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Deliverable 3 - Prototype and technical guidance for EO-based monitoring of peatland/wetland

JRC Project “Satellite based mapping and monitoring of European peatland and wetland for LULUCF and agriculture”

Milenov P., Sima A., Lugato E., Acquafresca L., Anastasakis K. and Devos W.

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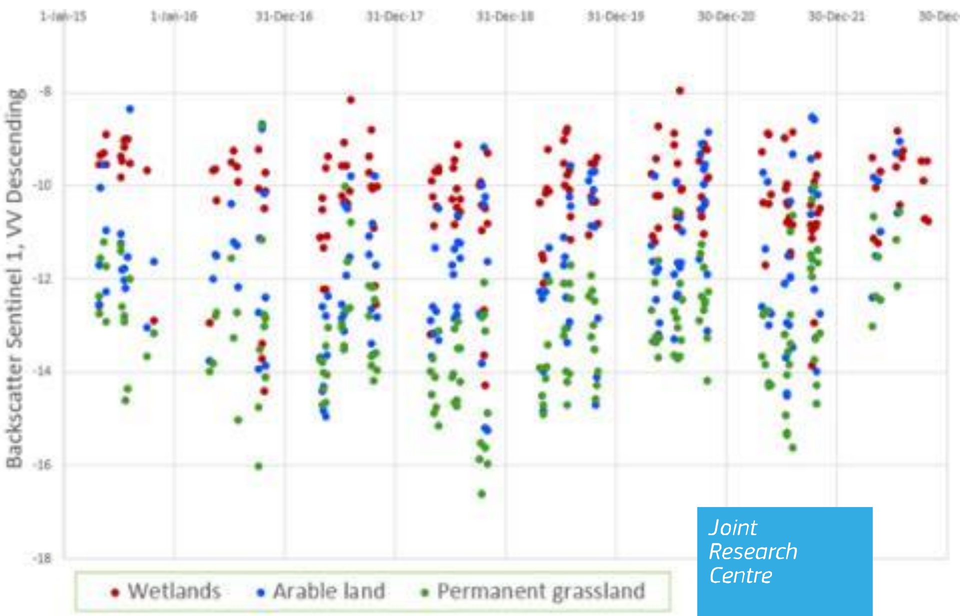

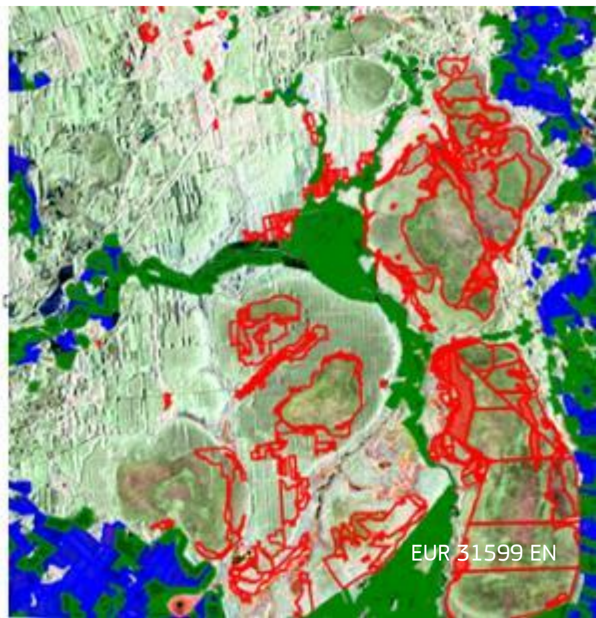

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Contents

Abstract

SEPLA stands for “Satellite based mapping and monitoring of European peatland and wetland for LULUCF and agriculture”. The main objective of the project is to ensure there are methods available for a comprehensive inventory of wetlands and peatlands and for the monitoring of their preservation and restoration by remote sensing and by regularly updated geo-datasets.

This report, formally the third and the last deliverable of the project, elaborates on a prototype and technical guidance for Earth observation-based monitoring of peatlands or wetlands. Methodologies for the semantic description of the land cover, land use and soil related aspects are proposed as a pre-condition for this framework for peatland monitoring. Adapting feature-level Checks by Monitoring concepts to deal with ecosystems and with natural processes, the document elaborates examples of monitoring scenarios and tests several Sentinel-derived signals and markers. The peatland monitoring complexity is addressed by its decomposition into smaller and more manageable components. This involves a controlled breakdown of the requirements, feasibility and timing, the elimination of unnecessary processing and the prioritization of queries towards specified expectations. The three key elements of the monitoring system are discussed: the observation method, the temporal phenomenon that reveals an attribute or characteristic and the spatial feature of interest that exhibits the observed phenomenon. Additional EO-based methods that rely on both passive and active satellite sensors are investigated. A proxy method based on multiannual farmers’ declarations for handling non-monitorable land aspects is described.

The report also documents a summary of study cases that explore the possibilities of discrimination between the managed grassland on organic and on mineral soils, the in-depth characterisation of areas on organic soils and a machine learning based peatland mapping approach. All analyses were performed using data provided by the participating Member States: Bulgaria, Denmark, Ireland and Latvia combined with publicly accessible data and products provided by Copernicus Sentinel data access and distribution services and the Copernicus Land Monitoring Services. Despite their promising outcomes, these study cases revealed that ground data collection will be essential for learning, optimisation and validation of the EO-based monitoring methods. Tailored regional-based approaches, relying on local contextual information and using EO-based solutions or Copernicus downstream services can be expected to contribute to a workable solution.

The report concludes that the satellite-based monitoring of peatland and wetland is a very complex, yet feasible task, but it requires multidisciplinary expert knowledge and diverse types of data. It also requires the integration of satellite data with ground data, with hydrological models or with ecosystem models. The establishment of a community of practice will likely be essential for an effective uptake of novel technology and for transfer of know-how.

Foreword

This report presents the results of the project SEPLA (satellite based mapping and monitoring of European peatland and wetland for LULUCF and agriculture), for a prototype for Earth observation-based monitoring of peatland/wetland, supported with example study cases based on data provided by the collaborating experts from several Member States (Bulgaria, Denmark, Ireland and Latvia).

The project was defined under the work programme signed between DG JRC and DG CLIMA, and implemented by the GTCAP team of JRC D5 Unit (Food Security). This report constitutes the third and the last deliverable.

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- the colleagues of GTCAP not explicitly mentioned as authors.

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Identification of the types of information extractions	Pavel MILENOV	Aleksandra SIMA, Wim DEVOS
Potential EO-based prototypes and techniques	Aleksandra SIMA, Pavel MILENOV	
Study areas	Aleksandra SIMA, Pavel MILENOV, Laura ACQUAFRESCA, Emanuele LUGATO	
Discrimination between areas on organic and mineral soils	Aleksandra SIMA	Pavel MILENOV, Laura ACQUAFRESCA, Jon SKØIEN, Emanuele LUGATO
Estimation of areas on organic soil, using unsupervised image segmentation	Pavel MILENOV	Aleksandra SIMA
Mapping of peatland areas using machine learning	Emanuele LUGATO	
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Executive Summary

This document reports on the proposal of a prototype and on the identification of elements of technical guidance for Earth observation-based monitoring of peatlands or wetlands. The description of the methodological framework starts with a summary of the revised semantic meta-model to describe the land cover, the land use and soil related aspects of peatlands and wetlands (section 2.1.1). This section also provides a framework to formalize information about the peatland as a unit of management, often under agricultural use, with relevant observable parameters of its bio-physical characteristics. It sets the background for understanding and setting up a peatland monitoring framework that is sketched in section 2.1.2. This project experienced that for peatlands, it is not trivial to define the spatial extent of the peatland as either a physical entity or as unit of management.

Section 2.1.3 provides practical guidance through the steps of creating a monitoring scenario for peatland restoration using the case of the rewetted Dragoman Marsh in Bulgaria. This marsh was subject to severe fire damage in 2020. Monitoring scenarios are essential to target image processing because they specify what and when observable events or activities could happen and what should not occur.

Section 2.2. summarises the satellite based remote sensing data and techniques that are potentially relevant to peatland monitoring. The potential relevance is determined by the physical characteristics of the EO platform linked to peatland manifestations for the consecutive stages in the scenario. This linkage is built from available ground data. There is also an example of a proxy method to evaluate the potential pressures on a peatland restoration process, based on the yearly farmers' declarations recorded in the Geospatial Application.

The description of the use cases starts with the characteristics of each study area investigated in the project (section 3.1).

Section 3.2 presents several candidate options for the discrimination between managed grasslands on organic and on mineral soils. These candidates include the European Ground Motion Service, Copernicus Vegetation Phenology and Productivity indices and the timeseries of Sentinel-1 and Sentinel-2 data. In most cases, managed grasslands on organic and on mineral soils can be better discriminated in the beginning of the growth season, because mineral soils are then usually dryer and warm up faster after the winter, compared to the wetter organic soils. This drives a faster vegetation development,.

Section 3.3 elaborates an in-depth object-oriented analysis of land cover classes and vegetation indices as a tool for accounting the spatio-temporal characteristics of peatlands, for mapping the boundaries of bogs and for characterising their preservation state.

Section 3.4 describes the results of a machine learning-based method for mapping peatland areas.

Section 3.5 presents a prototype platform for data visualisation and exploration that facilitates a user-friendly remote sensing data interpretation for the project stakeholders. This, in turn, supports knowledge exchanges.

Section 4 contains an overall discussion of various methodological and operational aspects of peatland monitoring and, indeed, some technological challenges. Non-EO peatland management aspects are briefly touched.

The document conclusions are provided in section 5: peatland monitoring will require novel EO-based solutions that integrate complementary sensors and signals and that is supported by local ground data. The likely absence of off-the-shelf monitoring solutions makes local tuning or developments inevitable. Peatlands are complex ecosystems with very diverse biotic and abiotic characteristics across Europe, even within the same peatland and habitat. Regional approaches that rely on local contextual information and use tailored EO-based solutions or Copernicus downstream services are needed. These developments will benefit from a sector wide expert community, local, national, and European, to ensure access to data and critical know-how.

1 Introduction

The purpose of this technical report is to outline and assess the feasibility of the processing methods and techniques that use Copernicus Sentinel data, to: (1) effectively and efficiently provide information on the status and change of the peatland/wetlands from the bio-physical point of view; (2) detect the impact of the natural and anthropogenic events (ex. farming activities) on their organic content, and (3) monitor the effect of the defined sustainable management practices and conducted restoration activities. It documents some prototype solutions, developed and tested on the basis of the local information and spatial data provided by the EU Member State experts participating in the SEPLA project. It builds upon the semantic assessment and data integration methods defined in Deliverable 1 and Deliverable 2 of the project (Milenov et al., 2022b, 2023).

Furthermore, the report identifies some of the main technical and technological obstacles that hinder the uptake of the monitoring approach over peatlands and wetlands and assesses the feasibility of using data, alternative to Sentinels, such as geotagged photos. It ventures into emerging technologies, such as AI, data shared by farmers (e.g. Farm Management Systems (FMS) data, and digital solutions for precision farming).

The technical report, inter alia, assesses the suitability of the methods for information extractions developed in the frame of the CAP Checks by Monitoring (CbM) to capture the status and monitor the evolution of the peatlands and wetlands, considering regional specificities and established local agronomic practices. This extends the CbM approach outside the geographical scope of the datasets applied in the EU Common Agricultural Policy (EU CAP) and helps to compile full territory inventories.

The outcomes of the case studies and analyses made aim to help EU Member States in the identification and setting-up of effective satellite-based solutions, complemented with relevant alternatives, for reliable monitoring of preservation and restoration of peatlands to address the urgent need to mitigate climate change, conserve biodiversity, and sustainably manage natural resources.

2 Methodological framework

2.1 Identification of the types of information extractions

2.1.1 Framework for the semantic description of the land cover, land use and soil related aspects

2.1.1.1 Conceptual challenges related to peatland mapping and monitoring

As elaborated by the previous SEPLA deliverables, defining, mapping, and monitoring peatlands can be a complex process due to the various peatland definitions in place and the range of local-specific characteristics that can be used to identify peatlands. Peatlands can be defined based on their vegetation, hydrology, soil characteristics, or the presence of peat (on the surface or beneath), although different countries and domain communities often use different methods and nomenclatures to describe and categorize such lands. Additionally, peatland characteristics can vary greatly in terms of their extent, depth, and composition, which can make their reliable mapping and effective monitoring a challenge. Remote sensing techniques using satellite imagery and LiDAR can be useful for mapping large areas, but additional ground-based surveys may be necessary to accurately characterize peatland properties such as peat thickness and vegetation composition. The proper definition and mapping of peatlands is a key prerequisite for setting-up and performing conservation and restoration efforts; therefore, it requires careful consideration of all the various factors that contribute to this complexity. The monitoring of the state and change of state of any phenomenon on land, requires all of the following: unambiguous localization, correct identification of the properties to observe and a proper set of the temporal granularity for the detection of the anticipated or unexpected property changes. Peatlands are complex real-world phenomena with "diffuse" spatio-temporal extents and a variety of manifestations. As most natural phenomena, their characteristics are continuous and their processes non-linear, making their formal conceptualization and representation, without rigorous prior discretization to finite elements challenging. This causes that, although there are means and tools to measure certain material properties of peatlands, the resulting observations are always reduced to a conceptually simplified representation in the GIS (Milenov, 2022a).

(Gomes et Velho, 1995) consider spatial data modelling for GIS as a special case of computational modelling of physical phenomena. The general modelling mechanism undergoes four levels of abstraction:

- The physical universe, which comprises the real-world entities that will be modelled in the computer.
- The mathematical universe, which includes a formal definition of the entities which are included in the model.
- The representation universe, which defines how the various continuous models are discretized.
- The implementation universe, where the data structures are associated with the discretized objects of the representation universe.

In the context of SEPLA, the physical abstraction relates to the notion of peatland, as real-world phenomenon, that people have. The mathematical abstraction leads to the spatial object, associated with the peatland being a triplet (S, A, f) where:

- S is a subset of the Euclidean plane, it is the geometrical support.
- A is a set of attribute values in specified domains $A_1,\ldots, A_n$,
- f is the attribute function of the spatial object, which associates, to each location in the geometrical support, a value on the set of attribute domains.

The representation of a spatial object consists in discretising both its geometric support and the attribute function in the GIS. The representation of geometric support consists in representing its topology and geometry.

The real problem with peatlands, and wetlands in general, is the formalization of the physical abstraction. It comes from the fact that the various domain experts have different notions of what peatlands are, depending on the application area and domain context, and build different abstractions depending on where their focus is. A typical example is the difference in the perception of peatlands between soil experts and ecologists; the former approaching it as an area of sedentary accumulated organic deposits, while the latter as a habitat area hosting specific plant and animal species. This issue was tackled in the semantic assessment phase of the SEPLA project. The different notions are further complicated by the fact that peatlands could be at different stages of anthropogenic influence; natural, managed or restored to their pristine conditions. They are often subject to protection and form part of designated areas. However, they were also evaluated in the past on their potential for agriculture or energy purposes. Consequently, their spatial boundaries were often defined on their social-economic and environmental purposes, and not strictly according to bio-physical parameters. The impact of such differences is illustrated in Figure 1.

Figure 1. Example of a protected wetland (Bulgaria). The blue outline represents the boundary of the area designated for protection under N2000 site. The brown outline represents the boundary of the histosols.

Source: SEPLA, Image: Google, 2023.

2.1.1.2 The "Waterfall"- based approach

A common approach towards the physical abstraction of peatland requires the adoption of both a convention for its formal conceptualization and an agreed vocabulary. The vocabulary should hold all necessary definitions and axioms that make the intended meaning explicit. The developed semantic meta-model, based on the Land Cover Meta Language (ISO 19144-2) and the EAGLE model (Arnold et al., 2016), provides the necessary elements to describe all peatland characteristics. However, it doesn't deal with the spatial and temporal aspects and thus, reflects neither the spatial heterogeneity of the peatland characteristics nor their change over time due to anthropogenic or natural factors.

Coherent and formal ontologies are essential for automated and machine-driven processes, and could be particularly useful for satellite-based solutions for peatland monitoring, based on machine learning.

Elements of the "Waterfall" ontology (Galton et Mizoguchi, 2009) are potentially suitable to reflect the complex character of peatlands. The approach is very close to the concept and the philosophy independently developed for the CAP Checks by Monitoring framework and some of the elements of the "Waterfall" approach are introduced in the draft Land Use Meta Language (future ISO 19144-3).

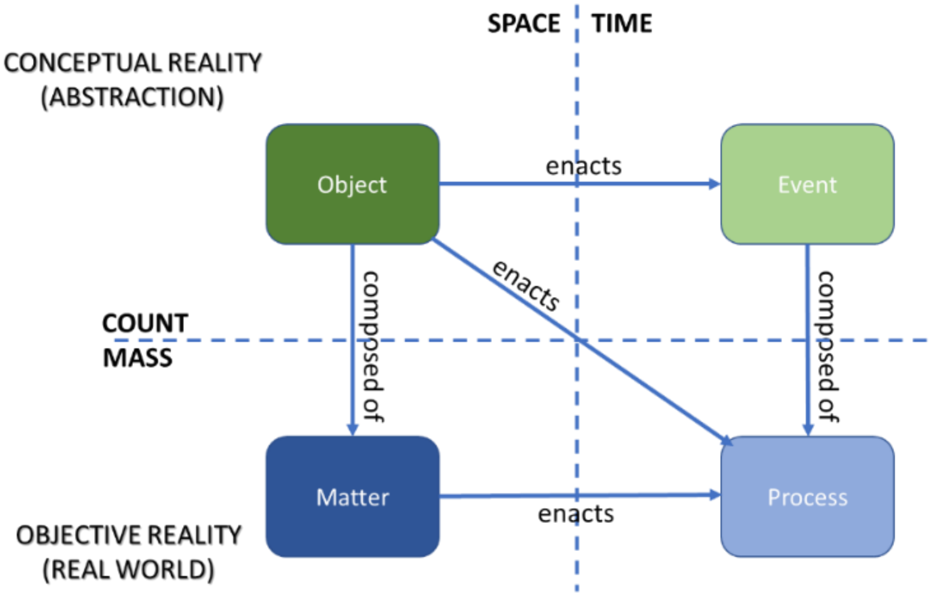
The Waterfall ontology introduces four key categories of physical phenomena – matter, process, objects and events. According to the model, peatland can be considered as a (bio) physical entity of natural or artificial origin (land objects) fixed to the Earth's surface. It is a collection of matter within a defined contiguous boundary in three-dimensional space. This physical entity is present as a singular feature at each moment of its existence. Even, if it could contain different types of matter, it is not divisible (or dissectible); a part of a peatland is no longer similar to the complete peatland. Instances of peatlands are discrete and countable individuals.

As the physical entities (land objects) shape matter, events frame a process in a particular "chunk" of time. Peatlands are subject to a variety of events, which are triggered by natural (bio)physical processes or disturbances, or result from human activities. These events have a start and end, and therefore duration. However long that duration, there will be a temporal granularity at which land event appears as instantaneous.

Events are not divisible; a phase of an event no longer represents the full event. Instances of events are also discrete and countable individuals.

In the way that matter enacts the process in the real world, the physical entity (object) enacts the events at the level of physical abstraction. There cannot be an event, without an affected object. (Figure 2).

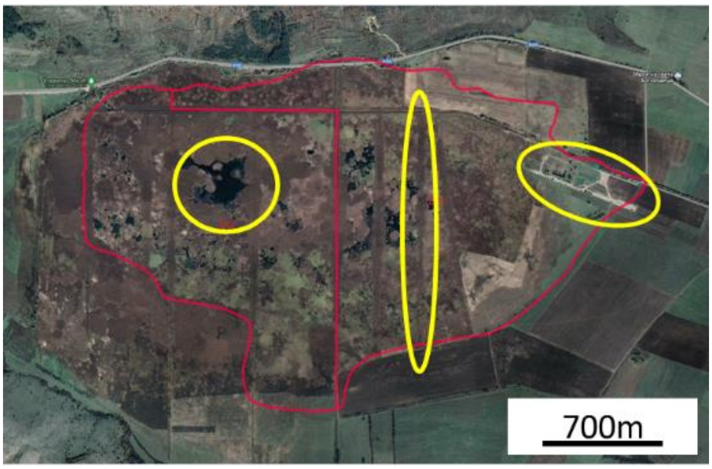
Figure 2. The four key categories of physical phenomena (Waterfall approach).



Source: SEPLA. Designed according to (Galton et Mizoguchi, 2009).

The proposed use of the Waterfall concept has two main advantages. First, it provides the necessary framework for the correct abstraction of the peatland at the physical level. This is the physical entity, called also "land object". Second, it resolves the long-lasting ambiguity of "land change" by allowing a proper conceptual differentiation between the change of a mere property of the physical entity and the change related to its partial or total disappearance. The concept stipulates that peatlands are present in their entirety at each moment of their existence. The key point here is that the change is always assigned to *something*, that is subject to the change. And for there to be a change, there must be some part or characteristic of that *something* that remains; otherwise, it will not be called "changed", but "vanished" or "disappeared". For example, a deciduous forest is changing its appearance from winter to summer from leafless to leafy, but there is always a typical component, i.e. the wooded body of the trees, that persists and acts as a reference for the given (phenological) process. This could be considered the essential element of the physical entity (land object).

Box 1: Illustration of the Waterfall-based concept: “physical entity” and “land change”

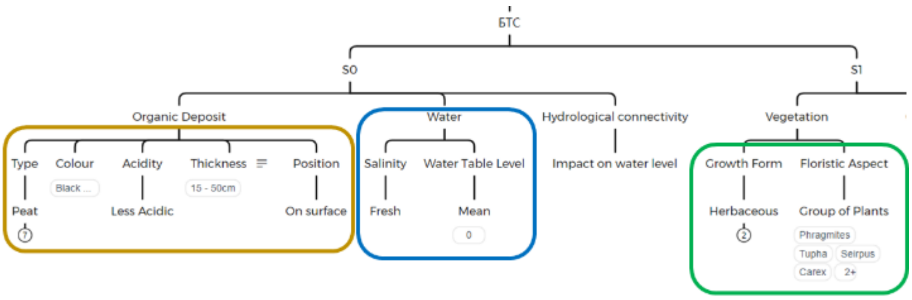


Source: SEPLA, image: Google, 2023.

The peatland shown in the picture is defined, as a physical entity, on the basis of the presence of accumulated organic deposits (histosols-terric). The extent of the organic soil is given in red outline. It is split into two parts along an administrative boundary, because the two parts belong to different municipalities and subsequently, territorial management responsibilities. The peatland is composed of different individual physical features (water bodies, ditches, clusters of vegetation) and each of them could be considered a physical entity of its own. However, they are integral elements of the entire peatland, and they have their role in the processes and life cycle of the entire peatland.

The physical features cannot be regarded in isolation. The airport on the eastern edge of the peatland can be considered a physical feature foreign to the peatland that evidences a change. However, unless there is evidence for the removal or loss of all organic soil beneath, this change can be considered still a change in properties of the peatland (removal of vegetation and partial soil sealing), rather than a change of its perimeter.

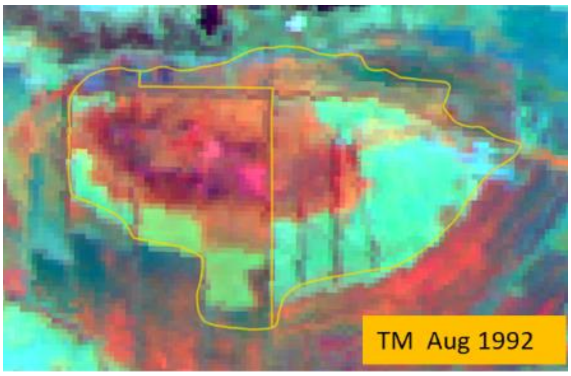
Illustration of the semantic passport of the peatland type above, showing the complexity of bio-physical characteristics.



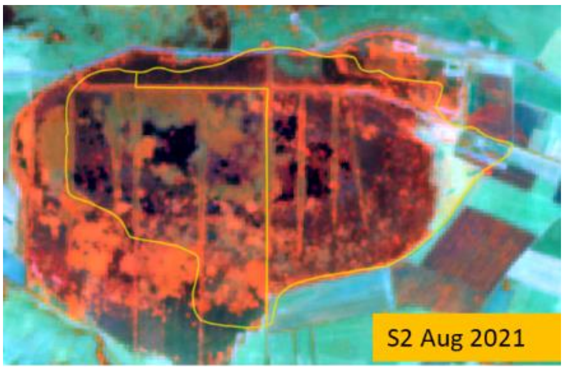
Source: SEPLA

State of the peatland in 1992, at a time when it was still degraded due to systematic drainage for agricultural purposes.

State of the peatland in 2021 after 30 years of restoration, through rewetting. The spatial extent of the peatland remained unchanged. The observed difference or change is related to the characteristics, state and distribution of the biotic material involved.



Source: Landsat, USGS



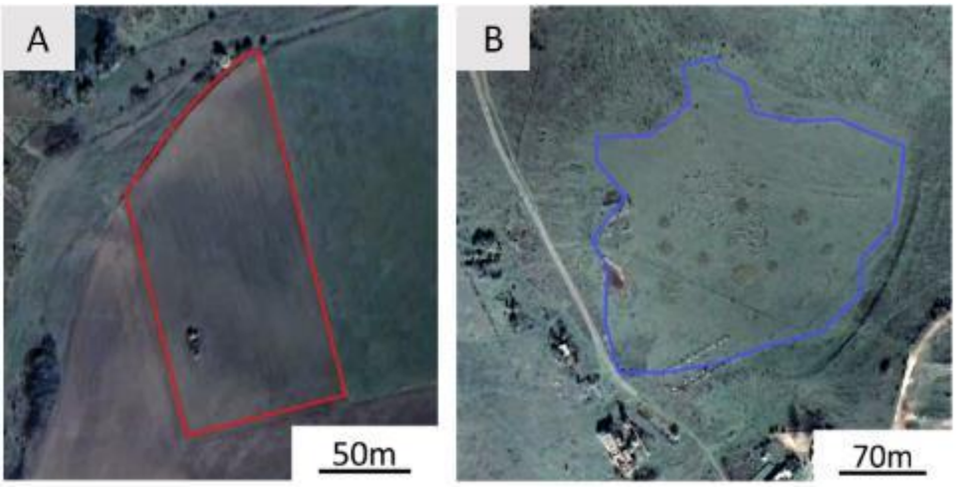
Source: CREODIAS, Sentinel-2, Copernicus Services

2.1.1.3 Introducing peatland as a unit of management

SEPLA deals with peatlands that are under a management regime or that are subject to a targeted set of actions for their preservation or restoration to a natural (pristine) state. Management implies use, purpose and activity. Box 1 illustrates the peatland as a physical entity that can be further subdivided into smaller entities depending on the type of management and the land custodian. These spatial entities could be called "single units of management". In the absence of a specific sectorially agreed definition, the Land Administration Domain Model - LADM (ISO 19152) can define the single unit of management as a single area (or multiple areas) of land. The land is defined (point 4.1.9 of LADM) as "the surface of the Earth, the materials beneath, the air above and all things fixed to the soil". The area is the extent of the associated subset of the 2-dimensional Euclidean plane. This notion of land should be extended to encompass the topsoil horizon as part of the system "soil-plant-atmosphere".

LADM names this "spatial unit" to refer to what physically is present on Earth. What makes it a single unit of management is the fact that all its material (one or multiple types) is engaged in an integral set of processes induced by the conducted or planned management. A good example is the agricultural parcel. It represents a piece of land, with the actual cropped area, the related technical area for the movement of the machinery and the associated landscape elements (field margins, ditches, hedges). These three subparts can be considered different physical things, forming entities in their own right, because they are subject to unique processes that result from differentiated farmer activities.

Figure 3. A) example of a unit of management under agricultural production; an agricultural parcel with arable land, containing a small woody landscape feature, inherently part of the parcel. B) example of a unit of management in the environmental and climate domains; an alkaline fen under N2000, subject to specific normative rules for the conservation of the peat and protection of the diverse plant communities of the habitat.



Source: Google, 2023.

By analogy with the physical entity (or land object), the single unit of management is also a particular level of physical abstraction, or feature in the context of ISO 19101. It has a spatial dimension and due to its "atomic" nature (ISO 19144-1), it could be considered also a geographic feature.

The CAP Checks by Monitoring (CbM) introduced the concept of Feature of Interest (FOI) to deal with the spatial aspect of a bio-physical phenomenon present on Earth that relates to agriculture (Milenov et al., 2021a). FOI is in fact the single unit of land that is, or is expected to be, subject to specified land management. It is the physical surface of the Earth where the specified agricultural practice will be performed. In farming business' terms, this surface would correspond to a particular cropped field, meadow, or orchard. SEPLA uses the FOI concept to deal with surfaces corresponding to managed or natural peatlands and wetlands.

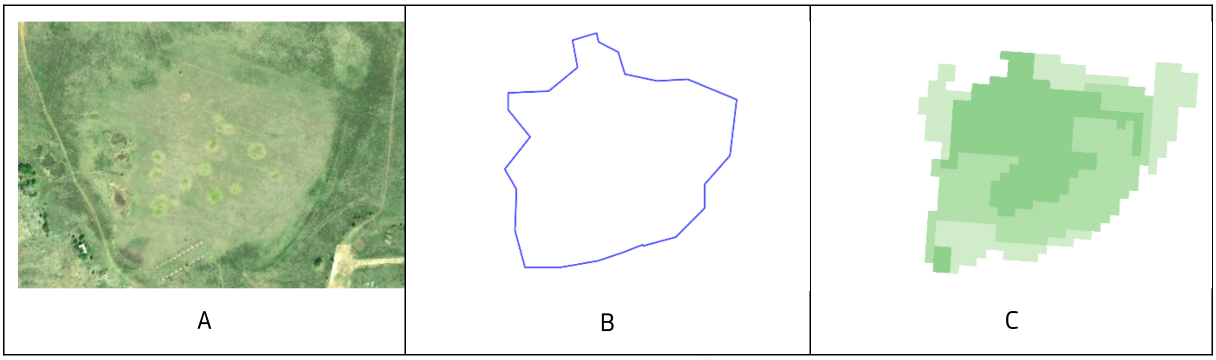
The FOI definition covers both the physical abstraction (single unit of management) and the mathematical abstraction (associated spatial object).

The feature of interest is a key element of the CbM and it plays a pivotal role in the CbM performance. CbM acknowledges that, while relatively coarser in terms of spatial detail, the strength of Copernicus Sentinel data lies within its very high temporal resolution. The sampling rate of the Sentinel data unlocks the systematic detection of short-time process periods and tell-tale events, associated with farming activities (ploughing, mowing) or any other management (peatland inundation, forest clearing). CbM could also provide detailed information on the temporal behaviour of natural processes, such as vegetation encroachment/recovery and water eutrophication. It can detect instant local natural or man-made disturbances, such as floods and fires.

Processing the vast amount of imagery still poses a major challenge, despite the progress of artificial intelligence and cloud computing. By working with a Sentinel signal extracted for a pre-defined spatial object, the FOI, rather than with individual pixels, CbM reduces this “data deluge” to something that is easily, reliably, and accountably managed. A method that uses the FOI and the CbM concept in general, could resolve the complexity of the peatland monitoring by breaking down the problem into smaller, logically coherent, parts that are dealt with separately (tiered approach) and by eliminating noise and unnecessary processing (reductive approach).

The CbM FOI has at least two digital representations (spatial features). The first is derived from any thematic spatial dataset where the given unit of management is delineated as a polygon and used as a geometric primitive. In the CAP context, the primary data source is the Geospatial Application, where the agricultural parcels, subject to CAP payment are annually declared. A second representation is derived from Satellite data (mostly Sentinel 1 and 2) and can be expressed in different ”value structures” - statistical metrics, clusters of image pixels, image image-objects. Both FOI representations serve to represent a single true unit of management (Figure 4).

Figure 4. A) Aerial image of a peatland (alkaline fen) considered a feature of interest. B) FOI polygon representation (spatial feature 1) as mapped in a N2000 geospatial dataset. C) FOI representation (spatial feature 2) as a cluster of image image-objects extracted from Sentinel-2 data in 2018, corresponding to the FOI.



Source: SEPLA, image A: Google, 2023.

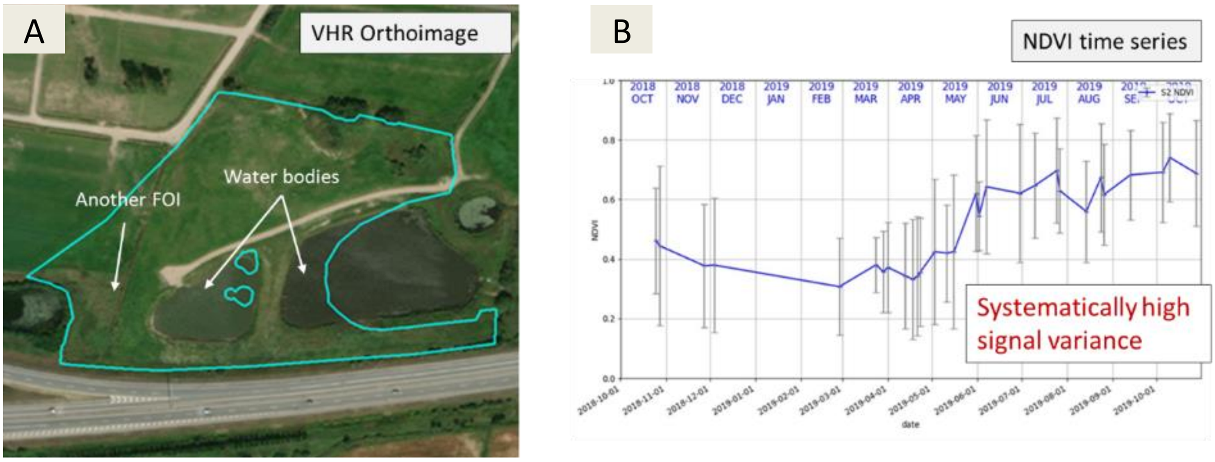
The two spatial representations of the FOI strive to be the closest match with the real spatial extent of the physical land management unit (the S of the mathematical abstraction). This is of key importance, as it will ensure that the extracted Sentinel signal can be unambiguously associated with the single unit of management and its bio-physical characteristics. As shown in Figure 4.C, the Sentinel signal identifies area image-objects outside the polygon representation (Fig.4.B), that behave as the alkaline fen and might be associated with it. This might be a potential trigger for the revision of the N2000 boundary.

The is one important difference in using the FOI concept in the context of peatland monitoring, in contrast with agricultural monitoring.

Thanks to the efforts of LPIS and GSA, most agricultural parcels and their FOI counterparts are defined usually based on well-defined visible physical boundaries and are expected to be homogeneous in their majority. For most agricultural practices, an FOI’s lifecycle lasts a single growing season; but agri-environmental commitments can cover consecutive years. For the latter, the polygon representation of the FOI could vary over time. To overcome this variation, the CbM applies a dedicated check for spatial congruency between the two FOI representations to ensure a consistent association between the Sentinel signal and the FOI and so remove any signal noise from possible mismatches.

In contrast to agricultural land, peatland and their FOI counterparts are usually identified with fuzzy or invisible boundaries (transition in vegetation density, gradients between soil units beneath the surface) and the area is expected to be heterogeneous. The peatland life cycle also spans decades, even centuries. Unless there is overwhelming evidence for the partial loss of a peatland’s essential element (peat decomposition, persistent water scarcity), the FOI should remain stable over the years. One can use the methods for spatial congruency between the two FOI representations to assess and monitor the spatial distribution of the biotic material within the physical entity, and its change over time (Figure 5).

Figure 5. A) A FOI of an agricultural parcel. its perimeter encloses other physical features (water bodies) and even sub-units of management. As seen in B) this creates systematic high variance in the signal time series. This FOI-level variance is considered "noise" while detecting farming practices but can be considered information if put in the peatland context.



Source: SEPLA, image in A: Google, 2023.

2.1.1.4 Relevant and observable parameters and bio-physical characteristics

Any monitoring of peatlands depends on their geographic location, their type, condition (pristine, drained, managed, restored) and the nature of the required interventions. There are some common generic parameters, such as: the **area of peatland** and the **local context parameters**, related to macro and mesoclimate. For some parameters, such as peat depth, a reliable reference should be established.

As discussed in the previous section, a proper delineation of the peatland is crucial for meaningful monitoring. Field-based information on the extent of peatlands is often combined with remote sensing and field measurements to provide more comprehensive geographically explicit data, reasonable accuracy and quantifiable uncertainties. Lawson et al. (2014) identified four features, detectable with the help of remote sensing, that distinguish pristine peatlands (especially tropical and/or non-forested peatlands) from surrounding non-peat ecosystems:

- lower total vegetation species richness (but hosting many characteristic species);
- distinctive vegetation structure;
- distinctive topography; and
- high water tables.

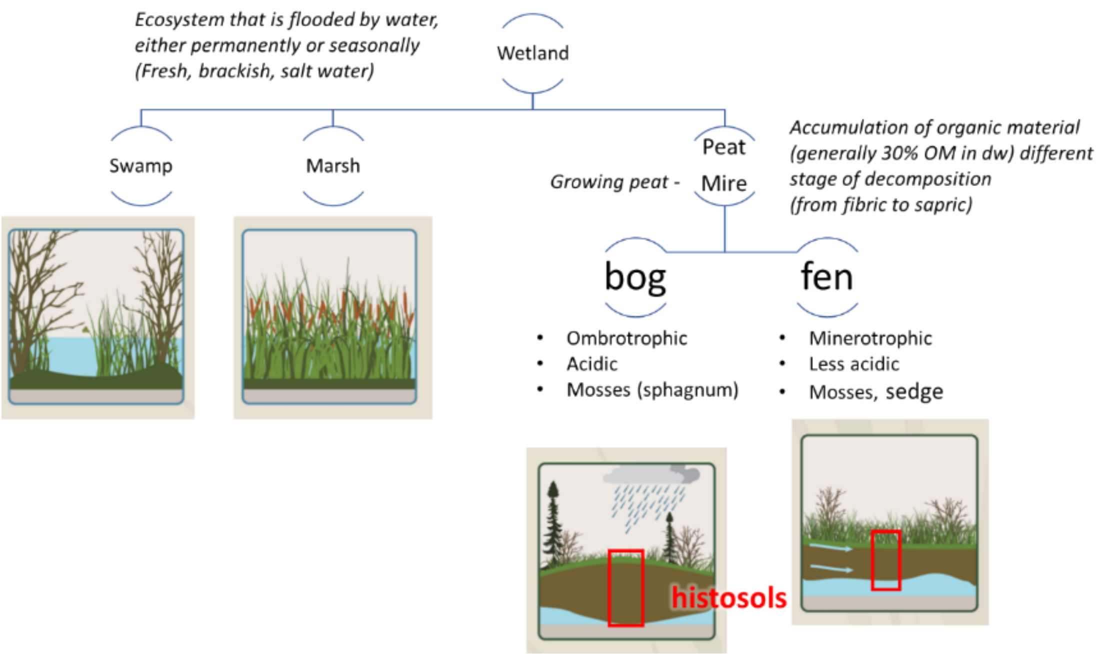
Distinctive vegetation structure and topography can directly be detected through remote sensing. For Central European peatlands, vegetation is found to be also a reliable indicator of the water table level (Couwenberg et al., 2011). As low vegetation species richness cannot often be reliably detected with remote-sensing systems, distinctive vegetation structure acts as a proxy.

Another "proxy" parameter derived from the above is vegetation wetness. It refers to the level of moisture or saturation within the plant cover or vegetation in a particular area. It indicates the degree to which plants are wet or damp, absorbing water coming from precipitation, surface water or soil moisture. Vegetation wetness can vary spatially and temporally, influenced by factors such as rainfall patterns, proximity to water bodies, soil composition, and recent evapotranspiration rates. It is an important aspect in ecological studies and environmental monitoring, as it can affect peat conditions, plant growth, ecosystem dynamics, and habitat suitability for various organisms.

Water table depth (WTD) is one of the major factors controlling the biogeochemical processes in peatlands and organic soils. Pristine peatlands are characterized by a shallow water table depth, which protects the remains of peat forming plants (e.g., Sphagnum spp., Carex spp.) from complete decomposition. In practice, water tables are measured at monitoring wells, but this does not provide information on a spatial scale that is required to evaluate area-wide effects of rewetting measures or increased drainage. Moisture-sensitive satellite sensors such as radar offer an efficient way to obtain systematic information about the status of peatlands with complete spatial coverage (Asmuß et. at, 2019). For effective land use planning and management, as well as for setting up the proper baseline, peat depth distribution is an important parameter. It helps to understand the full carbon stock in a peatland landscape (Parry and Charman, 2013). In many countries, peat depth is one of the key criteria that defines an area as a peatland, and determines whether it can be converted or not (FAO, 2020). However, peat depth can vary considerably within and between peatlands. Peat depth can be measured by (i) manual probing with a peat corer or metal rod, and (ii) ground penetrating radar (GPR). Where an accurate elevation model and geologic maps are available, peat thickness can be determined by identifying the peat bottom position which is the interface between the peat and the underlying mineral sediment, i.e. the difference between the peat surface and depth of the peat bottom.

The semantic assessment and data inventory of national datasets following the developed semantic meta model identify and highlight the key bio-physical characteristics of the different peatland types and their "monitorability" with Sentinels data. The resulted "semantic passports" indicate that the key discriminatory characteristics between peatlands, are often the results of their "genesis" and water source (ombrotrophic or minerotrophic), which governs their water table level and nutrient chemistry (Figure 6). Fens are nutrient-rich (minerotrophic) and have strong connections to groundwater. A fen often has a neutral pH all year and its vegetation is dominated by grasses, sedges, and rushes. With peat layer thickness increasing over time, it becomes more and more isolated from groundwater, relying ever more on precipitation for water and nutrients. In time, grasses and sedges are replaced by sphagnum (sp. Mosses) and woody vegetation. These peatlands are characterized by a thicker peat layer, high organic content and acidic conditions (Joosten & Clarke 2002).

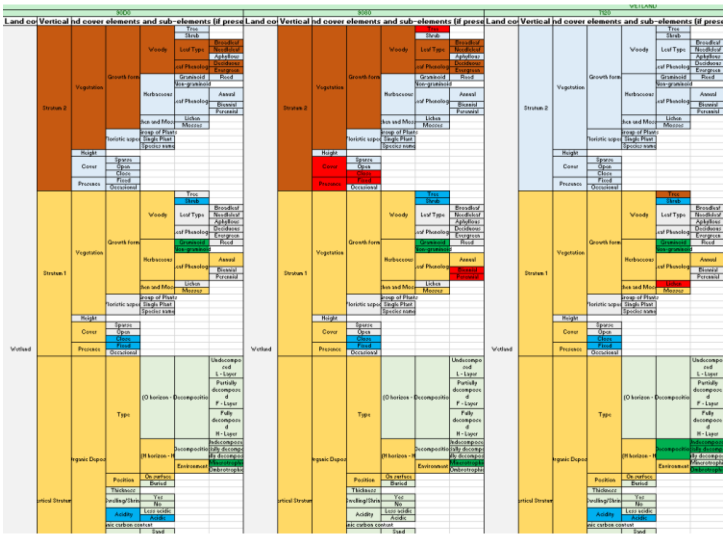
Figure 6. Stratification of the main types of wetlands.



Source: adapted based on https://www.heatherhinam.com/illustration

It goes without saying that those elements which are more discriminatory or are unique for the description of a given peatland are probably good candidates as parameters and as bio-physical characteristics for satellite-based monitoring. Noteworthy elements from the semantic meta-model are: vegetation type (woody or herbaceous), presence of upper vegetation strata, plant surface cover (sparse, open, close), vegetation phenology (for peatland under agricultural management); persistence and variability of water; vegetation heterogeneity and phenology (related also to soil texture), presence of vegetation species, as Sphagnum (related to the level of peat decomposition and soil acidity). Vegetation type and wetness, as well as its spatial distribution and phenology, are the common parameters that in combination could provide essential information on the type and status of the peatland, either pristine or managed. For the latter, the colour of the soil (hue, chroma and value) in the periods when the soil is not covered with vegetation (annual crops or temporal grassland on arable land) was considered as good candidate as well.

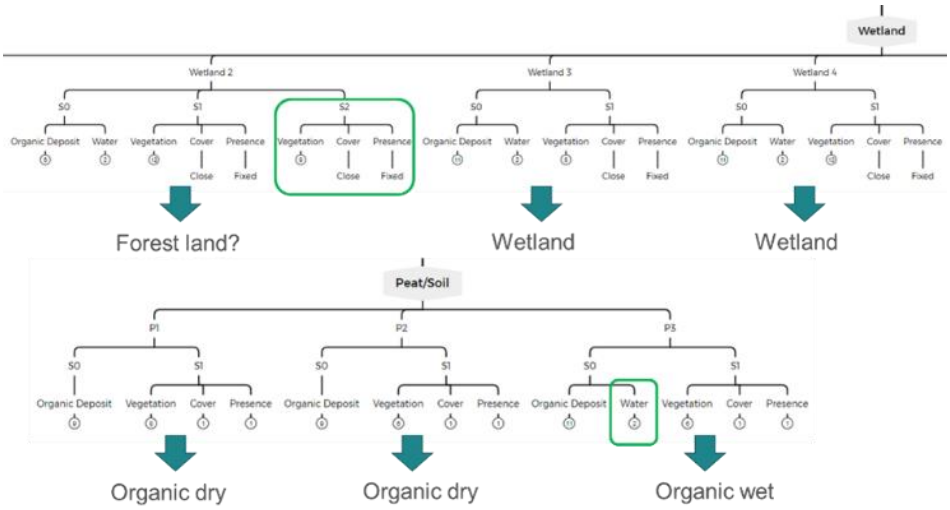
Box 2: Semantic Assessment in SEPLA



colour	number of classes where the given element is found
	1
	2
	3
	4
	>5

The semantic assessment in SEPLA comprised a semantic mapping towards a common semantic meta-model of the peatland-related classes from the national land cover, wetland, and soil nomenclatures of the EU Member States participating in the project. The exercise was done according to the methodology, described in deliverable 1 (Milenov et al., 2022b). EU MS experts provided feedback on the feasibility of the developed semantic meta-model and the possible improvements (ex, the inclusion of the "depth to peat" element). The resulting semantic passports were used to assess the consistency and quality of the classes concerning completeness, mutual exclusivity and hierarchical coherence. The passports were also used to allocate the class instances (mapped class-related features) to the processing chain for data integration and aggregation towards IPCC categories. The image on the left shows an extract of the semantic passports from a participating EU country. The different colours indicate how frequent the element is in the set of peatland-related classes.

