report. Luxembourg: Publications Office of the European Union, 2015.

Marquard, E., Weigelt, A., Temperton, V.M., Roscher, C., Schumacher, J., Buchmann, N., Fischer, M., Weisser, W.W. & Schmid, B. (2009): Plant species richness and functional composition drive overyielding in a six-year grassland experiment. In: Ecology, 90 (12), 3290-3302.

Matthews, M. W. (2011): A current review of empirical procedures of remote sensing in inland and near-coastal transitional waters. In: International Journal of Remote Sensing, 32 (21), 6855-6899.

McGarigal, K. (2015): Fragstats help: version 4. University of Massachusetts, Amherst.

MEA (2005a): Ecosystems and Human Well-being: Synthesis. A report of the Millennium Ecosystem Assessment. World Resources Institute, Washington D.C: Island Press.

MEA (2005b): Ecosystems and Human Well-being: Biodiversity Synthesis. World Resources Institute, Washington, DC: Island Press.

MEA (2005c): Ecosystems and Human Well-being: Current State and Trends, Vol. 1, Part IV, Chapter 28. Millennium Ecosystem Assessment. World Resources Institute, Washington D.C: Island Press.

Meier, C. (2003): Naturoasen im Kanton Zürich brauchen besonderen Schutz. Bericht zum Instrument der Schutzverordnung (SVO). InputUmwelt. Im Auftrag der Fachstelle Naturschutz Kanton Zürich. Zürich.

Merzlyak, M.N. & Chivkunova, O.B. (2000): Light-stress-induced pigment changes and evidence for anthocyanin photoprotection in apples. In: Journal of Photochemistry and Photobiology, 55(2000), 155-163.

Moses, W.J., Gitelson, A.A., Berdnikov, S. & Povazhnyy, V. (2009): Satellite estimation of Chlorophyll-a Concentration Using the Red and NIR Bands of MERIS – The Azov Sea Case Study. In: IEEE Geoscience and Remote Sensing Letters, 6 (4), 845-849.

Muñoz-Huerta, R.F., Guevara-Gonzalez, R.G., Contreras-Medina, L.M. Torres-Pacheco, I., Prado-Olivarez, J. & Ocampo-Velazquez, R.V. (2013): A Review of Methods for Sensing the Nitrogen Status in Plants: Advantages, Disadvantages and Recent Advances. In: Sensors 13 (2013), 10823-10843.

Office of Landscape, Agriculture and Environment (2016): Naturschutz bei Bauvorhaben. http://www.aln.zh.ch/ (Access: 08.08.16)

OAPC. Ordinance on Air Pollution Control. https://www.admin.ch/opc/en/classified-compilation/19850321/index.html (Status as of 15.07.16, Access: 02.09.16)

O’Connor, B., Secades, C., Penner, J., Sonnenschein, R., Skidmore, A., Burgess, N. D. & Hutton, J. M. (2015): Earth observation as a tool for tracking progress towards the Aichi Biodiversity Targets. In: Remote Sensing in Ecology and Conservation. doi: 10.1002/rse2.4. John Wiley & Sons Ltd. (Publisher).

Olff, H. & Ritchie, M.E. (2002): Fragmented nature: consequences for biodiversity. In: Landscape and Urban Planning, 58 (2002), 83-92.

Oliver, T., Roy, D.B., Hill, J.K., Brereton, T. & Thomas, C.D. (2010): Heterogeneous landscapes promote population stability. In: Ecology Letters, 13 (2010), 473-484.

Oliver, T.H., Heard, M.S., Isaac, N.J.B., Roy, D.B., Procter, D., Eigenbrod, F., Freckleton, R., Hector, A., Orme, C.D.L., Petchey, O.L., Proença, V., Raffaelli, D., Suttle, K.B., Mace, G.M., Martín-López, B., Woodcock, B.A. & Bullock, J.M. (2015): Biodiversity and Resilience of Ecosystem Functions. In: Trends in Ecology & Evolution, 30 (11), 673-684.

OpenStreetMap contributers. https://www.openstreetmap.org/copyright/en. (Access: 02.09.16).

Palmer, M.W., Earls, P.G., Hoagland, B.W., White, P.S. & Wohlgemuth, T. (2002): Quantitative tools for perfecting species lists. In: Environmetrics, 13 (2002), 121-137.

Palmer, S.C.J., Odermatt, D., Hunter, P.D., Brockmann, C., Présing, M., Balzter, H. & Tóth, V.R. (2015): Satellite remote sensing ofphytoplankton phenology in Lake Balaton using 10 years of MERIS obersvations. In: Remote Sensing of Environment, 158 (2015), 441-452.

Paquette, A. & Messier, C. (2011): The effect of biodiversity on tree productivity: from temperate to boreal forests. In: Global Ecology and Biogeography, 20 (2011), 170–180.

Pereira, H. M., Navarro, L. M. & Martins, I. S. (2012): Global Biodiversity Change: The Bad, the Good, and the Unknown. In: The Annual Review of Environment and Resources, 37 (2012), 25-50.

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., Bruford, M. W., Brummitt, N., Butchart, S. H. M., Cardoso, A. C., Coops, N. C., Dulloo, E., Faith, D. P., Freyhof, J., Gregory, R. D., Heip, C., Höft, R., Hurtt, G., Jetz, W., Karp, D. S., McGeoch, M. A., Obura, D., Onoda, Y., Oettorelli, N., Reyers, B., Sayre, R., Scharlemann, J. P. W., Stuart, S. N., Turak, E., Walpole, M. & Wegmann, M. (2013a): Essential Biodiversity Variables. In: Science, 339 (2013), 277-278.

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., Bruford, M. W., Brummitt, N., Butchart, S. H. M., Cardoso, A. C., Coops, N. C., Dulloo, E., Faith, D. P., Freyhof, J., Gregory, R. D., Heip, C., Höft, R., Hurtt, G., Jetz, W., Karp, D. S., McGeoch, M. A., Obura, D., Onoda, Y., Oettorelli, N., Reyers, B., Sayre, R., Scharlemann, J. P. W., Stuart, S. N., Turak, E., Walpole, M. & Wegmann, M. (2013b): Supplementary Materials for ‘Essential Biodiversity Variables’. In: Science, 339 (2013), 277-278.

Pettorelli, N., Owen, H.J.F. & Duncan, C. (2016a): How do we want Satellite Remote Sensing to support biodiversity conservation globally? In: Methods in Ecology and Evolution, 7(2016), 656-665.

Pettorelli, N., Wegmann, M., Skidmre, A., Mücher, S., Dawson, T.P., Fernandez, M., Lucas, R., Schaepman, M.E., Wang, T., O’Connor, B., Jongman, R.H.G., Kempeneers, P., Sonnenschein, R., Leidner, A.K., Böhm, M., He, S.H., Nagendra, H., Dubois, G., Fatoyinbo, T., Hansen, M.C., Paganini, M., de Klerk, H.M., Asner, G.P., Kerr, J.T., Estes, A.B., Schmeller, D.S., Heiden, U., Rocchini, D., Pereira, H.M., Turak, E., Fernandez, N., Lausch, A., Cho, M.A., Alcaraz-Segura, D., McGeoch, M.A., Turner, W., Mueller, A., St-Louis, V., Penner, J., Vihervaara, P., Berlward, A., Reyers, B. & Geller, G.N. (2016b): Framing the concept of satellite remote sensing essential biodiversity variables: challenges and future directions. In: Remote Sensing in Ecology and Conservation, doi: 10.1002/rse2.15.

Plascyk, J.A. (1975): The MK II Fraunhofer Line Discriminator (FLD-II) for Airborne and Orbital Remote Sensing of Solar-Stimulated Luminescence. In: Optical Engineering, 14 (4), 339-346.

Pouzols, F.M., Toivonen, T., Di Minin, E., Kukkala, A.S., Kullberg, P., Kuusterä, J., Lehtomäki, J., Tenkanen, H., Verburg, P.H. & Moilanen, A. (2014): Global protected area expansion is compromised by projected land-use and parochialism. In: Nature, 516 (2014), 383- 386.

Rey Benayas, J.M., Newton, A.C., Díaz, A. & Bullock, J.M. (2009): Enhancement of Biodiversity and Ecosystem Services by Ecological Restoration: A Meta-Analysis. In: Science, 325 (2009), 1121-1124.

Rocchini, D., Chiarucci, A. & Loiselle, S.A. (2004): Testing the spectral variation hypothesis by using satellite multispectral images. In: Acta Oecologica, 26 (2004), 117-120.

Rocchini, D., Delucchi, L., Bacaro, G., Cavallini, P., Feilhauer, H., Foody, G. M., He, K. S., Nagendra, H., Porta, C., Ricotta, C. Schmidtlein, S., Spano, L. D., Wegmann, M. & Neteler, M. (2013): Calculating landscape diversity with information-theory based indices: A GRASS GIS solution. In: Ecological Informatics, 17 (2013), 82-93.

Rocchini, D. (2015): Earth Observation for Ecosystem Monitoring in Space and Time: A Special Issue in Remote Sensing. In: Remote Sensing, 7 (2015), 8102-8106. doi:10.3390/rs70608102.

Rocchini, D., Boyd, D.S., Féret, J.-B., Foody, G.M., He, K.S., Lausch, A., Nagendra, H., Wegmann, M. & Pettorelli, N. (2015): Satellite remote sensing to monitor species diversity: potential and pitfalls. In: Remote Sensing in Ecology and Conservation, published by John Wiley & Sons Ltd on behalf of Zoological Society of London.

Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M. & Hashimoto, H. (2004): A continuous Satellite-Derived Measure of Global Terrestrial Primary Production. In: BioScience, 54 (6), 547-560.

Running, S.W. & Zhao, M. (2015): User's Guide Daily GPP and Annual NPP (MOD17 A2/A3) Products NASA Earth Observing System MODIS Land Algorithm. Version 3.0, For Collection 6, 2015.

Schindler, S., von Wehrden, H., Poirazidis, K., Hochachka, W.M., Wrbka, T. & Kati, V. (2015): Performance of methods to select landscape metrics for modelling species richness. In: Ecological Modelling, 295 (2015), 107-112.

Schleuter, D., Daufresne, M., Massol, F. & Argillier, C. (2010): A user's guide to functional diversity indices. In: Ecological Monographs, 80 (3), 469-484.

Schneider, W. (2011-2016): OSM extracts for Zuerich: Zuerich.osm.shp.zip. http://download.bbbike.org/osm/bbbike/Zuerich/. (Access: 05.07.16).

Secades, C., O'Connor, B., Brown, C. & Walpole, M. (2014). Earth Observation for Biodiversity Monitoring: A review of current approaches and future opportunities for tracking progress towards the Aichi Biodiversity Targets. Technical Series No. 72. Secretariat of the Convention on Biological Diversity, Montréal, Canada.

Shannon, C.E. & Weaver, W. (1949): The mathematical theory of Communication. University of Illinois Press, Urbana and Chicago.

Simpson, E.H. (1949): Measurement of diversity. IN: Nature, 163: 688.