Illustration of the semantic passport (represented in an object-oriented manner) and the allocation to the given IPCC wetland (sub) categories



Findings from the semantic assessment:

A particular class from a common European or international nomenclature can be subject to different local specifications. Example of NATURA 2000 class 7140 (*Transition mires and quaking bogs),* where the contextual aspects related to topography, climate and landform influence and "shape" in a specific way the land cover characteristics.

Landform	Mountain	
	Hill	
	Plateau	
	Plain	
Topography	Altitude	
	Slope	
Geography	Inland	
	Coastal	
Climate	Boreal	
	Cold temperate dry	
	Cold temperate wet	
	Warm temperate dry	
	Warm temperate moist	
	Mediterranean	

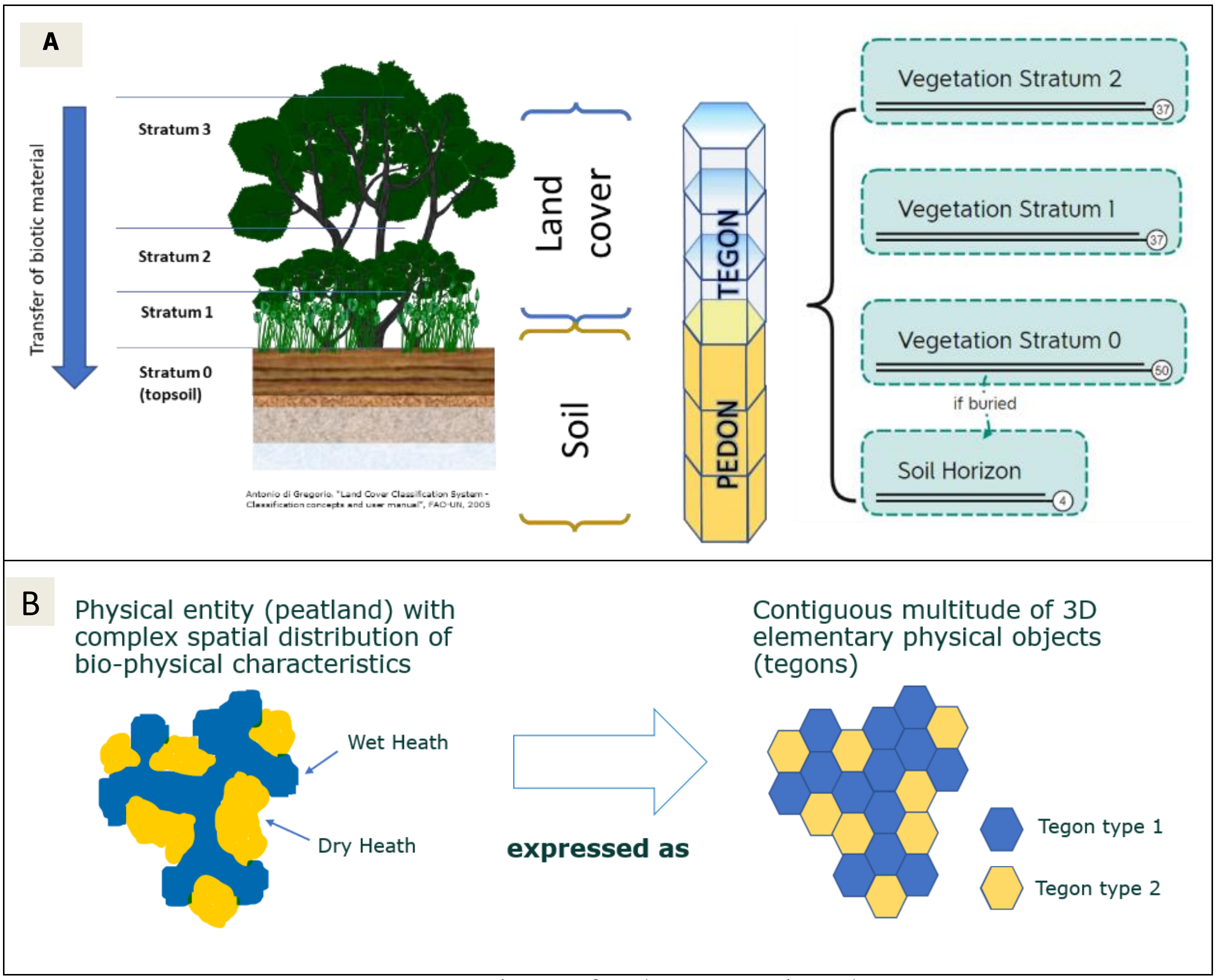
Credits to Līga Strazdiņa

Landform	Mountain	
	Hill	
	Plateau	
	Plain	
Topography	Altitude	>1500
	Slope	>10%
Geography	Inland	
	Coastal	
Climate	Boreal	
	Cold temperate dry	
	Cold temperate wet	
	Warm temperate dry	
	Warm temperate moist	
	Mediterranean	

Credits to http://www.e-ecodb.bas.bg/

The importance of spatial distribution and phenology of the vegetation, as candidate parameters for monitoring drives the need for a formal approach to describe spatial distribution and relationships between the different biotic materials of the peatland. As pointed out above, peatlands often include areas of different biotic nature, with diverse surface cover, varying height and dissimilar other characteristics. These areas could be treated as individual physical features but they are not, instead this spatial variability is handled by introducing the concept of tegon and pedon as the three-dimensional elementary biophysical bodies of land cover and soil, respectively. Tegon acts as the building block of the biotic material substrate of the peatland present above the topsoil, while the pedon acts as such for the topsoil horizon. Peatlands then can be considered as an intrinsic association of two or more tegons with a different biophysical characteristic that combined form this physical entity (land object) with its unique functional (in land use and ecosystem service terms) characteristics. Each of the elementary prisms in the different strata of the "tegon-pedon" column (called also “pair”) refers to a specific material that has an individual behaviour and life cycle. The tegon prisms’ properties and characteristics are described using the SEPLA semantic meta-model, whose semantic elements and biophysical characteristics are derived from the LCML ontology but are deliberately structured hierarchically. The main assumption is that a sufficiently dense and uniform set of observations will allow for a comprehensive assessment of the relationship between soil characteristics and the behaviour of the land cover feature above. Indeed, both are active parts of the dynamic system “soil-plant-atmosphere”. The tegon concept and the spatial distribution of different material substrates (called also land cover component) within the land cover classes is also well reflected in the Land Cover Meta Language (ISO 199-2) through LCML element “LC_HorizontalPattern”. More on the tegon concept could be found in (Devos and Milenov, 2013).

Figure 7. A) Schematic representations of: (a) a "tegon-pedon" column with the associated vertical strata from the semantic meta-model. B) expression of peatland's spatial distribution through a multitude of tegons.



Source: SEPLA, clipart in A from: (Di Gregorio et al., 2000).

Table 2 of the 2020 FAO report "Peatlands mapping and monitoring: Recommendations and technical overview" provides a list of parameters for monitoring peatlands, depending on their conditions (pristine, drained, restored). It further suggests the possible frequency for each parameter and its relevance, mainly in the context of GHG emissions and their reporting. Some of the parameters are common for all peatland conditions - the **extent of burnt area; soil moisture and ground water table –** although the suggested frequency of observations might vary**.** Others are specific to the peatland conditions, such as:

- surface subsidence (drained and restored peatlands)
- absence/expansion of artificial linear features, associated with drainage network (pristine/drained peatlands)
- return of native peatland species (restored peatlands)
- rewetting (restored peatlands)

There are also some parameters mentioned that relate to the local context (drainage basin, irrigation network, location of dams), local socio-economic factors (drainage-free land uses), and general socio-economic factors (profitability, livelihood, gender equity). In fact, the key to success for any monitoring would be to link the bio-physical state, or change of state of the peatland with human activities and natural events, by understanding how the peatland "functions" as a broader ecosystem service. This link is one of the key concepts behind the draft Land Use Meta Language (future ISO 19144-3), which revolves around "activity", "land events", "land object" and "land function".

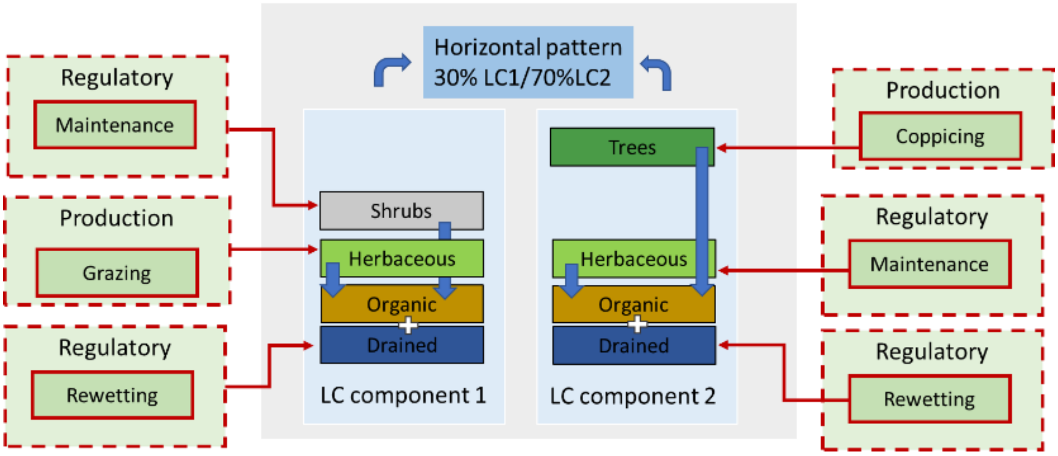
Land functions (Pérez-Soba et al., 2008), could be related to the capacity of the land to provide goods and services in an economic, climate-environmental, cultural, and societal context. They refer to the specific uses or activities that are associated with a particular area of land, but also to the various natural processes that take place within an ecosystem or environment. More than one Land Function can be present in the same place. They are fully related to the behavioural interaction of individuals or communities of individuals.

The semantic framework of SEPLA, combining LCML, tegon and pedon allows the formalization of these complex interactions between bio-physical characteristics of the peatland (land cover) and activities (land use) at the level of the individual land cover component and in each of its vertical stratum.

This, presumably, will help to:

1. Understand better how the given management (agricultural, conservation, restoration) impact the bio-physical aspect of the peatland, which is also critical for any land policy
2. Monitor the occurrence and effect of the management on peatland conditions
3. Develop higher tiers for emission estimates

Figure 8. The Land cover – Land Use interaction logic. The central schema represents a peatland type having two land cover components (tegon-pedon pairs) with different vertical strata and distributed biotic material. Each of the strata could be affected by a particular human activity (or set of activities), such as grazing rewetting, maintenance, aiming to provide certain goods and services.



Source: SEPLA

The special template for documenting the association between the farming activities and the bio-physical aspects of the agricultural land cover, was developed (Zielinski et al., 2022) in the scope of the CAP Checks by Monitoring. Its generic character and scalability allow its adaptation for use in the context of peatland monitoring. It will facilitate the identification of the proper types of information extraction, the relevant EO data / in-situ data required to derive this information and the associated automated processing options.

2.1.2 Framework for peatland monitoring

A land monitoring system is a system continuously observing and analyzing land use and land cover changes over time to provide decision-makers with correct and up-to-date information about the state of the land. This allows to make timely decisions about land management and land use planning. Such systems can make use of a variety of data, (e.g. registers, maps) and observations (e.g., remote sensing and ground data), to provide information for a wide range of applications, such as urban planning, forestry, agriculture, natural resource management, and disaster management.

The SEPLA project decided to use the concepts linked to the CAP parcel monitoring system described in (Devos et al., 2021), adapted for the purposes of peatland and wetland monitoring.

The six baseline elements of such a monitoring system are:

— The signals reflect a time series of Sentinel data values or their derivatives.

— The markers describe a factual observation of land-cover manifestation depicted in Sentinels signals.

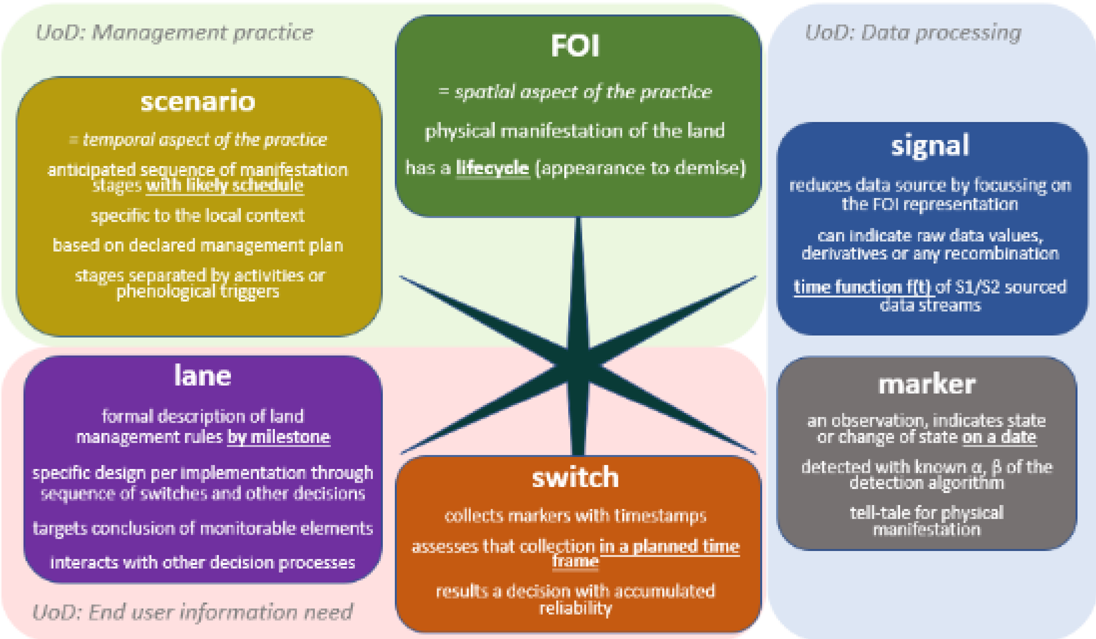
— The feature of interest (FOI) relates to the observable unit of land subject to the particular management practice.

— The scenario relates to the anticipated land cover behaviour (likely to be depicted by the signal) resulting from the management practice.

— A lane is a processing path leading to a required conclusion. It relies on the results of switches.

— A switch is a test mechanism collecting markers and resulting in a decision.

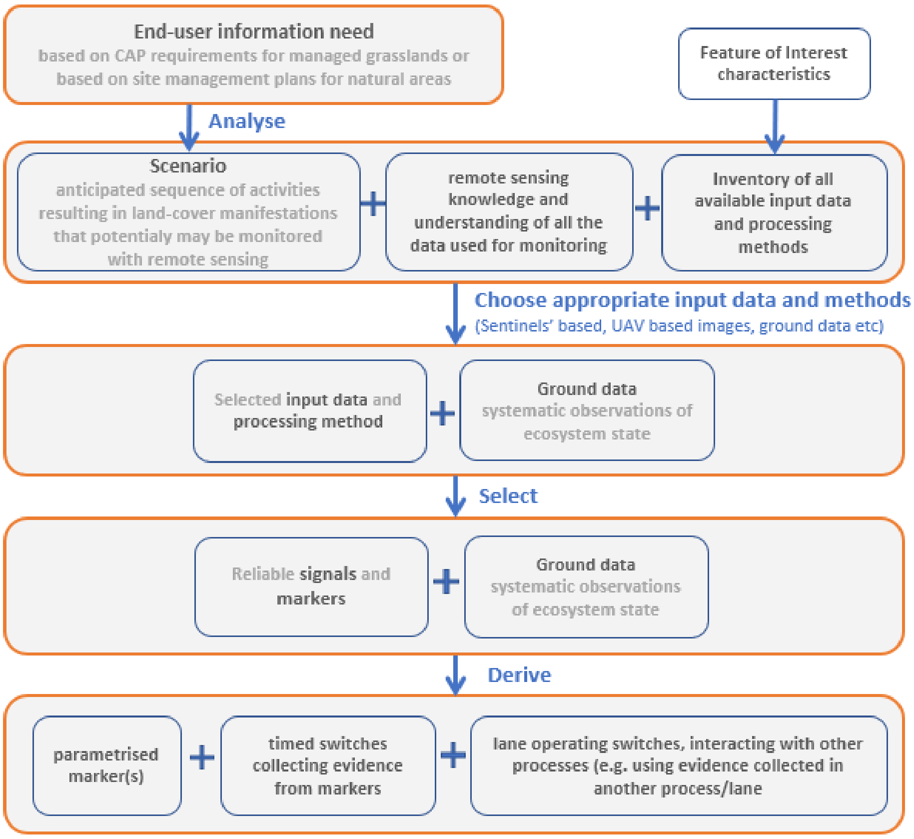
Figure 9. Key elements of a land monitoring system as proposed in (Devos et al., 2021). UoD: universe of discourse



Source: SEPLA, based on (Devos et al., 2021).

In land monitoring systems, the data processing workflow design (**Figure 10**) should be preceded by the analyses of requirements or milestones (universe of discourse (UoD): end-user information needs) that might be monitored using the available sensor/signal. In the case of the areas of natural protection such requirements/milestones could be found in so-called site management plans, similarly as they are developed for the Natura 2000 sites. Such plans include a detailed description of the ecological conditions of the protected areas with relevant challenges and opportunities for landscape protection and management. They also document protected species and natural or semi-natural habitats. These plans specify the objectives of management and protection measures (e.g. restoration of mire habitats), including the estimates of the necessary budget and define the implementing stakeholders' roles. The development of such plans is a complex task where all the stakeholders should be involved and a wide variety of data needs to be studied: the land cadastre/ownership rights register of the site and the surrounding areas, information about soil, water, peatland drainage and the habitats and ecosystem conditions. The plans can be developed by the nature conservation authorities, contracted environmental consultants or land managers or non-governmental organisations. They should be approved by the responsible authorities, e.g. for the Natura 2000 sites it should be the ministries for the environment.

Figure 10. Workflow of a land monitoring system design (based on Devos et al., 2021 and Zielinski et al., 2022).



Source: SEPLA, based on (Zielinski et al., 2022).

Based on the information included in the site management plans, an appropriate monitoring scenario can be derived (universe of discourse: management practice) to provide the anticipated sequence of activities that should trigger a targeted land cover change. The manifestations of these changes should be observable in remote sensing data. For example, if in the peatland restoration process drains are blocked (an activity on the ground), the water table level is expected to increase, sometimes reaching the ground surface. These interventions trigger changes in the vegetation type and density, i.e. dying trees (if they were present and not removed), successive encroachments of hydrophytes etc. A detailed description of the likely land cover changes is crucial for the design of the monitoring system and is further addressed in Section 2.1.

In parallel (**Figure 10**), the most appropriate FOI monitoring approach should be decided. The FOI population characteristics (e.g. size or shape restrictions) and the available input data and processing methods should be analysed to find the optimal monitoring approach.

In addition, the most effective/reliable signals and markers (UoD: data processing) should be selected based on remote sensing knowledge and signal analyses, supported by the appropriate ground data relevant to the monitored activity/ process (see example in section 2.1.3). Selected markers should be further parametrized/tuned (again, using that ground data) for optimal performance in the local conditions.

To increase the reliability of a monitoring system several markers relevant to the defined land cover change or indicating unwanted events (e.g. fire) or unwanted natural developments, should be used simultaneously and processed in the (processing) lane. For the collection and compilation of ground truth data, the guidance given in Annex IV of the CbM QA documentation (Devos et al., 2021b) could be used.

2.1.3 Building a Peatland/wetland restoration "scenario"

2.1.3.1 General provisions

The purpose of peatland monitoring is to inform stakeholders, to understand how a peatland's condition evolves and to assess the effectiveness of water management, restoration and conservation interventions, and its exposure to natural disturbances such as fires (FAO, 2020). As monitoring aims to assess the peatland from its multi-functional perspective, combining natural resources management with environmental and livelihood considerations. The design of the peatland "scenario" will depend on the peatland's conditions and management information needs.

For **pristine peatlands**, the scenario will look for: (1) persistence of the conditions, such as sufficient soil moisture and native vegetation, keeping the natural peatland in a "healthy" state; and (2) absence of activities or local natural disturbances (in sensitive periods) that could adversely affect its pristine state.

For **drained peatlands**, the scenario will look for: (1) absence of any notable and systemic surface subsidence, decreases of soil moisture and activities related to peat extraction; (2) absence of activities that further enhance and extend the drainage (building of channels, ditches, logging tracks) and extensive burnt areas, caused by frequent fires.

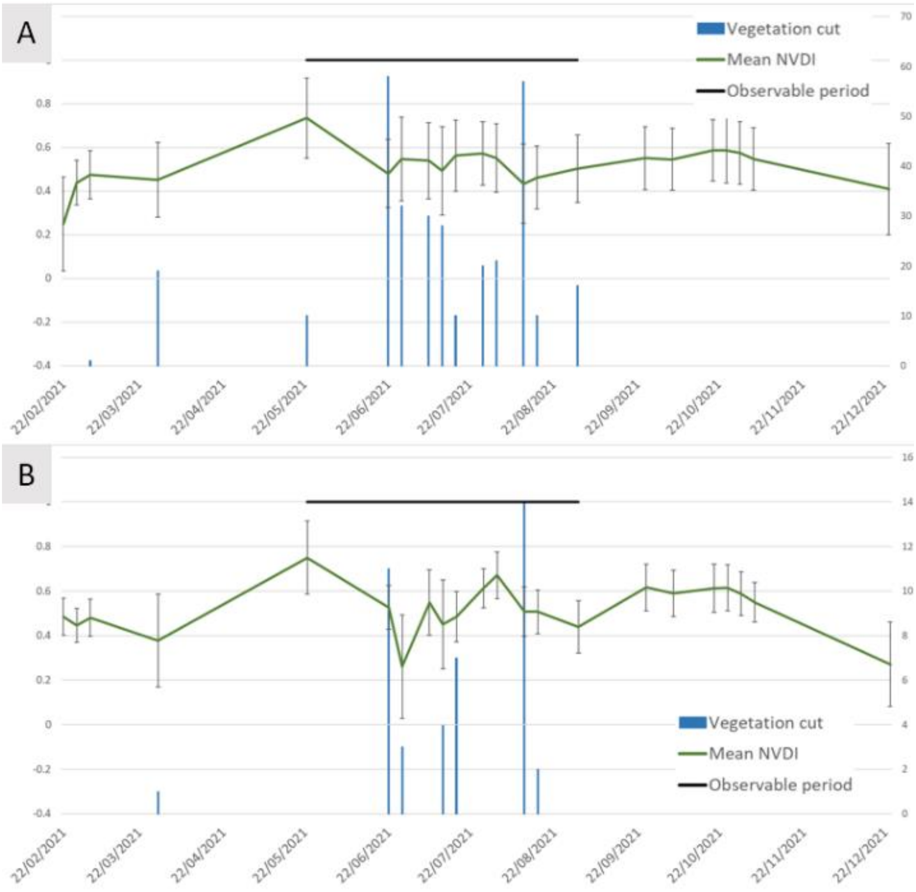
For **restored peatlands**, the scenario will look for: (1) the presence of persistent inundation and emergence of native plant species, evidencing the conduction of rewetting and replanting measures; (2) decrease of systemic surface subsistence rate and the eventual increase of the cyclic surface fluctuations, indicative for the seasonal peat shrinkage and expansion; (3) absence of activities that could adversely affect the peatland restoration (intensive agricultural activities, forest logging).

As the territorial scope of SEPLA is mostly restricted to peatlands under agricultural management, monitoring of degraded peatlands in agricultural land becomes the main focus. Their state should be either preserved (no further deterioration allowed) or reverted to its natural state (restoration measures are put in place).

2.1.3.2 Preservation of historically drained peat soils under agricultural management

The allowable agricultural practices and preservation measures foreseen on peatlands under agricultural management are likely to be defined in the CAP Strategic Plans of the EU Member States in the sections related to the implementation of GAEC standard 2 (GAEC 2) on the protection of wetland and peatland and under the voluntary Rural Development (RD) measures. In Europe, much of the peatlands under agricultural management were converted from their natural state to agriculture more than 30-50 years ago; thus, the surface of the affected peatland is completely deprived of its natural characteristics and the peat area now has an identical vegetation physiognomy (outer appearance), as the surrounding agricultural area. Under these conditions, the monitoring scenario will directly follow the principles and methodology laid down in the CAP Checks by Monitoring – the feature of interest (FOI), being the agricultural parcel and the stages being defined by the allowed/prescribed farming activities and phenology of the specific crop (Figure 9).

Figure 11. NDVI profile (extracted from Sentienel-2 time series on 4015 parcels) for a tillage detection scenario on temporary grasslands. The green line shows the mean and the vertical bar the standard deviation of the NDVI. The blue bars show the number of NDVI drops at parcel level per date (right axis), as the drop is a marker for probable tillage. For parcels outside N2000 areas and with no specific restrictions (A), the number of NDVI drops is significantly higher than for parcels within N2000 (B). A similar approach could be used for agricultural grassland on peat soils.



Source: SEPLA.

2.1.3.3 Restoration of drained peatlands to their natural state

In peatland restoration, the principal activity aims to improve the site hydrology and to restore the water table level as to create optimal conditions for peat formation. Depending on the degree of the peat ecosystem degradation, the aims of restoration, the site-specific technical possibilities, the project budget, the aspects of sustainability and the local landscape conditions, a variety of techniques may be used such as peat dams, other drain blockage and piling, tree removal, transfer of Sphagnum or introduction of other peat-forming vegetation (Pakalne et al., 2021). Peat formation requires a narrow range of water table levels because too low a water level boosts peat oxidation and too high a level inhibits plant production and increases water erosion. Peat decomposes 10 times faster when the peatland is drained than it builds up when the peatland is sufficiently wet (Convention on Wetlands, 2021) so peat soil wetness has to be maintained almost permanently. The hydrological regime of peatlands is linked with the trees and shrubs; in areas with high tree density, if an effective rise in the water table is expected after drain blocking, a decision on the need for felling or thinning of trees should be taken (Convention on Wetlands, 2021). Removal of trees may increase the changes of rewetting success, but it is expensive and requires specialised machinery to minimize the peat damage.

The peatland restoration through rewetting which creates water-saturated soil conditions is considered the classical option to stem high rates of peat loss through mineralisation and to foster new carbon storage (Zak and McInnes, 2022). Depending on the drainage history and the specific characteristics of sites under consideration, such as size, landscape position, soil properties and the presence of valuable species, different rewetting strategies might be applied. Three of the most promising are:

— Peatland inundation – (spontaneous) cessation/reversion of drainage measures.

— Topsoil removal – removal of upper degraded peat soils, often less than 30 cm thick, before rewetting (to mitigate nutrient export).

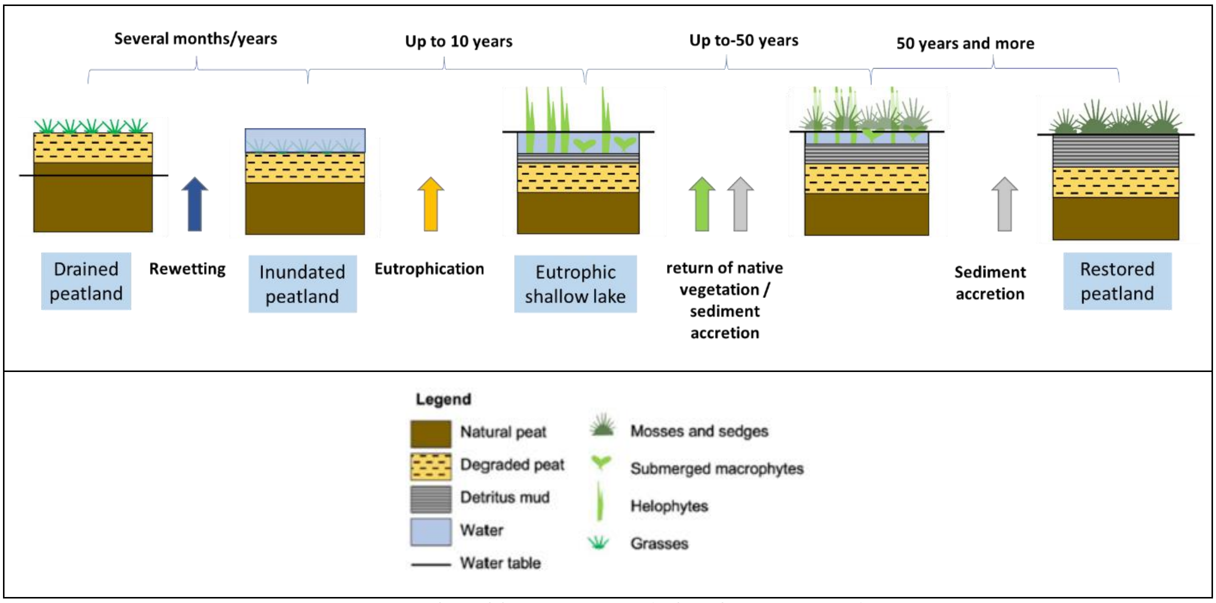
— Slow rewetting - more controlled and progressive rewetting.

The collected knowledge on topsoil removal and on slow rewetting is mostly gained so far from laboratory experiments, whereas the inundation strategy data comes mostly from field investigations. For that reason, the SEPLA project uses the peatland inundation with no topsoil removal, as a basis for its restoration scenario.

There are particular aspects to consider for the scenario of peatland restoration through rewetting, which make it less straightforward than the agricultural-based CbM approach. Some of the restoration activities, such as the blockage of canals and ditches, occur outside or near the perimeter of the peatland's FOI. Actions may have a higher latency, i.e., the time span from their occurrence to the detectable effect they induce on the relevant observable bio-physical characteristics. Lastly, the anticipated effect of the restoration activities may depend on other actions and events occurring in the vicinity of the peatland hydrological unit (regulation of dams, land uses changing the water discharge flow).

The design of the scenario starts with the identification of the anticipated sequence of activities (with their likely schedule), from the peatland restoration plan. A condition is that the activities will be manifested through an observable change in the state of the peatland. Ideally, these activities should be directly related to the anticipated change. Considering the simplest case, where all external and contextual conditions are favourable (sufficient precipitation and water availability, appropriate hydrological connectivity, lack of adverse anthropogenic pressures), the main activity in the rewetting strategy is the cessation of the drainage (ditch blocking, dam removal) and/or water pumping (Andersen et al., 2017). The resulting **stage of rewetting** can last from several months to several years depending on the local conditions. It can be influenced by the rate at which water is reintroduced to the peatland, the presence of drainage infrastructure that needs to be blocked or modified, and the natural hydrological characteristics of the peatland. Often and within 10 years, a subsequent **stage of eutrophication** will form eutrophic shallow lakes, through a combination of earlier farming practices, peat mineralisation and soil subsidence (Zak and McInnes, 2022). A process of the slow development of target vegetation over a period of up to 50 years takes shape (Kreyling et al., 2021) and marks an intermediate **stage of re-vegetation**. Finally, during a **stage of restoration** spanning over a period of more than 50 years, sediments are progressively accreted, detritus mud derived from the incomplete decomposition of above-ground plant biomass is accumulated, legacy nutrients in degraded soil layers are depleted, and a full restoration of ecological function can be expected (**Figure 12**).

Figure 12. Schematic illustration of the stages and the land cover manifestation of the "peatland rewetting" scenario, adapted from Figure 1 of (Zak and McInnes, 2022).



Source: adapted from Figure 1. in (Zak and McInnes, 2022).

A successful "roll-out" of this scenario is conditioned on the necessary set of "flanking" measures that would guarantee the protection of the "restoration" status of the peatland in question (ban of agricultural activity or adoption of paludiculture, a ban on drainage, public awareness, financial incentives to support local communities, etc.).

For the monitoring solution, table 1 below summarizes the anticipated stages and resulting land cover manifestations of the described scenario complemented with some optional ones at the end.

Table 1. An example of a scenario of peatland rewetting with the timeline of the anticipated stages and resulting land cover manifestations (based on Zieliński et al., 2022).

Time schedule	**Trigger activities**	**Stages/Events**	**Land cover manifestations**	**Spatial propagation of the event within FOI**
Beginning of the restoration, after tree removal (if planned)	Ditch blocking Dam build-up or removal Cessation of water pumping	Rewetting/ Drainage cessation	Extension of the wet vegetation along ditches, due to increased water table level	Intermittent
Up to several weeks or months/years after drain blockage		Rewetting/ Inundation	Increased water table level Inundated vegetation Remaining trees dying Water body formation	Gradual
Up to 10 years after drain blockage		Eutrophication	Previous herbaceous and woody plants gradually replaced by helophyte and macrophyte Formation of eutrophic shallow lake Algae blooming	Gradual
Up to 50 years after drain blockage		Re-vegetation	Gradual return of native vegetation (ex. mosses and sedges)	
50 years and more after drain blockage		Restoration	Accretion of sediments (replacing water) Accumulation of detritus mud Native vegetation (ex. mosses and sedges)	Gradual
Optional activities and stages				
All monitoring period	_	seasonal change of water table level	Drying out of vegetation native to wetlands	Gradual
Beginning of the restoration	Removal of trees and shrubs	Clearing	Change of land cover: coniferous trees removed	Immediate
The first phase of the restoration	Removal of the heavily degraded peat layer	Gradual appearance of peat forming vegetation	vascular plant species and mosses encroach the bare peat	Gradual

Beginning of the restoration, after the water table level is increased	Spreading of Sphagnum on bear soil	Growth of vegetation	Sphangum colonising the bear peat	Gradual
All monitoring period	_	Natural growth of unwanted/unvasive vegetation species	Sporadic plants of small trees, bushes	Gradual

Source: SEPLA.

Once the sequence of observable activities, stages and their manifestations is determined, the next step is to define the candidate markers that could timely detect the changes of state of the land cover triggered by the actions and subsequent natural processes. Each marker comes with a correspondent Sentinel signal.

The candidate parameters for monitoring a rewetting scenario are:

1. Ground water table (GWT) depth, as it is directly influenced by the cessation of drainage,
2. Vegetation wetness, as it could evidence persistence of water saturation,
3. Vegetation cover, physiognomy and phenology, as it could attest the change of vegetation type,
4. Water mirror to confirm the appearance/disappearance of water body (lake),
5. Surface subsistence to monitor the recovery of the water retention capacity of the peat,
6. Spatial heterogeneity of evidence the low vegetation richness of the restored peat ecosystem.

All the above parameters, except for surface subsidence and GWT are observable on peatlands with satellite-based technologies. Surface subsidence is detectable from space with inSAR methods; however, the problem is the chronic lack of stable points on the vegetated surface (often water saturated) that could be used as persistent scatterers to measure the surface movement. GWT depth is sometimes inferred from the soil surface moisture, which is influenced by it in the unsaturated zone through capillary forces. The capillary connection of the surface soil moisture to the water table depends on the physical properties of the peat (hydraulic conductivity and water retention characteristics), which are highly variable and depend, e.g., on peat type and degree of decomposition (Asmuß et al., 2019).

The marker selection drives the processing that leads to a decision within the applied scenario. The CbM framework defines seven types of information extractions that cover the spatio-temporal aspects of the physical phenomenon observed and the decision addressed within the scenario (Milenov et al., 2021b). Table 2 summarizes the possible types of information extraction, the candidate markers, and signals, associated with the anticipated manifestation stages.

Table 2. Types of information extraction, signals and markers relevant to the scenario of peatland restoration, specified above. Note: This list of signals and markers should be considered indicative and non-exhaustive for the reliable detection of all anticipated stages and manifestations.

Stage/ Event	State of land cover		Inf. extraction type	Signal 1 (S1)	Signal 1 behaviour	Marker 1 (M1)	Signal 2 (S2)	Signal 2 behaviour	Marker 2 (M2)
	Pre condition:	Post-condition:							
Rewetting/ Drainage cessation	low soil moisture (deep GWT) dry vegetation	high soil moisture (shallow WTD) wet vegetation	C1	SAR backscatter	increase↑ ↑	dS1/dt	NDWI	increase↑	dS2/dt

Rewetting/ Inundation	wet vegetation no surface water	inundated vegetation surface water	C1/ T2	SAR backscatter	drop↓↓	dS1/dt	MNDWI	increase↑↑	dS1/dt
Eutrophication	persistent surface water no or sparse algae	persistent surface water dense algae	C1	MNDWI	High	S1	MBR	increase↑↑	dS2/dt
Re-vegetation	no mosses and sedges	mosses and sedges	C1	PCA eigen values	change	dS1/dt	NDWI annual change	drop↓	dS2/dt
Restoration	water/ no mosses and sedges	accreted sediments, replacing water mosses and sedges	T2	MNDWI	drop↓	dS1/dt	NDWI annual change	drop↓	dS2/dt

Note: NDWI = Normalized Difference Water Index (B8 – B11)/(B8 + B11); MNDWI = Modified Normalized Difference Water Index (B3 – B11)/(B3 + B11), according to (Xu, 2006); SAR – Synthetic Aperture Radar; PCA eigen values = eigen vectors of the Principal Component Analysis (PCA), performed on selected spectral bands; MBR = Maximum Band Ratio (MBR), calculated by calculated by the OC4Me algorithm, applied on Sentinel-3 (Moutzouris-Sidiris and Topouzelis, 2021). The abbreviation of the spectral bands follows the Sentinel-2 convention.

Source: SEPLA.

The temporal granularity of all events framing the natural processes involved in peatland restoration (inundation, eutrophication, return of native vegetation) is years, even decades. The resulting change of state of bio-physical characteristics and the land cover is very slow and, in spatial terms, usually propagates gradually or intermittently over the peatland extent (FOI), exhibiting different paces over different parts of the restored peatland. For that reason, the events are associated with two types of information extraction:

— C1 (temporal variability within FOI representation) – when the event changes the distinct spatial pattern of one or many bio-physical characteristics of (FOI), but its essential nature from the land cover point of view remains the same (for example, the whole area is still considered a degraded peatland).

— T2 – evidence of a gradual land cover transition over the years - when the event changes the distinct spatial pattern of one or many given bio-physical characteristics of the (FOI), in a way that the essential nature from the land cover point of view changes (for example small eutrophic ponds increasingly emerge within the degraded peatland, until it becomes a eutrophic lake).

The gradual preparation progress of the changes and the resulting heterogeneous conditions on the FOI present during the restoration process call for the application of an object-oriented approach when deriving the signal metrics for the markers. As the transition between the different stages is rather gradual and diffuse, overlaps of events can occur expected.

For the decision-makers to use effectively the outcome of the monitoring of the peatland restoration scenario, all formal requirements should be translated into appropriate "monitoring process" rules:

— non-compliance rules: no traditional agricultural activity and no drainage activities during the restorations period,

— validity rules, e.g., confirmation that activities/phenomena are occurring and valid over the entire FOI,

— compliance rules: cessation of drainage.

The CbM processing elements of "switch and "lane" will then need to be elaborated for the operational implementation of these rules. These elements were not tackled in the SEPLA project.

2.1.3.4 *Peatland restoration and natural disturbance*

Local natural (or intentional) disturbances such as fires can have significant impacts on restored peatlands, undoing the progress made in their restoration and causing damage to the ecosystem. Fires can lead to the destruction of vegetation, including the re-established plant communities in restored peatlands. The loss of vegetation can disrupt the ecological balance, reduce biodiversity, and hinder the recovery of the peatland ecosystem. They can also impact the hydrological conditions of restored peatlands by affecting the water-holding capacity of the peat and altering the natural water flow patterns, leading to changes in the water table levels and potential drainage of the peatland.

One of the Bulgarian test sites in the SEPLA project hosts an important wetland on histosols, under restoration for more than 30 years, which suffered a severe fire in the winter of 2020. The team elaborated a restoration scenario, covering a limited period, which included the fire event to illustrate the potential of the EO data to provide evidence for an increased risk for occurrence, detect such disturbance and observe its effect on the peatland conditions.

The **Dragoman Marsh** is the biggest natural karst wetland in Bulgaria, located about 40 kilometres northwest of Sofia. The marsh is situated at the bottom of a drainless low-lying area, surrounded by hills and adjacent to a river of regional importance. The altitude of the marsh is 701 m and at spring high water it covers an area of about 400 ha. The soil type is predominantly histosols, resulting from the accumulation of organic matter over time. In terms of climate, Dragoman Marsh experiences a temperate continental climate typical of the region. Precipitation is relatively evenly distributed throughout the year, with slightly higher rainfall occurring in the spring and autumn months. Dragoman Marsh is renowned for its rich biodiversity and ecological importance. It is a Ramsar site and part of the Natura 2000 network, highlighting its conservation significance (**Figure 13**).

Figure 13. The Dragoman Marsh, Bulgaria.

Source: https://drumivdumi.com/

For years, Dragoman Marsh has played an important role in flood control and agriculture in the surrounding areas. In the 1930s, the marsh was drained through 11 drainage channels and a pump station, to make room for agricultural development. Drainage activities were halted in the early 1990s and the marsh began to revert to its original state. Although, no explicit information on the restoration measures and processes in Dragoman Marsh has been collected, the consultation of historic and recent satellite imagery (bottom pictures in Box 1) and up-to-date habitat maps evidence that the restoration process is following the stages of the peatland rewetting scenario described in the previous section. From 2013 to 2018, the marsh is mapped as part of two NATURA 2000 classes - 3150 (Natural eutrophic lakes) and 3140 (Hard oligo-mesotrophic waters with benthic vegetation of Chara spp.). At present, Dragoman Marsh seems in the advanced stage of restoration with substantial accretion of sediments and recovery of its native species, such as rush, sedge, and reed.

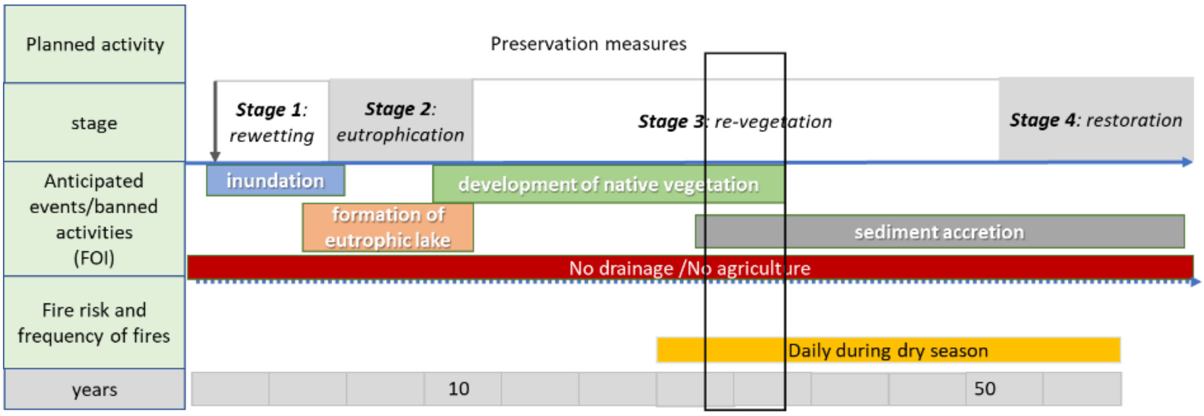
On the night of 22.01.2020, a fire started in the Dragoman Marsh, moving from the centre of the marsh towards its periphery, which suggests deliberate arson (one of the hypotheses involved poachers' activities). As a result of the fire, 80% of the reed vegetation in the peatland was destroyed. Fire fighting was particularly difficult due to the natural impoundment ponds, acting as obstacles for the firefighter and their equipment to reach the affected areas (**Figure 14**). The severity of the fire was magnified by the lowest water level since the restoration of the site in 1990s and the excessive accumulation of dry vegetation.

Figure 14. After the fire in Dragoman Marsh.

Source: left: https://priroda.parks.bg/, right: https://btvnovinite.bg/

Strictly speaking, disturbances, such as fires, are not a part of the planning scenario setup. However, they should be anticipated and incorporated as adverse and unwanted events, which nevertheless can occur. Normally, they are events with short duration (one to several days), which will simultaneously affect other lands in the direct vicinity of the FOI and hence represent an element of common local detection (which can be part of external wall-to-wall processing). Disturbances do not occur entirely random but are likely outcomes of a cumulative set of existing conditions (extensive drought, accumulation of dry vegetation, proximity to specific land uses and human activities). Taking that into account is a good practice in the monitoring system design. Figure 15 below provides a schematic representation of the timeline of the peatland rewetting scenario, taking on board the fire risk. As said above, it is assumed that Dragoman Marsh is in the <u>stage of re-revegetation</u>.

Figure 15. Timeline of the peatland rewetting scenario, with the current stage of Dragoman Marsh indicated.



Source: SEPLA.

SEPLA developed a set of markers (given in Table 3) for a simplified version of the peatland rewetting scenario of the Dragoman Marsh, focussed on the key manifestations associated with the re-vegetation stage and the known fire that occurred in 2020. The period covered by the scenario and the extracted signals was 2018-2022 (2 years before and 2 years after the event), which suffice to illustrate the implementation of the scenario concept.

Table 3. Types of information extraction, signals and markers relevant to the simplified scenario of Dragoman Marsh restoration.

Manifestation	State of land cover		Inf. extraction type	Signal 1 (S1)	Signal 1 behaviour	Marker 1 (M1)	Signal 2 (S2)	Signal 2 behaviour	Marker 2 (M2)
	Pre-condition:	Post-condition:							
Development of native vegetation	mosses and sedges	more mosses and sedges	C1	BR pdist	>0	S1	BR q50	>=7	S2
Fire conditions	Less dry vegetation	More dry vegetation	C1	PSRI mean	increase↑↑	dS1/dt	Precipitation	Low	S2
Fire occurrence	No burnt surface	Burnt surface	T3	NBR_BG mean	drop↓↓	dS1/dt	NDVI mean	drop↓↓	dS2/dt

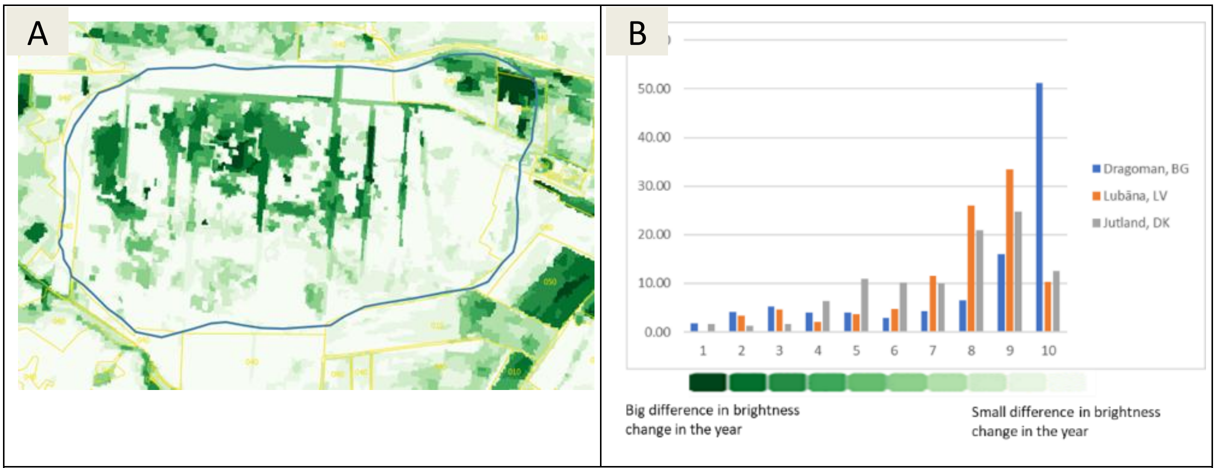
Note: PRSI = Plant Senescence Reflectance Index (B4 – B2)/B6; NBR_BG = Modified Burnt Ratio index ((B11 - B12) / (B11 + B12) + (B8A / 10000))*2 + ((B8A - B12) / (B8A + B12)) ; NDVI = Normalized Difference Vegetation Index (B8 – B4)/(B8 + B4). The abbreviation of the spectral bands follows the Sentinel-2 convention; BR pdist / BR q50 heterogeneity indices.