Skidmore, A. K., Pettorelli, N., Coops, N. C., Geller, G. N., Hansen, M., Lucas, R., Mücher, C. A., O'Connor, B., Paganini, M., Pereira, H. M., Schaepman, M. E., Turner, W., Wang, T. & Wegmann, M. (2015): Agree on biodiversity metrics to track from space. In: Nature, 523 (2015), 403-405.

Spasojevic, M.J., Bahlai, C.A., Bradley, B.A., Butterfield, B.J., Tuanmu, M.-N., Sistla, S., Wiederholt, R. & Suding, K.N. (2016): Scaling up the diversity-resilience relationship with trait databases and remote sensing data: the recovery of productivity after wildfire. In: Global Change Biology, 22 (2016), 1421-1432.

Stadt Zürich (Hrsg.) (2013): Gewässerzustand von Zürichsee, Zürichobersee und Walensee. Auswertungen der Untersuchungsergebnisse bis 2010. Stadt Zürich, Wasserversorgung, Qualitätsüberwachung.

Stadt Zürich (2016): Trinkwasser. Departement der Industriellen Betriebe. https://www.stadt-zuerich.ch/dib/de/index/wasserversorgung/trinkwasser.html (Access: 04.03.2016).

Stein, A., Gerstner, K. & Kreft, H. (2014): Environmental heterogeneity as a universal driver of species richness across taxa, biomes and spatial scales. In: Ecology Letters, 17 (2014), 866-880.

Steinbeiss, S., Bessler, H., Engels, C., Temperton, V.M., Buchmann, N., Roscher, C., Kreutziger, Y., Baade, J., Habekost, M. & Gleixner, G. (2008): Plant diversity positively affects short-term soil carbon storage in experimental grasslands. In: Global Change Biology, 14 (2008), 2937–2949.

Suding, K. N. & Goldstein, L. J. (2008): Testing the Holy Grail framework: using functional traits to predict ecosystem change. In: New Phytologist, 180 (2008), 559-562.

Tews, J. Brose, U., Grimm, V., Tielbörger, K., Wichmann, M.C., Schwager, M. & Jeltsch, F. (2004): Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. In: Journal of Biogeography, 31 (2004), 79-92.

Tilman, D. (2001): Functional Diversity. In: Levin, S. A. (Ed.) Encyclopedia of Biodiversity, Vol. 3, 109-120.

Tilman, D., Reich, P.B., Knops, J., Wedin, D., Mielke, T. & Lehman, C. (2001): Diversity and Productivity in a Long-Term Grassland Experiment. In: Science, 294 (2001), 843-845.

Tilman, D., Reich, P.B. & Isbell, F. (2012): Biodiversity impacts ecosystem productivity as much as resources, disturbance, or herbivory. In: PNAS, 109 (26), 10394–10397.

Tittensor, D. P., Walpole, M., Hill, S. L. L., Boyce, D. G., Britten, G. L., Burgess, N. D., Butchart, S. H. M., Leadley, P. W., Regan, E. C., Alkemade, R., Baumung, R., Bellard, C., Bouwman, L., Bowles-Newark, N. J., Chenery, A. M., Cheung, W. W. L., Christensen, V., Cooper, H. D., Crowther, A. R., Dixon, M. J. R., Galli, A., Gaveau, V., Gregory, R. D., Gutierrez, N. L., Hirsch, T. L., Höft, R., Januchowski-Hartley, S. R., Karmann, M., Krug, C. B., Leverington, F. J., Loh, J., Kutsch Lojenga, R., Malsch, K., Marques, A., Morgan D. H. W., Mumby, P. J., Newbold, T., Noonan-Mooney, K., Pagad, S. N., Parks, B. C., Pereira, H. M., Robertson, T., Rondinini, C., Santini, L., Scharlemann, J. P. W., Schindler, S., Sumaila, U. R., Teh, L. S. L., van Kolck, J., Visconti, P. & Ye Y. (2014): A mid-term analysis of progress toward international biodiversity targets. In: Science, 346 (2014), 241-244.

Tuanmu, M.-N. & Jetz, W. (2015): A global, remote sensing-based characterization of terrestrial habitat heterogeneity for biodiversity and ecosystem modelling. In: Global Ecology and Biogeography, 24 (2015), 1329-1339.

Tucker, C.J. (1979): Red and photographic infrared linear combinations for monitoring vegetation. In: Remote Sensing of Environment, 8 (1979), 27-150.

Turner, W., Rondinini, C., Pettorelli, N., Mora, B., Leidner, A. K., Szantoi, Z., Buchanan, G., Dech, S., Dwyer, M., Herold, M., Koh, L. P., Leimgruber, P., Taubenboeck, H., Wegmann, M., Wikelski, M. & Woodcock, C. (2015): Free and open-access satellite data are key to biodiversity conservation. In: Biological Conservation, 182 (2015), 173-176.

Van den Wyngaert, S., Salcher, M.M., Pernthaler, J., Zeder, M. & Posch, T. (2011): Quantitative dominance of seasonally persistent filamentous cyanobacteria (Planktothrix rubescens) in the microbial assemblages of a temperate lake. In: Limnol. Oceanogr., 56 (1), 97-109.

Verrelst, J., Alonso, L., Camps-Valls, G., Delegido, J. & Moreno, J. (2012): Retrieval of Vegetation Biophysical Parameters Using Gaussian Process Techniques. In: IEEE Transactions on Geoscience and Remote Sensing, 50 (5), 1832-1843.

Walker, B., Holling, C.S., Carpenter, S. & Kinzig, A. (2004): Resilience, Adaptability and Transformability in Social–ecological Systems. In: Ecology and Society, 9 (2), 5. http://www.ecologyandsociety.org/vol9/iss2/art5 (Access: 02.09.16).

Wang, R., Gamon, J.A., Emmerton, C.A., Li, H., Nestola, E., Pastorello, G.Z. & Menzer, O. (2016): Integrated analysis of productivity and biodiversity in a southern Alberta prairie. In: Remote Sensing, 8 (214), doi:10.3390/rs8030214.

Wetzel, F.T., Saarenmaa, H., Regan, E., Martin, C.S., Mergen, P., Smirnova, L., Ó Tuama, É., García Camacho, F.A., Hoffmann, A., Vohland, K. & Häuser, C.L. (2015): The roles and contributions of Biodiversity Observation Networks (BONs) in better tracking progress to 2020 biodiversity targets: a European case study. DOI: 10.1080/14888386.2015.1075902 Taylor & Francis.

Weyermann, J., Damm, A., Kneubühler, M. & Schaepman, M.E. (2013): Correction of Reflectance Anisotropy Effects of Vegetation on Airborne Spectroscopy Data and Derived Products. In: IEEE Transactions on Geoscience and Remote Sensing, (99), 1–12.

Wong, N.H. & Yu, C. (2005): Study of green areas and urban heat island in a tropical city. In: Habitat International, 29 (2005), 547-558.

WWEA (2016a): Beurteilung Seezustand. Zürichsee. Office of Waste, Water, Energy and Air, Gewässerschutz. Baudirektion Kanton Zürich. http://www.awel.zh.ch/internet/baudirektion/ awel/de/wasser/messdaten/ seequalitaet. html, (Access: 22. 03.2016)

WWEA (2016b): Stickstofbelastung der Zürcher Seen seit 1950. Office of Waste, Water, Energy and Air, Gewässerschutz. Baudirektion Kanton Zürich.

WWEA (2016c): Entwicklung Phytoplankton seit 1982. Zürichsee. Office of Waste, Water, Energy and Air, Gewässerschutz. Baudirektion Kanton Zürich. http://www.hw.zh.ch/chemie/see/01_Ph.pdf (Access: 30.03.2016).

WWEA (2016d): Phosphorbelastung der Zürcher Seen seit 1950. Office of Waste, Water, Energy and Air, Gewässerschutz. Baudirektion Kanton Zürich.

Zika, M. & Erb, K.-H. (2009): The global loss of net primary production resulting from human-induced soil degradation in drylands. In: Ecological Economics, 69 (2009), 310-318.

7 Appendix

7.1 Full list of Aichi Biodiversity Targets

Strategic Goal A: Address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society

Target 1
By 2020, at the latest, people are aware of the values of biodiversity and the steps they can take to conserve and use it sustainably.

Target 2
By 2020, at the latest, biodiversity values have been integrated into national and local development and poverty reduction strategies and planning processes and are being incorporated into national accounting, as appropriate, and reporting systems.

Target 3
By 2020, at the latest, incentives, including subsidies, harmful to biodiversity are eliminated, phased out or reformed in order to minimize or avoid negative impacts, and positive incentives for the conservation and sustainable use of biodiversity are developed and applied, consistent and in harmony with the Convention and other relevant international obligations, taking into account national socio economic conditions.

Target 4
By 2020, at the latest, Governments, business and stakeholders at all levels have taken steps to achieve or have implemented plans for sustainable production and consumption and have kept the impacts of use of natural resources well within safe ecological limits.

Strategic Goal B: Reduce the direct pressures on biodiversity and promote sustainable use

Target 5
By 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced.

Target 6
By 2020 all fish and invertebrate stocks and aquatic plants are managed and harvested sustainably, legally and applying ecosystem based approaches, so that overfishing is avoided, recovery plans and measures are in place for all depleted species, fisheries have no significant adverse impacts on threatened species and vulnerable ecosystems and the impacts of fisheries on stocks, species and ecosystems are within safe ecological limits.

Target 7
By 2020 areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity.

Target 8
By 2020, pollution, including from excess nutrients, has been brought to levels that are not detrimental to ecosystem function and biodiversity.

Target 9
By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment.

Target 10
By 2015, the multiple anthropogenic pressures on coral reefs, and other vulnerable ecosystems impacted by climate change or ocean acidification are minimized, so as to maintain their integrity and functioning.

Strategic Goal C: To improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity

Target 11
By 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes.

Target 12
By 2020 the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained.

Target 13
By 2020, the genetic diversity of cultivated plants and farmed and domesticated animals and of wild relatives, including other socio-economically as well as culturally valuable species, is maintained, and strategies have been developed and implemented for minimizing genetic erosion and safeguarding their genetic diversity.

Strategic Goal D: Enhance the benefits to all from biodiversity and ecosystem services

Target 14
By 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well-being, are restored and safeguarded, taking into account the needs of women, indigenous and local communities, and the poor and vulnerable.

Target 15
By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration, including restoration of at least 15 per cent of degraded ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification.

Target 16
By 2015, the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization is in force and operational, consistent with national legislation.

Strategic Goal E: Enhance implementation through participatory planning, knowledge management and capacity building

Target 17
By 2015 each Party has developed, adopted as a policy instrument, and has commenced implementing an effective, participatory and updated national biodiversity strategy and action plan.

Target 18
By 2020, the traditional knowledge, innovations and practices of indigenous and local communities relevant for the conservation and sustainable use of biodiversity, and their customary use of biological resources, are respected, subject to national legislation and relevant international obligations, and fully integrated and reflected in the implementation of the Convention with the full and effective participation of indigenous and local communities, at all relevant levels.