Source: SEPLA.

In the “re-vegetation stage”, the main process is the development of vegetation native to the peatland, such as reeds, sedges, and mosses. Since this “land cover” transition is very slow and gradual, the process and its durations can be effectively traced with a sampling rate of one observation per year. However, the markers used for the corresponding observation - BR pdist and BR q50 - are complex and they account for the spatial-temporal behaviour of the peatland over the entire year. They form a pair of two statistical metrics (based on quartiles) calculated on the histogram of the distribution of detected image image-objects within the FOI, which are derived from spectral-based multitemporal image segmentation. Each image-object is classified according to the percentile of the maximum difference of the annual brightness changes, derived from the green (B3), red (B4) and NIR (B8) bands of Sentinel-2, it belongs to. These bands were selected for their documented sensitivity and response to vegetation and their higher spatial resolution (10 meters). More details on the segmentation method are given in Section 3.3. of this report. The segmentation method and the derived metrics are based on the work described in (Milenov et al., 2021a) The working assumption is that the Dragoman Marsh is already in a state where sedges and mosses cover a substantial area of the peatland having a low amplitude of phenology dynamics. This is expected to manifest itself as a low spatio-temporal variation of the spectral-based image image-objects within the FOI and as a skewed histogram of the classified image-objects towards known classes associated with low variation (**Figure 16**). When the values of both markers are above the set thresholds, they confirm that the vegetation behaviour adheres to what is expected for peatlands under restoration. The two markers are complemented with a third one (not shown in Table 3) that checks whether the annual mean of NDWI, stays within a given range.

Note that this pair of spatio-temporal markers uses cumulative data over several Sentinel-2 observations; thus, it produces an outcome at the end of the life cycle (similar to a crop classification). It was found useful to track the progress of the peatland restoration in the longer term and the response to eventual adverse effects; however, the pair’s latency is too high for near real-time detection of spontaneous short-term incidents such as fire.

Figure 16. A) Thematic raster map resulting from multitemporal segmentation of B3B4B8 of cloud-free S2 images, evenly spread throughout 2019. White image-objects represent areas with a low dynamic of B3B4B8 over the year. The green area represents areas with high B3B4B8 dynamics. B) comparison of the histogram of the distribution of the labelled classified image-objects, according to their area share, for the Dragoman Marsh, with the classes of similar peatlands (bogs) in the SEPLA test sites in Latvia and Denmark. C) the formulas for the pair of spectral based markers



C

$$BR\ pdist = \frac{(p25 + p75)}{2} - p50;$$

with p25, p50 and p75, being the 1st, 2nd and 3rd quartile of the sorted set N_k, respectively

N-number of image-objects per class k in the FOI, k – class number [1;10],

$$BR\ q50 = \ q50;$$

with q50, being the 2nd quartile (median) of the sorted set of classified image-objects in the FOI

Source: SEPLA.

The presence of conditions favourable for fire is checked with a marker which looks at the accumulation of dry vegetation. It observes the steady increase of the PSRI and it is complemented with a marker observing precipitation amounts, using ERA5[1] data from the Copernicus Climate Service.

The occurrence of a fire is checked with a marker NBR_BG - a modified burnt ratio index, based on Sentinel-2 bands B11, B12 and B8A, developed by the Bulgarian Paying Agency and shared with SEPLA. The marker filters out commission errors, such as fallow land treated with ashes from burnt manure. It is complemented with a marker based on the NDVI.

A log of the actually detected markers is given in **Figure 17** below.

The fire occurred on 22.01.2020. The NBR_BG marker (**Figure 17**A) detected the fire in the first acquired Sentinel-2 observation after its occurrence (24.01.2023), when a notable part of the NBR_BG -1 standard deviation envelope dropped below zero. On 08.02.2020, a spike in the NBR_BG was associated with the presence of snow. From the supplement burnt area mask created (**Figure 17**B), it was evident that the fire has affected most of the peatland and has spread beyond its FOI.

The PSRI marker (**Figure 17**C) detected an increase of the PSRI values beyond the range of -0.1 to 0.2 normal for green vegetation (Zang et al., 2018) in the month before the fire (Dec 2019), which is typical for the vegetation cycle of the peatland. There was also a decrease in precipitation (**Figure 17**D) in the autumn of 2019, compared to other years (data derived from ERA5-Land Climate Aggregations – Total Precipitation).

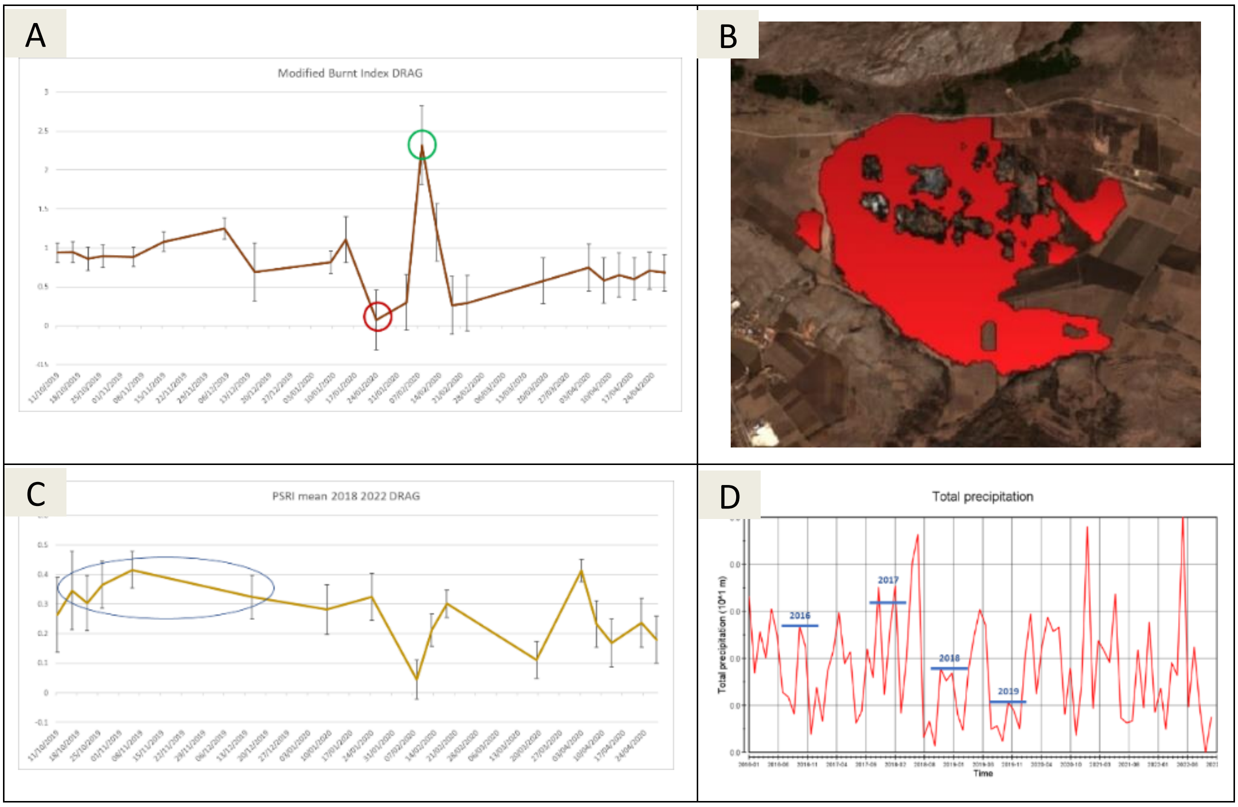
The markers BR pdist and BR p50 tracking the development and maintenance of native vegetation (**Figure 17**E) confirmed the disturbance in the vegetation's spatio-temporal behaviour in 2020. Both marker values dropped beyond their thresholds. However, values began to approach their pre-fire levels, indicating potential peatland

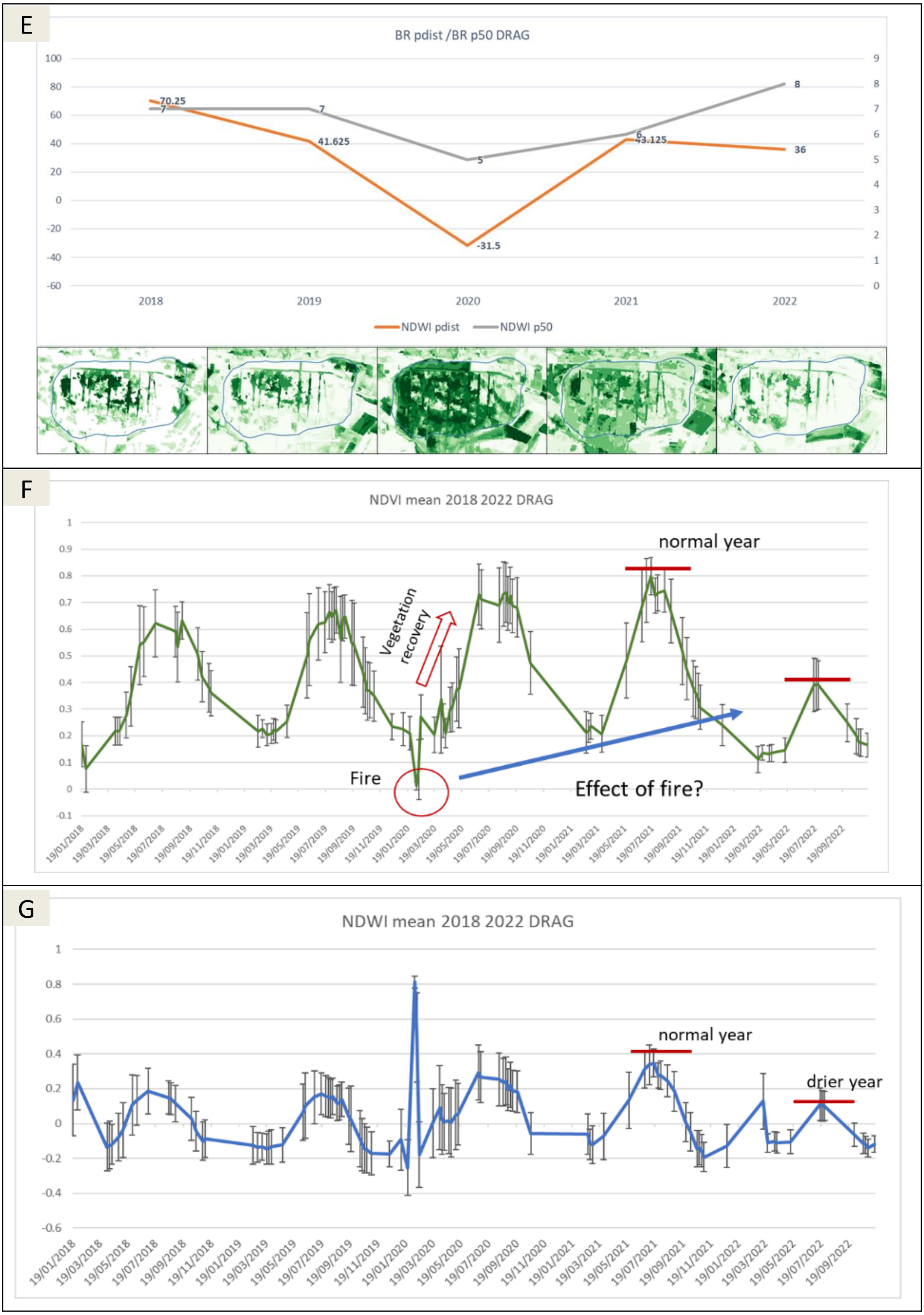
[1] ERA5 is the fifth generation ECMWF atmospheric reanalysis of the global climate covering the period from January 1940 to present. ERA5 is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

recovery. This trend is also visible from the distribution of the image-objects shown below the graph. The ground information collected confirmed steady reed vegetation recovery, already in the first 4 months despite the low water levels.

There was an interesting observation made by the NDVI time series (**Figure 17**F) used by the complementary marker for fire. After the event, the vegetation phenology seems to get back to normal in 2021; however, the NDVI peak in 2022 (a drier year) was much lower than in 2021 and also lower compared to other wetlands in the area not affected by the fire. This lower peak might be a result of the decrease in storage capacity and potentially surface moisture availability, which might affect the recolonization of the peatland with native species in the longer run (Tompson, 2012). The presented scenario indicated that peatland disturbances have likely caused a decrease in the hydrological potential for native vegetation recovery, which may impact peatland ecohydrological resilience (Sherwood et. al, 2013).

Figure 17. The outcome of the markers from the peatland restoration scenario for Dragoman Marsh.





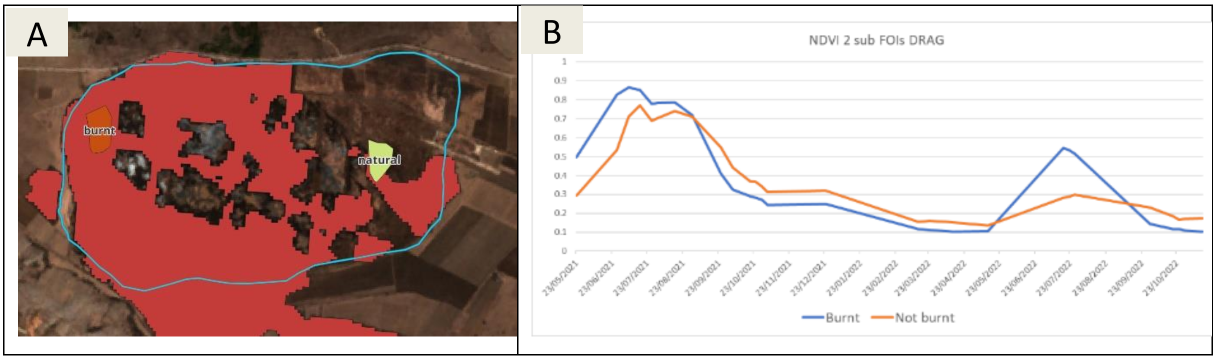
Source: SEPLA.

Considering the vast extent of the peatland (almost 300 ha) and its heterogeneous character in terms of land cover and land use (**Figure 18**), the observations made on the signal behaviour over the entire FOI of the peatland should be detailed at the level of the individual land cover types as sub FOIs. Areas in the natural state should be separated from areas that are still retained under extensive agricultural management, as those located in the north-eastern corner of the peatland. Separate monitoring scenarios should be introduced for those areas affected by the fire. For example, the additional analysis of the signal behaviour at the level of candidate sub-FOIs revealed that although the drop of the NDVI in the summer of 2022 compared to the summer of 2021 is systematic over the vegetated areas, those that were burnt do display a higher NDVI than the non-burnt (Figure 15). This might be an indication that in the affected by the fire, native vegetation is locally outcompeted by more dry-adapted species such as shrubs (Tompson, 2012).

Figure 18. Sentinel-2 images before and after the fire. Drainage channels as still well-visible.

Source: JRC Big Data Analytics Platform (BDAP).

Figure 19. A) Two sub-FOI on naturally vegetated areas within the peatland – one within the burnt area and one at its border. B) The individual time series of both sub-FOIs. The one entirely in a burnt area has a higher NDVI.



Source: SEPLA.

Box 3: Stakeholders' needs from SEPLA
During the bilateral discussion with the EU Member State experts and setting up the pilot tests, it became clear that one of the main technical problems is the accurate outline of the extent of the degraded peatlands under agricultural management. The semantic assessment revealed discrepancies between different expert communities on how peatland should be defined. Also, most of the EU countries define the peatland based on the available peat soil, rather than the visible native plant communities. The lack of land cover manifestation on the ground due to the native vegetation removal, makes the establishment of the proper FOI, well defined in terms of non-disputable borders, for the monitoring very challenging, if not impossible. The next section of this report focuses on methods and tools for the identification and determination of the area under agricultural management located on peat soils.

2.2 Potential EO-based prototypes and techniques

2.2.1 Earth observation signals and associated methods

Remote sensing offers the possibility of non-disruptive detection and characterisation of peatland ecosystems, and when time series are available, allows for the monitoring of the dynamics of the ecosystem changes. This is especially important in the presence of sensitive habitats and species, in complex terrain, often inaccessible due to its hydrological properties (Czapiewski et al., 2022). Nonetheless, because peatland as the actual object of interest is underground and the ecosystems are very complex, the remote sensing analyses remain challenging and the best results may be obtained when several techniques and methods are combined (Minasny et al, 2019; Dronova, 2015).

Since one of the objectives of SEPLA was to propose observation methods that use freely available remote sensing data; the summary below includes mostly data provided by the Copernicus services, derived from Sentinel-1 and Sentinel-2 data.

2.2.1.1 Interferometric Synthetic Aperture Radar

Interferometric Synthetic Aperture Radar (InSAR) uses at least two radar images of the same area, acquired at different times, to measure ground surface deformation or assess the coherence between the two images. InSAR surface motion measures the displacement of the Earth's surface between two SAR acquisitions. It is calculated by comparing the phase difference between the pair of SAR images and converting it into a measure of surface displacement. This technique is particularly useful for monitoring peatlands, which are subject to changes in ground surface elevation, so called “bog breathing” (e.g. Price, 2003) but also due to erosion, and accumulation (Bradley et al., 2022).

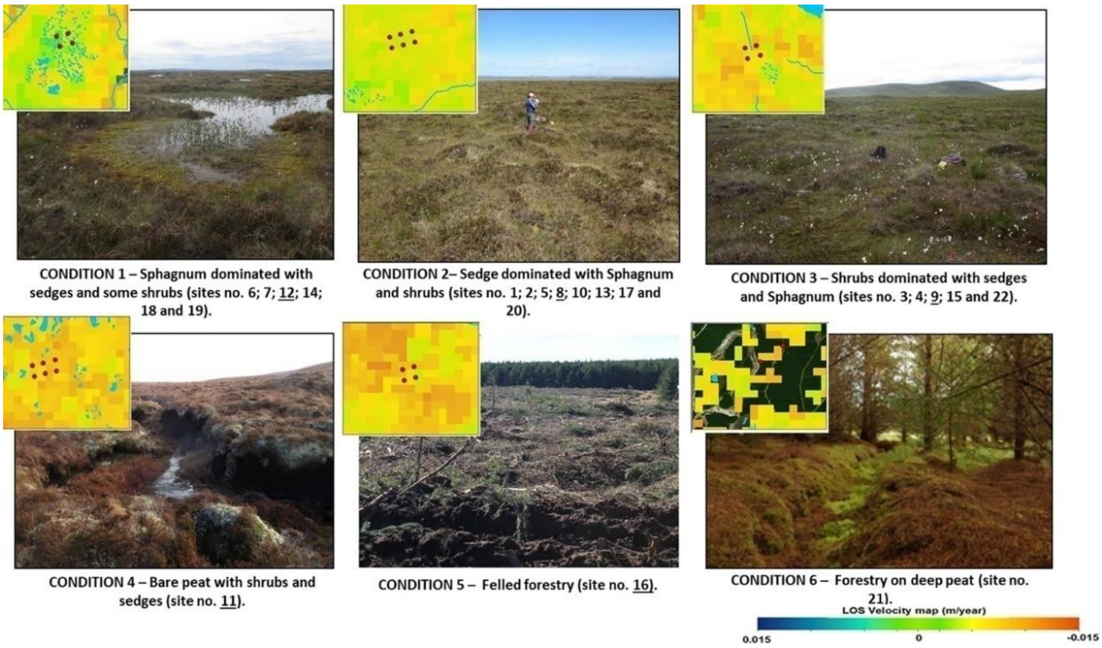
The relationship between the surface motion and ecohydrology in peatlands is documented in several studies (Fiaschi et al., 2019; Tampuu et al., 2020; Bradley et al., 2022; Alshammari et al., 2020). The degradation of peat is linked to its ability to retain water and elasticity. Degraded sites are less elastic and exhibit a lower surface movement amplitude with changing water conditions (Lui and Lennartz, 2019). Sites with preserved near natural conditions with peats on relatively flat surfaces are poorly drained and therefore wet and typically dominated by Sphagnum Moses, which have a great capacity for water storage, resulting in peak water absorption and seasonal swelling of the surface late in the year (November to February) in the Atlantic region (Bradley et al., 2022; Alshammari et al., 2020). In drier, more degraded peat sites, with more sedges and shrubs and fewer Sphagnum Moses the capacity to store water is smaller and they reach the peak water holding capacity earlier in the year (Bradley et al., 2022; Alshammari et al., 2020).

When considering the surface velocity the positive values of multiannual average velocity are typically dominated by Sphagnum Moses. Peatlands that have been degraded, drained (with man-made drainage), afforested or remain bare (bare peat), consistently show negative long-term (multiannual) average velocities regardless of topographical setting (Bradley et al., 2022; Alshammari et al., 2020), with the bare peat reaching the highest negative surface motion velocity values.

When looking at different management classes, the least negative values of multiannual average velocities are associated with areas under conservation management and the highest negative values are observed for forest-to-bog restoration approach which typically triggers compaction and degradation of the peat from heavy machinery during the removal of conifer stands (Bradley et al., 2022).

The line of sight (LOS) velocity data represents measurements projected along the imaginary line which connects the sensor with the target point. Positive values indicate uplifting of the surface, negative values involve surface subsidence. Examples of peatlands in different preservation states and their corresponding surface motion velocity (m/year) expressed by the line of sight (LOS) velocity values are shown in the figure below.

Figure 20. Example of peatlands in different preservation states and their corresponding surface motion velocity. Condition 1 represents a peatland with well preserved, near-natural state, with positive average velocity values (marked in darker green) indicating a good eco-hydrological state. Conditions 2 and 3 represent degraded states (but with the presence of Spahangum) and medium surface motion velocities. For Conditions 4 and 5 the average annual velocity has the highest negative values, indicating peat subsidence and shrinking. In condition 6 the availability of the data is limited due to tree cover. The red points indicate the pixels used in analyses presented in the paper cited below.

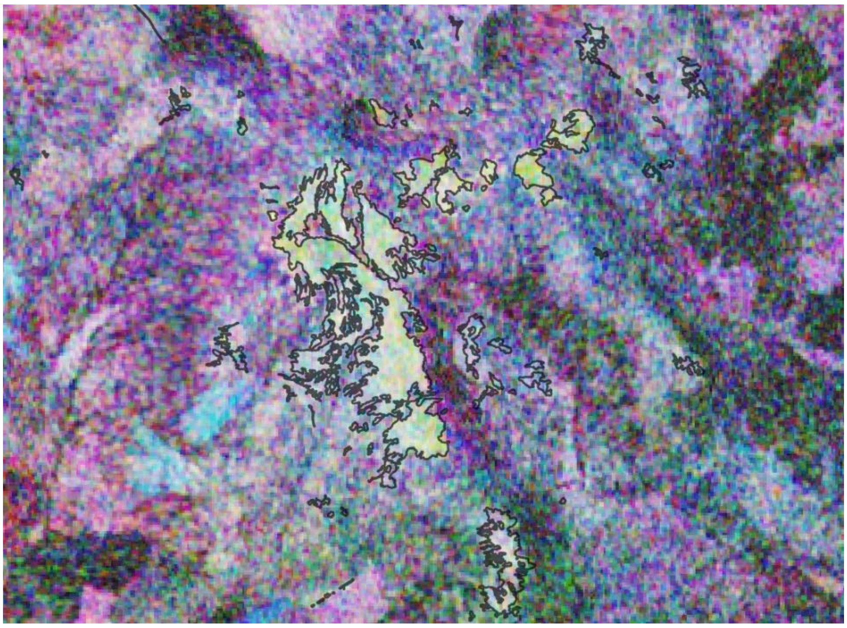


Source: Alshammari et al., 2020, Figure 3.

Until recently the inSar data have been mostly derived at high spatial resolution from data provided by aerial radar sensors, that are costly to get. Since 2022 the Sentinel-1 based inSAR products covering the EU territory (and Iceland) are freely available in the scope of the European Ground Motion Service (EGMS). The data processing methodology applies multi-interferogram techniques that analyse time series of differential full-resolution Sentinel-1-based SAR interferograms to minimise noise related to different sources and to derive displacements over time and average velocities for individual Measurement Points (Kotzerke et al., 2022). Although for near natural peatlands, where the seasonal and multiannual land cover change is very slow, the EGMS often provides Measurement Points, for the peats covered with managed grasslands (that are the main scope of SEPLA), the measurement points are very few or none. This is due to the vegetation changing its appearance throughout the seasons or vegetation cycle, the diffuse backscattering mechanism of vegetation layers and the changes in the geometric state of vegetation such as plant growth, mowing, grazing, motion due to wind etc. Each of these impedes the possibility of finding stable and reliable measurement points. According to (Kotzerke at al., 2022) the applications of EGMS to the measurement of plant/tree growth, terrain deformation monitoring under forest areas or grassland are not realistic.

The second type of the inSAR product is the InSAR coherence, which measures how similar two SAR images captured on a different date are. The coherence between the two images is represented by a value between 0 and 1, where 1 indicates perfect coherence and 0 indicates no coherence. The temporal and spatial variation of the inSAR coherence provides useful information about the hydrological condition and the vegetation cover. Coherence measurement has been used to map the area inundated with surface water and different wetland types (e.g. Canisius et al.,2019; Tamuu et al.,2020).

Figure 21 Detection of Bare Peat in Ireland using a composite image of 3 Sentinel 1 COH6 (coherence 6 days apart) images from spring, summer and autumn. Vectors represent bare peat classes as mapped in the OSI Land Cover dataset, 2018.



Source: SEPLA, CREODIAS, Copernicus Services.

2.2.1.2 Sentinel-2 time series and Sentinel-1 backscatter

Among optical data that rely on reflected sunlight from an object's surface in the visible, near-infrared, and shortwave-infrared wavelengths, vegetation and water content indices are the most often used for peatland monitoring:

- Normalized Difference Vegetation Index (NDVI) is used to detect the presence of photosynthetically active vegetation and distinguish between different vegetation types and their state (for peatlands, e.g. Rastogi et al, 2019),
- The Normalized Difference Water Index (NDWI, Gao, 1996) is based on the data registered in near-infrared and short-wave infrared ranges and is sensitive to the water content in vegetation (for peatlands, e.g. Lees et al, 2020). Water absorbs SWIR light, while vegetation reflects it, resulting in lower NDWI values in areas with wet vegetation cover and higher NDWI values in areas with dry vegetation cover.

Other often mentioned indices are:

- Chlorophyll Index (CI) is designed to detect changes in chlorophyll (in peatlands e.g. Harris et al, 2009).
- The Moisture Stress Index (MSI) is used to evaluate the effects of water stress on plant health (in peatlands e.g. Harris et al, 2009),
- The Water Index (WI) and its modifications, i.e. floating water band index (fWBI) are used to estimate the plant water concentration (for peatlands, e.g. Harris et al, 2009; Rostgi et al, 2019).

A practical limitation linked with the optical sensors and their passive way of capturing data is linked to cloud cover, limiting the amount and frequency of suitable images, especially when captured from a satellite platform. Over wetlands and peatlands where the cloud cover is frequent, active remote sensing techniques, involving radar or lidar are particularly useful.

Synthetic aperture radar (SAR) backscatter imagery, e.g. provided by Sentinel-1, can be used to detect changes in surface roughness, which can be indicative of changes in water content. The Sentinel-1 C band beam at a 5.6 cm wavelength is reflected off any water surface and the lack of backscatter clearly exposes that water surface. The beam also partly penetrates through the vegetation and topsoil layer and is affected by surface roughness, dielectric properties, and moisture content. The higher the soil water content, the higher the dielectric constant, resulting in increases in the backscatter signal. Therefore, the radar data constitute a promising source of spatial information on soil moisture and groundwater table depths (WTD), yet require more studies (e.g. Asmuß et al, 2019; Tampuu et al, 2021; Räsänen et al, 2022; Toca et al, 2023).

2.2.1.3 Copernicus vegetation phenology and productivity indices

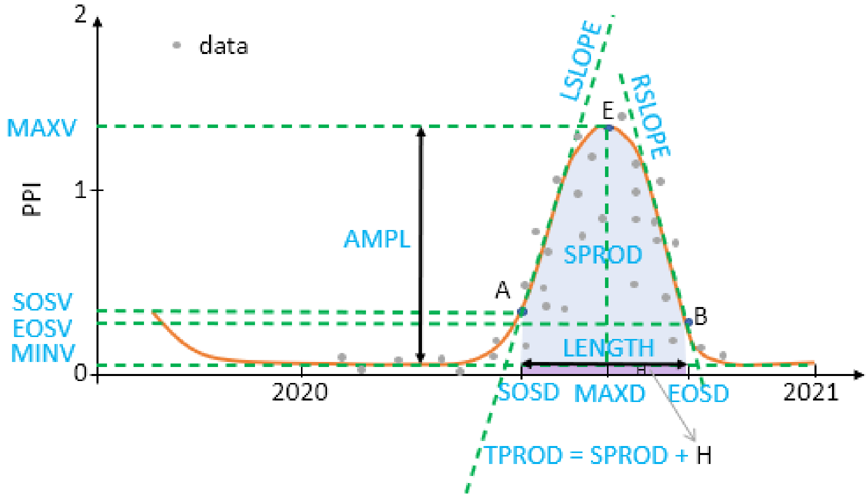
Vegetation phenology describes the plant life cycle events across the growing seasons. Monitoring of vegetation phenology and productivity (VPP) indices may provide very important inputs for an assessment of the status and change of ecosystems, habitats and land cover. Phenological and productivity metrics derived from remote sensing can indicate land use patterns and capture ecosystem changes from the local, to the continental and global scale (Smets et al., 2021) and provide the status and inter-annual variability of ecosystems. Therefore, they may be also very useful in assessments of the impacts of human activity on climate change and on ecosystem degradation. Phenology trends, such as changes in the start, the end date or the length of the vegetation growing season or productivity trends may be used to estimate the carbon uptake and to plan climate mitigation and adaptation measures (Van Hoolst et al., 2022). The phenology data also reflect vegetation responses to local natural disturbances such as droughts, storms, insect infestations, and human activities.

As a part of the Pan-European component, the Copernicus Land Monitoring Service (CLMS) produces and disseminates High-Resolution Vegetation Phenology and Productivity product suite (HR-VPP) at high spatial resolution (10m x 10m). The product is part of the CLMS Pan-European component, managed by the European Environment Agency (EEA). The indices are "derived from the Sentinel-2 constellation (Sentinel-2A and Sentinel-2B) with a revisit time of 5 days. They are generated over the entire EEA39 (32 member countries, the UK and 6 cooperating countries in the Western Balkans) from January 1 of 2017 onwards with a daily, 10-daily and yearly frequency" (Smets et al., 2021).

Three different types of products are provided by the CLMS service (Smets et al., 2021):

- The raw Vegetation Indices are generated near real-time and provide for every pixel the status of the vegetation vigour expressed by: Leaf Area Index, Fraction of Absorbed Photosynthetically Active Radiation, Normalized Difference Vegetation Index and Plant Phenology Index (PPI);
- The Seasonal Trajectories are provided yearly after the end of the vegetation growing season and derived as a regular time-series of every 10 days;
- The vegetation phenology parameters (VPPs) are derived from the Seasonal Trajectories of the PPI index, on a yearly basis.

Figure 22. The Vegetation Phenology Parameters describe the vegetation development in the season with 13 parameters. The start of the season is defined by the date (SOSD), the PPI value (SOSV) and the slope of the greening curve (LSLOPE). Analogous values characterise the end of the season: date (EOSD), the PPI value on that day (EOSV) and the slope (RSLOPE). The length of the vegetation season (LENGTH), the minimum and maximum PPI value of the season (MINV and MAXV) and the corresponding dates (MIND, MAXD), the amplitude (AMPL), and the seasonal (SPROD) and total productivity (TPROD) values are also provided.



Source: SEPLA based on Figure 1 in (Smets et al., 2021).

The vegetation phenology parameters are produced for up to 2 seasons (depending on the location). The thirteen vegetation and productivity metrics are provided for each pixel per season. They describe the yearly vegetation development by indicating e.g. the day of the start and the end of the growing season (SOSD, EOSD), and the corresponding PPI values (SOSV, EOSV), length of the growing season (LENGTH) or annual productivity (TPROD). All parameters are depicted in **Figure 22**.

2.2.1.4 Other signals

Hyperspectral sensors that capture high spectral resolution data across multiple very narrow spectral bands of the electromagnetic spectrum can be used to identify different vegetation types and discriminate between different soil types and water depths (e.g. Kalacska et al, 2018). With the increased availability of hyperspectral data (several satellite sensors in space and more affordable airborne and even drone-based cameras), the growth of well-documented spectral libraries and the fast pace of data processing automation, this remote sensing technique becomes more accessible for the broader public. The Copernicus Hyperspectral Imaging Mission for the Environment (CHIME) mission (Celesti et al., 2022) aims at speeding up the hyperspectral imagery uptake process. CHIME-A is planned to be in orbit in 2028, followed by CHIME-B in 2030, The visible-to-shortwave infrared data will feed new Copernicus services that support sustainable agriculture and biodiversity management, soil properties characterization, sustainable mining practices and environment preservation (Celesti et al., 2022).

Although satellite LiDAR (light detection and ranging) based instruments are not yet available, airborne LiDAR data[2] can provide information on the topography, vegetation canopy structure, and water depth of the area (Carless et al, 2019). Accurate information about the slope contours and drainage patterns allows to model or predict where water gathers or could inundate the peat surface. These are conditions for an “active”, peat-forming raised bog habitat to develop (Pakalne et al, 2021). LiDAR information on the structure, height and density of the vegetation is useful to classify vegetation types and assess the health of the ecosystem.

2.2.2 Ground data and collection tools

Effective monitoring of peatland or restoration state requires a range of ground data providing information on the state of different ecosystem components and thus allowing to conclude the effectiveness of the preservation or restoration efforts. Ground data constitute the best source to calibrate, train and validate remote sensing based monitoring methods.

Soil moisture content sensors, water table sensors (automated data loggers) and devices providing hydrological data such as water quality or flow rates can help determine whether the water levels are stable enough to support healthy peatland vegetation and hydrology. Where the restored peatland is retaining water or functioning as a natural water filter, improving water quality is critical for maintaining a healthy peatland ecosystem. Water level observations are relevant not only for the evaluation of rewetting and weather conditions, but are also important for interpreting ecosystem photosynthesis and transpiration in GHG model estimates (Pakalne et al., 2021).

Measuring peat depth, i.e. with peat probes, can quantify the peat that has been damaged and determine the accumulation from restoration efforts.

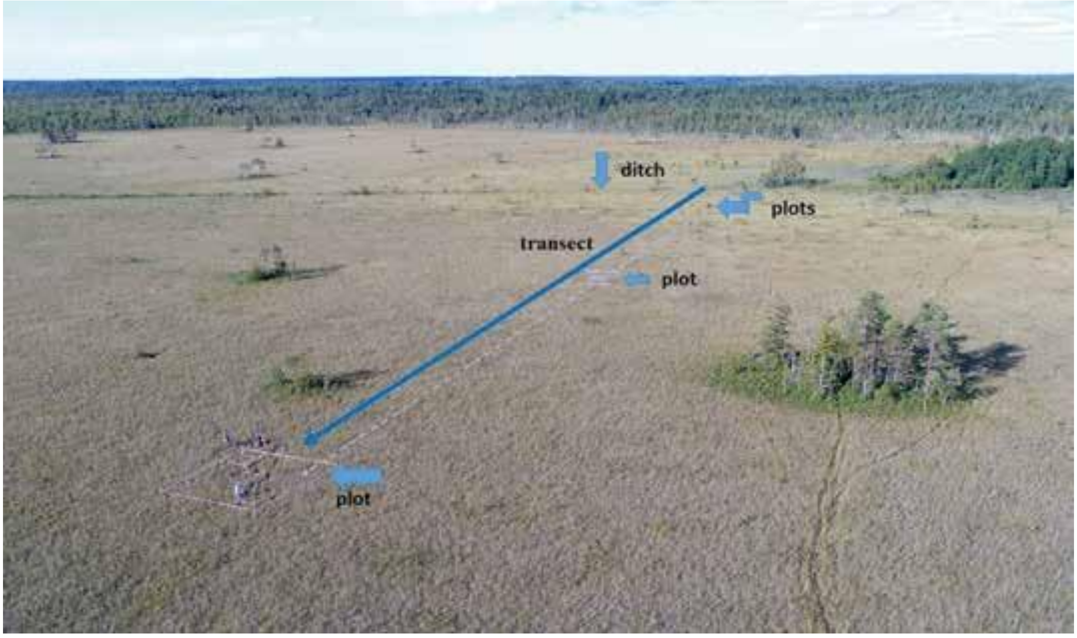
Measuring greenhouse gas emissions (i.e. carbon dioxide, methane, and nitrous oxide) with gas analysers or chambers, may provide information on the change of emissions from peatlands in their preservation or restoration process.

The vegetation cover is a good indicator of GHG fluxes from peat soils as it reflects long-term water level conditions and affects GHG emissions via assimilating supply and aerenchyma formation. The GHG fluxes estimation methodology includes mapping of different species groups indicative of specific water level classes. Monitoring the vegetation cover and density can help track the success of preservation or restoration efforts or identify areas that may need further intervention (i.e. removal of invasive species, adjustment of the water level etc). The extent of the vegetation monitoring depends on many factors and varies from few plots, most often quadrants of size 5-10m x 5-10m, documented manually by precise description and mapping of plant species, their state and the area that they cover within the plot, to a complete site mapping survey, i.e. using very high-

[2] Already applied by some EU Member States participating in SEPLA

resolution, often multispectral, images (with ground sampling distance of few centimetres) captured from a drone platform.

Figure 23. Example of four vegetation monitoring plots in the Suursoo-Leidissoo peatland in Estonia, part of the largest and most complex restoration site in the LIFE Peat Restore project (LIFE15 CCM/DE/000138).



Source: Pakalne M. et al. 2021. Best Practice Book for Peatland Restoration and Climate Change Mitigation. Experiences from LIFE Peat Restore Project. University of Latvia, Riga, 184 p. Photo: R. Pajula. Figure 16.

Figure 24. Documentation of species for vegetation monitoring in Suursoo-Leidissoo peatland in Estonia (LIFE15 CCM/DE/000138, LIFE Peat Restore). The vegetation monitoring was performed in permanent plots with a size of subplots depending on functional plant type: trees and shrubs (10m x 10m), dwarf shrubs and herbaceous plants (2m x 2m), bryophytes (0.25m x 0.25m).

Source: Pakalne M. et al. 2021. Best Practice Book for Peatland Restoration and Climate Change Mitigation. Experiences from LIFE Peat Restore Project. University of Latvia, Riga, 184 p. Figure 9.

Drone-based data collection allows to efficiently capture data in a non-invasive manner, and provide access to areas that are difficult to reach or could be easily damaged by human incursion. Mapping should be repeated on a periodic basis, e.g. annually or bi-annually (Pakalne et al., 2021). To allow for data comparison between different acquisitions/field campaigns, the plant species richness, plot size and location have to be standardized, and the taxonomic level of the inventory has to be fixed (Pakalne et al., 2021).

Figure 25. Example of NDVI data provided by Sensefly eBee Sequoia fixed-wing drone equipped with a multispectral camera (capturing data in green, red, near-infrared, red-edge part of the light spectrum). The documentation provided for vegetation monitoring in Suursoo-Leidissoo peatland restoration in Estonia (LIFE15 CCM/DE/000138, LIFE Peat Restore).

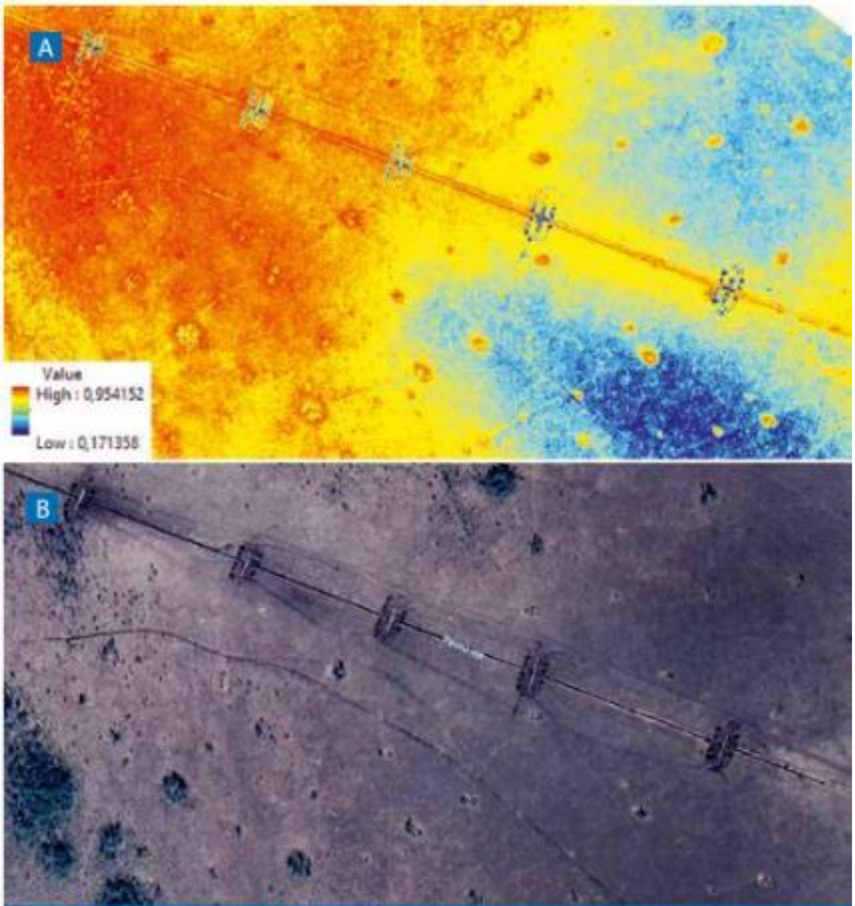


Figure 27. *NDVI map (A) from July 16, 2021 compared to Google Earth satellite photo (B) from May 4, 2021, the eastern part of Suursoo-Leidissoo project peatland with a fen and Pennu ditch with recently built dams. Lower NDVI values (blue) indicate near-natural alkaline fen communities; higher values (red and orange) indicate more drained fen with dominance of Molinia caerulea. NDVI map (A): R. Pajula.*

Source: Pakalne M. et al. 2021. Best Practice Book for Peatland Restoration and Climate Change Mitigation. Experiences from LIFE Peat Restore Project. University of Latvia, Riga, 184 p., Figure 27.

Monitoring of wildlife populations, through regular observations by experts, using monitoring cameras or photo traps, can help determine whether the restored peatland is providing suitable habitat for wildlife and contributing to biodiversity conservation (Mackin et al., 2017).

Last, but not least, come geotagged photos that can be very useful for peatland state or restoration monitoring. When acquired in a standardised and systematic manner (from well-defined, stable viewpoints, pointing into specific repeatable direction) they can provide visual documentation of the condition of the peatland and help to identify changes in vegetation cover, water levels, and other important features.

The collection of ground data is invaluable to calibrating, training, optimisation and validating remote sensing-based monitoring methods.

2.2.3 “Proxy” methods for non-monitorable aspects (e.g. in restoration)

Peatland restoration is primarily undertaken where it is both feasible within the hydrological and biological constraints and justifiable from a socio-economic perspective. While the potential exists to create new markets and financial incentives through wetland restoration, which can benefit the wider human community (Jurasinski et al., 2020), peatland restoration is often opportunity-driven, and opportunities will vary.

As previously mentioned, the aim of the restoration is to bring back the peatland into balance with its natural environment, while redefining its role in the socio-economic context. The effect of restoration measures such as rewetting and revegetation depends on local environmental and socio-economic circumstances. Depending on the goal of the monitoring process, bio-physical (e.g. plant and animal species, vegetation structure, connectivity), and socio-economic factors (e.g. local livelihoods, profitability and gender equity of wet livelihood options) could be analysed in order to understand the evolution of peatland status and possible threats (FAO, 2020). Information on the latter is collected in administrative databases or collected through statistical surveys. Some of the data, as territorial planning, national forest inventories or parcel data from administrative registers for agricultural payments under CAP, are geographically explicit. By using geographic information systems it is possible to integrate socio-economic and other data in the peatland monitoring. For example, the parcel-based data on the annual agricultural uses, collected in the Integrated Administration and Control System (IACS) of the EU countries for CAP payments, could be used to understand the degree of potential pressures on the peatland from neighbouring agricultural activities.

To illustrate this, the SEPLA team used the parcel declaration data covering the test site in Bulgaria for the last 15 years, provided by the Bulgarian Paying Agency. The Bulgarian authorities have been collecting this data in geographically-explicit manner, since the beginning of their CAP implementation in 2007. This analysis builds on preliminary work for the preparation of IACS data for the purposes of LULUCF reporting, done in the scope of a dedicated JRC pilot (Ivanova-Stoyanova and Stoeva, 2021).