Target 19
By 2020, knowledge, the science base and technologies relating to biodiversity, its values, functioning, status and trends, and the consequences of its loss, are improved, widely shared and transferred, and applied.

Target 20
By 2020, at the latest, the mobilization of financial resources for effectively implementing the Strategic Plan for Biodiversity 2011-2020 from all sources, and in accordance with the consolidated and agreed process in the Strategy for Resource Mobilization, should increase substantially from the current levels. This target will be subject to changes contingent to resource needs assessments to be developed and reported by Parties.

7.2 Candidate List of Essential Biodiversity Variables

Table A-1: Candidate list of Essential Biodiversity Variables. EBVs are grouped into six classes: Genetic composition, species populations, species traits, community composition, ecosystem function and ecosystem structure.

EBV Class	**EBV**	**Measurement and scalability**	**Temporal sensitivity**	**Feasibility**	**Relevance and related CBD 2020 targets**
Genetic composition	Co-ancestry	Pairwise relatedness among individuals or inbreeding coefficient of selected species, within and among populations of each species.	Generation time	Available for many species but few populations, and little systematic sampling over time.	This variable provides a good measure of the genetic independence of allele frequencies among individuals and their susceptibility to lowered fitness. Targets: 12.
	Allelic diversity	Allelic richness from genotypes of selected species (e.g. endangered species and domesticated species) at multiple locations (statistically representative of the species distribution).	Generation time	Data available for several species and for several locations, but little global systematic sampling.	It is one the most used variables to measure genetic diversity, and can support the estimation of indicators such as "Trends in genetic diversity of selected species" and the "Red List Index". Targets: 12, 13.
	Population genetic differentiation	Gene frequency differentiation (Fst and other measures) among populations or of a subpopulation compared to the metapopulation of selected species.	Generation time	Data available for many species but often for a limited number of populations. Easy to augment datasets.	Beta diversity analogue; this variable captures the variation among populations. This variable can also help to identify local genetically-based adaptation and help provide a 'population adaptive index'. Targets: 12, 13, 15.
	Breed and variety diversity	Number of animals of each livestock breed and proportion of farmed area under each local crop variety, at multiple locations.	5 to 10 years	Large datasets have been compiled by national organizations and FAO for livestock breeds, but there is insufficient systematic sampling for coverage of local crop varieties.	It is an essential variable to estimate the indicator "Trends in genetic diversity of domesticated animals and cultivated plants". Target: 13.
Species populations	Species distribution	Presence surveys for groups of species easy to monitor, over an extensive network of sites with geographic representativeness. Potential role for incidental data from any spatial location.	1 to >10 years	Presence surveys are available for a larger number of species than population counts and can make use of existing distribution atlas. Some efforts for data compilation and integration exist (GBIF, IUCN, Map of Life). There is an increasing trend for data contributed by citizen scientists (Observado, iNaturalist).	Abundance & distribution of populations/taxon per se is an intuitive biodiversity metric with public resonance. Abundance & distribution contributes to extinction risk indicators and indicators of supply of ecosystem services associated with particular species. Range shifts are expected under climate change. Targets: 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15.
	Population abundance	Population counts for groups of species easy to monitor and/or important for ecosystem services, over an extensive network of sites with geographic representativeness.	1 year	Population counts underway for a significant number of species in each of the following groups: birds, butterflies, mammals, plankton, important fisheries, coral reef fishes. Most of these extensive networks are geographically restricted. Much of the data are currently being collected by citizen science networks.	
	Population structure by age/size class	Number of individuals or biomass of a given demographic class of a given taxon or functional group at a given location.	1 year	Available for some managed species (hunting and fisheries), usually geographically restricted.	

Species traits	Phenology	Timing of periodic biological events for selected taxa/phenomena at defined locations. Examples include: timing of breeding, leaf coloration, flowering, migration, oceans flow pattern shifts, intermittent flows in rivers, extant of wetlands.	1 year	Several ongoing initiatives (Phenological Eyes Network, PhenoCam, ClimateWatch, etc.), some making use of citizen science contributions.	Phenology is expected to change with climate change. Targets: 10, 15.
	Body mass	Body mass (mean and variance) of selected species (e.g. under harvest pressure), at selected sites (e.g. exploitation sites).	1-5 year	Data available for many important marine fisheries, but little data available for bushmeat and other exploited species groups.	There is evidence that mean body mass of some species may be changing in response to pressures such as harvesting. Targets: 6, 7.
	Natal dispersal distance	Record median/frequency distribution of dispersal distances of a sample of selected taxa. In marine species larval lifetime it may be a useful surrogate.	>10 years	Banding/marking and observation data available for some birds, mammals, turtles, fish, temperate trees	Required in order to assess the impact of habitat fragmentation on species, project the spread of invasive species, project the impact of climate change on species and to combine with abundance data to assess extinction risk. Targets: 5, 6, 9, 10, 11, 12, 15.
	Migratory behaviour	Presence/ absence/ destinations/ pathways of selected migrant taxa.	1 to >10 years	Banding/ marking/ tagging and observation data available for some birds, mammals, turtles, fish and butterflies.	Migratory behaviour is expected to change under climate change and habitat fragmentation. Riverine migrations are expected to be susceptible to damming etc. Targets: 5, 6, 10, 11, 12.
	Demographic traits	Effective reproductive rate (e.g. by age/size class) and survival rate (e.g. by age/size class) for selected taxa at selected locations.	1 to >10 years	Data available for some fisheries, birds, mammals, reptiles, plants, and other taxa, but little trend data available.	Necessary to combine with other factors for assessing extinction risk and vulnerability to threats. Targets: 4, 6, 8, 9, 12, 15.
	Physiological traits	For instance, measurement of thermal tolerance or metabolic rate. Assess for selected taxa at selected locations expected to be affected by a specific driver.	1 to >10 years	Some data available for corals, lizards, amphibians and insects.	May determine susceptibility to climate change impacts and may change under climate change. Targets: 4, 6, 8, 9, 12, 15.
Community composition	Taxonomic diversity	Multi-taxa surveys (including by morphospecies) and metagenomics at selected *in situ* locations at consistent sampling scales over time. Hyper-spectral remote sensing over large ecosystems.	5-10 years	Many intensive long-term research sites have excellent but uncoordinated data, and there are abundant baseline data for many locations in the terrestrial, marine and freshwater realms. Metagenomics and the possibilities of remote sensing are emerging fields.	This is a basic measure of interaction of species i.e. which species live together. It is the basis of community classification and ecosystem health assessments. Functional type composition of the ecosystem is often derived from species composition of observed communities. Targets: 8, 10, 14.
	Species interactions	Studies of important interactions or interaction networks in selected communities, such as plant-bird seed dispersal systems.	5-25 years	Some studies have monitored the structure of species interaction networks such as mutualistic networks (pollination and seed dispersal), soil food webs, host-parasite and herbivore-plant interactions. There is a lack of global or regional representativeness of these studies.	Global change is affecting species interactions, which are determinants in ecosystem functioning and services. Targets: 7, 9, 14, 15.

Ecosystem Function	Net primary productivity	Global mapping with modelling from remote sensing observations (FAPAR, ocean greenness) and selected *in situ* locations (eddy covariance).	<=1 year	A network of regional networks of *in situ* measurements exists (FLUXNET), and some global maps based on models and remote sensing are available. GCOS is also addressing this EBV.	Indicator of the energy flow through ecosystems and a measure of health/degradation; Supports biodiversity at multiple dimensions/trophic levels, regulates climate, impacts on human wellbeing, possible indicator of shifts into alternate ecosystem states; underpins all production-based ecosystem services. Targets: 5, 8, 14.
	Secondary productivity	Measurement of secondary productivity for selected functional groups, combining *in situ* , remote sensing, and models. Example functional groups include: fisheries, livestock, krill, and herbivorous birds.	1 year	FAO and national statistics on fish and livestock production.	Important for assessing ecosystem functioning and ecosystem services. Targets: 6, 7, 14.
	Nutrient retention	Ratio of nutrient output from the system to nutrient input, measured at selected *in situ* locations. Can be combined with models and remote sensing to extrapolate regionally.	1 year	Some intensive monitoring sites have nitrogen saturation monitoring in some acid-deposition areas; phosphorus retention monitoring in some impacted rivers and estuaries.	Nutrient loss or accumulation affects biodiversity and ecosystems services. Targets: 5, 8, 14.
	Disturbance regime	Type, seasonal timing, intensity and frequency of event-based external disruptions to ecosystem processes and structure. Examples: sea surface temperature and salinity (RS), scatterometry for winds (RS), trawling pressure (*in situ*), flood regimes (*in situ*), fire frequency (*in situ* , RS), cultivation/ harvest (RS), windthrow and pests (*in situ*).	1 year	Abundant data is available for several perturbations, sometimes at the global scale, although harmonization and integration is needed.	Key determinant of ecosystem function, structure and composition; changes in the disturbance regime lead to changes in biodiversity. Targets: 5, 7, 9, 10, 11, 14, 15.
Ecosystem structure	Habitat structure	Remote sensing measurements of cover (or biomass) by height (or depth) classes globally or regionally, to provide a 3-dimensional description of habitats.	<=1 year	Global terrestrial maps available with RS (e.g., LIDAR). Marine and freshwater habitats mapped by combining RS and *in situ* data.	Proxy for biomass in ecosystems; key determinant of habitat suitability for biodiversity; basis for land cover classification. Relevant for targets: 5, 11, 14, 15.
	Ecosystem extent and fragmentation	Local (aerial photo and *in situ* monitoring) to global mapping (satellite observations) of natural/semi-natural forests, wetlands, free running rivers, coral reef live cover, benthos cover, etc.	1-5 years	Global maps of forests, assessment of fragmentation for major river basins, and local to regional maps of coral reefs already exist, but comparable observations over time are limited and a distinction between natural and modified ecosystems (e.g. natural forests versus plantations) is often not made.	This is a key measure of human impacts on ecosystems. It can be used to derive indicators such as extent of forests and forest types, mangrove extent, seagrass extent, coral reef condition. Targets: 5, 7, 10, 14, 15.
	Ecosystem composition by functional type	Functional types can be directly inferred from morphology (*in situ*) or from remote sensing.	5 years	Implicitly part of current ecosystem maps. Some models (e.g. DGVMs, marine ecosystem models) are based on functional groups.	This is a basis for ecosystem classification and lends itself to remote sensing. It can be used to predict ecosystem function and ecosystem services. Targets: 5, 14, 15.

7.3 Meteorological data for GPP estimation

Table A-2: Meteorological data of 26. June 2011: Temperature, relative humidity and global SW radiation used to calculate VPD, LUE and PAR.

Time [UTC]	Station	Temperature [°C]	Relative Humidity [%]	Global SW radiation [Wm^{-2}]
10:00	Zürich	23.5	50.1	916
	Affoltern	24.1	49.0	887
	Kloten	23.8	49.1	894
11:00	Zürich	24.6	46.4	955
	Affoltern	25.1	44.7	926
	Kloten	24.7	45.8	944
12:00	Zürich	26.3	40.8	945
	Affoltern	26.2	42.3	920
	Kloten	26.0	40.9	942
Mean		**24.92**	**45.46**	**925.44**

Table A-3: Parameters necessary for the computation of actual LUE (e_{actual}) for different vegetation types. LUE was calculated for coniferous and deciduous forest, crops and grassland.