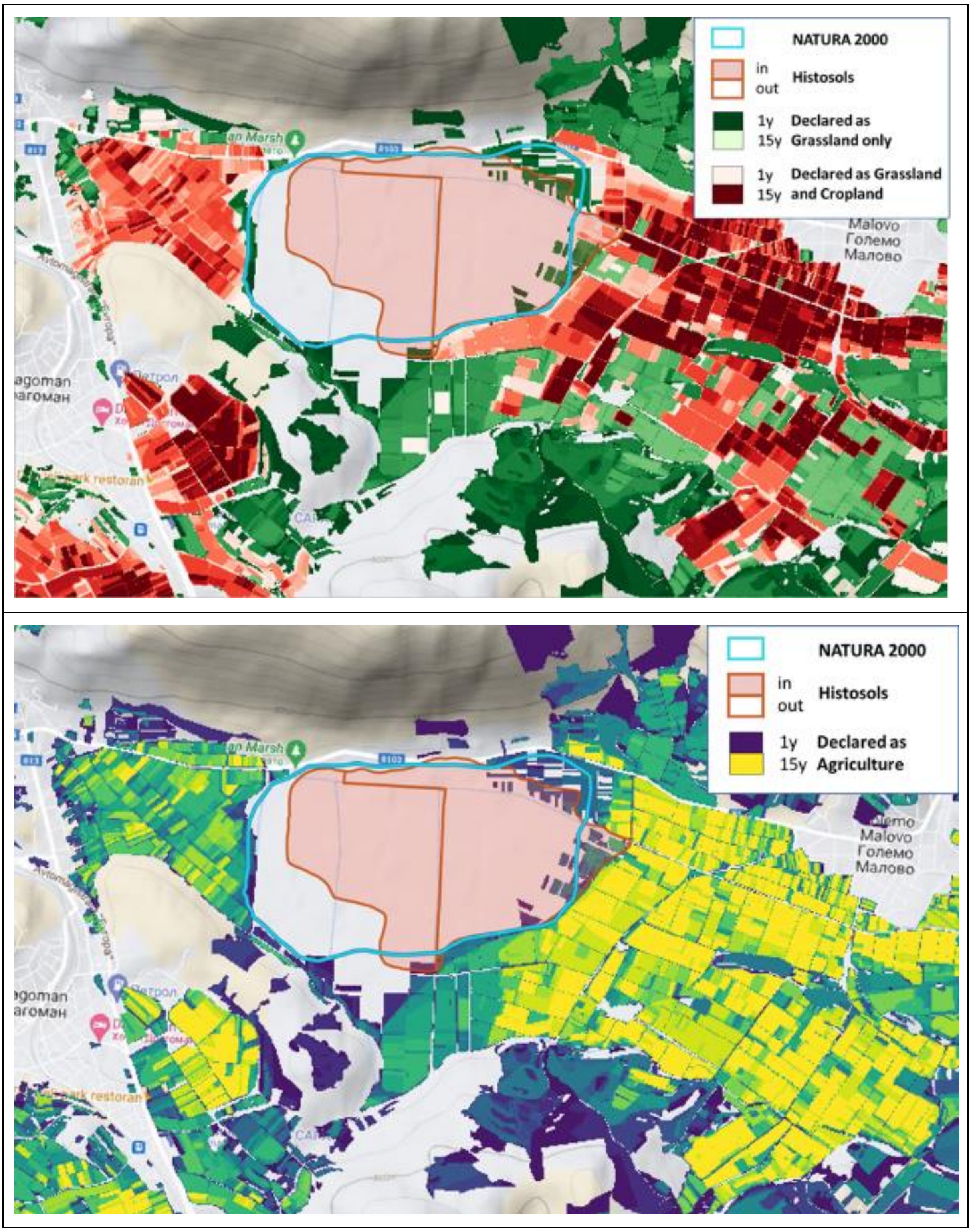
SEPLA team translated the land use and crop types from the national nomenclature to the IPCC sub-categories on Cropland and Grassland. The resulting vector datasets from the yearly declaration were rasterized in a 10-meter grid and compiled into a 15-layer image stack. The raster processing produced a set of thematic maps showing the intensity of the agricultural use, with the following layers:

1. Grid cells declared for agricultural purposes, with the number of years declared,
2. Grid cells declared for Cropland and Grassland, with the number of years declared as Cropland,
3. Grid cells Grassland ONLY, with the number of years it was declared as Grassland,

since the first year of CAP implementation in Bulgaria, which is 2007.

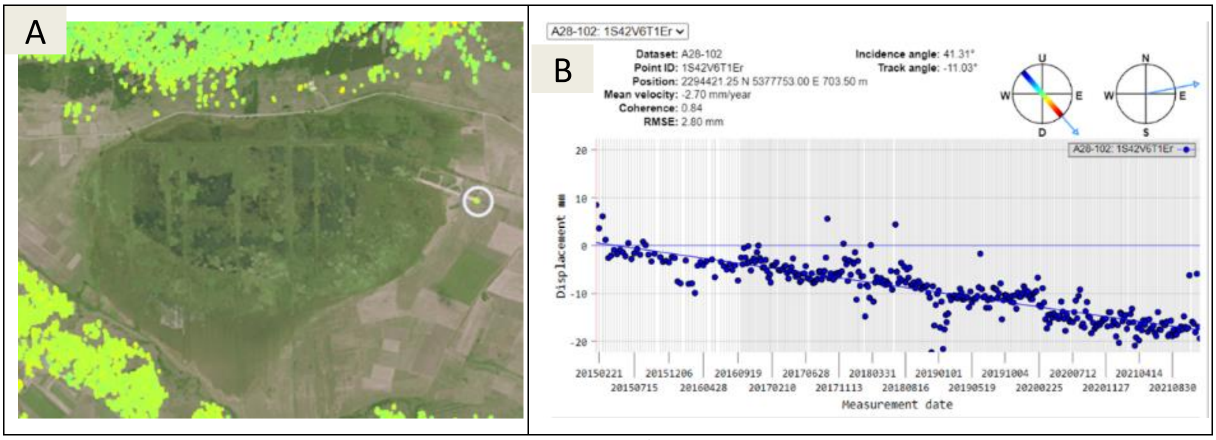
The raster maps were used to check for the potential pressures from agriculture on the Bulgarian peatland “Dragoman Marsh”, which is under restoration. The spatial overlay with the N2000 border of the habitat showed that there are no parcels with intensive agricultural activity related to arable or permanent cropping within the site (**Figure 26**). Agricultural use seems limited to grassland parcels under extensive grazing within the eastern sector of the site. This is allowed by the national rules. Some of these parcels are on histosols. However, there is relatively intense arable cropping happening in close proximity to the western and south-eastern border of the peatland site. This could adversely affect the water availability in the peatland and increase the risk of fires, due to occasional stubble burning (generally banned in Bulgaria). Potential evidence for a decreased water retention capacity could be the area of the small airfield located at the Eastern border of the site and within the extent of the histosols. This area shows systematic surface subsidence of 20 cm during the last 6-7 years, as shown in the data from the European Ground Motion Service (**Figure 27**).

Figure 26. Top: Maps of the intensity of the agriculture related to Cropland and Grassland, according to IPCC. Green shades correspond to areas declared for Grassland only. Red shades correspond to areas declared for Grassland and Cropland. Bottom: Maps of the intensity of agriculture. Blue to yellow shades show the number of years the area was declared for agricultural purposes.



Source: SEPLA and Google, 2023.

Figure 27. A) Image of the peatland with the measured point (persistent scatterer) marked with a circle. B: The vertical point displacement from 2015 to 2021.



Source: European Ground Motion Service.

3 Developed use cases

3.1 Study areas

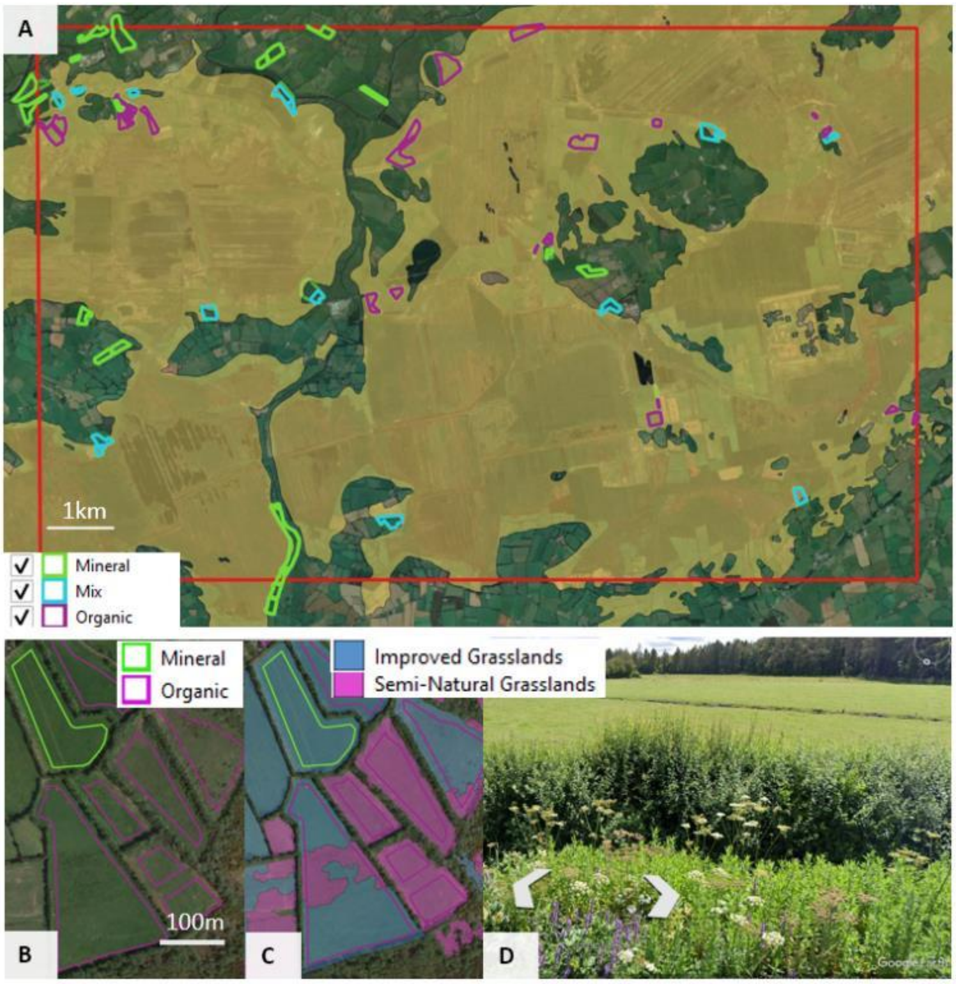
3.1.1 Offaly, Ireland – cutover peat

In the study area in Offaly, Ireland, the organic soils include the class of *cutover peat* comprising cut away bogs or/and drained raised and blanket bogs (Cut, marked in light orange in the figure below). The soil map used as the data source was created as an "enhancement of the land cover map by increasing the classification and spatial resolution of many of the land cover thematic classes, namely; Bog & Heath, Cut Bog, Cut & Eroding Bog, Wet Grassland and Dry Grassland". "The map was produced using an expert rule based classifier and the land cover classes in combination with other thematic maps, including: subsoil maps Digital Elevation Model (DEM) derivatives and a derived line from the Ireland Peatland Map (Hammond, 1978) demarking the limit of lowland blanket bog." (Faely et al., 2009)

The LPIS class "Low input permanent pasture" includes areas that are permanent pastures extensively grazed and managed with low inputs and sustain a greater variety of plants and wildlife to promote a grassland management system that through appropriate grazing levels and restriction on fertiliser and pesticide use results in a more diverse sward with an increase in flora and fauna. This type of pasture should include a minimum of four grass species (excluding Ryegrasses), for example, cocksfoot, timothy, bent grasses, fescues, sweet vernal or Yorkshire fog and a minimum of three other non-grass plant species, for example, plantain, chickweed or trefoils which must be reasonably dispersed throughout the field. There must be less than 30% Ryegrass cover. Grass cannot be cut for hay or silage except, on an exceptional basis, between 1 September 2018 and 30 November 2018 inclusive. Parcels cannot be topped between the 15th of March and the 15th of July annually.

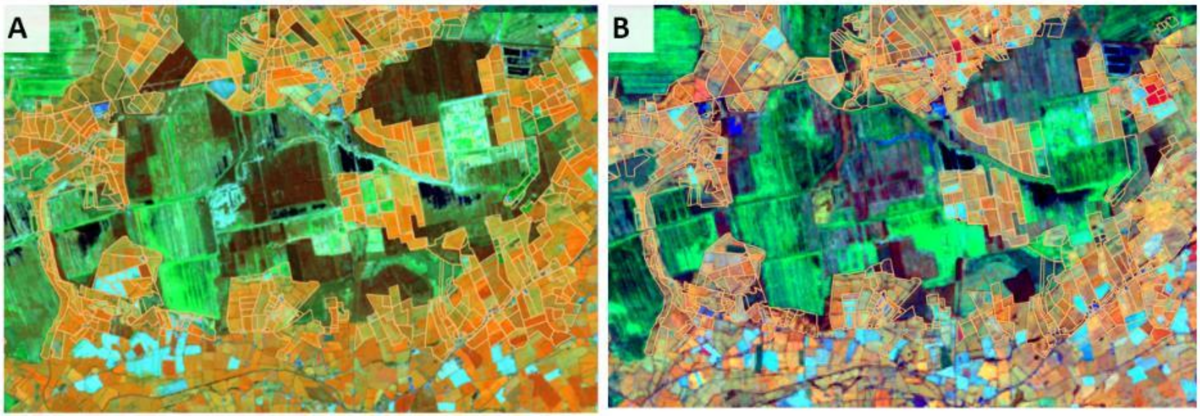
To evaluate the feasibility of discriminating managed grasslands on mineral and on organic soils, a sample of polygons within the LPIS class "Low input permanent pasture" on both organic and mineral soils was selected. Limited access to the LPIS data (area of interest of 13km x 18km) and rarity of the "Low input permanent pasture" crop class meant that only 56 LPIS reference parcels were selected. When the reference parcels included rows of trees or hedges (visual assessment based on VHR satellite imagery available in Google Maps) that could possibly influence the results of the statistics, these parcels were split or limited to cover relatively homogenous land cover. In the end, 22 polygons on mineral soils, 31 polygons on organic soils and 14 on mixed soils were available for analysis within the "Low input permanent pasture" crop class in the LPIS. To limit the influence of objects on the parcel borders and their shadows on the results of the statistics, a negative buffer of 10m was applied to the polygons.

Figure 28. Study area in Offaly, IE – A) overview of the area, cutover peat marked in yellow; B) polygons in mineral and organic soil and C) their land cover classes; D) example view to one of the polygons in organic soil.



Source: SEPLA, images: Google, 2023.

Figure 29. A) Area with cutover peat and bare peat in Offaly, as seen from Sentinel-2 in April 2021. The LPIS parcels enclosing the adjacent agricultural areas are shown in yellow. Colour infrared (NIR, SWIR1, RED). B) Same area as seen from Landsat TM in September 1998. Colour infrared (NIR, SWIR1, RED).

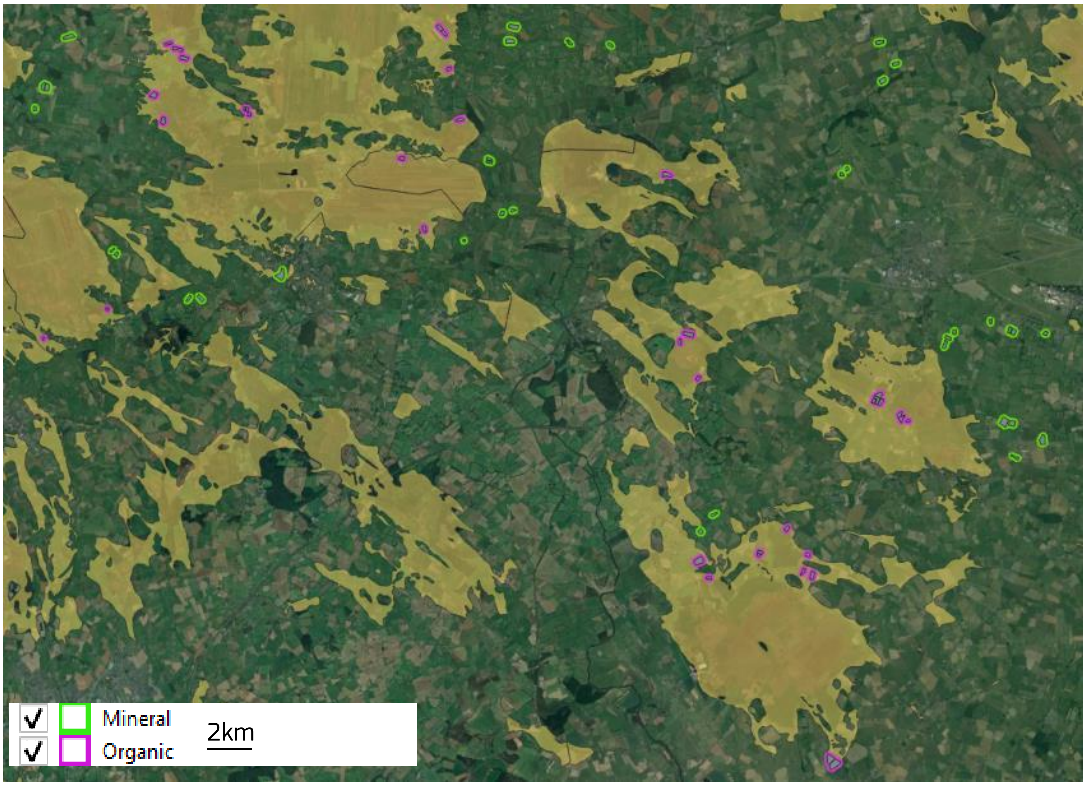


Source: Landsat, USGS and CREODIAS, CopernicusServices.

3.1.2 Kildare, Ireland – cutover peat

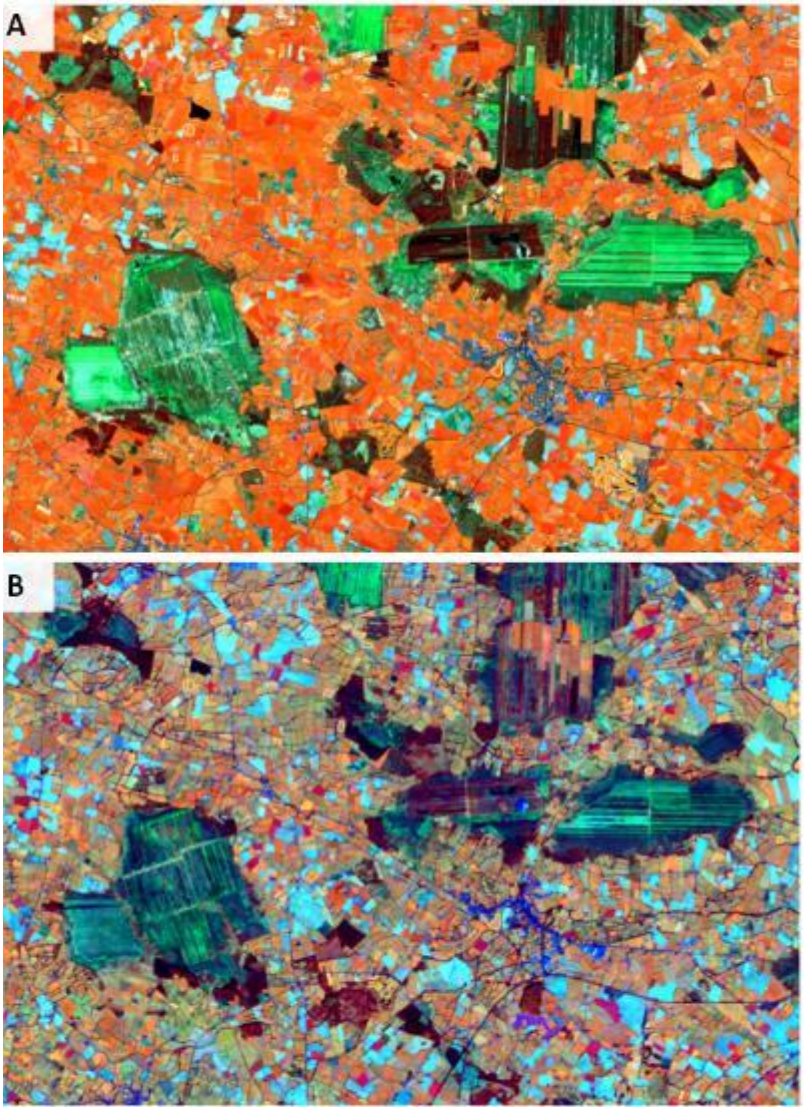
After more LPIS data were kindly made available to extend the analysis, an additional 37 polygons on organic and 37 polygons (cutover peat) on mineral soils were prepared, within the “Low input permanent pasture” crop class. They are located in the county of Kildare, between the Offaly and Wicklow sites. This time, the polygons were digitized from scratch to minimise the workload and the land cover heterogeneity and avoid unwanted features such as trees (and their shadows), hedges, ditches etc.

Figure 30. Study area in Kildare, IE – cutover peat marked in yellow.



Source: images: SEPLA and Google, 2023.

Figure 31. A) Area with cutover peat in Kildare, as seen from Sentinel-2 in April 2021. Colour infrared (NIR, SWIR1, RED). B) Same area seen from Landsat TM in February 1998. Colour infrared (NIR, SWIR1, RED).



Source: Landsat, USGS and CREODIAS, CopernicusServices.

3.1.3 Wicklow, Ireland – blanket bog

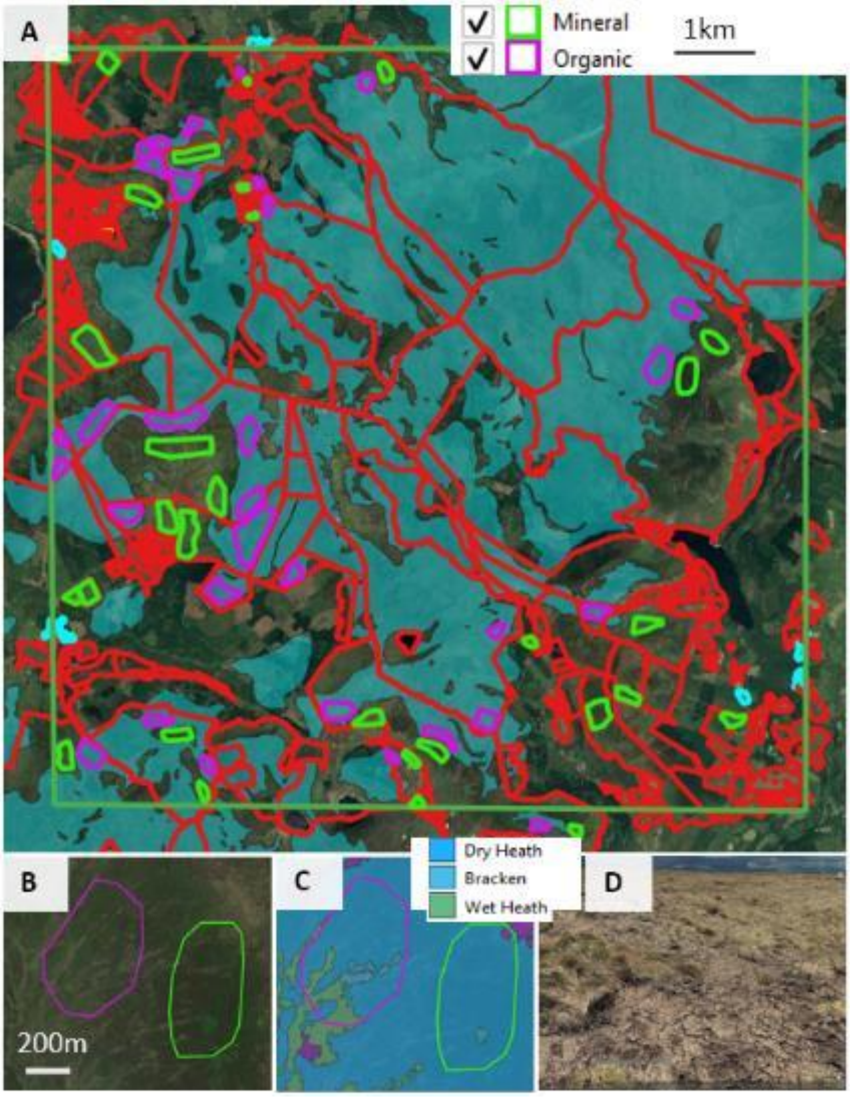
The study area in Wicklow (**Figure 32**) covers mountainous terrain, mostly in the Wicklow National Park (extent of the Special Areas of Conservation shown in **Figure 33**), with semi-natural vegetation used as pastures. Due to only 11 Low Input Permanent Pasture parcels covering solely mineral soils, the polygons were selected within the Permanent Pasture LPIS crop class (marked in red) covering areas with grassland and declared as grassland in the preceding five years or more. The land must be maintained in a state suitable for grazing or cultivation. The most common activity on parcels is grazing. Grass conservation (Silage & Hay), topping, fertiliser application, reseeding, spraying and controlled burning are other activities that take place in these parcels. Permanent grassland includes productive ryegrass-dominated swards, less productive swards that include rush and other non-grass herbaceous species and heather area which is grazable and where grass and herbaceous species are not predominant.

The organic soils are represented by blanket bogs (marked in turquoise) that are usually associated with highland areas where poor drainage enabled the build-up of oxygen-starved, partially decomposed biomass.

31 polygons covering mineral (**Figure 32**; marked in green) and 31 polygons (**Figure 32**; marked in purple) covering blanket bogs were selected for the mineral/organic soils discriminatory analysis based on visual assessment of the soil, slope, DEM, LPIS and the VHR satellite data available in Google Maps. Whenever possible, the polygons were selected in pairs, mineral and organic, in close vicinity to each other, and in areas with similar

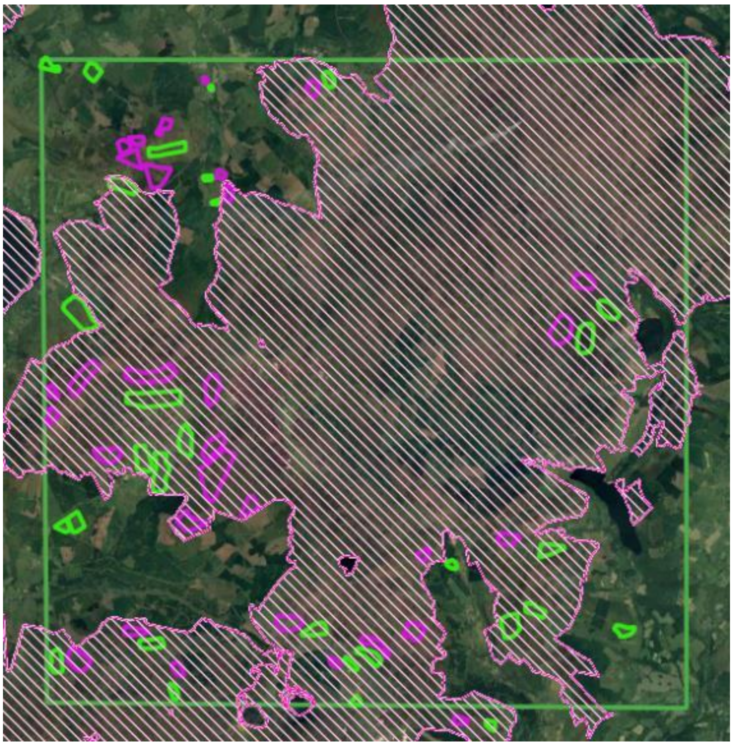
land cover and sloping conditions (the area of Wicklow is mountainous). 4 out of the 31 polygons representing Permanent Pasture on organic soils were selected outside of the LPIS parcel boundaries, ensuring the close vicinity to the pair polygon on mineral soils and the overlaying land cover (Ordnance Survey Ireland land cover data) classes corresponding to near-natural permanent grassland.

Figure 32. Study area in Wicklow, IE; A) overview of the area – blanket bog marked in turquoise, the LPIS parcels in red; B) examples of digitised polygons and C) the covering land cover classes; D) example view to the organic polygon.



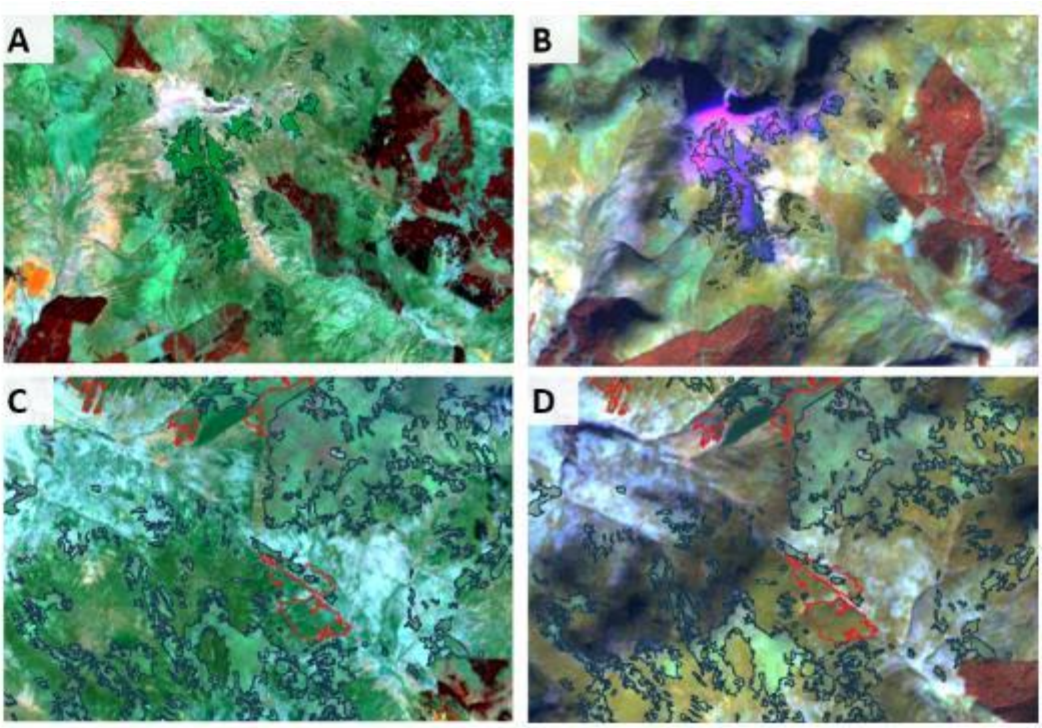
Source: images: SEPLA and Google, 2023.

Figure 33. Study area in Wicklow, IE. Extents of the Special Areas of Conservation are crosshatched in pink.



Source: images: Google, 2023, boundaries of the Special Area of Conservation: https://webservices.npws.ie

Figure 34. A) Area with bare peat in Wicklow, as seen from Sentinel-2 in April 2021. Bare Peat mapped in 2018 is shown in black outline. Colour infrared (NIR, SWIR1, RED). B) The same area seen from Landsat TM in February 1998. Colour infrared (NIR, SWIR1, RED). C) Area with cutover peat and blanket bog in Wicklow, as seen from Sentinel-2 in April 2021. Mapped cutover peat (shown in red outline) and blanket bog (in dark blue outline). Colour infrared (NIR, SWIR1, RED). D) The same area seen from Landsat TM in February 1998. Colour infrared (NIR, SWIR1, RED).



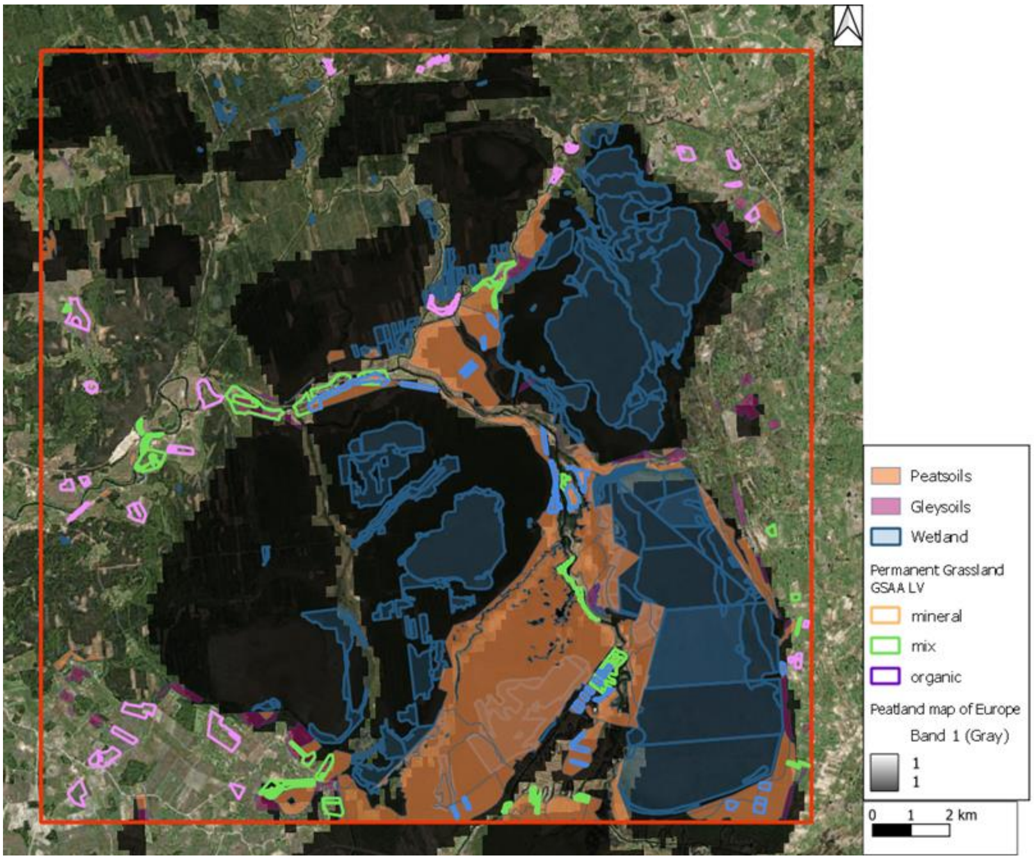
Source: Landsat, USGS and CREODIAS, CopernicusServices..

3.1.4 Lubāna mitrāju, Latvia – peat soils

The area analysed is limited to an area of interest of 20km x 20km situated nearby Lubāna mitrāju peatland and the selection of the parcels for the statistical analysis has been performed on Geospatial Aid Application (GSAA) parcels declared in 2021 as Permanent grasslands. 90 parcels were selected: 30 of them on organic soils, 30 on mineral soils and 30 with the presence of both soil types, as shown in the figure below. The polygons on mineral soils have been selected to ensure there is no overlap with the Peatland Map of Europe (Tanneberger et al., 2017), while the polygons on organic soils have been selected within the peat soils class of soil data provided by the Latvian National Nature Conservation Agency as part of the "E2SOILAGRI" project. The peat soils class contains a peat layer of at least 40 cm thick. The GSAA origin implies that agricultural activity occurs.

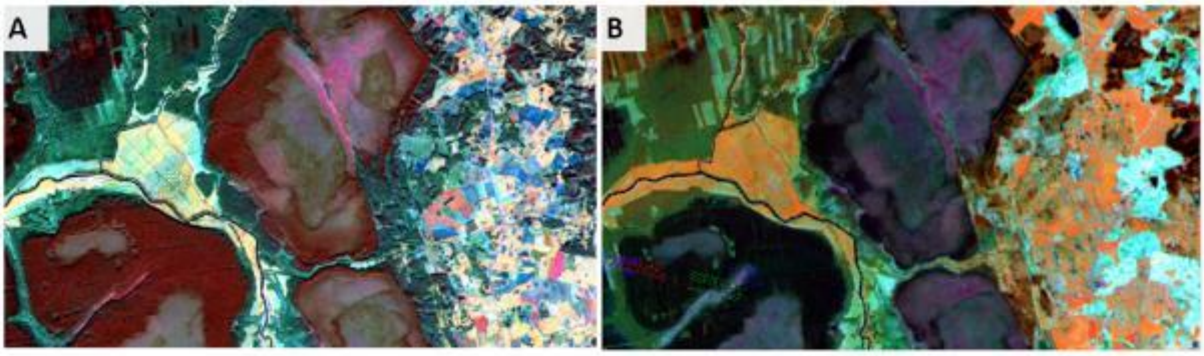
This site was also used in a test using image segmentation methods to capture and update the extent of the natural bogs.

Figure 35. Study area in Latvia.



Source: SEPLA.

Figure 36. A) Bogs in the Latvian test site as seen from Sentinel-2 on 31.10.2021. B) Same area as seen from Landsat TM on 16.05.1988

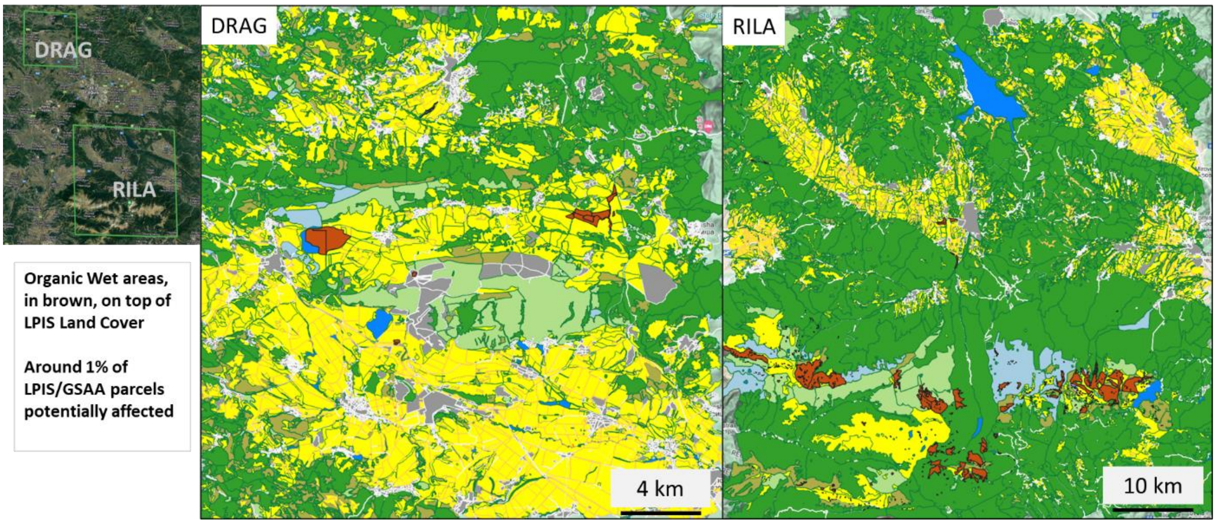


Source: Landsat, USGS and CREODIAS, CopernicusServices..

3.1.5 Dragoman Marsh and Rila, Bulgaria – Transitional Mires and Quaking Bogs

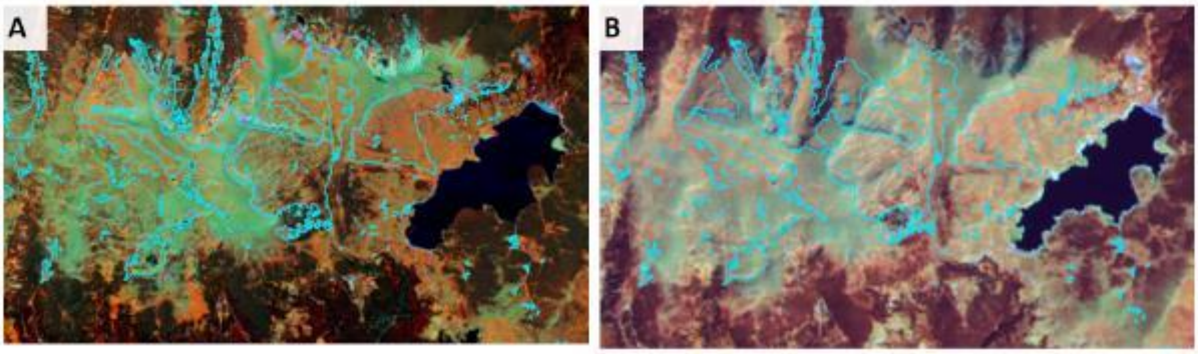
Two sites have been selected in Bulgaria, DRAG in the Sofia plain measuring 25km x 25km and RILA in the mountain range south of the city, measuring 50km X 50km. They have been selected for the different types of peatlands occurring in the sites, their distinct topography, hydrology, and climate and because the entire area has been already studied in a previous JRC project on a similar subject (Ivanova-Stoyanova and Stoeva, 2021). As in all Bulgaria, the region has limited, but well clustered wetlands on histosols, most of which are part of the vast network of N2000 sites in the country. In the DRAG site, the focus was on the "Dragoman Marsh", which is in a state of advanced restoration for the last 30 years. A simplified monitoring scenario was developed to illustrate the detection and monitoring of local natural disturbances, as fires, and their impact on the peatland conditions (see section 2.1.3). In the RILA site, the focus was on the peatlands located in the sub-alpine and alpine belt of Rila Mountain, which are used for extensive grazing. They were part of the testing of the data integration methodology (involving soil, wetland and IACS parcel data), for the compilation of the IPCC sub-categories on wetlands for the purpose of the LULUCF reporting (Milenov et al., 2023).

Figure 37. Satellite image and land cover maps of the Drag and Rila sites



Source: SEPLA.

Figure 38. A) Alpine peatlands in the RILA test site as seen from Sentinel-2 on 17.07.2021. B) The same area seen from Landsat TM on 02.09.1992.

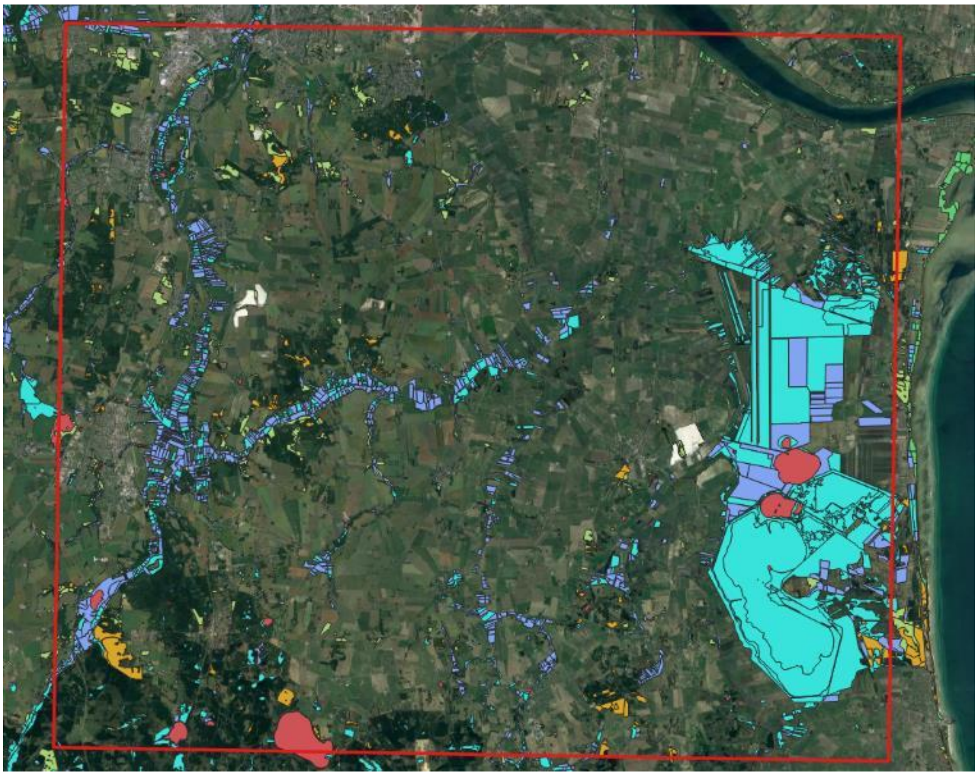


Source: Landsat, USGS and CREODIAS, CopernicusServices.

3.1.6 Lille Vildmose, Denmark – raised bog

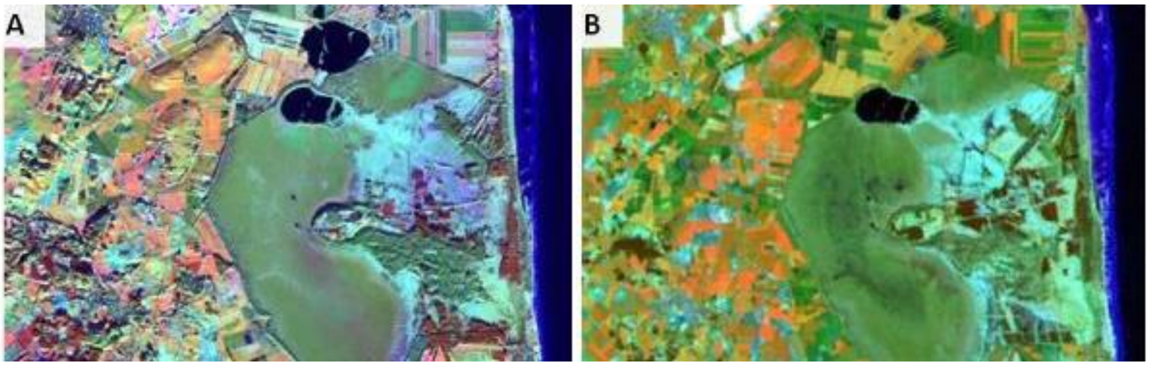
The Danish test site is located in Lille Vildmose, which is a large wetland complex situated in the north-eastern part of Jutland, Denmark. It covers an extensive area of peatlands, forests, and open water. Lille Vildmose is renowned for its extensive peat deposits, which have formed over thousands of years. Peat soil, rich in organic matter, dominates the landscape. The peat accumulates in waterlogged conditions, creating a unique and valuable habitat for specialized plant species. The site was used for the testing of the data integration methodology, based on the detailed measurement data on soil organic carbon and ground water table level, for the compilation of the IPCC sub-categories on wetlands for the purpose of the LULUCF reporting (Milenov et al., 2023). In addition, it was also used in a test of using the image segmentation method to capture and update the extent of the natural bogs.

Figure 39. Study areas in Denmark.



Source: SEPLA, image: Google, 2023.

Figure 40. Left: Raised bog in the Danish test site as seen from Sentinel-2 on 20.12.2021. Right: As seen from Landsat TM on 05.06.1991.



Source: Landsat, USGS and CREODIAS, CopernicusServices.