Land cover	e_{max} [kgC/m^2/d/MJ]	$\text{Tmin}_{\_min}$ [°C]	$\text{Tmin}_{\_max}$ [°C]	$\text{VPD}_{\_min}$ [Pa]	$\text{VPD}_{\_max}$ [Pa]	VPD_{scalar}	e_{actual} [kgC/MJ]	e_{actual} [gC/MJ]
Conif. Forest	0.000962	-8	8.3	650	4600	0.27	0.000259658	**0.259658169**
Decid. Forest	0.001165	-6	9.94	650	1650	1.07	0.001165	**1.165**
Crop	0.001044	-8	12.02	650	4300	0.29	0.000304952	**0.304952114**
Grassland	0.00086	-8	12.02	650	5300	0.23	0.000197183	**0.197183019**

7.4 Heterogeneity of forest LAI

To visualize heterogeneity of LAI, a heterogeneity map based on the SHDI was produced for forest area (Fig. A-1). Mapping SHDI based on the neighborhood of each pixel gives an overview on the spatial heterogeneity of forest in the study area. Red color indicates high heterogeneity, and blue color indicates low heterogeneity of LAI. Forest edges tend to higher SHDI values, while areas within forest patches show lower heterogeneity. The forest patch at the northeastern corner of the study area shows remarkably high heterogeneity.

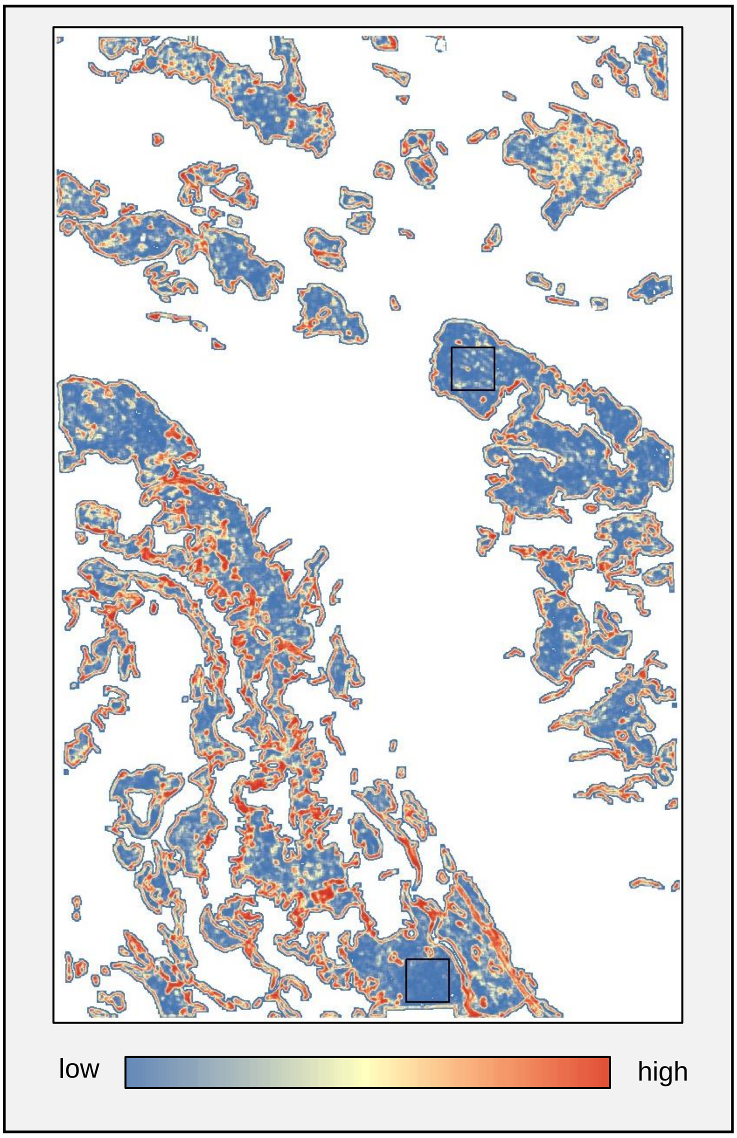

Figure A-1: Shannon's diversity index (SHDI) of forest LAI, with high heterogeity indicated as red, medium heterogeneity as yellow and low heterogeneity as blue. SHDI yields high values along forest edges. The black framed squares indicate the location of the pixels that were compared to GPP values (see chapter 3.3.3).