3.2 Discrimination between managed grasslands on organic and mineral soils

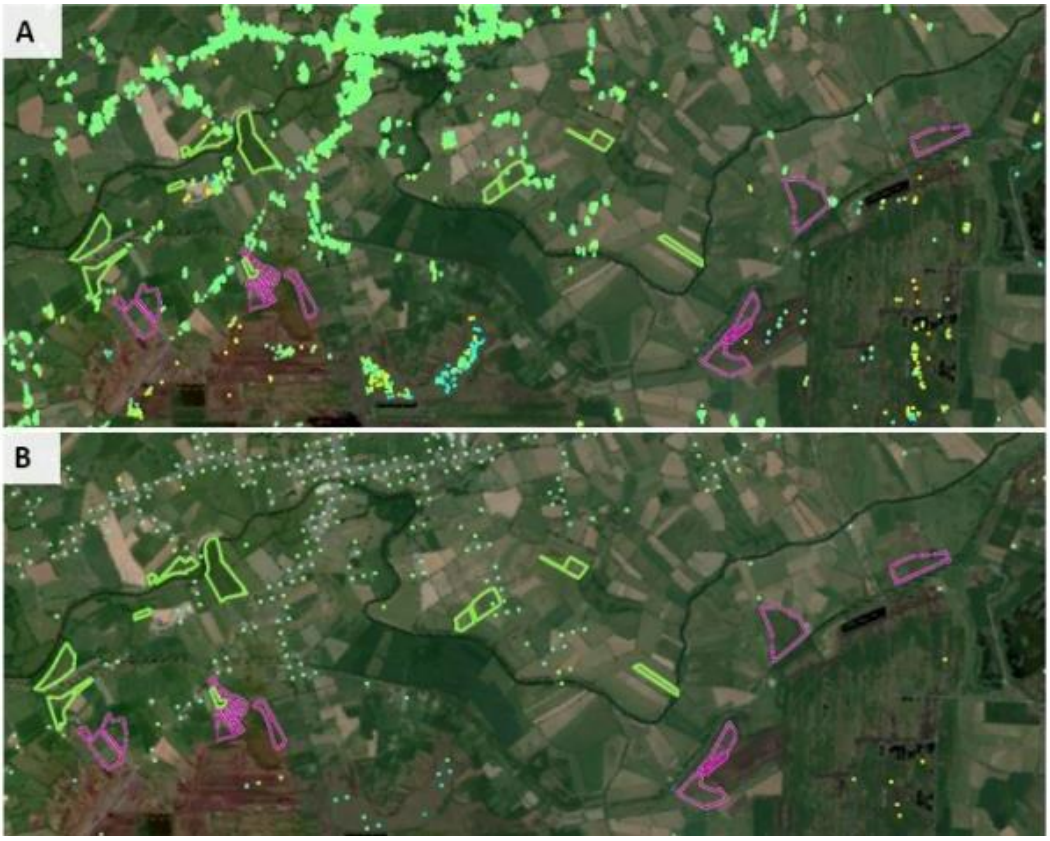
Ongoing national scale surveys aim to provide high-quality up-to-date soil maps that include classes relevant to peatlands, but such data sets are often not yet available. The national experts actively participating in the project expressed a demand for remote sensing solutions that discriminate between agricultural areas on mineral and organic soils. In response, the team explored the potential of several methods and Copernicus based datasets.

3.2.1 The European Ground Motion Service

The Product User Manual of the European Ground Motion Service (Kotzerke et al., 2022), states that the service is not meant to provide data relevant to grasslands. Nevertheless, the availability of the inSAR measurement points (persistent scatters) was evaluated for the polygons representing managed grasslands on organic and mineral soils.

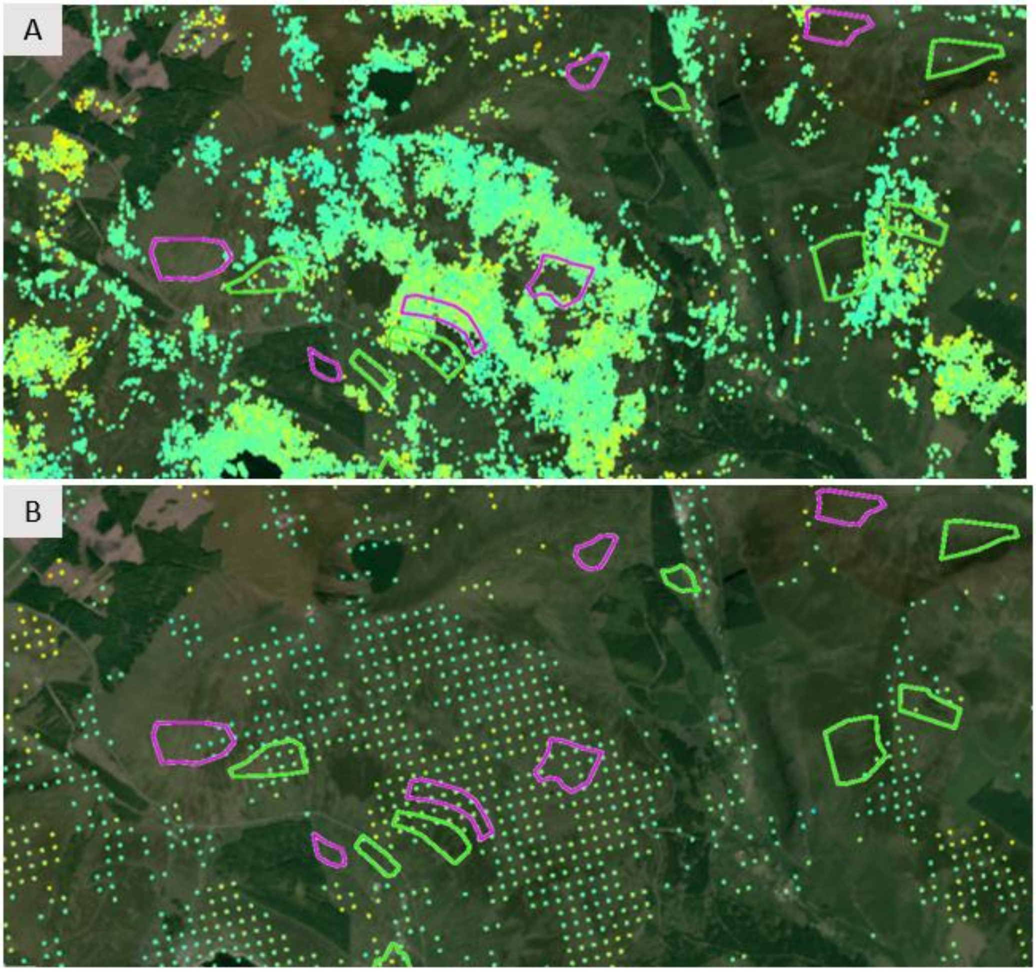
The availability of the EGMS measurement points was explored in the study areas of Offaly (Figure 41) and Wicklow in Ireland (Figure 42).

Figure 41. Example of the European Ground Motion data in Offaly, IE. A) measurement points with the ground motion data expressed relative to the satellite line of sight (Calibrated, Level 2B); B) 100m x 100m grid of ground motion data interpolated based on the calibrated product and representing the vertical ground displacement (Ortho, Level 3). Low input permanent pastures on organic soils are marked in purple, on mineral soils – in green.



Source: SEPLA and EGMS data viewer.

Figure 42. Example of the European Ground Motion data in Wicklow, IE. A) measurement points with the ground motion data expressed relative to the satellite line of sight (Calibrated, Level 2B); B) 100m x 100m grid of ground motion data interpolated based on the calibrated product and representing the vertical ground displacement (Ortho, Level 3). Permanent pastures on organic soils are marked in purple, on mineral soils – in green.



Source: SEPLA and EGMS data viewer.

Not surprisingly, very few surface motion measurement points were available for the managed agricultural landscape and in managed grasslands in Offaly (see Figure 41). In the study area in Wicklow, covered by more stable near-natural vegetation, i.e. wet and dry heath or sedges, more surface motion points were available in the EGMS (), but still in insufficient quantities to allow for an in-depth analysis and a comparison between polygons in mineral and organic soils.

3.2.2 Copernicus Vegetation Phenology and Productivity indices

To assess whether the yearly Vegetation Phenology and Productivity parameters offer a reliable source of information to discriminate between managed grasslands in mineral and organic soils, the mean values of the 13 VPPs were derived from the raster data and compared for samples of polygons selected in four study areas (3 in Ireland and one in Latvia).

3.2.2.1 Study area

The study areas used in this test were:

- Offaly, Ireland – polygons within Low Input Permanent Pastures with no mowing allowed – in mineral and organic soils (cutover peat soil class);
- Kildare, Ireland – polygons within Low Input Permanent Pastures with no mowing allowed – in mineral and organic soils (cutover peat soil class);

- Wicklow, Ireland – polygons within Permanent Pastures and covered with semi-natural vegetation – in mineral and organic soils (blanket bog soil class);
- Lubāna mitrāju, Latvia – polygons within Permanent Pastures and covered with semi-natural vegetation – in mineral and organic soils (peat soil class).

More details about the samples and study areas can be found in section 3.1.

3.2.2.2 Data and software used

All the raster data representing the Vegetation Phenology and Productivity parameters were downloaded (13 geotiff raster files per year) from the www.wekeo.eu platform. The VVP products from the years 2017-2021 were available and all were used in this assessment (resulting in 13 x 5 = 56 raster files processed for every study site). Six zonal statistics were computed for the polygons on mineral and organic soils using QGIS software: the number of pixels in the polygon, mean, median, standard deviation, minimal and maximal value.

3.2.2.3 Data preparation and processing

For every VPP parameter (13 in total) in every studied year, the mean values of pixels within the selected polygons on mineral and organic soils were evaluated and compared. The samples (on mineral and on organic soils) were tested whether they follow the normal distribution. The goodness of fit was evaluated using Shapiro-Wilk and Anderson-Darling tests. The variances of samples representing polygons on mineral and organic soils in each year were evaluated to conclude if they are equal using 'Brien [.5], Brown-Forsythe, Levene, Barlett and 2-sided F tests.

- In the case of samples having equal variance and normal distribution, sample means were compared with a pooled T test.
- With unequal variance and normal sample distribution, the unequal variance (Welch) T test was used to estimate if the samples were different statistically.
- With equal variance and NOT normal sample distribution the Mann-Whitney test was used to evaluate if the samples were significantly different.
- With NOT equal variance and NOT normal sample distribution, the Mann-Whitney test was used to evaluate if the difference was significant.
- All analyses are performed using JMP Statistical Discovery from SAS.

3.2.2.4 Analysis of results

An example of the performed assessment is given below using the analysis of the day of the start-of-season (SOSD) for the polygons in Offaly, Ireland.

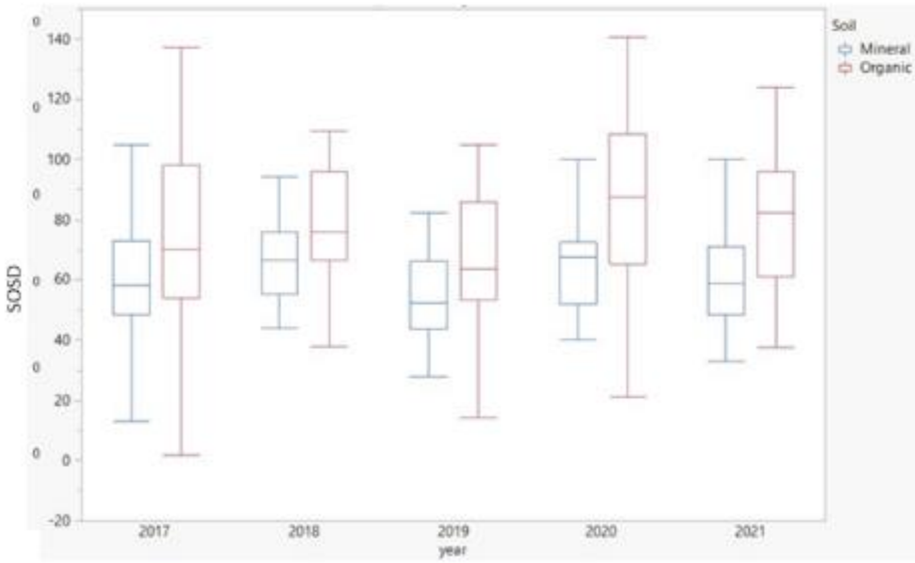
The means of the day of the start-of-season values were computed for all polygons and a comparison was made between the results for polygons on mineral and organic soils for every year separately. In all mineral and organic samples in all years, samples did follow the normal distributions, except in 2020 on mineral soils. The variances of mineral and organic samples were equal except in 2020. These (see details in section 3.2.2.3) comparisons of the sample means (95% confidence interval) indicate a significant difference between SOSD values on mineral and organic soil in all the years. The sample means and their standard deviations are reported in **Table 4** and plotted in **Figure 43**.

Table 4. The day (of the year) of the start-of-season for polygons on mineral and organic soils in Offaly, Ireland for the years 2017-2021.

SOSD	Organic		Mineral		SOSD mean difference
	Mean	Std dev	Mean	Std dev	
2017	74.3	31.2	55.9	25.0	18.4
2018	79.8	17.9	68.7	16.8	11.1
2019	67.2	21.7	52.8	18.8	14.4
2020	86.7	27.1	67.4	18.8	19.3
2021	78.7	22.6	60.6	16.7	18.1
average	77.3		61.1		16.3

Source: SEPLA.

Figure 43. The day of start-of-season for polygons on mineral and organic soils in Offaly, Ireland for years 2017-2021.



Source: SEPLA.

The day of the start-of-season values are larger for parcels on organic soils, indicating the vegetation season starts on average 16 days later in the year than on the mineral soils.

Analogous analyses were performed for all the VPP parameters in all 4 study sites. Details of the analysis can be found in the project repository. Below a summary of the results is provided.

3.2.2.5 Summary and discussion of the results

The results of the analysis are summarised in **Table 5**. The persistence of the differences between the means of parameters for the samples on mineral and organic soils is reported by indicating the number of years in which the difference was statistically significant. The index trends are also reported by the arrows, with the arrow pointing up to indicate a higher mean index value, and the arrow pointing down to indicate lower index values.

The VPP indices with the most persistent differences in mean values on mineral and organic soils in all 4 study sites were (marked in green in **Table 5**):

— Average vegetation index of minima on the left and right sides of each season (MINV), with persistently higher mean Plant Phenology Index (PPI) values for the polygons on mineral soils in all the years in all the study sites, except for 2 years in Wicklow, Ireland, when the difference was statistically not significant.

— Total productivity (TPROD) with persistently higher productivity values for the polygons on mineral soils in all the years in all the study sites, except for 2 years in Offaly, Ireland, when the difference was statistically not significant.

— Seasonal productivity (SPROD) with persistently higher productivity values for the polygons on mineral soils in all the years in all the study sites, except for 2 years for Offaly, Ireland and one year for Latvia, when the difference was statistically not significant.

Other VPP providing persistent results in most of the study areas are (marked in orange in **Table 5**):

— Vegetation index at the day of the start-of-season (SOSV), with persistently higher mean PPI values for the polygons on mineral soils in all the years in the three study sites in Ireland, except for one year in Offaly, when the difference was statistically not significant.

— Vegetation index at the day of the end-of-season (EOSV) with persistently higher mean PPI values for the polygons on mineral soils in all the years in the three study sites in Ireland, except for one year in Offaly, when the difference was statistically not significant.

— Day of the start-of-season (SOSD) with persistently higher values for the polygons on organic soils in all the years in the study sites in Offaly, Kildare and Latvia, except for 2 years in Kildare, when the difference was statistically not significant.

Table 5. Summary of differences significance and trends in all the analysed VPP indices in four test sites. The most persistent results in all the sites are marked in green (at least 3 years with significant differences in every site). The most persistent results in a majority of the sites are marked in orange at least 3 years with significant differences in 3 sites.

VPP parameter	Offaly (cutover peat)			Kildare (cutover peat)			Wicklow (blanket bog)			Lubāna mitrāju, Latvia		
	Years with a significant difference	Mineral	Organic	Years with a significant difference	Mineral	Organic	Years with a significant difference	Mineral	Organic	Years with a significant difference	Mineral	Organic
SOSD	5/5	↓	↑	3/5	↓	↑	0/5	-	-	5\5	↓	↑
SOSV	4/5	↑	↓	5/5	↑	↓	5/5	↑	↓	1\5	↑	↓
EOSD	2/5	↑	↓	0/5	-	-	0/5	-	-	2\5	↑	↓
EOSV	4/5	↑	↓	5/5	↑	↓	5/5	↑	↓	0\5	-	-
MAXD	2/5	↓	↑	2/5	↓	↑	1/5	↓	↑	1\5	↓	↑
MAXV	2/5	↑	↓	5/5	↑	↓	4/5	↑	↓	0\5	-	-
MINV	5/5	↑	↓	5/5	↑	↓	3/5	↑	↓	5\5	↑	↓
AMPL	2/5	↑	↓	5/5	↑	↓	3/5	↑	↓	0\5	↓	↑
LSLOPE	0/5	-	-	2/5	↑	↓	2/5	↑	↓	3\5	↓	↑
RSLOPE	0/5	-	-	2/5	↑	↓	0/5	-	-	3\5	↓	↑
SPROD	3/5	↑	↓	5/5	↑	↓	5/5	↑	↓	4\5	↑	↓
TPROD	3/5	↑	↓	5/5	↑	↓	5/5	↑	↓	5\5	↑	↓
LENGTH	4/5	↑	↓	3/5	↑	↓	1/5	↑	↓	3\5	↑	↓

Source: SEPLA.

The vegetation season starting (SOSD) earlier for polygons on mineral soils may be linked with the lower water content of these soils (when compared to wetter organic soils), requiring a shorter time to get warmer after the winter and to get into conditions optimal for the vegetation to start. The natural vegetation native to saturated organic soils is often manifested with very low values vegetation index values (Pakalne et al. 2021) throughout the season. This is expressed also in the results summarised above, with the average vegetation index of minima on the left and right sides of each season (MINV), the index values at the start (SOSV) and the end of the season

(EOSV), seasonal (SPROD) and total productivity (TPROD) reaching higher values on mineral soils and lower on organic soils.

Although the results summarised above seem consistent, logical and encouraging, one should keep in mind that in these grasslands, grazing, and in some study areas also mowing, is allowed and sometimes even required. The intensity of these activities may undoubtedly influence the values of vegetation indices representing the state and amount of biomass on the ground. Although the samples of polygons on organic and mineral soils were selected within one declared land use type with a specific maintenance regime, the management intensity at the parcel level was not verified.

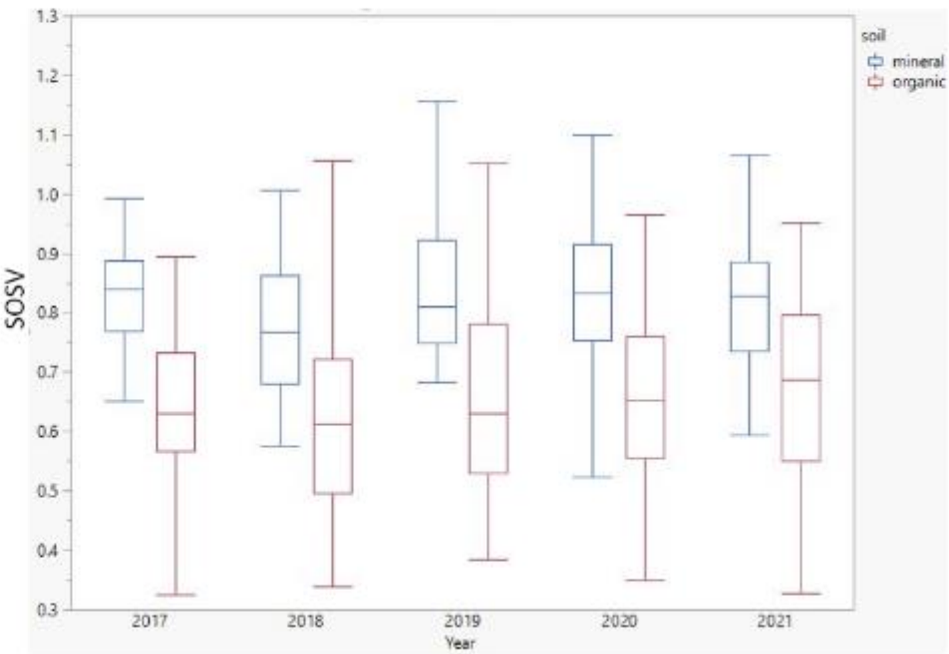
The differences in results obtained in the various study sites are most probably linked with different land cover types ranging from managed (relatively homogeneous) grasslands in Offaly and Kildare, through more heterogeneous and semi-natural vegetation in Wicklow and ending with a mix of both in the polygons selected in the study site in Latvia.

3.2.2.6 Pragmatic use case: k-nearest neighbours analysis

Although for several VPPs the differences between means of samples on mineral and organic soils were statistically significant, the difference in the actual index values may be too small to reliably adjudicate the soil class within the underlying parcel population. To evaluate the usefulness of the VPP indices to discriminate between grasslands on mineral and organic soils, the k-nearest neighbour classification analyses were performed.

In the study area of Kildare the results of the analysis reported above were carefully evaluated and a parameter with the largest difference in the mean values and the smallest overlap between the mineral and organic sample confidence intervals was selected, namely the vegetation index at the start-of-season.

Figure 44. The vegetation index [PPI] on the day of start-of-season for polygons on mineral and organic soils in Kildare, Ireland for years 2017-2021.



Source: SEPLA.

For every polygon X in the study area of Kildare the average value of the SOSV index was recorded (v) with the intention to assign it to the mineral or organic class based on the following procedure:

- Within the sample K-nearest neighbouring polygons on mineral and K-nearest neighbouring polygons on organic soils were selected.
- Average values of the SOSV index were computed for all polygons in the mineral (m) and organic (o) sets.

— Polygon X was assigned to the class (mineral or organic) for which the mean absolute value ((m) or (o) respectively) was the closest to the mean value (v) of the polygon.

This procedure was repeated for all 74 polygons in Kildare. The correctness of the assigned classes for the vegetation index at the start of the season (SOSV) depending on k-nearest neighbours is reported in the table below.

Table 6. The correctness of the assigned classes (mineral, organic) for the vegetation index at the start or season (SOSV) for 5 years in Kildare, depending on the number of k-nearest neighbours.

SOSV	k=5	k=10	k=15	k20	average
2017	0.74	0.77	0.77	0.80	0.77
2018	0.70	0.72	0.76	0.73	0.73
2019	0.76	0.68	0.74	0.69	0.72
2020	0.66	0.70	0.76	0.73	0.71
2021	0.65	0.65	0.65	0.62	0.64
average	0.70	0.70	0.74	0.71	

Source: SEPLA.

These results, considering the simplicity of used algorithms, availability of the VPP data, and relatively low workload required to run similar analyses, are encouraging. There seems to be no effect of increasing the number of neighbours. This may be linked to the fact that the entire Kildare study site is relatively small (35km x 23km) and in such short distances the ecosystem conditions are not changing enough to influence the results. It is interesting that t method correctness decreases with time, i.e. the results obtained using the data from 2017 are on average 13% more correct than the ones obtained using data from 2021. This could be linked to the varying VPP data quality, relying on the number of cloudless Sentinel-2 observations every year, or arguably, with the progressive drying out of the grassland on organic soils and the transition of its vegetation towards that covering mineral soils

3.2.3 Sentinel-1 and Sentinel-2 time series analysis

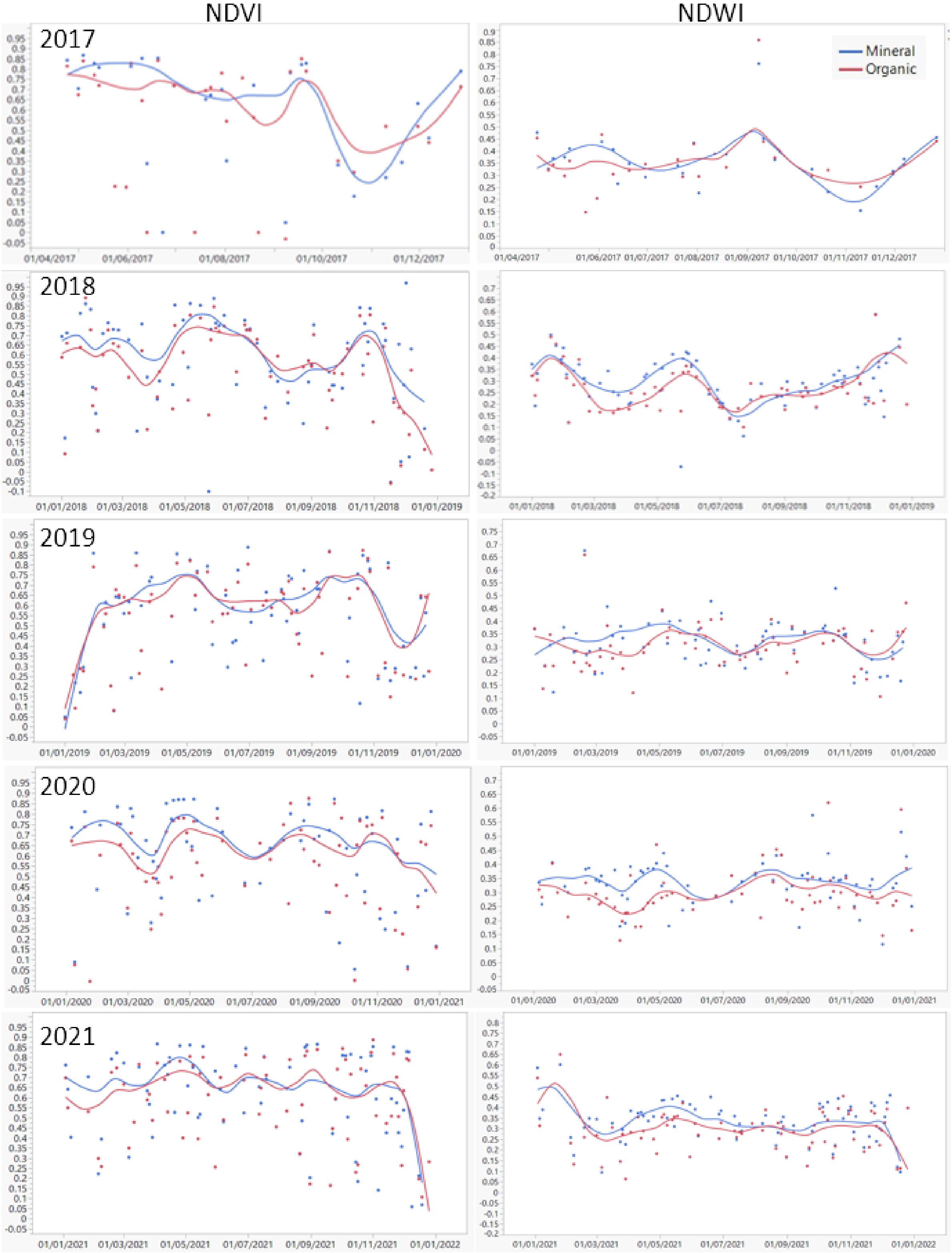
3.2.3.1 NDVI and NDWI

The time series of Normalized Difference Vegetation Index and Normalized Difference Water Index values were derived from Sentinel-2 data using Google Earth Engine (Gorelick et al., 2017) for the years 2017-2021 for the sites in Offaly, Wicklow, Dragoman and Lubāna mitrāju. The following reports on the analysis in Offaly and Wicklow.

The NDVI index measures the difference between the reflectance of near-infrared (NIR) and red light to assess vegetation type, state and density. The NDWI index is measuring the difference in reflectance between near-infrared (NIR) and shortwave-infrared (SWIR) bands. It is an indicator of the water content in the observed biotic substance. Wetland and peatland vegetation often have distinctive spectral characteristics (Pakalne et al., 2021), but it may not necessarily be the case for managed grasslands on organic soils.

Figure 45 and **Figure 47** present trends in the NDVI and NDWI values in study sites in Offaly and Wicklow. The points in the plots represent the mean index value for all the polygons in the sample of polygons on organic and mineral soils. The lines express the trends and are shown to facilitate the interpretation of the results. Although the indices' behaviour varies from one year to another, some general observations can be made. In the Offaly test site, which covers managed grasslands, where grazing is allowed but mowing is banned, the NDVI and NDWI indices show very similar values for grasslands on organic and mineral soils during most of the year. A separation between the index values for the polygons in mineral and those in organic soils is observable in the first months of the vegetation season, i.e. between the beginning of March and mid-April in most years. This is consistent with the analysis of the VPP indices values showing the vegetation season starting later (one-two weeks) on organic than on mineral soils.

Figure 45. Average daily NDVI and NDWI values for polygons in mineral (in blue) and organic (in red) soils in Offaly. Indices computed based on Sentinel-2 data with cloud cover <=20%.



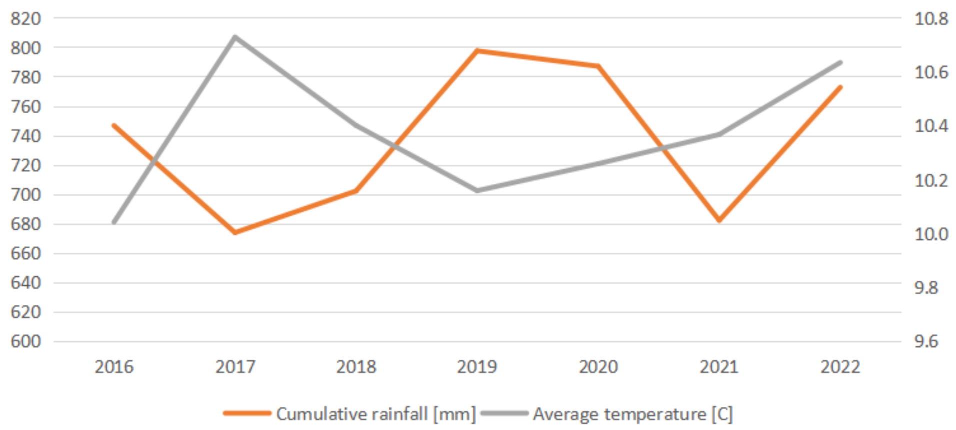
Source: SEPLA.

The seasonal changes of the NDVI and their amplitude vary from one year to another. The patterns are strongly influenced by the intensity of grazing which was not a part of this case study. The occasional very low NDVI values in the winter months are caused by either snow cover or, outside of the winter season, by residual clouds and cloud shadows. The NDWI plots present a more regular pattern between the years, with an effect of the summer and higher plant water stress visible in all the years except 2021. The mean NDWI values for polygons on organic soils seem to have lower NDWI values for most of the year, indicating a drier vegetation state than in the polygons on mineral soils.

In the study site in Wicklow, the analysed polygons are covered by semi-natural grassland in mountainous areas, where the management intensity is much lower than in Offaly. The vegetation is dominated by dry and wet heath, sedges and grasses. The indices patterns are much more stable and repeatable between the years (despite similar weather trends in both study sites – compare **Figure 46** and **Figure 48**) and throughout the vegetation season. The average NDVI values in Wicklow are smaller than the ones in Offaly. Blanket bogs dominated by sedges, heath and mosses exhibit only small changes in vegetation throughout the year. Mosses do not die back during winter and have the ability to grow all year-round. Heather (e.g. Calluna vulgaris) and cotton grasses also do not die back during winter. They turn from green to rusty brown, with deergrass eventually dying back by late winter.

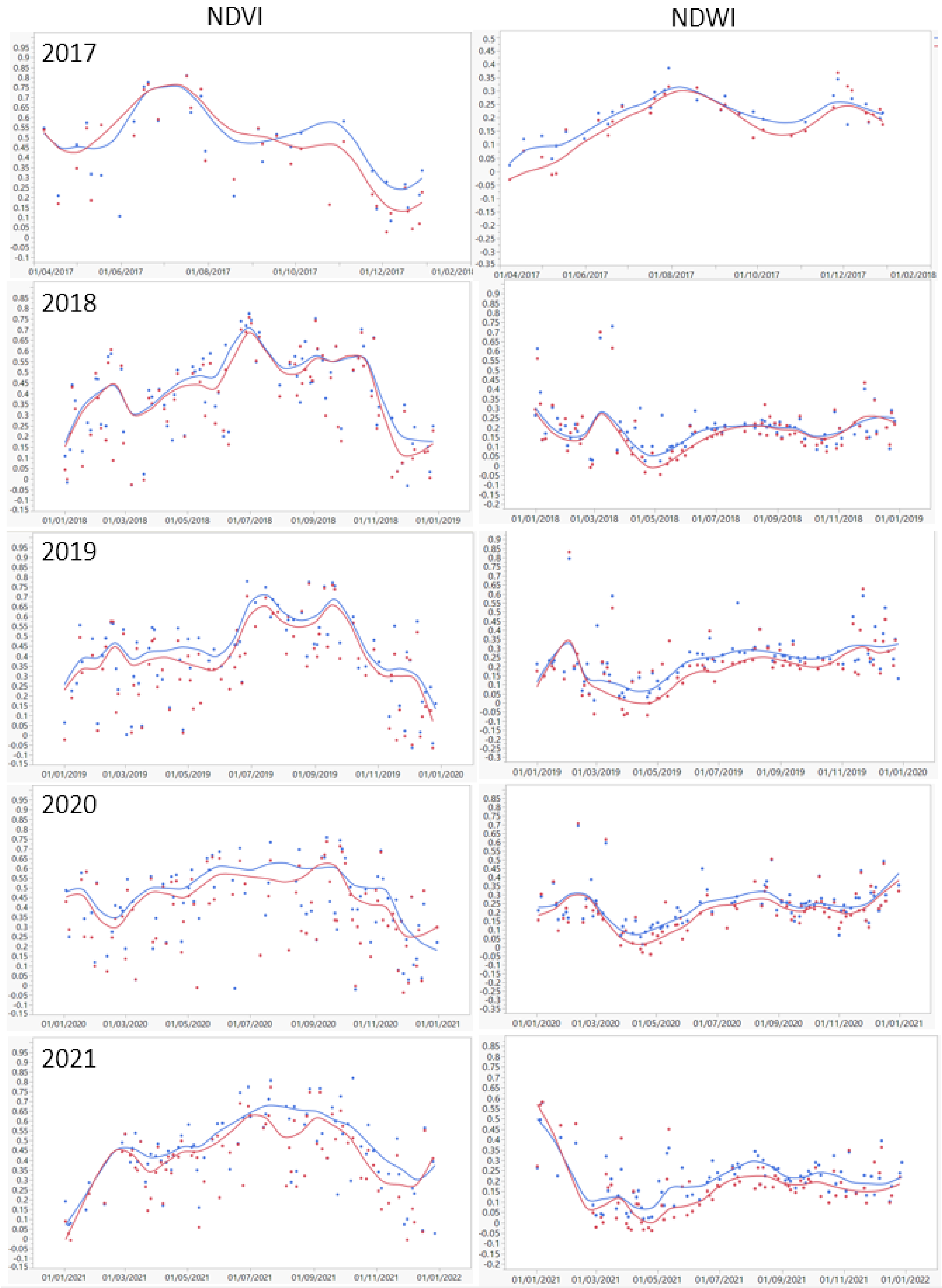
The polygons on organic soils have slightly lower mean values of the NDVI and NDWI than the ones on mineral soils. This is consistent with observations in other studies, e.g. (Pakalne et al., 2021) where the restoration of Suursoo-Leidissoo peatland in Estonia is documented (among other restoration examples). Authors, having access to the ground data from the restoration site (not the case of the SEPLA project), concluded that: "Lower NDVI value indicates more natural and valuable communities, while higher NDVI value reflects lower naturalness and stronger impact of drainage" (Pakalne et al., 2021). This is because the plant growth and the amount of green biomass in natural mires are limited by the high water table levels. In drained/degraded organic soils aeration is better and therefore the total biomass and the vascular vegetation cover are higher. The delay in the start of the vegetation season on organic soils observed in the site in Offaly is not visible in Wicklow. This is also consistent with the results of VPP indices analysis indicating no significant differences in the day of the start of the season (SOSD) values.

Figure 46. Yearly rainfall (left axis in mm) and temperatures (right axis in degrees Celsius) at the Oak Park Station (50km away from the Offaly study site).



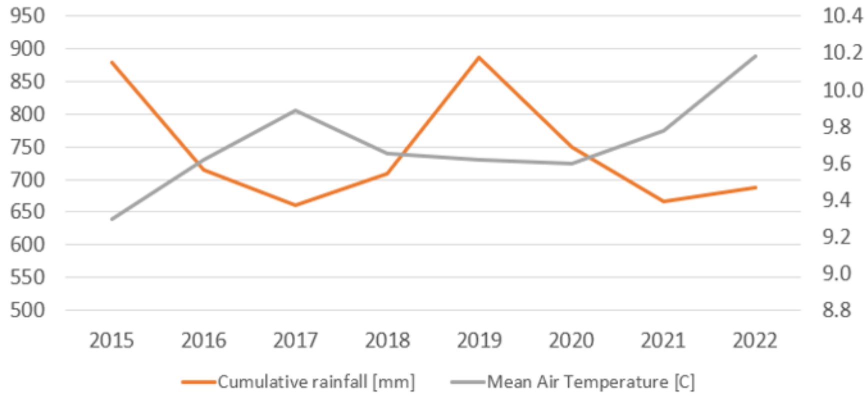
Source: SEPLA based on data from www.met.ie

Figure 47. Average daily NDVI and NDWI values for polygons in mineral (in blue) and organic (in red) soils in Wicklow. Indices computed based on Sentinel-2 data with cloud cover <=20%.



Source: SEPLA.

Figure 48. Yearly rainfall (left axis in mm) and temperatures (right axis in degrees Celsius) at the Dublin Airport Station (30km away from the Wicklow study site).



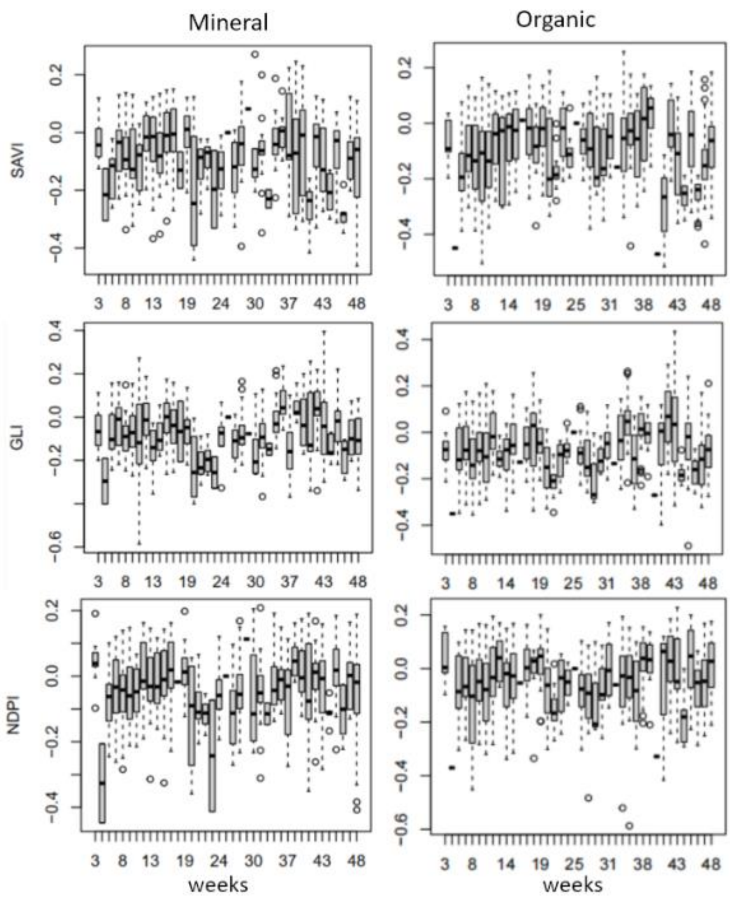
Source: SEPLA based on data from www.met.ie

3.2.3.2 Other indices on organic and mineral soils

The methods (Zielinski et al., 2022) and tools (SALMS R package) developed in the Checks by Monitoring Outreach project were used to derive and analyse time series of raw Sentinel-2 bands and 13 vegetation, soil and water indices for the study area in Offaly in the year 2021. This exploratory test aimed at finding a candidate discriminating index that could be further tested in a longer time span and in more sites. in **Figure 49** are the results obtained for the samples in mineral and organic soils; they were very close to each other, similar to the case of the multiannual NDVI and NDWI analysis results presented in the section above. The correlation of p50 (median) values for the raw Sentinel-2 bands and the derived indices was computed separately for the samples polygons in mineral and organic and is presented in **Figure 50**.

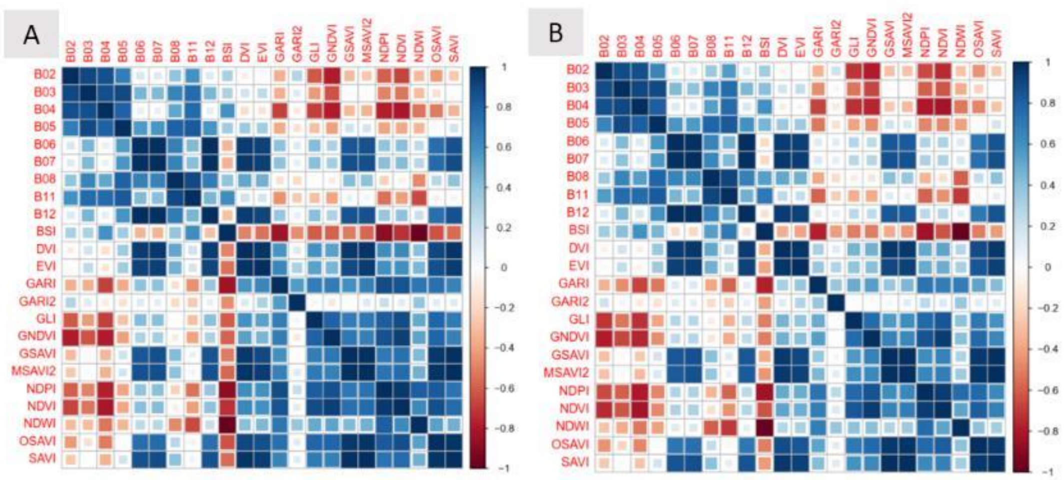
As expected, figures A and B are very similar, with very small differences in correlation for very few indices. Nonetheless, such analysis may be useful for providing priority for further testing of the indices, e.g. when looking for candidate signals for new markers in the land monitoring system. For example, considering the very high correlation between the NDVI, Bands B02, B03, B04, GNDVI and NDPI indices, a priority for further testing could be given for only one of them.

Figure 49. Example of the soil-adjusted vegetation index (SAVI), green leaf index (GLI) and the normalised differential phenology index (NDPI) values for polygons on mineral and organic soils in Offaly, Ireland. Indices derived from Sentinel-2 data covering the entire year 2021.



Source: SEPLA and [SALMS R package.]()

Figure 50. Correlation of p50 (median) values for all cloudless Sentinel-2 observations in 2021 in Offaly, Ireland, for the polygons within low input permanent grasslands located on A) organic and B) mineral soils.



Source: SEPLA and [SALMS R package.]()

As the evaluated indices didn't hold a good discriminator candidate for more extensive testing, this exploratory testing had no follow-up.

3.2.3.3 Sentinel-1 backscatter

The time series of Sentinel-1 backscatter values were derived using Google Earth Engine (Gorelick et al., 2017) for the years 2017-2021 for the sites in Offaly, Wicklow, Kildare and Lubāna mitrāju.

As mentioned above, the in-depth radar analysis of the peatland hydrology is very complex and challenging even with ground data on the ground water table level available (which is not the case of this project) (Toca et al., 2023). What follows is an interpretation of the data from Wicklow is presented, analogue to the result discussion presented in (Mueller et al., 2022) and in (Toca et al., 2023).

The data for all polygons in mineral and organic soils in Wicklow were derived from 591 Sentinel-1 images captured from a single orbit with values from both vertical–vertical (VV) and vertical–horizontal (VH) polarization. The data were split into ascending and descending orbit datasets (**Figure 51**).

According to literature (Toca et al., 2023 and Mueller et al., 2022), data from an ascending orbit is the most appropriate for wetness assessment due to the evening overpass of the study site. At such timethe dew effect is expected to have minimal to no effect. The incidence angle difference between images was small (ranging from 30.0° to 32.5°), and therefore, local incidence angle correction was not applied. No time averaging or temporal smoothing was applied. The weather filtering can be beneficial for time-series de-noising (Toca et al., 2023) but different criteria would need to be applied, depending on the purpose of the analysis. In the case of Wicklow, if days with daily precipitation above 20mm were filtered as suggested in (Bechtold et al., 2018), 72 out of 591 images (12%) should be removed. If days with any precipitation should be discarded (Benninga et al., 2019), 82% of all observations would need to be removed. Detailed (i.e. hourly observation of precipitation and temperature) meteorological data and ground data on the soil and vegetation moisture are needed to correctly apply such data filtering.

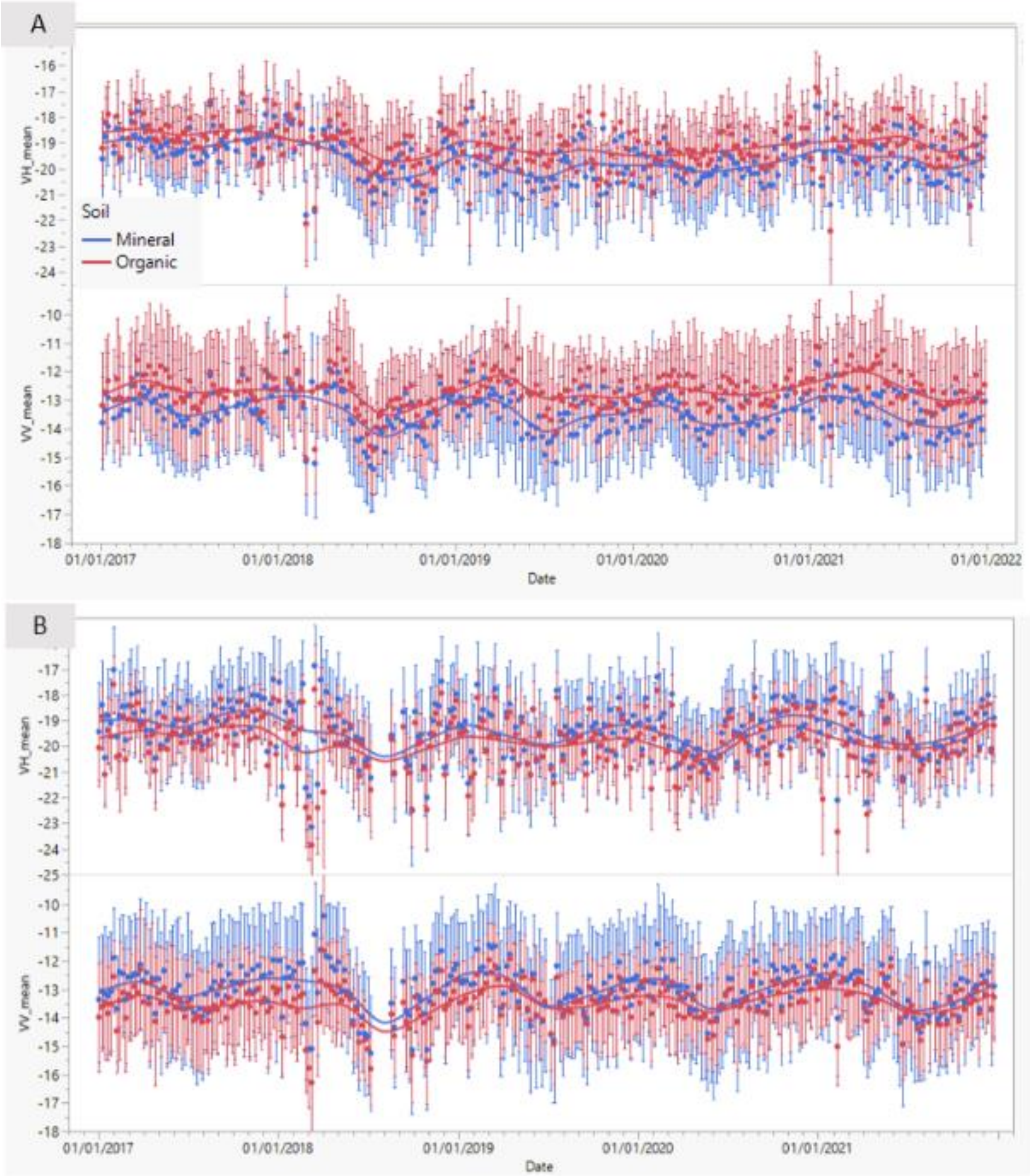
The polygons on organic soils exhibit smaller (0.5dB in VH and 1.0dB in VV) yearly variation in amplitude in the S1-backscatter than the polygons on mineral soils.

Relatively wet near-natural sites experience smaller fluctuations in the water table level than mineral soils with more vascular vegetation. Higher backscatter values are observed in the autumn and winter season when the water table level is typically closer to the surface, and lower backscatter values in spring and summer when the water table level drops.

This drop is reinforced by the presence of more vivid and denser vegetation in the spring and summer that further reduces the amount of backscatter returning to the sensor and results in even lower signal values in these months.

In the ascending orbit, from the evening satellite overpass, the backscatter of the polygons on organic soils is higher than the one of mineral soils but the situation is the opposite for the morning satellite pass of the descending orbit. (Mueller et al., 2022) observed a similar pattern for the backscatter of coniferous forests and attributed it to the changing vegetation water content levels during the day. “In the morning the water storage of the plant is replenished after refilling during the night” (Mueller et al., 2022). Lower backscatter values in the evening suggest that the daily change of vegetation water storage due to evapotranspiration is detectable. The effects of dew present on the vegetation in the morning could also influence this difference. The difference between the ascending and descending orbits is larger for the polygons on organic soils and less pronounced for the polygons on mineral soils.

Figure 51. Mean VH and VV polarised backscatter Sentinel-1 values with 1 standard deviation error bars for polygons in mineral (in blue) and organic (in red) soils in Wicklow. A) ascending orbit (evening overpass); B) descending orbit (morning overpass).



Source: SEPLA.

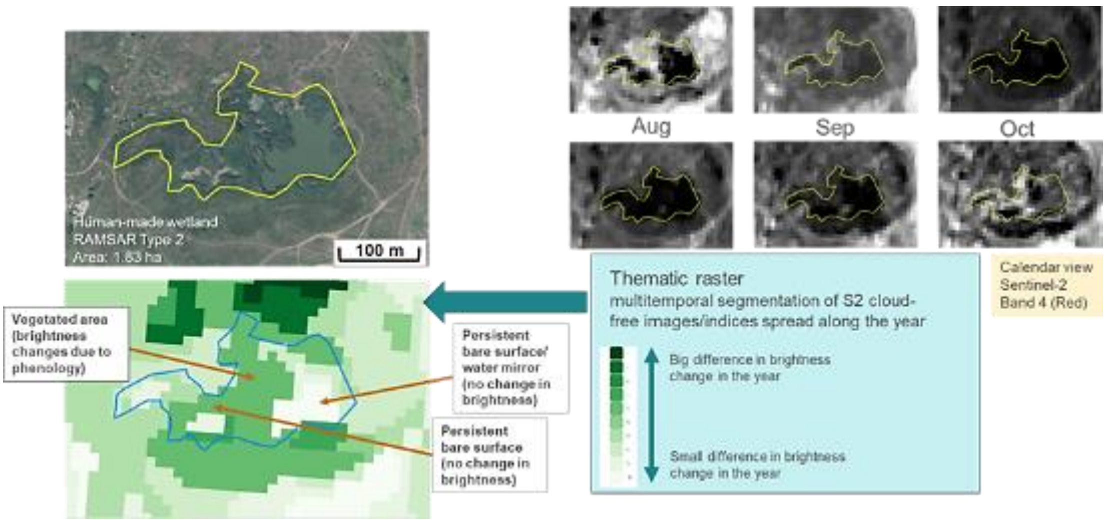
3.3 Estimation of areas on organic soil, using unsupervised image segmentation

3.3.1 Methodological approach

The purpose of the method is to assess the heterogeneity of the vegetation behaviour within the features of interest (FOI) and to look into its impact on the NDVI and NDWI time series. It applies object-oriented image analysis (OBIA) and deals with pixel clusters within the geometric object (polygon) representing the FOI, which are produced from the annual Sentinel-2 image stack through multi-temporal segmentation. In this approach, the extracted image-objects and their spatial aggregations, together with the FOI polygons are treated as spatial objects that have an intrinsic topological interconnection (Tasdemir et al., 2012). This interconnection between the hierarchical object layers allows for a more comprehensive contextual analysis.

The underlying idea of the developed method is that every biophysical feature/phenomenon on Earth's surface has a certain behaviour that depends on its material (biotic or abiotic) and its properties. If one assumes that, each specific type of matter has a particular temporal behaviour associated with its life cycle, one ought to be able to locate a certain type of land phenomena by the dynamics captured during observation, without the need to explicitly tackle its structural-physiognomic aspect. A similar approach could be used to “map” areas of distinct soil and wetness conditions, caused by their landscape position and topography which affect the vegetation phenology (**Figure 52**).

Figure 52. Illustration of the object-oriented image analysis (OBIA) concept to “map” distinct vegetation behaviour in wetlands.



Source: SEPLA and CREODIAS, Copernicus Services.

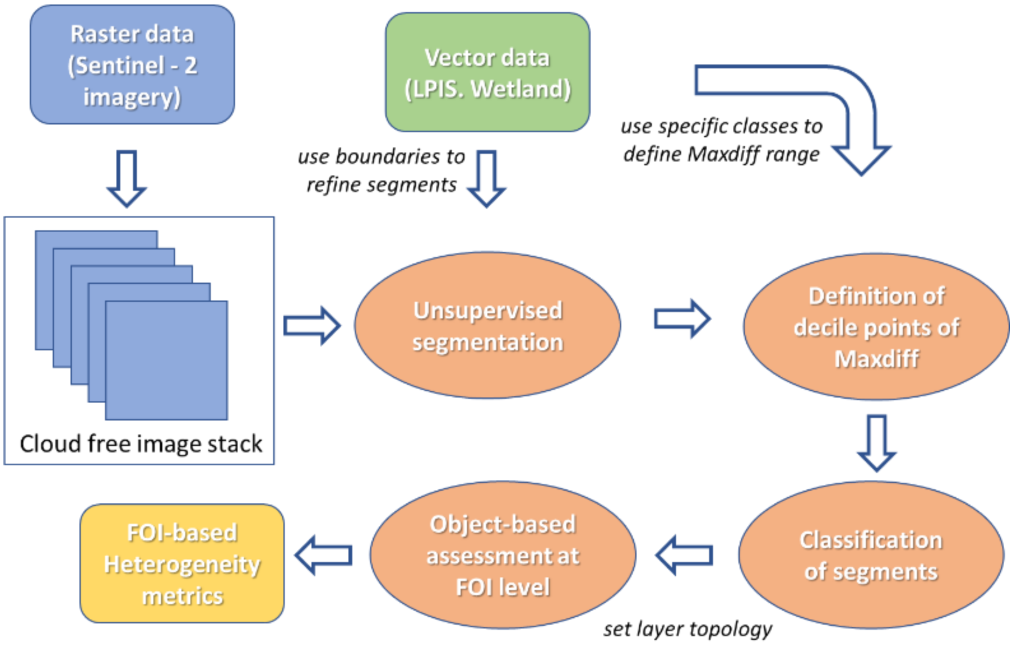
For most of these SEPLA tests, the method relies on a segmentation of raster files representing the Normalized Difference Water Index – NDWI[3] (Gao, 1996) derived from the infrared (B8) and shortwave infrared (B11) bands of all cloud free Sentinel 2 images (L2A – atmospherically corrected) within a predefined period. It groups pixels using the “region grow” method, based on criteria for relative homogeneity The aim is to detect areas on the ground that behave in a particular way, with respect to vegetation cover and vegetation water content. Band 8 was chosen over band 8A because of its higher spatial resolution (10 meters). The remaining spectral bands acquired at a spatial resolution of 20 meters were re-sampled to 10 meters. Each NDWI image is considered an individual "raster layer" in the processing workflow. Relevant vector datasets, as digital wetland maps and LPIS are rasterized and added as layers to further refine the image-object boundaries. For some specific testing (e.g. the peatland restoration scenario), the methods used either the NDVI or a combination of selected Sentinel bands at 10 meter resolution only, such as B3, B4 and B8.

For each resulting image-object, the normalized maximum absolute difference in the mean intensity in all "image layers" for the selected period is calculated. The resulted “mean intensity range” is used as a parameter

[3] It is also known as Normalized Difference Moisture Index - NDMI

of the dynamics of the surface reflectance of the biotic component present on the ground (Roshan Pande-Chhetri, 2017). With some approximation, one could consider it an effective indicator of the temporal behaviour of the vegetation. The values of the decile groups in the Maxdiff histogram are calculated: (1) for the complete set of image-objects in the Sentinel-2 scene and (2) for those image-objects entirely located within specific areas of interest. These areas of interest, derived from the ingested vector datasets, are intended to outline specific types of land cover or land use and filter the range of the Maxdiff histogram to a targeted physical phenomenon. This "targeted" approach for the histogram range was found to remove in most of the cases the noise and to "clean" the signal to its principal components relevant to the observed phenomenon, defined by the FOI (**Figure 53**).

Figure 53. Schematic representation of the processing flow, according to (Milenov et al., 2021a).



Source: SEPLA .

Each image-object is classified into the decile group to which it belongs. Each decile group is treated as a class corresponding to a certain range of dynamics of vegetation behaviour and water content. The initial clusters are subsequently aggregated by additional spatial-based rules (border index, proximity), that consider the classes and topology among the initial image-objects and their iterative aggregates. Ultimately, the entire FOI of the peatland is considered[4] and different metrics depicting the spatial-temporal heterogeneity of the peatland are generated.

3.3.2 Mapping the extent of raised bogs

From the semantic analysis done in SEPLA on the peatland classes, it became evident that the peatland type of raised bog retains stable surface characteristics related to its vegetation (plant height and cover of the sphagnum moss) throughout the year. At the same time, the presence of the green vegetation and the associated water content is steadily kept within a specific range (**Figure 54**). Such behaviour is easily detected on time series from the optical Sentinel-2 sensors.

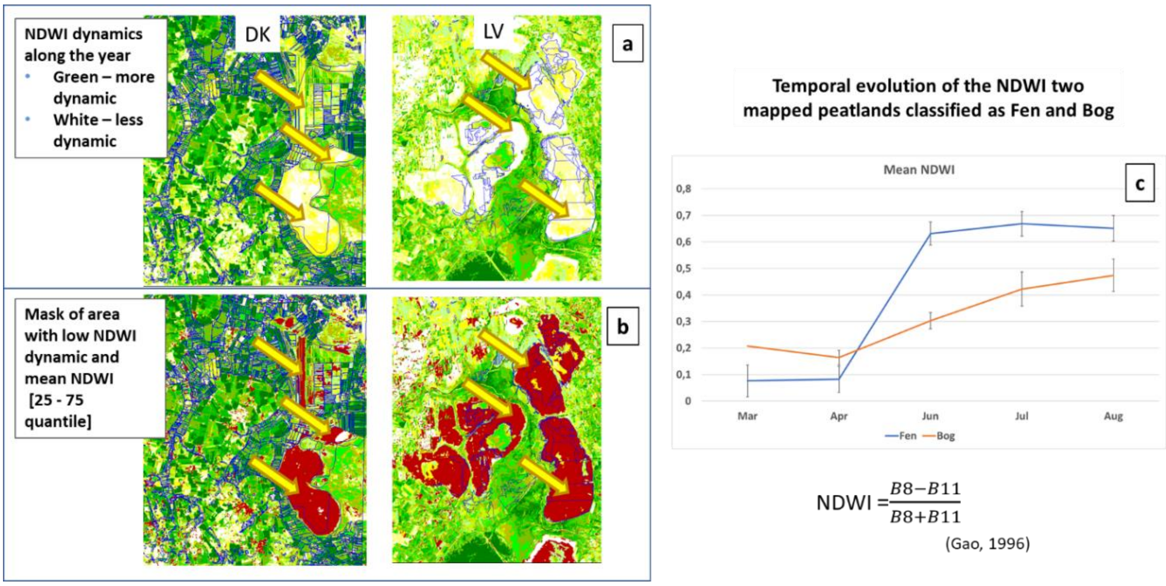
First, image-objects classified with the two least dynamic class labels are selected. Those with mean NDWI within the range given by the 25-quantile and 75-quantile calculated from the NDWI histogram for the entire scene, are retained to form a mask of potential areas with raised bogs (**Figure 54b**). Checks against local peatland data from a test site show that such mask comprises all previously mapped raised bogs (Figure Y, b). Many commission errors relate to urban settlements with associated vegetation, which could be easily masked

[4] Treated as a polytegon, consisting of tegons with different bio-physical characteristics and temporal behaviour.

out using national land cover data or the Pan-European High-Resolution Layers (CLMS-HRL). Comparison during the year between the mean NDWI values of raised bogs and fens show a difference, especially during the summer period, explained by the different type of vegetation and its phenology – mosses for bogs; grasses and woody vegetation for fens (**Figure 54c**).

The visual assessment of the results showed satisfactory capture of the peatland outline with marginal omissions. The commission errors outside urban areas are not frequent and may be related to sparsely vegetated areas and fallow land.

Figure 54. Application of the unsupervised segmentation approach on the Danish and Latvian test sites. (a) the segmentation "map" produced (b) a mask of the area behaving as raised bogs (c) a trend analysis of the NDWI behaviour for fens and bogs.



Source: SEPLA.

Box 4: Image segmentation – "Maxdiff" parameter

The analysis and classification of the extracted segments (image objects) relies on the "Maxdiff" parameter available in Trimble eCognition Developer, used to design the ruleset and test the method. It represents the maximum difference in mean intensity in the whole layer stack of the Sentinel multi-temporal composite for the selected period. It is calculated according to the equation given below:

$$\textit{Maxdiff} = \frac{\max_{i,j\in K_b} |\acute{c}_i(v) - \acute{c}_j(v)|}{\acute{c}(v)} \text{, with value range } \left[0, \frac{1}{K_b} c_k^{max}\right]$$

Input parameters

— *i, j* are the individual image layers

— $\acute{c}(v)$ is the brightness of image object v

— $\acute{c}_i(v)$ is the mean intensity of the pixel values in the image layer i of image object v

— $\acute{c}_j(v)$ is the mean intensity of the pixel values in the image layer j of image object v

— c_K^{max} is the brightest possible value of the intensity in the image layer k

— K_b is the number of image layers with positive weight values for brightness with $K_b = \{k \in K: w_k = 1\}$, where w_k is the weighting factor of the image layer.

More information on the method is given in (Milenov et al., 2021a) and (Trimble eCognition Suite, 2023).

3.3.3 Study cases and outcomes

The next sub-sections present some use cases where the segmentation approach was applied to provide further insights on the candidate areas on organic soil in the Irish test areas, using the spatial-temporal variability of the bio-physical characteristics within the FOIs.

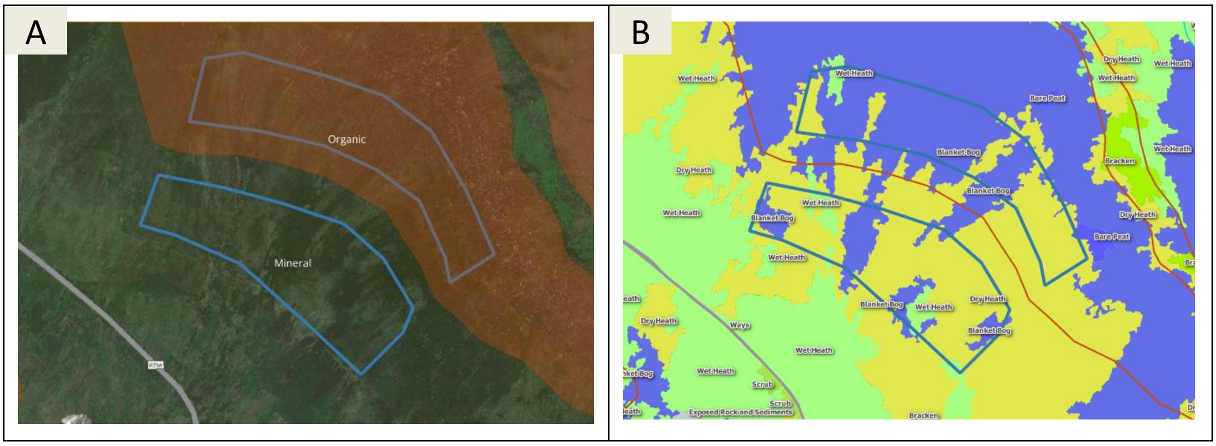
The unsupervised segmentation was performed separately on the NDWI and NDVI raster layer stack, derived from 4 to 5 cloud-free Sentinel images evenly distributed throughout 2021 to capture the main phenological stages (one per season). The resulting image-objects were classified according to the decile ranges of the Maxdiff histogram derived from the mean NDWI values of all image-objects located within the LPIS parcels with agricultural land. After numerous tests with different settings, the segmentation parameters as scale, compactness and shape were set to have the maximum spatial detail without significant over-segmentation.

3.3.3.1 ***Single Pair Test***

The purpose of the test is to show how the heterogeneous characteristics of the sampled polygons (FOI representations) used in the above tests for discrimination between areas on organic and mineral soils, could influence the phenology information derived from the NDWI (or NDVI) time series.

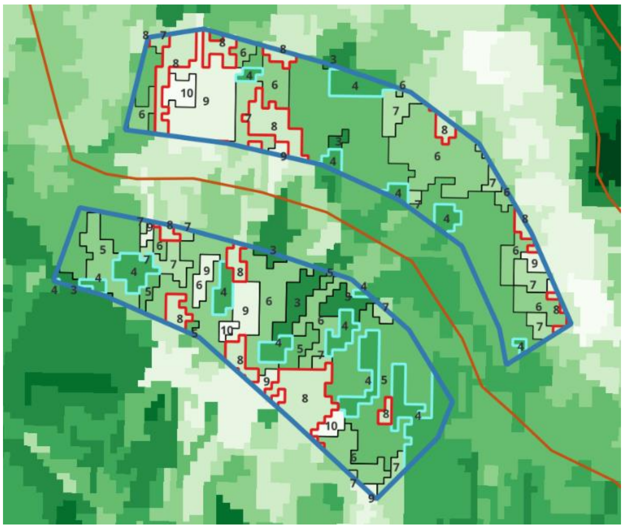
Two neighbouring FOIs are selected from the sampled polygons on permanent grassland in the Wicklow area - one located on organic soil and one on mineral soil. They represent a different type of land cover, according to the OSI land cover map – with different shares of blanket bog and dry heath – and are located within an undulating landscape (**Figure 55**). From the resulting image-objects, shown in **Figure 56**, those assigned to classes 4 and 8 were chosen. The choice was mainly driven by the aim to have classes with similar distribution in the FOIs, but sufficiently distant in the Maxdiff histogram.

Figure 55. A) Positions of the two FOIs part with respect to the boundary between organic and mineral soils. B) The two FOIs overlaid on the OSI land cover dataset.



Source: SEPLA.

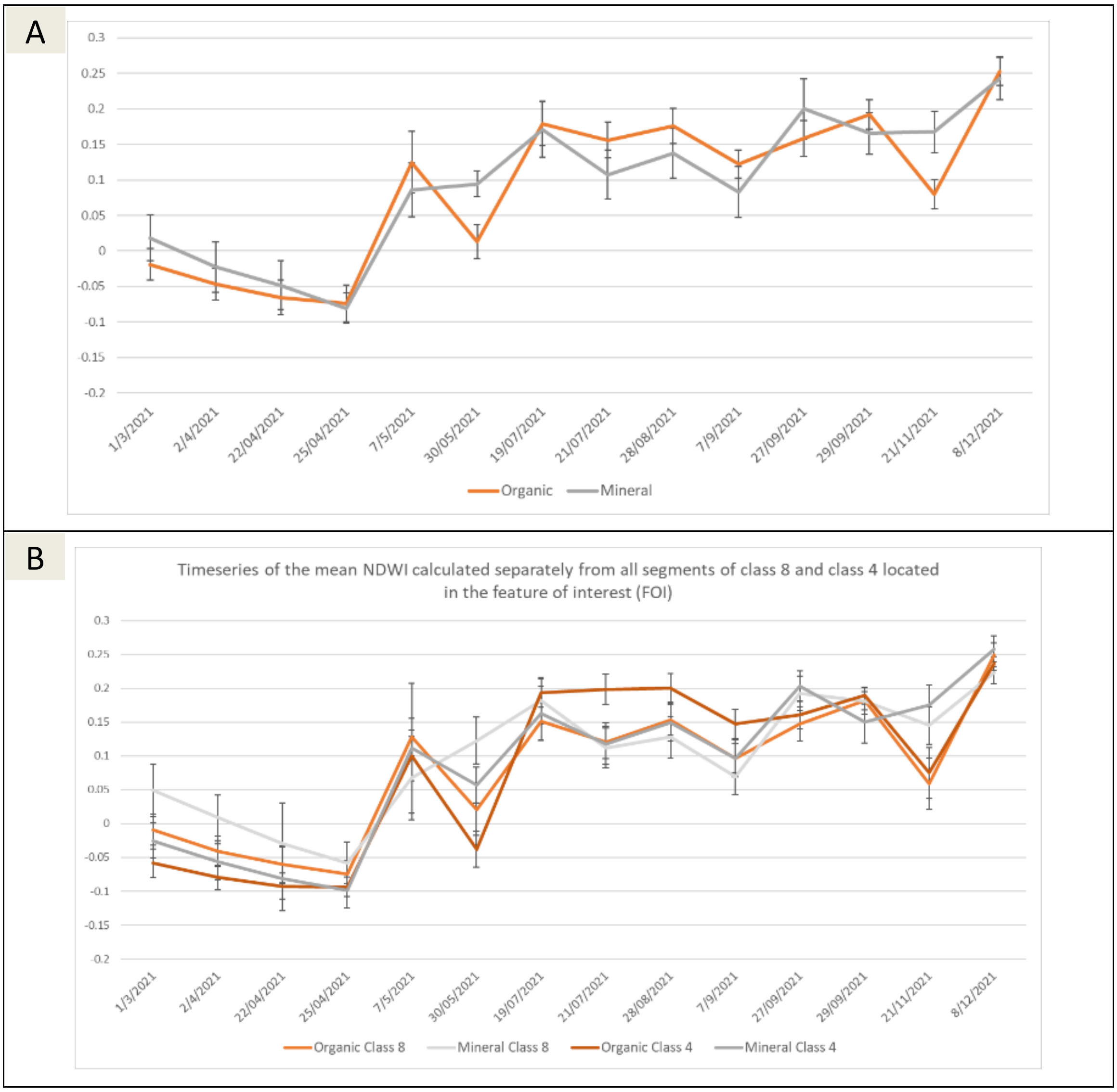
Figure 56. Distribution of the image-objects with their class labels within the two FOIs, with the image-objects from classes 4 and 8 highlighted, in cyan and red respectively.



Source: SEPLA.

The graphs in **Figure 57** show the mean NDWI time series for polygons in organic and mineral soils extracted from: (a) the entire FOI and (b) the image-objects from class 4 and class 8 separately, which act in this case as sub-FOIs. It can be seen that although the trends at the sub-FOI level are similar to that of the entire FOI, there are some notable differences; for example, the image-objects of class 4 on organic soil have distinctly higher mean NDWI values than those from class 8 on organic soil in the period of July 2021; the latter being very close to the values of class 4 and 8 on mineral soils. This temporal behaviour of these “sub-features” is likely linked to the influence of the specific vegetation, hydrological conditions and topography within the FOI. However, there is no obvious correlation between the distribution of the classified image-objects and the OSI land cover polygons.

Figure 57. A) Time series of the mean NDWI calculated from all image-objects located in the feature of interest (FOI). B) Time series of the mean NDWI calculated separately from all image-objects of class 8 and class 3 located in the feature of interest (FOI).



Source: SEPLA.

3.3.3.2 ***Ireland – assessing the extent of peat areas using multitemporal NDWI/NDVI and multispectral B8B11B4 analysis***

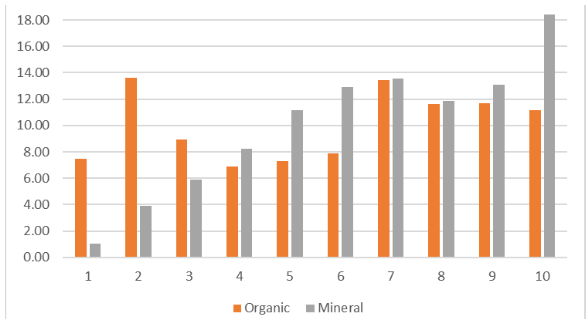
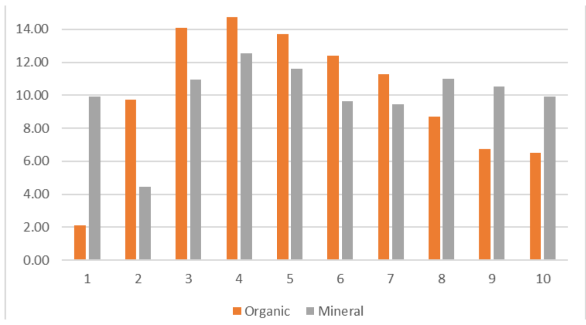
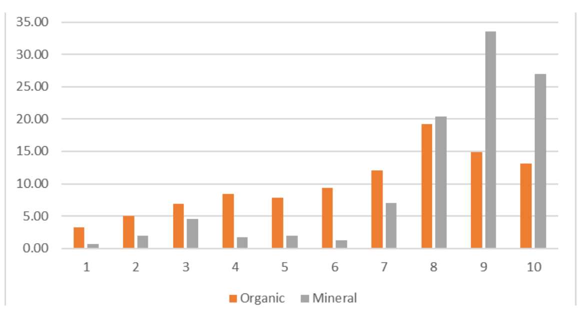
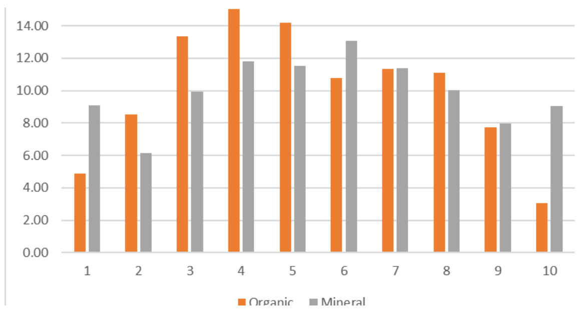
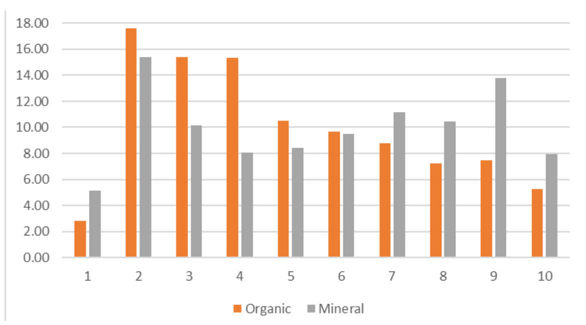
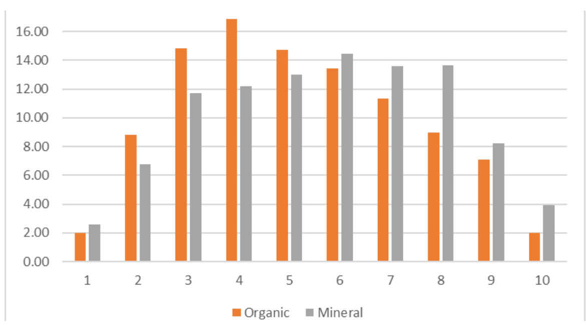
3.3.3.2.1 Sites Offaly and Wicklow

The purpose of this small use case is to complement the tests for discrimination of permanent grasslands on organic and mineral soils using the phenology parameters described above. It applies the OBIA approach to look for differences in the distribution of the classified image-objects between the two groups. The segmentation approach was applied to the test FOIs prepared for Offaly and Wicklow. The image-objects have been derived from the NDWI and NDVI time series for 2021. In addition, for Wicklow, a segmentation was performed on a single spring image (25.04) on bands B8, B11 and B4. The decile points for the 10 classes for each of the signals were defined based on the Maxdiff histogram range, extracted from the image-objects located in the LPIS parcels related to the agricultural area.

Based on the LPIS parcels kindly provided by the Irish Paying Agency for the period 2017-2021 and the LPIS QA population reported annually, a short assessment of the dynamics of the LPIS reference parcel, used as the basis of the FOI samples was made. The results show that the reference parcels are stable in terms of geometry and type of agricultural land cover, with some marginal changes of geometry in some isolated cases. Since, in Wicklow, the aim was to have a sufficient sample of pairs on both sides of the soil class boundary with similar land cover (wet/dry heath) and slope conditions, few (4) of the sample FOIs were located outside the LPIS reference parcels. These 4 were classified as permanent grassland after an ad-hoc visual photointerpretation of the satellite imagery.

Separate graphs with the distribution of the image-objects area per decile class for the two populations of FOIs (polygons on organic and mineral soil) have been prepared, for each of the signals extracted. The results are shown in **Figure 58**. The numbers (1-10) in the horizontal axis indicate the decile range of the histogram of the maximum difference of the signal value extracted from the Sentinel-2 time series (observed period: 2021) - 1 refers to the highest maximum difference and 10 refers to the lowest maximum difference.

Figure 58. Distributions of the classified image-objects for Offaly and Wicklow.

<table>
<tr><td>Distribution of the classified image-objects according to their area share (in %) found within the test polygons (Offaly - NDWI – all 2021)</td><td>Distribution of the classified image-objects according to their area share (in %) found within the test polygons (Wicklow – NDWI 2021)</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Distribution of the classified image-objects according to their area share (in %) found within the test polygons (Offaly – NDVI – all 2021)</td><td>Distribution of the classified image-objects according to their area share (in %) found within the test polygons (Wicklow – NDVI – all 2021)</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Distribution of the classified image-objects according to their area share (in %) found within the test polygons (Wicklow - B8B11B4 – one date 25.04.2021)</td><td>Distribution of the classified image-objects according to their share (in %) found within the test polygons (Wicklow - B8B11B4 – one date 25.04.2021)</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Source: SEPLA.

A visual assessment reveals some notable differences for Offaly in the distribution of the classified image-objects derived from the annual mean NDWI. Contrary to Offaly, in Wicklow there is no visible difference. This could be explained by the topography and type of peat present on both sites. The polygons in Offaly cover cutover peat, situated on a flat terrain and surrounded by intensive agriculture. The test polygons are located on grassland parcels, created after the drainage and cutting of the upper peat layer. The homogeneous surface characteristics and low farmer input leave enough opportunity for the soil wetness differences to "manifest" themselves though the vegetation phenology. The polygons in Wicklow cover other types of peatlands, such as blanket bogs and wet heath, located on undulating terrain causing a complex topography. Test parcels here are semi-natural permanent grasslands located on and between these peatlands exhibiting heterogeneous vegetation cove, through inclusions of scrub and bracken. In such a landscape, with mid-slopes and depression, any potential differences between organic and mineral soils are easily "lost". Nevertheless, there is some difference between the distribution of the image-objects from the single spring image.

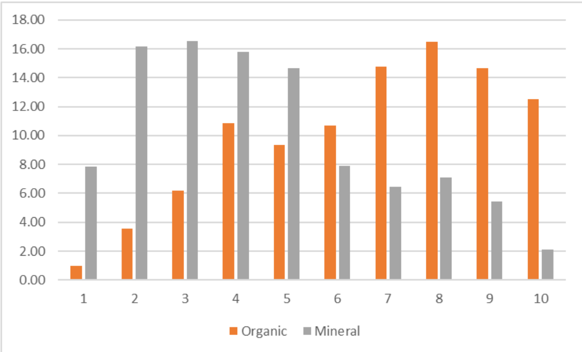
The distributions derived from the annual mean NDV show no difference in either site – Offaly and Wicklow.

3.3.3.2.2 Kildare

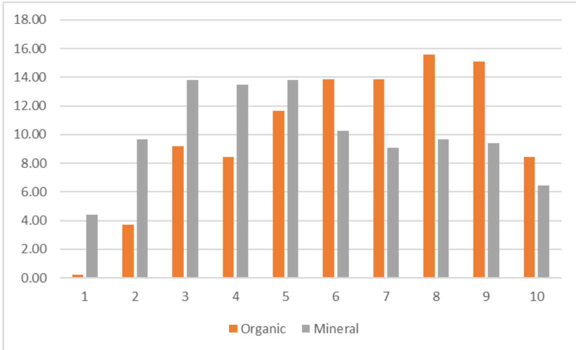
The data preparation and processing for this site were similar as for Offaly and Wicklow. The image-objects have been derived from the NDWI time series for 2021. In addition, segmentation was performed on a single spring image (25.04) on bands B8, B11 and B4 for several consecutive years from 2018 till 2022 (2020 excluded). Separate graphs with the distribution of the image-objects' area per decile class for the two populations of FOIs (polygons on organic and mineral soils) for each of the signals extracted are shown in **Figure 59**. The numbers (1-10) in the horizontal axis indicate the decile range of the histogram of the maximum difference of the signal value extracted from the 2021 Sentinel-2 time series; 1 refers to the highest maximum difference and 10 refers to the lowest maximum difference.

Figure 59. Distributions of the classified image-objects for Kildare.

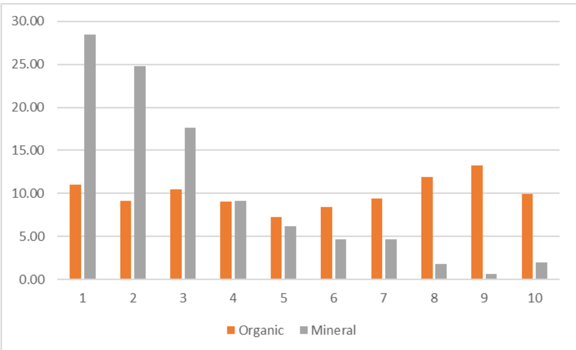
Distribution of the classified image-objects, according to their area share (in %) found within the test polygons (Kildare – NDWI – all 2021)



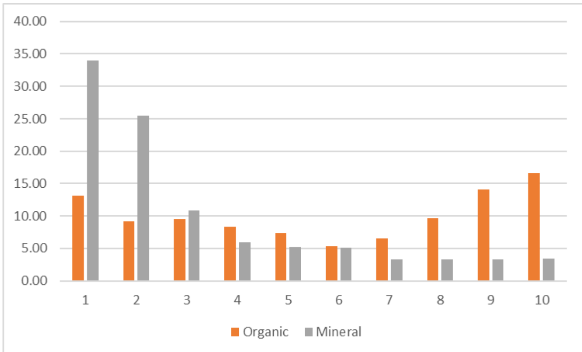
Distribution of the classified image-objects, according to their share (in %) found within the test polygons (Kildare -NDWI)



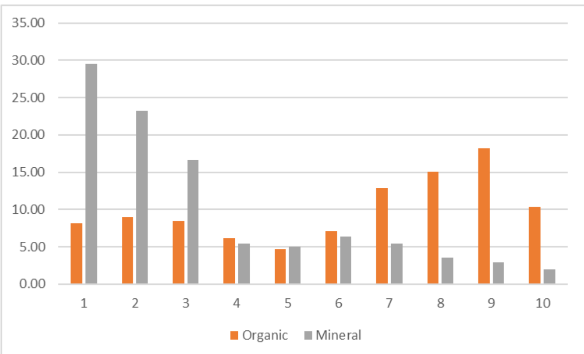
Distribution of the classified image-objects, according to their area share (in %) found within the test polygons (Kildare - B8B11B4, 2018)



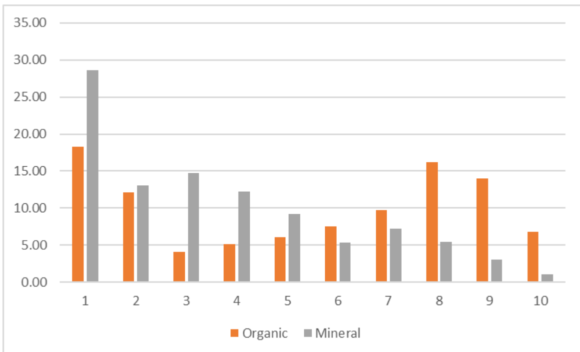
Distribution of the classified image-objects, according to their area share (in %) found within the test polygons (Kildare-B8B11B4, 2019)



Distribution of the classified image-objects, according to their area share (in %) found within the test polygons (Kildare-B8B11B4, 2021)



Distribution of the classified image-objects, according to their area share (in %) found within the test polygons (Kildare - B8B11B4, 2022)



Source: SEPLA.

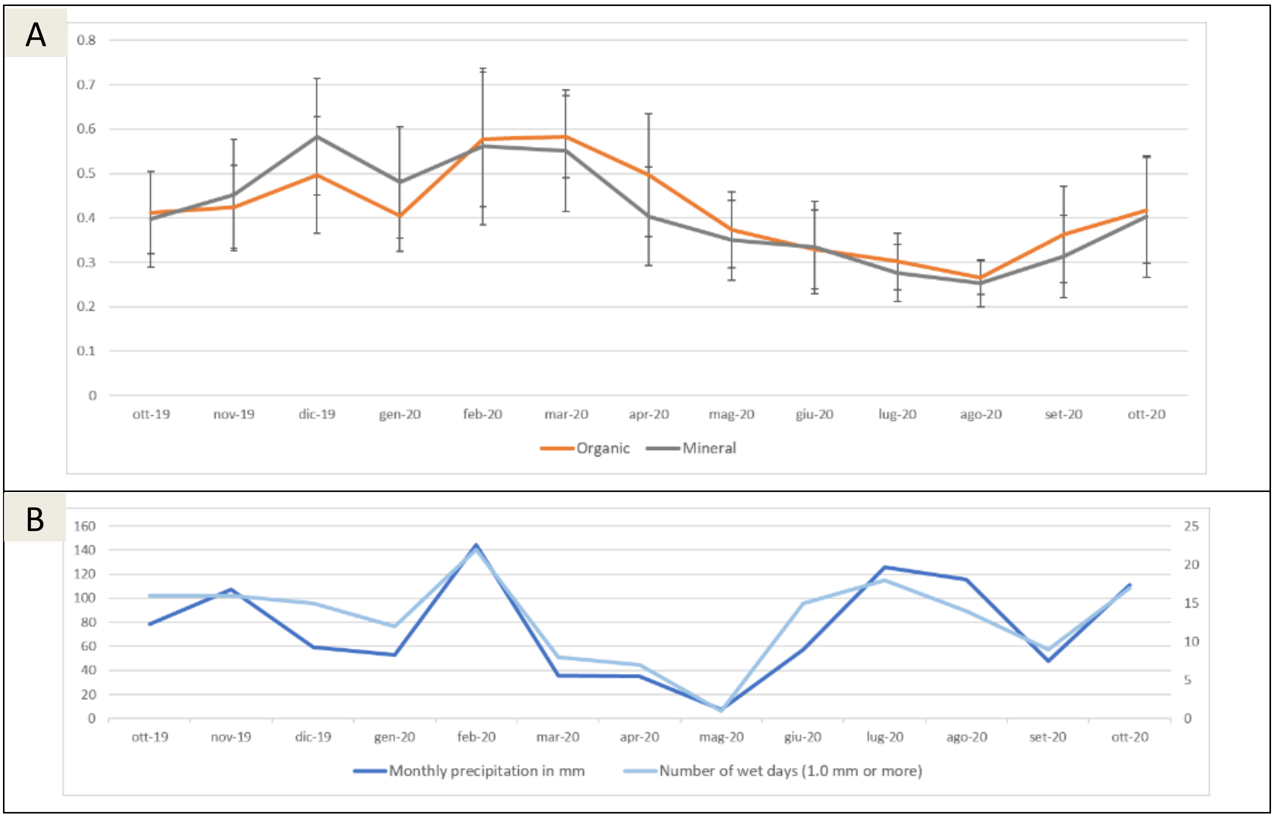
The distributions of the classified image-objects for organic and mineral in Kildare, derived from the annual mean NDWI, are quite distinct. Both are unimodal but skewed in opposite directions; the mineral, towards the classes with higher amplitude of vegetation water content, the organic towards those with lower amplitude. This could be an indicator for an expected lower variance of the water content in vegetation on organic soils, when the soil is saturated, since for most of the related image-objects the variance of the NDWI is low. They somehow align with, or at not contradict the findings of the test on VPP indices, where the total and seasonal productivities (TPROD and SPROD) were found with persistently higher values on the polygons (FOIs) on mineral soils for most of the years and sites.

The difference in the distribution is even more apparent from the segmentation of the single spring image and it is persistent in all assessed years. Here, the distribution of the image-objects from the polygons on mineral soil is skewed towards the classes showing the higher spectral variability, which corresponds to emerging vegetation. The opposite is observed for the distribution of the image-objects from the polygons on organic soil; they trend towards classes with low spectral variability, related to bare soil. Again, this aligns with the findings of the test on the VPP indices, where the day of the start-of-season (SOSD) was found with persistently higher values on the polygons (FOIs) on organic soils for most of the years and sites.

The availability of a 6-day coherence data set from Sentinel-1 generated for the JRC CbM outreach project gave another possibility to observe the vegetation behaviour of the polygons in Kildare. Time series of the median average value of the 6-day coherence (VH polarization) were produced for the polygons located on either organic or mineral soil. Coherence values were taken at regular time intervals in the fourth week of each month.

The results, given in **Figure 60**, show an earlier drop in the 6-coherence for the polygons on mineral soil at the beginning of the season. This could be related to earlier vegetation development compared to the polygons on organic soil and could be another source for confirming the result from the VPP indices test.

Figure 60. A) Time series of the 6-day coherence from Sentinel-1 for the polygons on mineral and on organic soil in Kildare. B) Rainfall measurement from the nearby station EDENDERRY (BALLINLA).

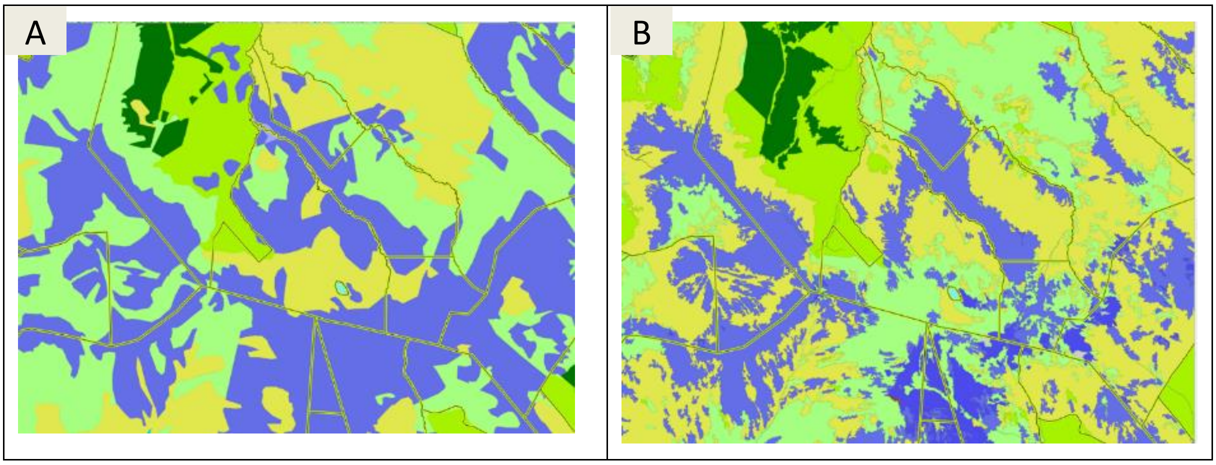


Source: SEPLA.

3.3.3.3 Vegetation dynamics and land cover; the complex land cover situation is Wicklow

The results from the tests on the VPP indices on the Wicklow site, showed that the signal analysis towards notable differences in the test polygons on organic and on mineral soils was largely inconclusive. One of the main reasons was the complexity of the landscape and the diversity and heterogeneity of its land cover. This is also evident from land cover datasets that were produced independently (**Figure 61**).

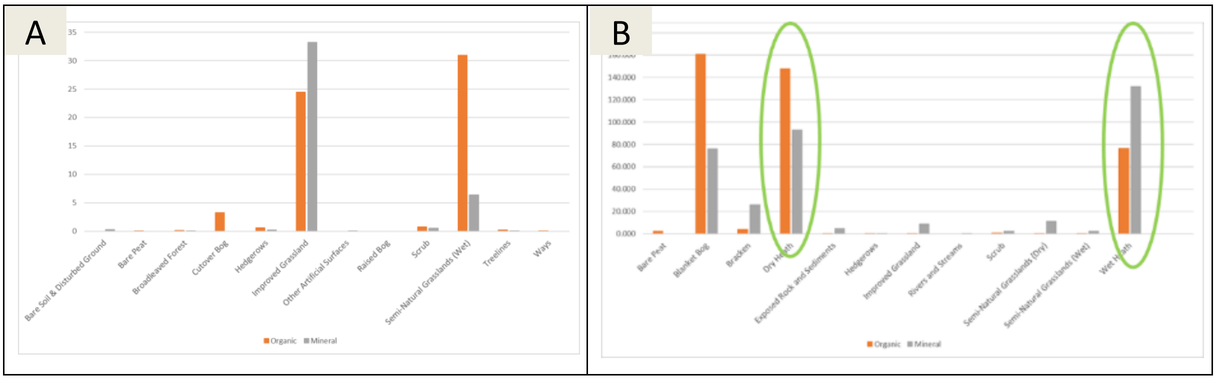
Figure 61. Land cover datasets produced over Wicklow A) Copernicus Local Product, N2K, 2018, Minimum Mapping Unit (MMU) of 0.5 ha. B) National Land Cover, Ordnance Survey Ireland, 2018 Variable Minimum Mapping Unit (MMU): 0.01-0.1ha.