7.5 Plots of SHDI vs. GPP

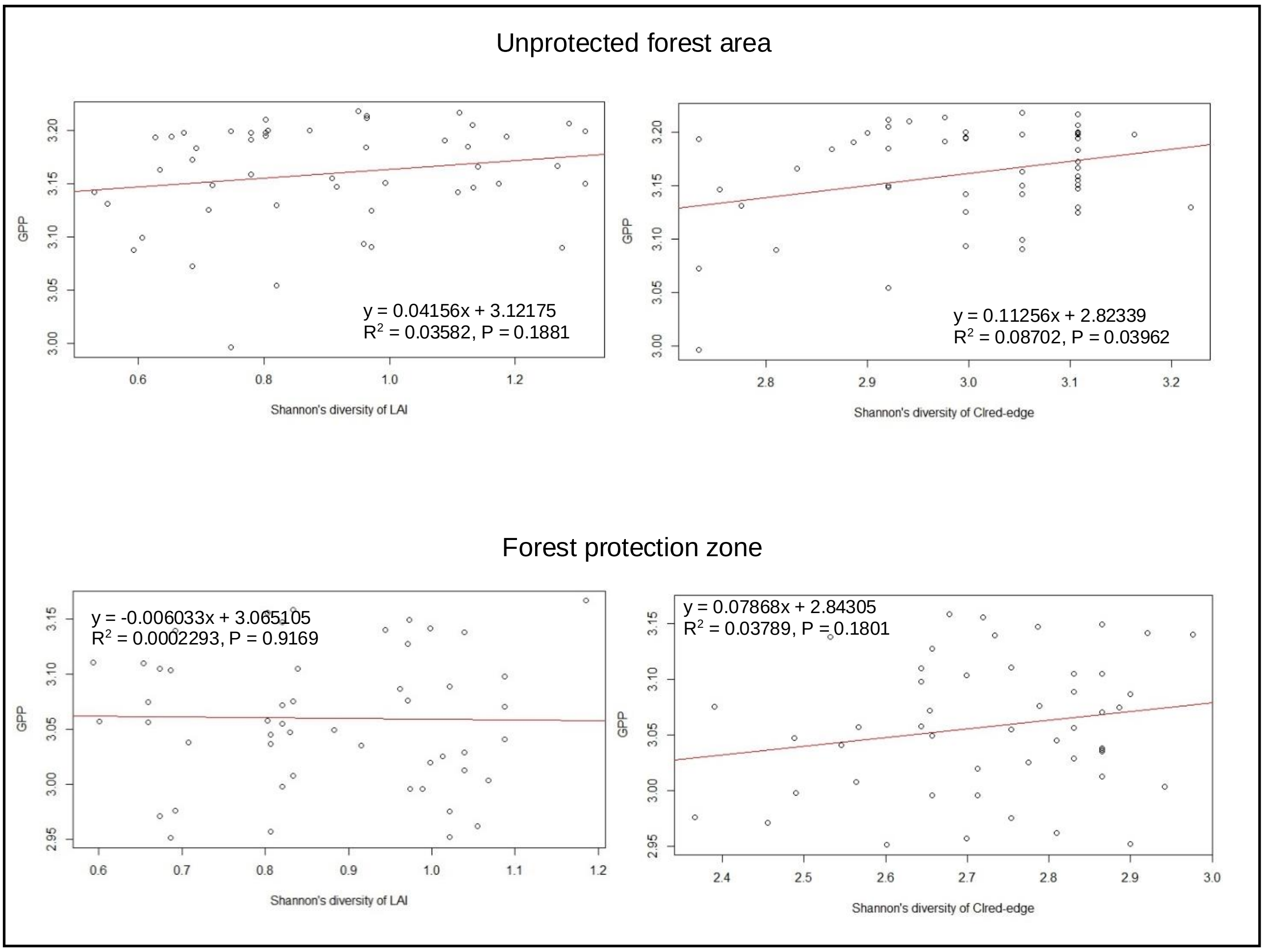

Figure A-2: Shannon's diversity index (SHDI) of LAI and $\mathrm{CI}_{\text{red-edge}}$ *versus* GPP for a 1 km^2 square area of unprotected forest area (top) and an area within the forest protection zone of the cantonal protection enactment (bottom). Spatial resolution is 20 m.

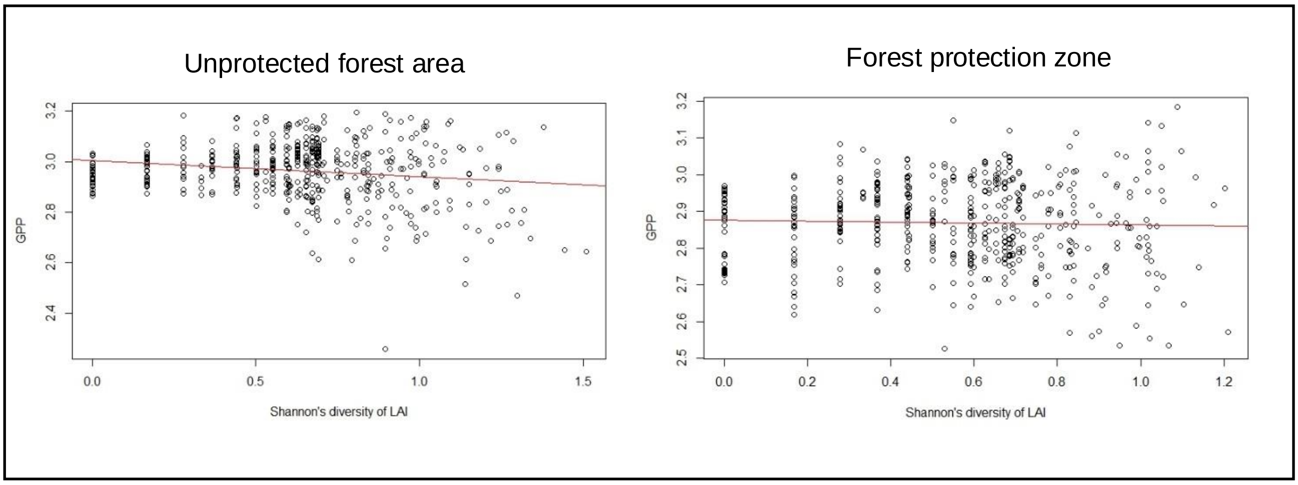

Figure A-3: Shannon's diversity index (SHDI) of LAI *versus* GPP for a 1 km^2 square area of unprotected forest area (left) and an area within the forest protection zone of the cantonal protection enactment (right) using a spatial resolution of 2 m.

Personal declaration:

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.