Source: SEPLA.

The OSI classes present in the test polygons in Offaly are related to managed (improved) and semi-natural grasslands, which largely correspond to one type of land cover from the LPIS (low input grassland). Contrary, the OSI classes present in the test polygons in Wicklow (blanket bog, dry and wet heath) refer to a mixture of various non-herbaceous components and geographic features. As seen in **Figure 62**B, the two groups of test polygons in Wicklow contain mapped features related to blanket bog, wet heath and dry heath in different proportions. Although the higher share of blanket bog in the test polygons on organic soil was expected, it was interesting to also observe a higher share of dry heath, which is not related to peatland according to the Irish experts.

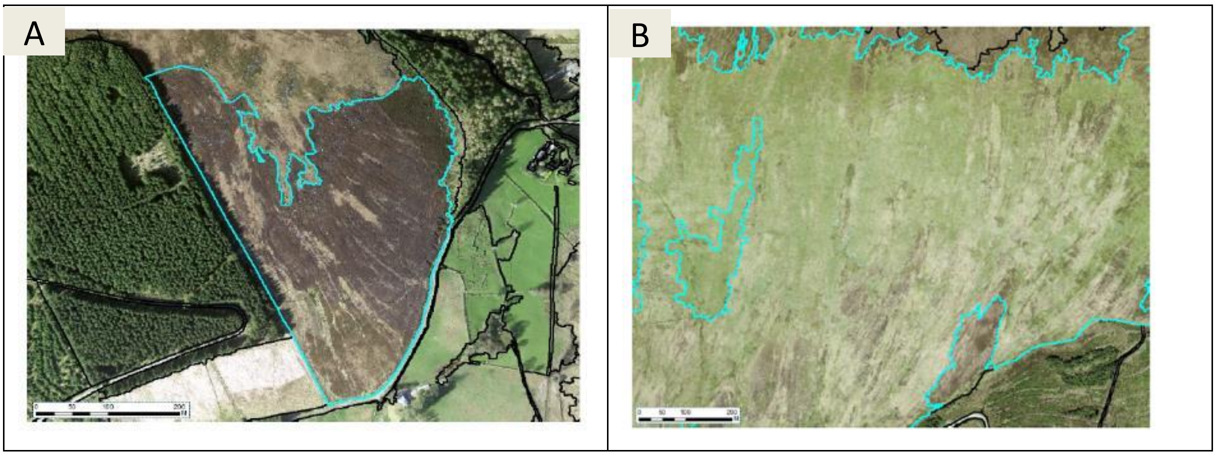
Figure 62. A) Distribution of the OSI land cover classes, according to their total area (in ha) found within the test polygons in Offaly B) Distribution of the OSI land cover classes, according to their total area (in ha) found within the test polygons in Wicklow.



Source: SEPLA.

From the OSI interpretation manual, it seems that both "Wet Heath" and "Dry Heath", refer to areas with relatively shallow peat, with an important difference being the presence of moor-grass in "Wet Heath". "Dry Heath" can contain heather, which seems to develop on peatlands that are drying. In both classes, the organic layer might be too shallow to qualify as peatland, but it certainly points to an organic-rich soil. Often wet heath grades in and out of the blanket bog and dry heath and forms mosaics with these and other semi-natural upland classes (**Figure 63**).

Figure 63. Examples of OSI land cover classes A) 621 Dry Heath, B) 621 Wet Heath.



Source: SEPLA.

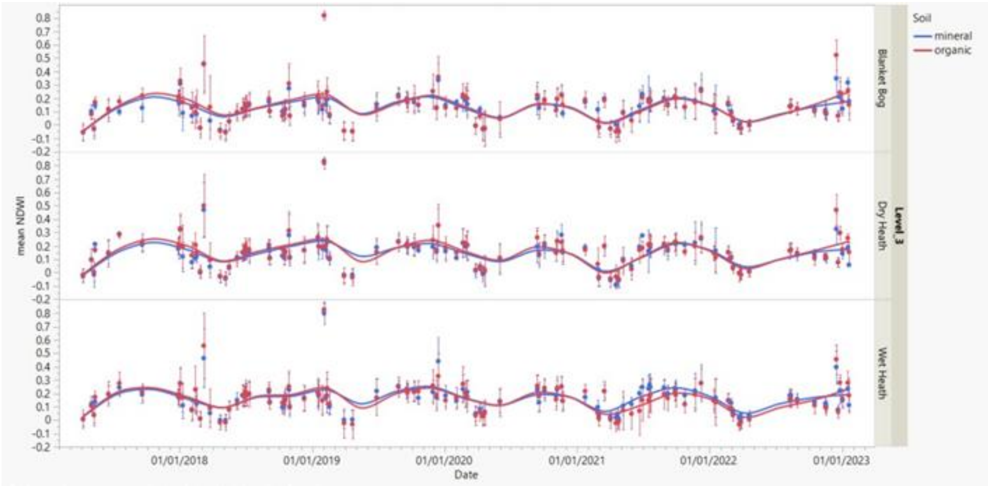
Blanket bog typically dominates the landscape with intermittent pockets of other landscape features such as outcropping rock, heath, pools and shrub vegetation. Weathering and erosion can form island-like peat hags which can be readily confused with wet heath. According to the OSI interpretation manual, blanket bog displays a very low seasonal variation in biomass intensity (NDVI) whereas wet heath can have a strong seasonal increase in biomass from spring to summer. Blanket bog is normally found on the lower to midsection slopes whereas wet and dry heath, often dominate on upland slopes.

The objective of the small test use case made was to analyse observed differences in the spatio-temporal behaviour of these three OSI land cover classes in unsupervised segmentation of the NDWI/NDVI timeseries. The OSI land cover polygons classified as “blanket bog”, "wet heath” and “dry heath” were grouped per OSI land cover class and per soil type. The following data were extracted:

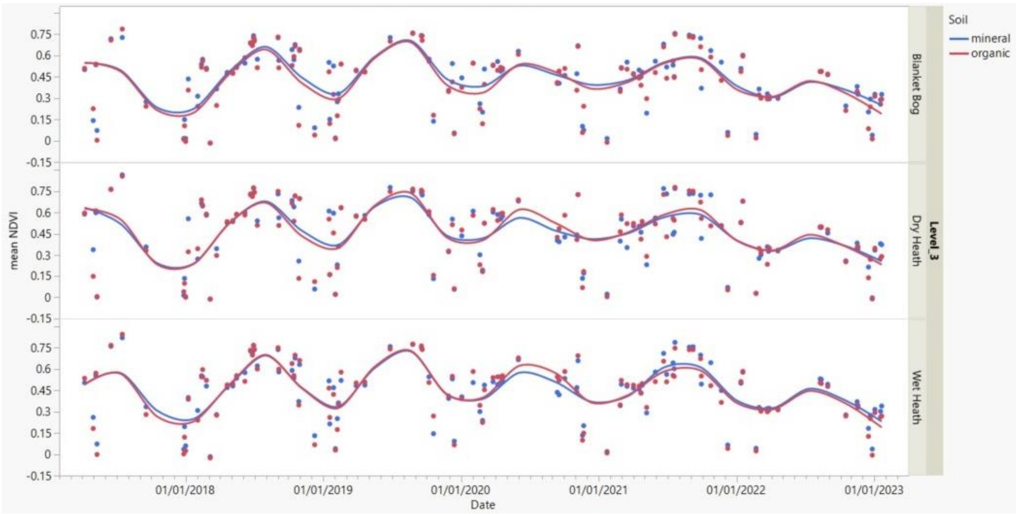
- a pair of time series (organic and mineral) of the mean NDWI and mean NDVI calculated from the population of polygons for each class;
- a pair of time series (organic and mineral) of the mean S1 backscatter (in both VH and VV polarizations) calculated from the population of polygons for each class;
- clusters from the unsupervised segmentation (the OBIA approach) of the annual NDWI and NDVI and their Maxdiff distributions per class and grouped per soil type.

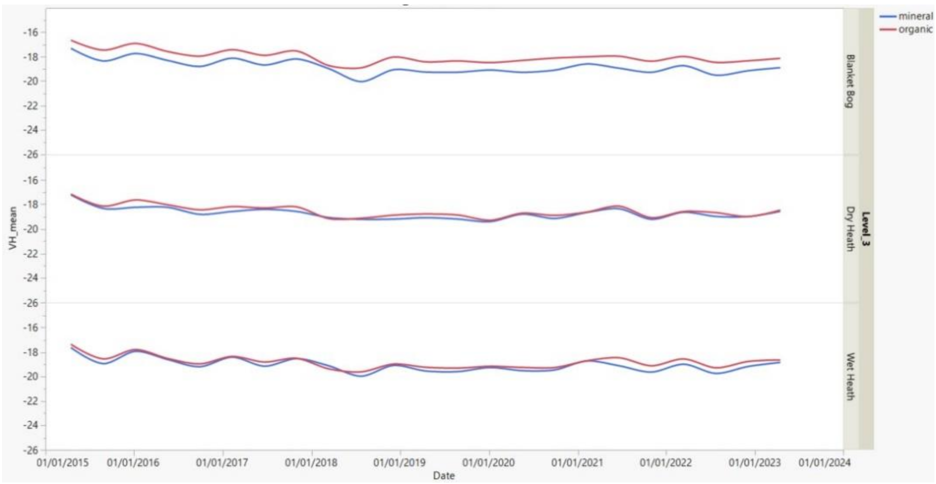
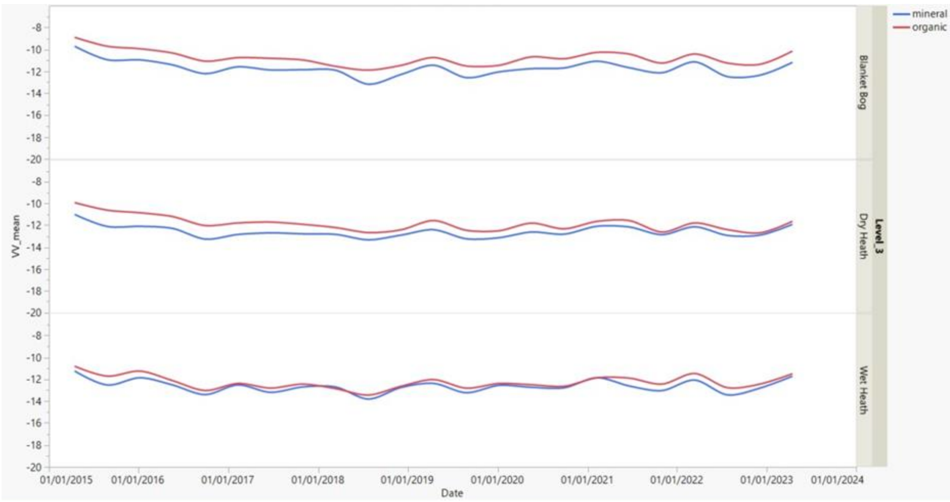
Figure 64. Results obtained from S1 backscatter, S2 NDWI/NDVI and image segmentation in the study site in Wicklow. The land cover polygons were clipped to the extent of the test area.

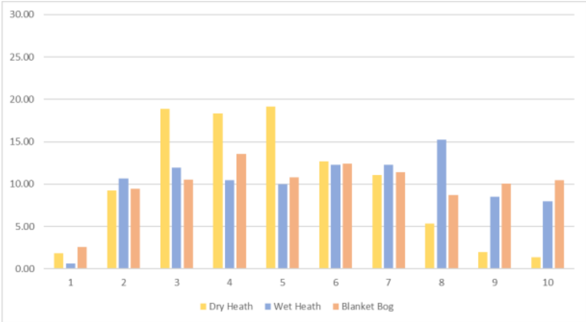
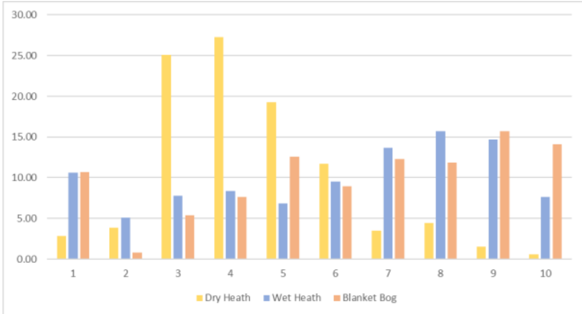
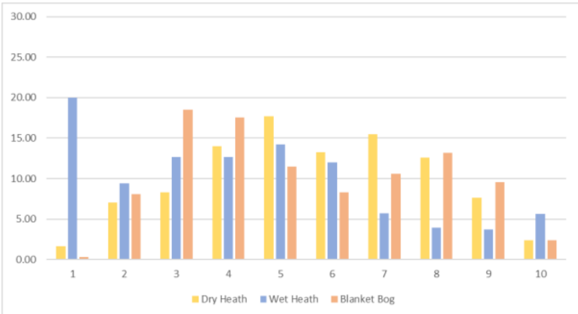
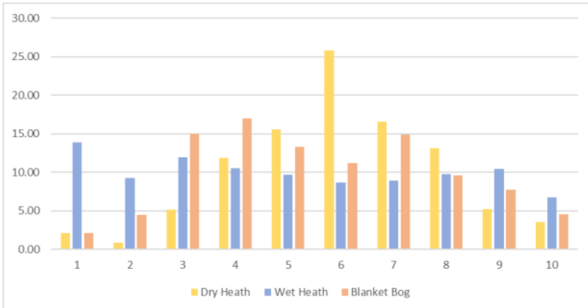
Time series of the mean NDWI of the land cover polygons per class located on both organic and mineral soils (period 2017-2023).



Time series of the mean NDVI of the land cover polygons per class located on both organic and mineral soils (period 2017-2023).



Time series of the mean backscatter (VH polarization) of the land cover polygons per class located on both organic and mineral soils (period 2017-2023, trends only).

Time series of the mean backscatter (VV polarization) of the land cover polygons per class located on both organic and mineral soils (period 2017-2023, trends only).


<table>
<tr>
<td>Distribution of the NDWI-based classified image-objects, according to their share (in %) found within the land cover polygons located on organic soil – year 2021,</td>
<td>Distribution of the NDWI-based classified image-objects, according to their share (in %) found within the land cover polygons located on mineral soil – year 2021,</td>
</tr>
<tr>
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>Distribution of the NDVI-based classified image-objects, according to their share (in %) found within the land cover polygons located on organic soil - year 2021,</td>
<td>Distribution of the NDVI-based classified image-objects, according to their share (in %) found within the land cover polygons located on mineral soil - year 2021,</td>
</tr>
<tr>
<td>
</td>
<td>
</td>
</tr>
</table>

Source: SEPLA.

The annual NDWI and NDVI trends from 2018 to 2023 do not reveal any notable difference of the temporal behaviour between the OSI land cover classes and between the organic and mineral groups within each class. Some small differences that are visible in one year, are not in another. The NDVI trends do not reveal the lower NDVI variations anticipated for blanket bog. A reason for this could be the inherent presence of scattered or clustered heath and shrub within the blanket bog polygon which contributes strongly to the increase of the NDVI amplitude. Nevertheless, the histogram distribution of the NDVI-based classified image-objects on wet heath shows a preference towards the more dynamic decile classes, suggesting that the expected higher NDVI variation on wet heath occurs at the sub-FOI level.

The S1 backscatter in VH polarization provides a slightly different picture with a notable higher variation of the signal on blanket bog, compared to the other land cover types. On VV polarization, the backscatter signal on organic soil seems a little bit higher.

The histogram distribution of the NDWI-based classified image-objects on dry heath is slightly skewed towards the deciles related to higher annual variance in both groups of test polygons. Although dry heath has on average a similar NDWI trend as wet heath, is the more homogeneous character and the less persistent water saturation, makes the seasonal fluctuations more pronounced.

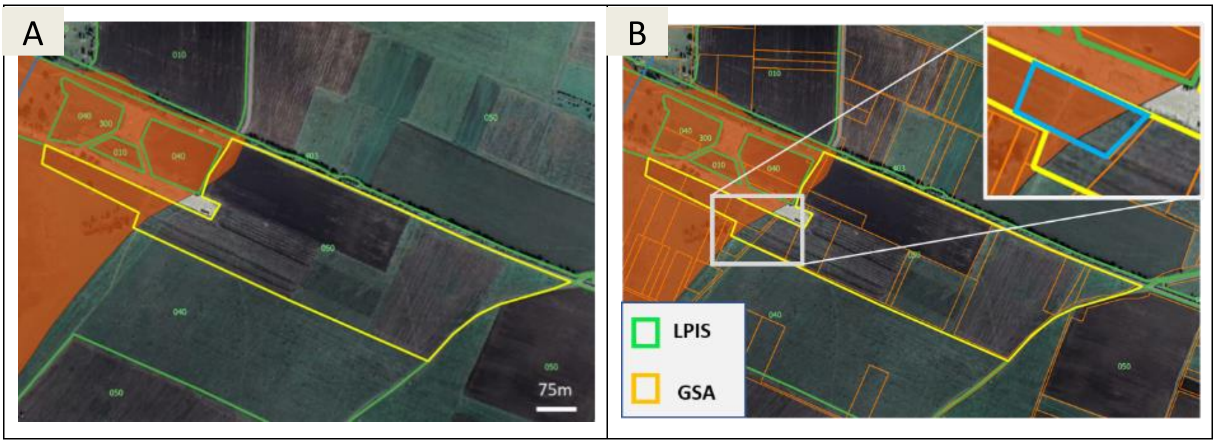
Overall, one could hypothetically state that while both “Wet Heath” and “Dry Heath” are at the borderline between peat and organic-rich soils due to their shallow peat layer, only “wet heath” would qualify as peatland because its more inundated character preserves the peat forming conditions.

3.3.3.4 Determination of the boundary between organic and mineral soils in Offaly using object-based image approach

The outcomes of SEPLA on the methodology for the creation of IACS-carbon theme" (published in SEPLA Deliverable 2; Milenov et al., 2023) highlighted issues with the ambiguity of the boundary of drained peatland under agricultural management. Areas with peat soils, following identified through national definitions, are subject to protection according to the "conditionality" rules of the EU Common Agricultural Policy (GAEC standard 2 on the protection of wetlands and peatlands). The location of these areas should be geographically explicit in the so-called "IACS-carbon theme". Since these are mostly identified from historic soil maps, there is often no visible surface evidence of the current boundary. This could be an issue especially when the LPIS reference parcels, used by the farmers, partially overlap with areas under GAEC 2. EU Member State experts involved in SEPLA called for EO-based criteria to bring evidence on the actual extend of organic soils within agricultural parcels, where such soils are suggested by the soil datasets.

The objective of this test use was to check whether the object-based image approach (OBIA) would be suitable to confirm the boundary between organic and mineral soils when it crosses the LPIS reference parcels. The OBIA applicability depends on the size and shape of the reference parcels, as well as the type and number of agricultural parcels inside. LPIS parcels that are too small or elongated would not allow generation of any meaningful image-object intersections (Milenov et al., 2021a). Some types of reference parcels (production block, topographic block) hold numerous agricultural parcels with different land cover and land use, making the analysis of the image-objects at the LPIS parcel level challenging. The design of the test had to accommodate these specificities and select as FOIs, only LPIS parcels or sub-parcels with one single agricultural land cover and a substantial area of intersection with the organic soil polygon (**Figure 65**).

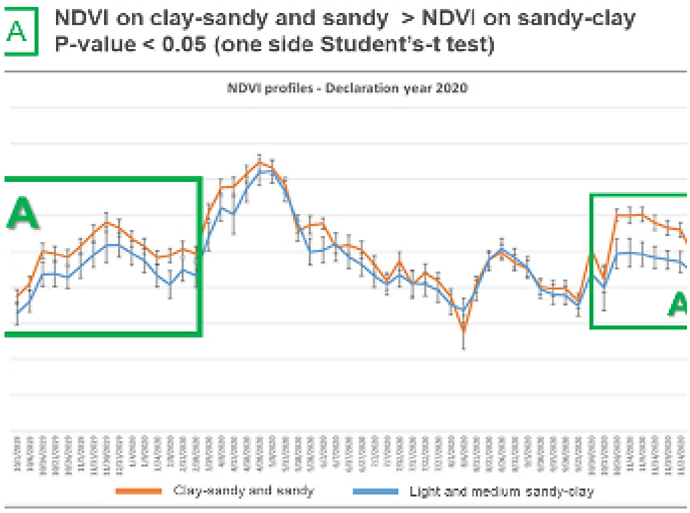
Figure 65. A) Tested reference parcel (yellow perimeter) partially overlapping with the organic soil layer (orange hash). B) The tests select only the GSA-sub-parcel (blue perimeter), that complies with the requirements for land cover homogeneity and partly overlaps with organic soil layer.



Source: SEPLA

There are different approaches towards using OBIA for "confirmation" of the soil boundary within the FOI, depending on the type of agricultural land cover. When the FOI represents permanent grassland, the herbaceous vegetation covers the surface all year; there are no periods where the soil is bare and visible from above. In this case, the dynamics of some key land cover characteristics (such as vegetation phenology) could be used to eventually "map" areas with distinct soil and wetness conditions. Organic soils are expected to have lower temperatures in the spring months, which would lead to slower and less intensive phenological growth (**Figure 66**), compared to mineral soils (Milenov, 2022). This was also well-evidenced by the results from the VPP tests, presented in Section 3.2.2.

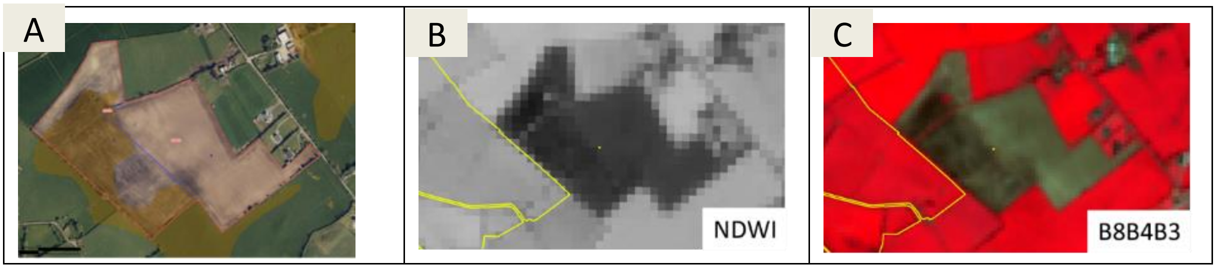
Figure 66. NDVI time series of parcels on permanent grassland left in a state suitable for grazing, on soils with different textures. The NDVI on soil with higher clay content (23.6 - 30.4% of clay) is significantly lower in a certain period of the year.



Source: (Milenov P., 2022).

When the FOI is covered by arable land, there are periods when the soil is bare and visible from above. In this case, it would be more appropriate to rely on the soil colour to "delineate" the distinct soil and wetness conditions. Besides, crop phenology could be overly influenced by crop-specific agronomic practices and farmer inputs such as fertilizers. Organic soils, in general, are expected to have a darker colour value (according to Munsell colour system) due to the higher organic matter content and wetness (**Figure 67**).

Figure 67. A) Reference parcel in spring 2021 with confirmed presence of organic soil in the south-eastern part. B) NDWI image from the same period (25.04.2021) C) colour infrared image (band combination B8B4B3). The darker colour of the organic soil is well visible, especially in the colour infrared.

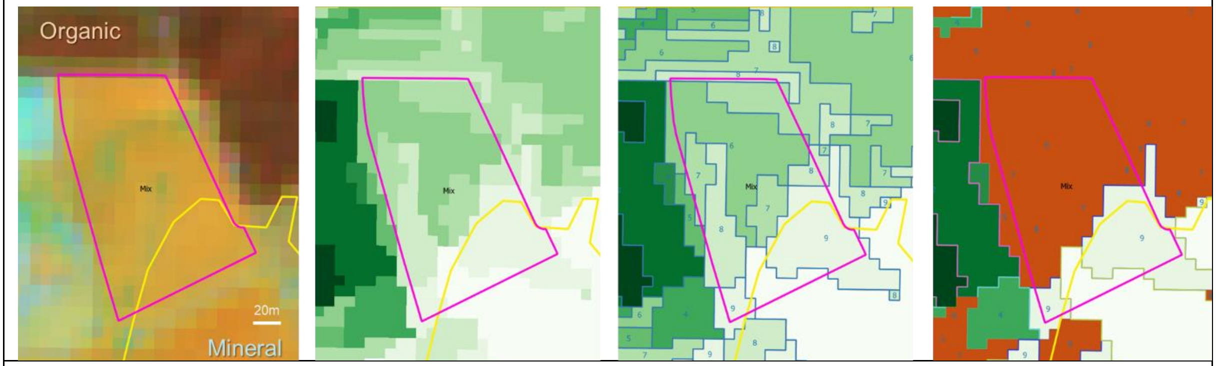


Source: SEPLA.

For this use case, the thematic raster data derived from the OBIA on multi-temporal NDWI and NDVI images, and the single band image (B8B1B4) were reclassified. The image-objects referring to classes with the lowest change in phenology or lowest overall (intra-band) brightness. were combined into a candidate OBIA raster mask of organic soil. As the contributing image-objects cluster image information in meaningful perimeters, the boundary of that raster mask should be better for locating the boundary between the organic and mineral soils than a simple pixel-based mask based on the soil organic content values (see SEPLA Deliverable 2, Milenov et al., 2023).

Figure 68. Illustration of the OBIA raster mask on low input grassland (top) and arable land (bottom). From left to right: FOI intersected with the organic soil mask; thematic raster from OBIA; thematic raster from OBIA with class labels; the OBIA raster mask in pale red. The boundary between the organic and mineral soils classes is shown in yellow.

Multiple Sentinel-2 images in the year, NDWI



Single Sentinel-2 image, spring, B8B11B4

Source: SEPLA and CREODIAS, CopernicusServices.

For the test, 12 FOIs on low input grassland, partly covered by the organic soil mask (from soil classes related to peat in Ireland) were selected for the site of Offaly. Also selected were 16 FOIs on arable land, intersected by the organic soil mask and having the expected darker colour on spring VHR orhoimagery. The parcel geometries, together with the boundary of the organic soil mask, were overlaid on the thematic rasters derived from the OBIA. The correspondence between the organic soil mask and several OBIA raster masks generated with different settings was visually assessed:

— On low input grassland:

- OBIA_NDWI: based on NDWI, where the Maxdiff range was derived from the image-objects of the entire Sentinel-2 scene;
- OBIA_NDWI_LPIS: based on NDWI, where the Maxdiff range was derived from the image-objects of the LPIS parcels on agricultural land only;
- OBIA_NDVI: based on NDVI, where the Maxdiff range was derived from the image-objects of the entire Sentinel-2 scene;
- OBIA_NDVI_LPIS : based on NDVI, where the Maxdiff range was derived from the image-objects of the LPIS parcels on agricultural land only.

— On arable land:

- OBIA_B8B11B4: based on B8B11B4, where the Maxdiff range was derived from the image-objects of the entire Sentinel-2 scene;
- OBIA_B8B11B4_LPIS: based on B8B11B4, where the Maxdiff range was derived from the image-objects of the LPIS parcels on agricultural land only.

During the visual assessment, the following observations were collected:

1. Is the boundary detected by the OBIA raster mask (Y/N)?
2. What is the underlaying gradient (1 to 9) of the change between the image-object classes on both sides of that boundary (only if the previous answer is Y)?
3. What is the quality of the boundary location of the OBIA raster mask in distance from the soil boundary (1-good; 0 -poor)?

During the visual assessment on arable land, some additional observations were made on the spring Sentinel-2 image (bare soil presence, visibility of the soil boundary).

Results of the assessment are presented in **Table 7** and **Table 8** below.

Table 7. Results of the visual assessment of the OBIA raster mask for low input grassland.

OBIA_NDWI_LPIS			OBIA_NDWI			OBIA_NDVI_LPIS			OBIA_NDVI		
Boudary detected?	Gradient of class change	Quality of boundary	Boudary detected?	Gradient of class change	Quality of boundary	Boudary detected?	Gradient of class change	Quality of boundary	Boudary detected?	Gradient of class change	Quality of boundary
N	0	0	N	0	0	N	0	0	N	0	0
N	0	0	N	0	0	N	0	0	N	0	0
N	0	0	Y	2	1	Y	1	1	Y	2	0
N	0	0	N	0	0	N	0	0	N	0	0
Y	1	1	Y	1	0	Y	2	1	Y	2	0
N	0	0	Y	2	0	Y	1	0	N	0	0
Y	2	1	Y	1	0	N	0	0	N	0	0
N	0	0	N	0	0	N	0	0	N	0	0
Y	1	0	Y	1	1	N	0	0	N	0	0
Y	1	1	Y	1	0	N	0	0	N	0	0
Y	1	1	Y	1	0	Y	2	1	Y	2	0
Y	1	0	Y	1	1	Y	2	1	Y	1	0

Source: SEPLA.

Table 8. Results of the visual assessment of the OBIA raster mask for arable land.

OBIA_B8B11B4_LPIS			OBIA_B8B11B4			Observations of Sentinel-2 from 25.04.2021
Boudary detected?	Gradient of class change	Quality of boundary	Boudary detected?	Gradient of class change	Quality of boundary	
Y	1	1	Y	1	0	bare soil, darker colour present
Y	1	1	Y	1	0	bare soil, darker colour present
Y	2	1	Y	3	0	bare soil, darker colour present
N	0	0	N	0	0	vegetated, darker colour absent
Y	2	1	Y	2	0	vegetated, darker colour present
Y	2	1	Y	2	0	bare soil, darker colour present
Y	2	1	Y	3	0	bare soil, darker colour present
N	0	0	N	0	0	vegetated, darker colour absent
N	0	0	N	0	0	vegetated, darker colour absent
Y	2	0	Y	1	1	bare soil, darker colour present
Y	2	0	Y	2	1	vegetated, darker colour present
N	0	0	N	0	0	bare soil, darker colour absent
Y	5	1	Y	4	0	vegetated, darker colour present
Y	2	1	Y	3	0	bare soil, darker colour present
Y	1	1	Y	2	0	bare soil, darker colour present
N	0	0	N	0	0	bare soil, darker colour absent

Source: SEPLA.

The results for the FOIs on low input grassland show that about 35% of the soil boundaries escaped detection. The OBIA based on NDWI detected more cases than the NDVI. Sometimes it seems that the Maxdiff derived from the entire Sentinel-2 scene provides more soil-relevant detail for the classification of image-objects through the subtle differences that are not available in the Maxdiff derived from the LPIS population. The poor detection of the soil boundary on grassland could be attributed to reasons such as the: lack of sufficient cloud-free Sentinel-2 observations and the possibility of over-segmentation. It could also be that there are no changes in the vegetation phenology to be picked up by the OBIA method, or that the soil boundary location is not precise enough for the given cartographic scale (1:5 000).

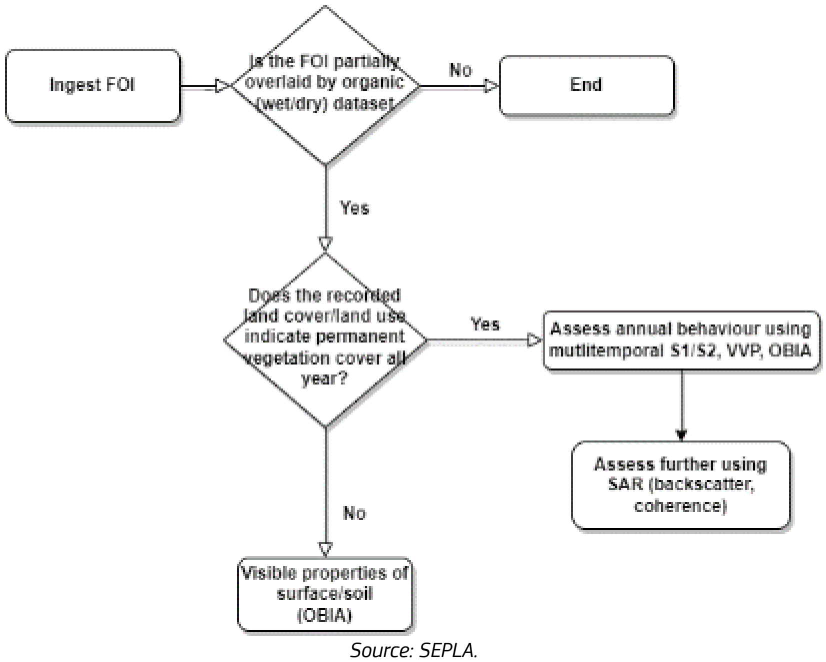
Results for the FOIs on arable land show 100% detection for those FOI where soil/vegetation colour differences are visible in the Sentinel-2 image. Both Maxdiff approaches show equal performance; however, the one based on the LPIS population provides a better boundary location in distance from the soil boundary. The gradient between classes is between 1 and 2 on average. Those 5 cases where there is no colour difference in Sentinel-2 might be an indication of ongoing soil mineralization or, as with the grassland, the occurrence of an imprecise soil boundary.

In summary, the OBIA applied on bare soil seems a promising EO-based method for detecting and confirming the location of soil boundaries. The main obstacle seems the need for sufficient cloud free Sentinel-2 data during the appropriate bare soil time. The detection of the intra-parcel soil differences in grasslands is more challenging. For grasslands, pixel-based methods based on similar vegetation indices or phenology parameters as VPP could be more appropriate, especially when complemented with SAR based methods (**Figure 69**).

However, there are some important OBIA points to raise:

- Soil type affects the colour of the bare soil and the vegetation behaviour, **but there are other factors playing a role (i.e. wetness etc).**
- A direct association between generated clusters and mappable areas is not possible, since the **image-objects cannot be directly related to the physical features, reflected in the LPIS (as GIS database)**.
- Soil and wetness data comes with great uncertainty; a possible way to mitigate its impact on GAEC 2 implementation would be to **reduce the cardinality between the reference parcels (LPIS) and agricultural parcels (GSA)**.

Figure 69. Possible workflow for selection of the appropriate EO-based method for determination of the boundary between organic and mineral soils within LPIS parcels.



Source: SEPLA.

3.3.3.5 Comparison between pixel based and object-based approaches

In the object based image analysis clusters can be grouped in layers with topological relationships, allowing a more comprehensive spatial analysis than pixel-based approaches can allow. However, OBIA is rather complex, computing intensive and suffering from inherent conceptual issues (Hay and Castilla, 2006) By contract, a pixel-based approach offers a more resource efficient and practical solution alternative.

This last use case compares object and pixel based-approaches for detecting areas of bare peat in the areas of Offaly and Wicklow.

Exposed bare peat soils can occur where raised and blanket bog systems are cut and harvested and where upland blanket bog is eroded. They often occur in the immediate vicinity of intact or degraded raised (or blanket bog) complexes, as is the case in Offaly and Wicklow.

The applied pixel-based method shares the same philosophy as the OBIA. It tries to assess the area through the spatial-temporal behaviour of the vegetation. However, instead of building aggregating meaningful image-objects, it processes at the level of the individual image pixel. For each pixel, it calculates the mean and the standard deviation from the same NDWI image stack used for OBIA. Then it calculates the Sentinel-2 Signal-to-Noise Ratio (SNR) as described in Section 2.2 of (Milenov et al., 2021a).

The basic equation used is given below:

$$\text{SNR}= \frac{M}{\sigma}\,;$$

with the input parameters being:

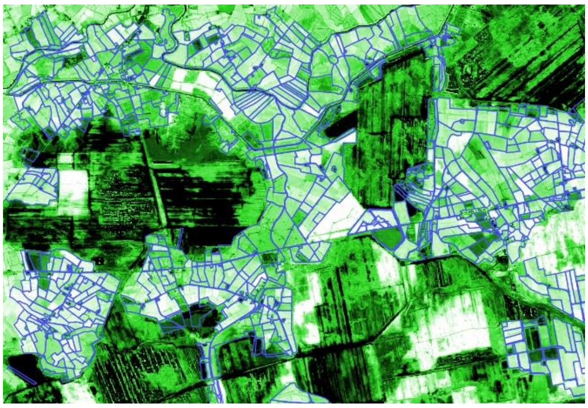
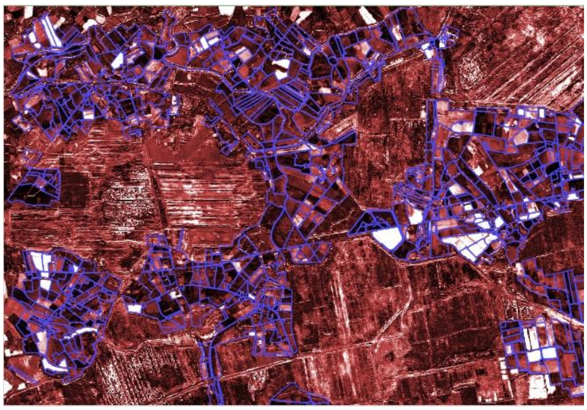
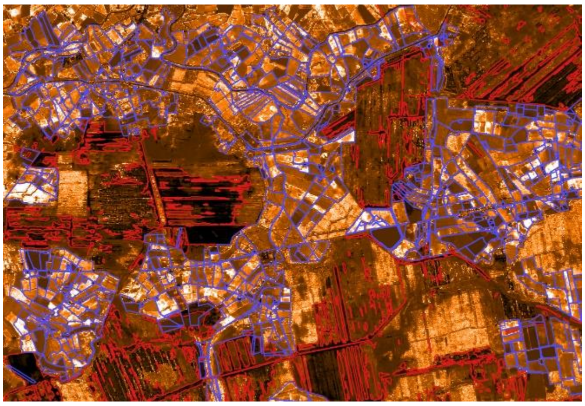
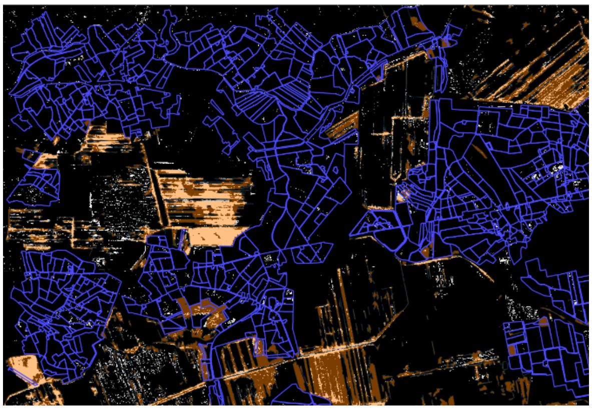
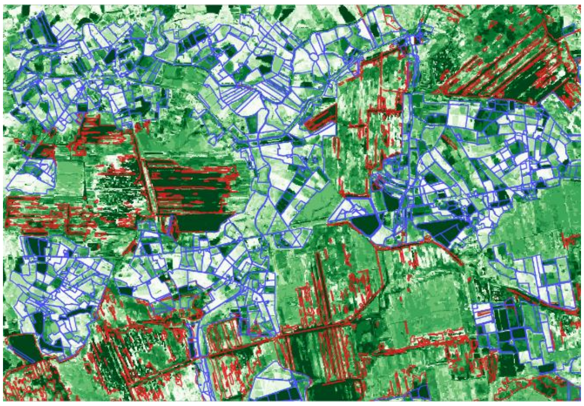
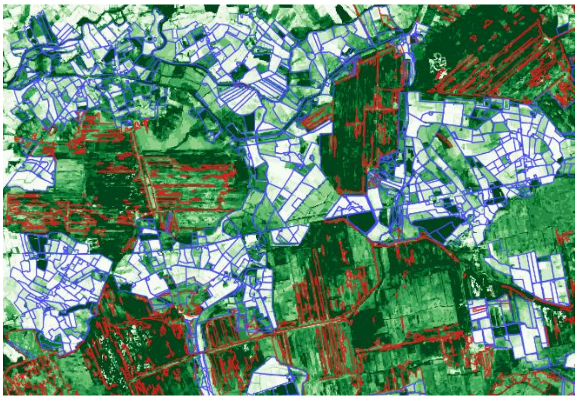
M – (mean) average value of the NDWI;

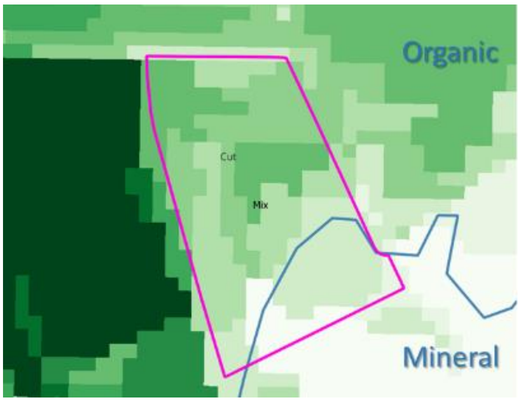
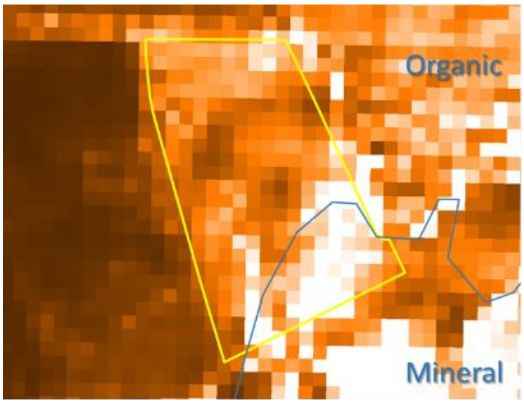
σ – standard deviation of the NDWI.

Both the mean and the standard deviation are calculated from the Level 2A product of Sentinel-2, which is atmospherically corrected.

Results obtained for test sections in Offaly and Wicklow are given below. They show that both OBIA and pixel based approaches yield similar results.

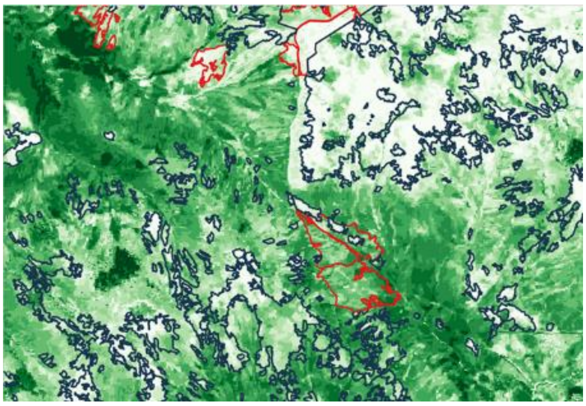
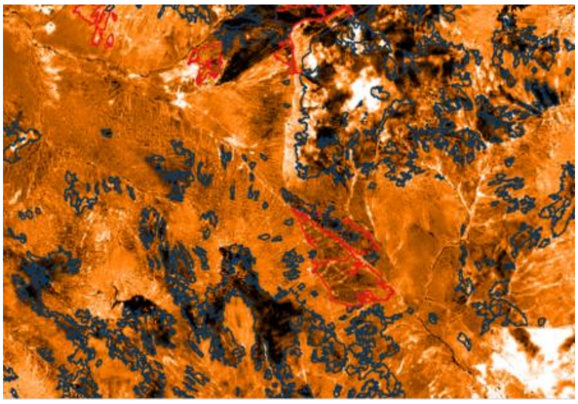
Figure 70. Results of the OBIA and pixel based approaches for detection of bare peat in Offaly.

Mean NDWI derived from 4 cloudfree Sentinel-2 observations evenly spread in 2021 (light green – high mean NDWI; dark green – low mean NDWI).	StDev NDWI derived from 4 cloudfree Sentinel-2 observations evenly spread in 2021 (light red to white – high StDev NDWI; dark red – low StDev NDWI).
	
Raster of Single-to-Noise Ratio (Mean/StDev). Almost dark areas represent the lowest SNR.	Binary mask where all pixels with SNR values lower than -6, are classified to “1”. They correspond, to a certain degree, to the bare peat mapped in the OSI land cover dataset (shown in transparent orange).
	
Multitemporal segmentation of NDWI from 4 cloudfree Sentinel-2 observations evenly spread in 2021 (light green – lower variability of NDWI; dark green – higher variability of NDWI). Dynamic range derived from LPIS polygons. Bare peat from OSI LC is outlined in red.	Multitemporal segmentation of NDVI from 4 cloudfree Sentinel-2 observations evenly spread in 2021 (light green – lower variability of NDWI; dark green – higher variability of NDVI). Dynamic range derived from LPIS polygons. Bare peat from OSI LC is outlined in red.
	

Parcels partially intersected by the organic mask. The classified image-objects from the NDWI segmentation are given in different shades of green. These covering mineral soil are with a lighter shade of green. The gradient of change between the image-object classes on both sides of that boundary is one third of the StDev of the class values in the entire scene.	Parcels partially intersected by the organic mask, overlaid with pixel-based SNR raster. Pixels covering the mineral soil are with significantly higher SNR than those of organic soil. The gradient of change between the pixel values on both sides of that boundary equals the StDev of the pixel values in the entire scene, making the difference in the NDWI behaviour more apparent compared to OBIA approach.
	

Source: SEPLA.

Figure 71. Results of the OBIA and pixel based approaches for detection of bare peat test section in Offaly.

Multitemporal segmentation of NDWI from 4 cloudfree S2 observations evenly spread in 2021 (light green – lower variability of NDWI; dark green – higher variability of NDWI). Dark areas correspond at a certain degree to the mapped cutover peat (shown in red outline) and blanket bog (in dark blue outline).	Raster of Single-to-Noise Ratio (Mean/StDev). Almost dark areas are where the SNR is the lowest. Dark areas correspond at a certain degree to the mapped cutover peat (shown in red outline) and blanket bog (in dark blue outline). The difference in the NDWI behaviour in the SNR raster is more apparent compared to OBIA approach.
	

Source: SEPLA.

3.4 Mapping of peatland areas using machine learning

3.4.1 Methodological approach

Given the potential capacity of Vegetation Phenology and Productivity parameters to discriminate the behaviour of growing vegetation on organic vs mineral soils (section 3.2.2.), a machine learning approach was explored for predicting organic soils in low input permanent pasture parcels.

3.4.2 Study area and data

The cutover peat area of Offaly was selected, as described in detail in section 3.1.1. For this purpose we identified, a total of 265 observations (22 polygons on mineral, and 31 on organic soils, with VPP parameters extracted from 2017 to 2021).

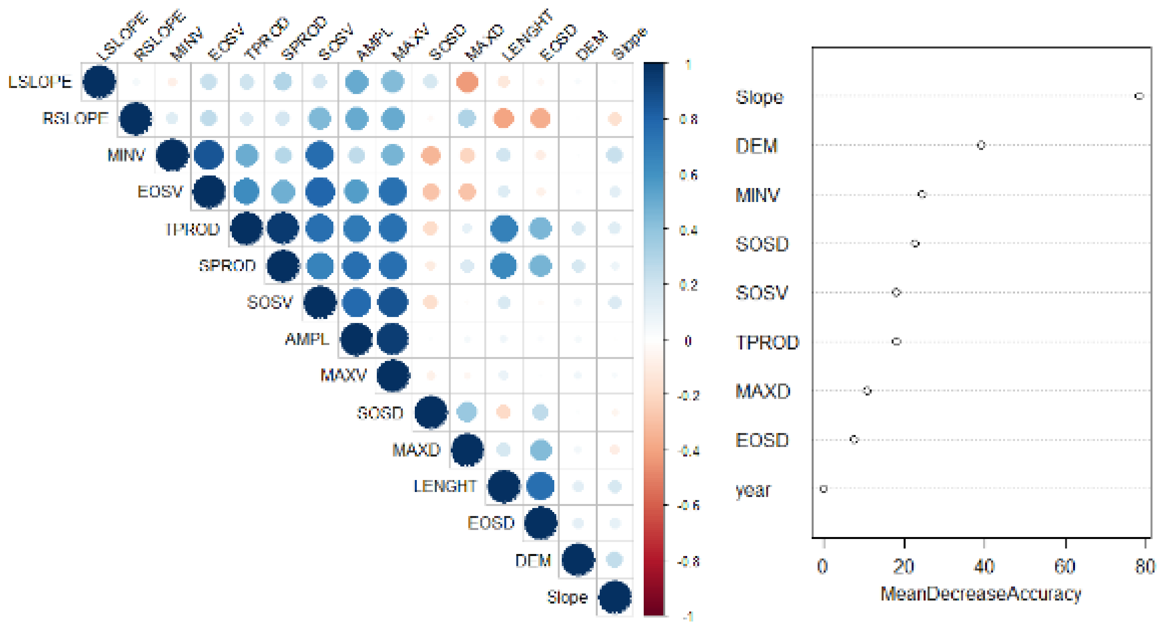
Parameters describing the terrain (DEM and Slope) were added to the dataset.

3.4.3 Methods and software used

The machine learning applied was a Random Forest from the R package (randomForest). Based on the correlation between the VPP parameters (**Figure 72**) and the Variable Importance in the model, SOSD, SOSV, EOSD, MAXD, TPROD, MINV, DEM, Slope and year were selected for the test.

The dataset was divided into Training and Validating sub-dataset of parcels, which were kept independent during the splitting procedure (about 75% of data was used for training and the remaining for validation). The cross validation was also repeated 100 times, randomly splitting the dataset at each time.

Figure 72. Correlation matrix of the parameters extracted (left) and variable importance plot of the selected variables in the Random Forest model (right).



Source: SEPLA.

3.4.4 First results

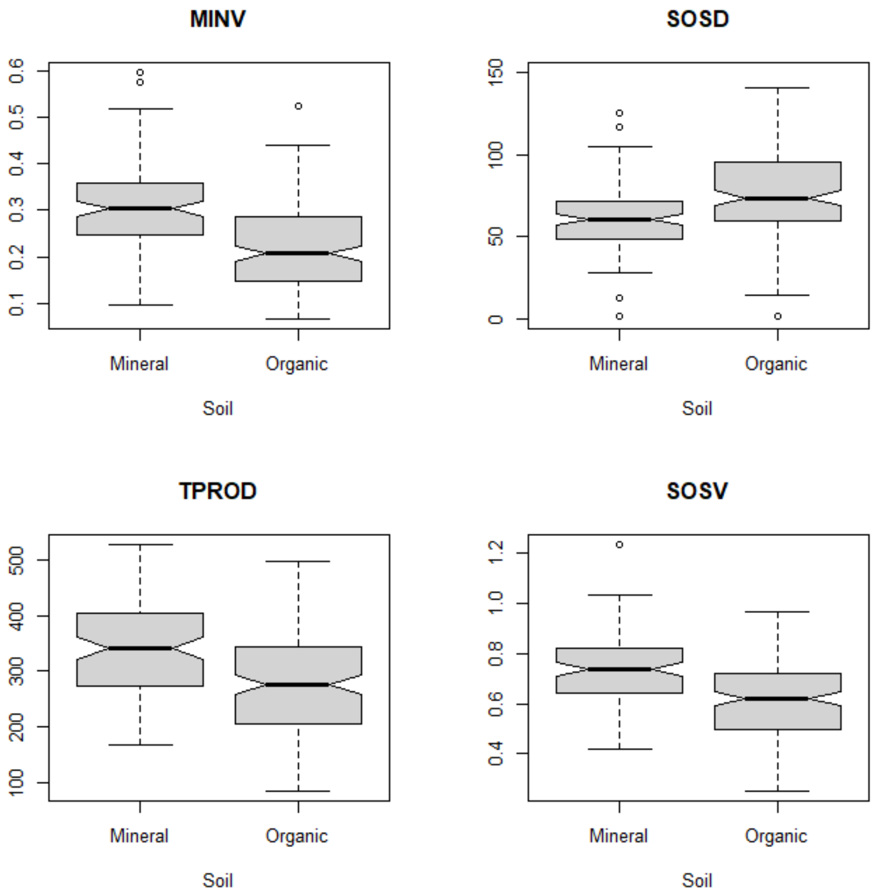
The preliminary results showed moderate performances of the Random Forest model, with an average classification error of 36% and 13% for mineral and organic parcels, respectively. The terrain contributed strongly to the model prediction, since bogs that are located in relatively flat areas had a part of their organic layer removed during the past century.

The VPP parameters minimum vegetation index (MINV), day of the start of the season (SOSD) and total productivity (TPROD) better explained the variance. The vegetation growth in organic soils seems delayed and initially lower compared to mineral soils, while cumulatively less productive (**Figure 72**).

This preliminary analysis in the cutover peat area of Offaly suggest that behaviour of the vegetation could be used to predict the presence of organic soils permanently covered. More observations are needed to build a robust model and a subsequent validation with independent datasets in other cutover peat areas is fundamental. A more in-depth analysis could aim at:

- collecting more training data,
- testing other machine or deep learning models,
- using other covariates from optical and radar signals from Sentinel,
- performing the validation in independent areas.

Figure 73. A boxplot of the VPP parameters in low input permanent pasture covering mineral and organic soils (see par 2.2.1.3 for VPP index explanation).



Source: SEPLA.

3.5 Data visualisation and exploration platform

An experimental view platform was set up to prototype a technical framework for EO-based monitoring of peatland/wetland. It is based on the technical components of the CAP Checks by Monitoring and offers an easy-to-use interface to explore the parcel level potential of Sentinel data to detect events and processes affecting peatlands and wetlands under agricultural use.

3.5.1 Platform design and implementation

The technical development of this data visualization and exploration platform used Streamlit, an open-source Python library that simplifies the process of creating custom web apps for machine learning and data science. The platform relies on the "calendar_view" Python package (https://jrc-cbm.readthedocs.io/en/latest/uc_calendar.html) to download, process, and display Sentinel-1 and Sentinel-2 data products. This package is specifically designed to operate on "parcels" provided as input. The extracted Sentinel-1 and -2 data for the specific parcels are then displayed in a "calendar view", which combines the temporal and spatial dimensions of Sentinel-derived data in an intuitive layout. Data extraction from the backend is done through the JRC RESTful API (https://jrc-cbm.readthedocs.io/en/latest/api_overview.html) which uses Flask, a lightweight python web application framework, to deal with the DIAS account. JRC RESTful service requests are handled through predefined logical query names configured with specific parameters to extract Sentinel data for all individual parcels. The result integrates front-end flexibility and interactivity with easy back-end data retrieval.

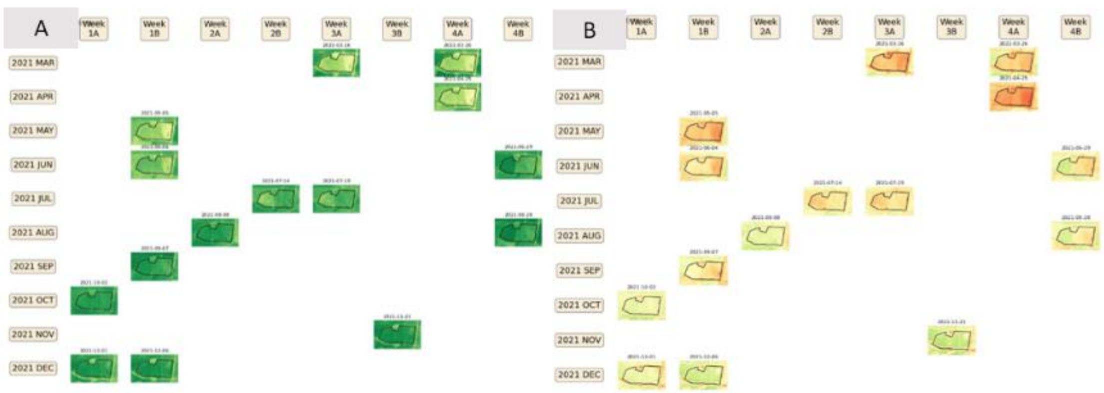
3.5.2 Data visualization examples

Visual data exploration facilitates the identification of the relevant types of information extraction and the appropriate EO data / in-situ data as well as the associated automated processing options.

The following data visualisation options are available:

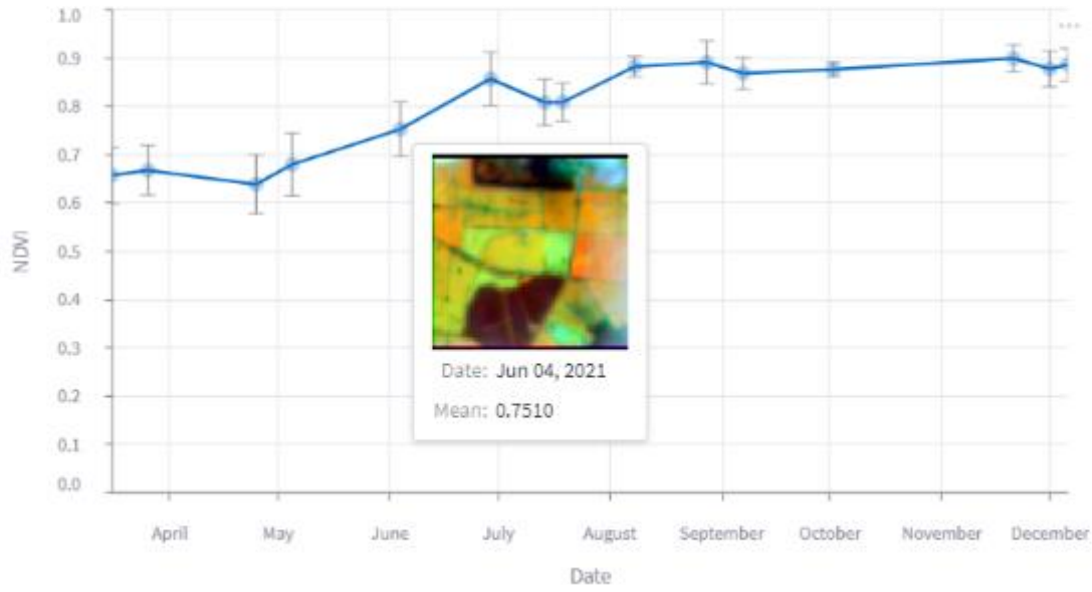
- Image time series, half-weekly Sentinel-2 based products extracts (**Figure 74**);
- Interactive plots of mean and std time series computed per parcel for NDVI, bare soil index and Sentinel-2 bands values (**Figure 75**);
- Static plots of mean and std time series computed per parcel for NDVI, bare soil index, Sentinel-2 bands and Sentinel-1 coherence and backscatter values (static pre-generated .png images);
- View of individual image extracts and enhanced products (stretched, image combinations) (**Figure 76**).

Figure 74. Example of the Sentinel-2 based time-series image extracts in "calendar view". Half weekly A) NDVI and B) Bare soil index. s.



Source: https://cap.users.creodias.eu/sepla/

Figure 75. Example of the interactive plots of mean and standard deviation time series computed per parcel for NDVI. When hovering over a point on the curve, an enhanced false colour composite image (bands B08, B11, B04) shown allowings for easier interpretation of the individual index values and for identification of unmasked clouds or cloud shadows.



Source: https://cap.users.creodias.eu/sepla/

Figure 76. Example of the interactive widget to visualise A) enhanced false colour composite Sentinel-2 image extracts (bands B08, B11, B04) and B) the corresponding Sentinel-1 backscatter. The dates of the image extracts to be displayed can be selected using the horizontal slider above each image view.

Source: https://cap.users.creodias.eu/sepla/

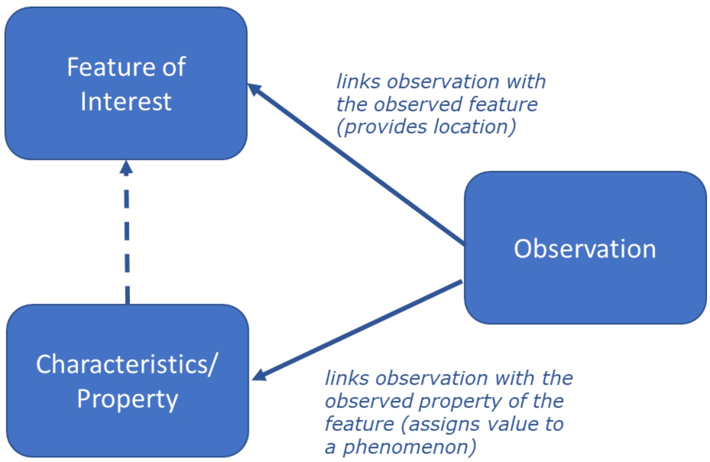
Data extracts covering the years 2021 and 2022 in Offaly and Wicklow test sites were made available for the project participants.

4 Discussion

4.1 Methodological aspects

The proposed methods and developed use cases showed the complexity of peatlands as a physical and functional entity. The question which are the most appropriate EO-based signals and tools for peatland monitoring does not have a unique answer. Different observation methods would be needed to address the various aspects and properties of the peatland. One peatland characteristic would require more than one signal and processing method. The interlinkage of the different bio-physical characteristics, their dynamics and the combined impact on a peatland's ecosystem condition and its capacity to provide ecosystem services, are even more challenging to fathom. The accelerating climate change and multiple ecological crises, where peatland plays a pivotal role, are urging the scientific and technical community to address peatland restoration in every aspect, everywhere and all at once. But holistic monitoring solutions are challenging to implement with such complex ecosystems. The monitoring system sketched in this deliverable, based on the principles of Checks by Monitoring in CAP, helps addressing such complexity by decomposition into smaller and more manageable components. This involves a controlled breakdown of the requirements, feasibility and timing, elimination of unnecessary processing and prioritizing queries into known expectations. Checks by Monitoring rely on the setup and relation of 3 key elements – the observation method, the phenomenon that reveals a property or characteristic and the feature of interest that bears that property (**Figure 77**). The success of the monitoring depends on the reliability of the observation result to estimate the value of the feature-of-interest properties.

Figure 77. Simplified representation of the relation between observation, observed property and feature of interest (ISO 19156).



Source: SEPLA, Adapted from ISO 19156, 2011.

This project showed that for peatlands, defining the spatial extent (FOI) of the peatland either as a physical entity or as unit of management is not trivial. Yet, the spatial datasets at the national level offer some appropriate FOI candidates; the most obvious sources being the wetland and soil maps. Such spatial data on wetlands often refers to functional or land use units within a specific regulatory framework, rather than to distinct physical entities; the priority in the class definition is put on ecosystem types and plant communities and a single habitat type can end up in different classes through local specifications. Soil classes are specific on soil genesis, morphology but provide certain information on the associated vegetation (**Figure 78**). The resulting confusion calls for a prior semantic assessment and data integration for the "construction" of the most reliable FOI from the available input data. Apart from the semantic meta-model of SEPLA, there are also other more generic tools available that could help EU Member States to document and deconstruct the national nomenclatures applied, such as the EAGLE model (https://land.copernicus.eu/eagle) and the LCHML tools https://github.com/cnr-stiima-vci/LCMLUtils/tree/master/lcmlutils (Mosca et al., 2020)

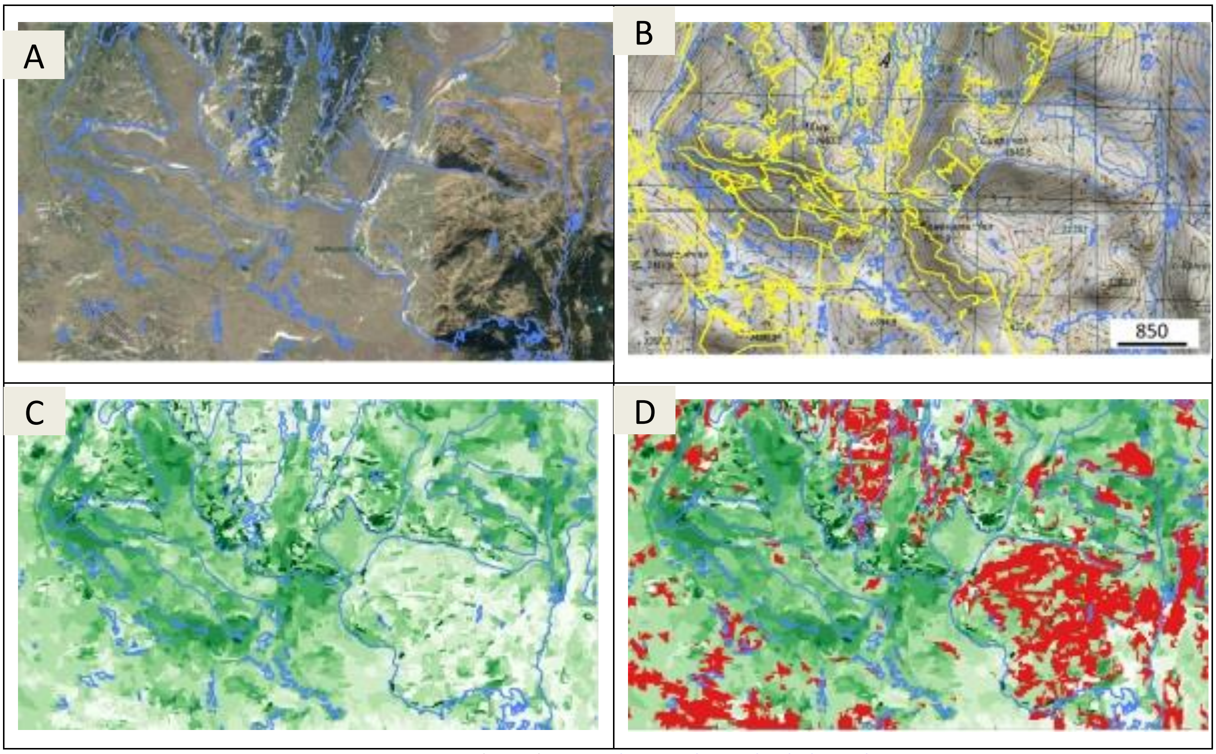
Figure 78. Statistics for the number of types of classifiers used from the semantic-meta model for describing the national wetland and soil classes of an EU Member State, participating in SEPLA

Source: SEPLA.

Another particularity of peatland monitoring is that it is defined by both the biotic substrate over the topsoil (land cover) and the topsoil itself. Change detection in the land cover, the traditional application domain of the EO, will not imply an immediate change of the peatland's FOI, because the characteristics of the topsoil are not substantially altered. Observing both land cover and soil characteristics requires an integration of remote sensing methods from both passive and active sensors, complemented by field-based observations.

On some peatlands due to their genesis, environment, location, and management, a proper establishment of a FOI and setting up of a scenario will be almost impossible (**Figure 79**). In such cases, more traditional approaches based on yearly wall-to-wall products, such as those offered by the Copernicus Land Services (CLMS), would be more appropriate (**Figure 80**).

Figure 79. A) Alpine peatlands in RILA test site, shown with a blue outline on Google Earth Imagery. B) The same peatlands shown on top of the digital national topographic map, with shaded relief. The GSA declarations from 2021 are shown in yellow outline. As seen, peatlands do not have sharp boundaries; they represent a diverse association of various physical features (lakes, outcrops, dwarf shrubs); their characteristics are largely defined by the complex topography. Large parts of the peatland are qualified as alpine grassland and used by farmers for grazing (sheep, goats). Boundaries between agricultural parcels are invisible. C) Multitemporal segmentation of NDWI from 4 cloud-free S2 observations evenly spread in 2021, evidencing the heterogeneity of NDWI behaviour within the mapped wetlands (light green – lower variability of NDWI; dark green – higher variability of NDWI). D) Areas of mean NDWI between 25 and 75 quartiles, shown in red.



Source: SEPLA and Google, 2023. http://web.uni-plovdiv.bg/vedrin/

For peatlands under agricultural management, detection of the impact of the natural and anthropogenic events (ex. farming activities) on their conditions and organic content, is largely covered by the traditional CbM setup as explained in Section 2.1.3.2 of this report.

The complexity of the processes of peatland/wetland restoration and the limitations of the earth observation data mean that specific monitoring proxies (methods) are needed to monitor restoration measures. These need to comply with the following requirements:

- use of timely and frequent data collection, spatially appropriate (in situ field observations and automatic loggers),
- mapped outputs (spatial datasets), at a scale reflecting the restoration project implementation,
- integration with other systems (CAP, designated areas, GHG inventory systems, etc.),
- compatible with IPCC AFOLU guidelines and applicable refinements, to the degree feasible.

Indicators/proxies used in the method(s) should examine: (1) land use change; (2) water levels/hydrology; (3) vegetation; (4) surface subsidence.

Ideally, a combination of these topics would lead to a systematic monitoring solution that estimates the annual flux of GHG from the monitored areas and the GHG impact of any implemented measures (certification schemes, carbon farming actions, etc).

Integrating EO/in-situ data into the modelling of adaptation and mitigation options is not trivial. It requires a prior analysis and an understanding of the concepts and semantics of land cover data in the model. Often, the data cannot be directly fed into the model, because that data does not represent a measurement of the bio-physical variable expected by that model. Instead, it offers information interpreted via a cultural or epistemological context. SEPLA provided a conceptual framework enabling the semantic disambiguation/decomposition of the land-related EO/in-situ data (Milenov et al., 2022a) and allowing for the identification and preparation of the exact data components required by the model.

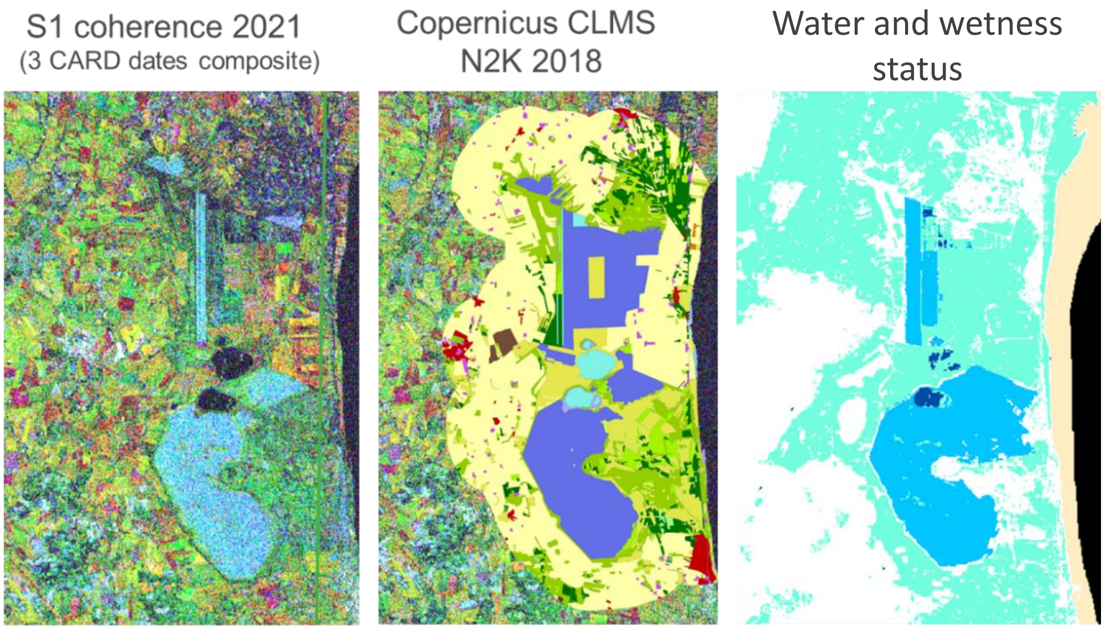
4.2 Operationalization aspects and technological challenges

At a technical level, the preservation and restoration of all agricultural land with a high level of stored carbon, including peatlands and wetlands, can be administered through the LPIS, at the level of the reference parcel. This can be achieved through an intelligent and locally tuned interaction of the different IACS spatial datasets, with other thematic information or raw data from outside. JRC has developed a dedicated methodology (Luketic et al., 2015) for integrating third-party thematic data, such as NATURA 2000. The approach is not restricted to agricultural land or CAP procedures; the methodology may also help build systems for the remuneration of land managers based on emission reductions or sink enhancement, under carbon removal certification initiatives or 'carbon farming'. This geo-localized information could support policy planning (e.g. identifying high risk areas where the action is urgently needed, establishing the baseline etc.). At the same time, it should help move towards adequate monitoring, validation and reporting of other GHG fluxes (e.g. from eco-schemes or agri-environment commitments under Pillar 2 for carbon farming). A closer synergy between these land policies is a clear gain in terms of efficiency and reducing the burden on Member States and other stakeholders.

The requirement for geographically-explicit land use conversion data (Regulation (EU) 2018/1999) and the encouragement to apply Tier 3 methodology (Federici et al., 2015), require a higher technology uptake for monitoring the net climate impacts of and on land use, forestry and agricultural sectors. This uptake aligns with that of Earth observation programs like GEOSS and Copernicus. The relevant methodologies and achieved results could be compared with the large dataset of surface observations available (e.g. LUCAS and IACS). The benefits of the IACS in the context of LULUCF could be further capitalized upon when deployed as in-situ data during the development and validation of specific products based on EO and GNSS technology.

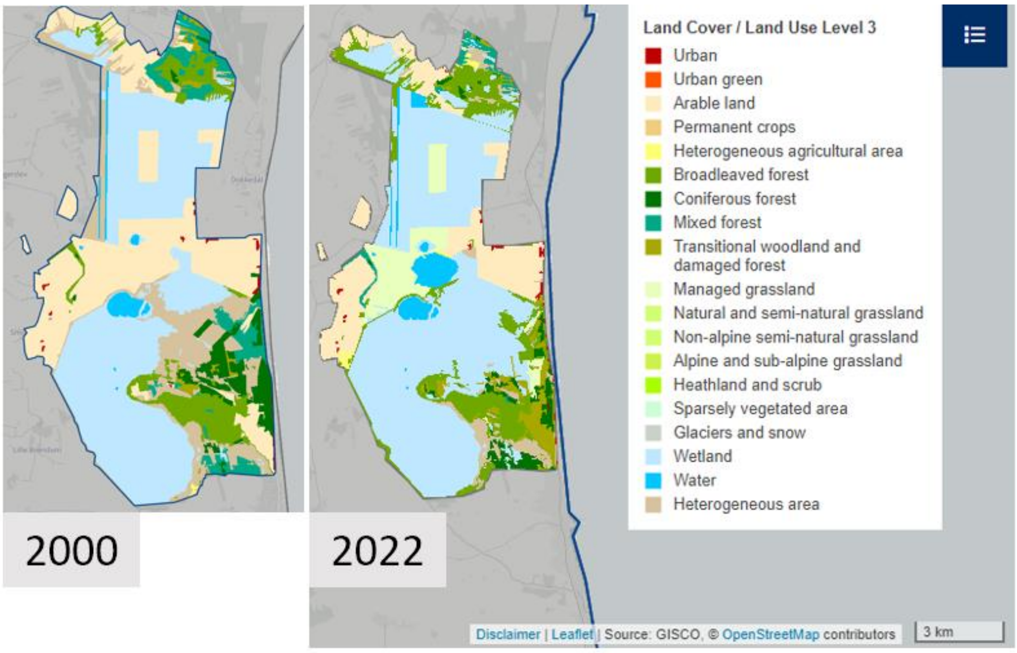
Remote sensing, as a non-disruptive method, offers the possibility for detecting and characterising peatland ecosystems, and for monitoring their dynamics. The best results may be obtained when several techniques and methods are combined (Minasny et al, 2019; Dronova, 2015). Several thematic Copernicus Land Monitoring Service's products and web tools exist that could provide ancillary information on the peatland, i.e. the N2K 2018 dataset, the Water and Wetness status data or the Grassland Watch web tool (see **Figure 80** and **Figure 81**). Due to the early start of operations, CLMS could help also peatland monitoring by providing historic trends and possible benchmarks.

Figure 80. Examples of ancillary data sources for mapping peatlands and wetlands: Sentinel-1 coherence data, N2K 2018 dataset and the Water and wetness status products depicting the area of Lille Vildmose in Denmark.



Source: CARD produced in JRC CbM Outreach project, N2K 2018 and the Water and wetness status dataset provided by the Copernicus Land Monitoring Services.

Figure 81. Lille Vildmose in Denmark in 2000 and 2022 mapped in the Grassland Watch (prototype) web tool providing access to time series graphs of key indicators for selected grass-dominated Natura 2000 sites (also known as N2000 or N2K).



Source: https://bm-eugis.tk/cop4n2k_app/

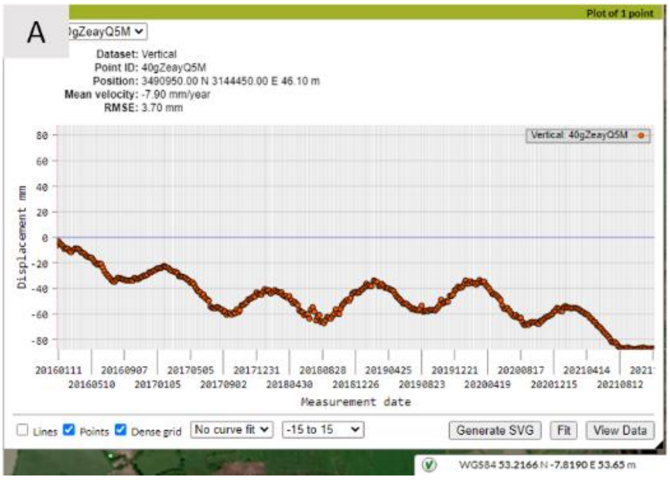
As shown in section 3.2.1, the European Ground Motion Service is not suited to provide suitable data in areas with a lack of stable points which serve as persistent scatterers to track the surface movement (i.e. inundated areas, agricultural land). Nonetheless, some surface motion measurement points can be found in areas with semi-natural vegetation or in intact bogs, presuming that vegetation has very low seasonal dynamics. An example of such data is shown in box 5 below.

In remote sensing-based methods for land monitoring, and especially satellite-based methods, the presence of clouds and cloud shadows in images can be an issue, especially in cloudy regions, where rainfed peatlands are located. The frequent presence of fog and haze above wetlands and humid areas may additionally limit the number of images suitable for surface reflectance measurements and modelling behind indices of other products. Although cloud cover and cloud shadow detection algorithms are constantly being improved, the effect of their omittance is still cumbersome and prevents seam-less, fully automated time series analyses (Zhou et a., 2020). With the slow pace of the land cover changes in peatlands, the requirements linked to temporal data frequency may be less stringent than in the case of monitoring of agricultural practices, where weekly observations are a minimum to date practices. Still, with temporarily sparse observations, some markers may be missed or detected with delay. Snow cover and other local disturbances in the time series of Sentinel-2 and Sentinel-1 data should also be considered.

Cumulative vegetation indices such as the Vegetation Phenology and Productivity which are annually derived from multi-date Sentinel-2 data, are suitable if only targeted events and activities l occur during the actual period when observations are cumulated. For example, on grasslands under management, grazing or mowing is expected. These practices will result in an “artificial” decrease of the biomass and thus influence the VPP value, as well as any object-oriented image analysis based on them. Hence, the VPP values on managed grassland are only meaningful in designated areas where the land use is restricted, e.g. when grazing is allowed only during the short window.

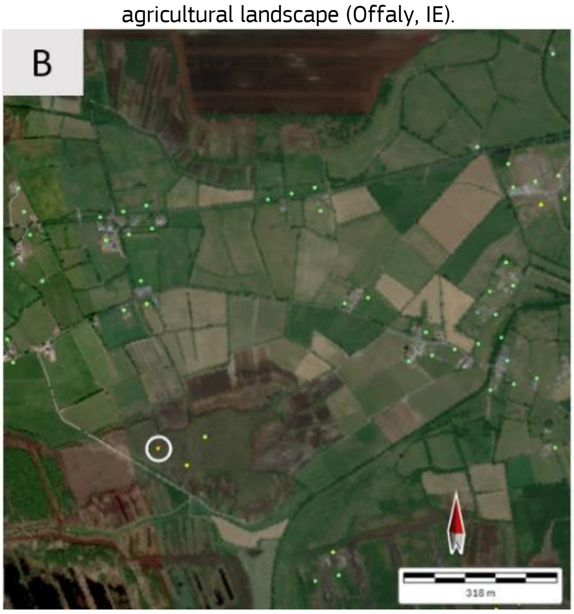
Box 5: An example of InSAR surface motion data in the assessment of the peatland state

An example of a vertical surface displacement in time for a point on raised bogs in Offaly, IE (point marked with a white circle in B).



The data presented in figures A and B represent a point located within the cutover peat class (modified peat: cut or drained raised or blanket bog) of the soil data and within the Intact peat bogs class of the Ordnance Survey Ireland (OSI) land cover data, defined as "intact, high bog/dome sections of a raised bog complex, containing sphagnum moss vegetation species". According to this class description, such areas are typically surrounded by an area of cut/degraded peat and may be subject to internal or peripheral drainage assuming that although drained transition to another landcover type has not yet begun.

The EGMS grid points (Ortho, Level 3) in the managed agricultural landscape (Offaly, IE).



The surface motion data indicate a drying out of the area during 2016 and 2017 (negative surface motion velocity and subsidence of the surface by around 20mm yearly. In 2018 and 2019 the surface velocity is close to zero (with very small positive values of the surface velocity, but at the level of the data RMSE values), suggesting the state of the peat was relatively stable. In 2020, after the minimal water content during the summer, the surface did return to the altitude of the previous winter and so another surface subsidence was observed at the level of -20mm. This behaviour can be at least partially explained when looking at the historical weather data from a weather station in the area (see **Figure 46**). The year 2017 was dry and relatively warm causing fast drying out (minimal water level around the end of August) and with a shortage of rainfall, the peat layer was not able to return to its previous state resulting in surface subsidence. That is partly linked to the relatively quick pace of changes in vegetation composition in drought conditions, where vascular plants replace Sphagnum mosses and decrease the capacity of the ecosystem to retain water (Mäkiranta et al, 2018) and build new biomass.

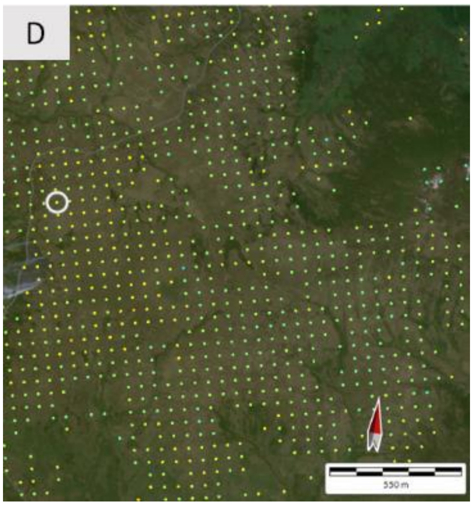
In 2018, the cumulative rainfall was not much higher than in the previous year, but the temperatures were lower. In 2019 and 2020 the rainfall was higher still and with the lower air temperatures and the peat reverted to its maximal surface level at a time of the maximum water retention (around February). Increased biomass production is suggested by very small positive values of the motion velocity, even if within the data RMSE. High temperatures in the summer of 2020 and a dryer end of that year resulted in the peat shrinking again. As a result, the level of the peat surface at the time of maximal water retention around the end of February 2021 was 60 mm lower than in February 2016.

A similar drying-out effect can be observed in the EGSM data for a point located in blanket bogs in Wicklow and represented in figures C and D. There are however differences between the two sites: the velocity of the surface motion and the seasonal amplitudes of the surface motion in the raised bog in Offaly are much higher than in the blanket bog in Wicklow. Furthermore, the timing of the extrema of the surface motion in the year is different: the maximum water retention point, when the peat surface reaches the highest level, falls around February for the raised bog in Offaly and December/January for the blanket bog in Wicklow. These differences can be explained by the difference in peat layer thickness, in bulk density and in preservation state. The area of intact raised bog in Offaly is dominated by Sphagnum species indicating wet soil condition (shallow ground water table). The area in Wicklow is more degraded due to former bog-cutting activities and is covered by vascular plants with isolated patches of Sphagnum mosses, indicating a deeper groundwater table. The Wicklow site drainage and degradation are confirmed by the inter-seasonal surface level oscillations that appear to be out of phase (Alshammari et al., 2020).

A more in-depth analysis of this case study cannot be done and validated without ground data. Geotagged photos could confirm the land cover status, measurements of the ground water table depth and the daily meteorological data the observed the surface motion.

An example of a vertical surface displacement in time for a point representing blanket bogs in Wicklow, IE.

The EGMS grid points (Ortho, Level 3) in the semi-natural grassland (Wicklow, IE).



Source: EGMS data viewer.

With the complexity of the peatland ecosystems and their heterogeneous nature, all remote sensing methods should be calibrated and validated with appropriate ground data. Detailed studies of restoration sites that need more precise mapping than what is provided by the Copernicus services, can rely on multispectral, hyperspectral and lidar data from aerial- or drone-based platform. Photogrammetric techniques can produce accurate digital surface models from images (RGB) captured by drones (Pakalne et al., 2021).

The extrapolation of results from one site to another should be done with due care. Optimisation of the methods and monitoring system parameters may be required for each individual site.

4.3 Peatland management

Peatlands as ecosystems provide a range of ecosystem services, such as carbon storage, water regulation, and biodiversity conservation and constitute a unique biological, environmental and economic resource. Their management should safeguard their environmental, social and economic functions and respect their local, regional and global services (Clarke et al, 2019).

This requires that strategic objectives and actions for implementation are set on a scale larger than national. The European Commission proposed a set of legally binding targets for all Member States to restore wildlife on land, rivers and the sea in the proposal of the Nature Restoration Law published in June 2022. The proposed peatland restoration targets are set in Article 9(4):

"For organic soils in agricultural use constituting drained peatlands, Member States shall put in place restoration measures. Those measures shall be in place on at least:

(a) 30 % of such areas by 2030, of which at least a quarter shall be rewetted;

(b) 50 % of such areas by 2040, of which at least half shall be rewetted;

(c) 70 % of such areas by 2050, of which at least half shall be rewetted.

Member States may put in place restoration measures, including rewetting, in areas of peat extraction sites and count those areas as contributing to achieving the respective targets referred to in the first subparagraph, points (a), (b) and (c).

In addition, Member States may put in place restoration measures to rewet organic soils that constitute drained peatlands under land uses other than agricultural use and peat extraction and count those rewetted areas as *contributing, up to a maximum of 20%, to the achievement of the targets referred to in the first subparagraph, points (a), (b) and (c)."*

A debate between the ecologist and the peatland users is still ongoing. Drained peatlands are used not only for agriculture but also for forestry and peat extraction for energy production (albeit in small areas). On one hand, strict nature conservation may impact the local socio-economic situation. On the other hand, ecologists call for the extension of legally binding requirements of rewetting and for increased percentages of land use other than agricultural (European Habitat Forum, 2022).

The conflicts between protection and production usually result in "win-lose" situations with the more powerful stakeholders as winners. One such example could be the widely spread practice of peat extraction for energy or horticulture that doesn't consider peatland conservation issues or preparation of post-extraction plans (Joosten, 2002). There can also be "lose-lose" situations in which all stakeholders lose, for example, the Indonesian Mega Rice Project commenced in 1996. "The project is now referred to as one of the biggest environmental disasters in Indonesia's history, not only because it enabled massive peat fires but also because the project—the objective of which was large-scale irrigated rice cultivation in the peat swamps—produced almost no rice." (Goldstein, 2016) This project was abandoned two years after it started, after the drainage of 1.2 million hectares of wetlands, mostly peatlands. Approximately 0.5 million hectares of tropical peat swamp forest were destroyed and investments of $US 500 million were made (Joosten, 2002). The amount of carbon released from drained peat fires in successive years has made Indonesia one of the world's largest CO_2 emitters (Hooijer et al., 2006).

The pressure to simultaneously preserve and use peatlands for production is greater than ever before. The growing demand for agricultural land leads to land clearing and drainage of peatland areas; the awareness of the global environmental problems caused by deforestation and greenhouse gas emissions increased the calls for peatland conservation. The balance between conservation and production may be optimised by an integrated approach to planning and management based on sustainable use principles. All the stakeholders should work together to develop a landscape scale site management plan (suitable to build a land monitoring scenario – see section 2.1.3), that considers the economy, the local society and culture, the rehabilitation of the degraded peatland and efficient implementation of policies (Safford et al., 1998).

With increased wildfire frequency and severity observed on a global scale and expected to grow (Nelson et al., 2021), land management plans should also involve fire prevention methods, especially in peatlands. All levels of fire prevention should be considered from education and marking the site with "high-risk of fire" warning signs, through the construction of physical barriers for the fire such as shallow dikes filled with bare mineral soil, rocks, water or a fire break around the peatland site (Nelson et al., 2021), to hi-tech fire detection systems. When historic data to track the status of peatland evolution and restoration is lacking, one possibility (as shown in Section 2.1.3.4) to assess a peatland's health and restored capacity is the speed of its response to shocks, such as fires or droughts.

The various LIFE Strategic Projects undertaken in different EU Member States are a great source of information about the practical solutions, the controversy and the challenges linked with the implementation of the EU policies on biodiversity, climate change, and environmental sustainability. Some offer examples of excellent restoration project summaries and lessons learned: Mackin et al., (2017) or Pakalne et al., (2021).

In their recommendations for the EC proposal of the Nature Restoration Law the NGO European Habitat Forum (2022) recommended setting up a mandatory system of peatlands restoration to monitor the long-term biodiversity and climate benefits of the measures. Feedback from such monitoring systems could improve or optimize the land management and restoration practices on peatlands. To date, not all, often very costly, peatland restoration efforts have been fully successful (e.g. at Cloonshanville Bog). Monitoring investments need to be planned and designed carefully over a long-term horizon (Pakalne et al., 2021, Mackin et al, 2017). The observations and concepts provided in this document aim to constitute a prototype of such a land monitoring system.

4.4 SEPLA’s lessons learnt

4.4.1 Technical

It came as no surprise that peatlands are complex ecosystems, influenced by vegetation, soil, topography and water. The main message of this report is that their effective monitoring requires the adoption of **novel EO-based solutions, supported with local ground data and context information**, that go beyond the classical land cover mapping and change detection approaches.

This complexity implies that there will be **no likely off-the-shelf monitoring solution**, so local tuning or developments will be inevitable. The extrapolation of results from one site to another should be performed with due care. Despite the promising case study results, remote sensing analyses remain challenging and the best results are likely obtained when several techniques and methods are combined. Regional-based approaches that rely on local contextual information and use tailored EO-based solutions or Copernicus downstream services are needed.

Where the nature and location of the peatland do not allow the application of feature-based frameworks (e.g., Checks by Monitoring), more traditional wall-to-wall products, like those offered by the CLMS could be investigated, i.e., the N2K 2018 dataset, the Water and Wetness status layer, Resolution Vegetation Phenology and Productivity, etc. Additional input can come from dedicated habitat mapping and monitoring projects and initiatives, such as EU Grassland Watch, Biodiversa+ or EuropaBON

Specific monitoring proxy methods are needed to monitor the restoration or preservation state. These should comply with the following requirements:

- use of timely and frequent EO-based data collection, spatially appropriate,
- reliance on in-situ spatial datasets at a scale reflecting the restoration or preservation project implementation,
- integration with other systems (CAP IACS, monitoring of habitats and designated areas, GHG inventory and reporting, and others),
- compatibility with IPCC AFOLU guidelines and applicable refinements when feasible.

Indicators and proxies used in the method(s) should examine: (1) land use change, (2) water levels and hydrology, (3) vegetation and (4) surface subsidence.

Ideally, a combination of these topics would lead to a systematic monitoring solution that also contributes to the annual flux estimations of GHG from the monitored areas and the GHG impact of the implemented measures (under certification schemes or carbon farming actions).

Detailed studies of restoration sites may need more precise mapping than what is provided by the Copernicus services. Regular aerial- or drone-based multispectral, hyperspectral and lidar data may be needed, provided the budget allows. Alternative to the lidar data, digital surface models may be derived from existing aerial- or drone-based images using photogrammetric techniques.

From a technical perspective**, preservation and restoration of all agricultural land with a high level of stored carbon,** including peatlands and wetlands, can be managed through the LPIS reference parcel. This involves some interaction of the different IACS spatial datasets, with other thematic information or with raw data from external sources. Such an approach is not technically restricted to agricultural land or CAP procedures. A similar methodology may help the build-up of systems for the remuneration of land managers for emission reductions and sink enhancement under carbon removal certification initiatives or for ‘carbon farming’. This geo-localized information could support policy planning (e.g., identifying high risk areas where the action is urgently needed or establishing the baseline).

For peatlands under agricultural management, the impact assessment of an occurring event (excluding. farming activities) on soil conditions and organic content, could be largely covered by extending a Checks by Monitoring setup.

4.4.2 Organisational

Effective peatland management and monitoring requires the engagement of and coordination among the different actors both at the national level (agricultural and environmental administration, mapping agencies or research institutes) and at the level of local stakeholders and managers. This diverse community of practice is essential for the uptake and the appropriate tuning of novel technology because it alone can address critical success factors such as ground data access and transfer of know-how. Research and support activities at the European level could ensure a level of standardisation and validation of EO components and would help shoulder development costs.

SEPLA has been set up as a project in the traditional sense, with clear boundaries on time, staff and scope. The complexity of the topic put strains to these resources. Community building could receive more attention for future initiative.

5 Conclusions

Peatlands and wetlands are hot topics because of their role in biodiversity conservation and carbon capture and storage. Remote sensing promises timely detection of changes, early identification of areas at risk and input for effective decision-making on conservation and restoration efforts. Earth observation-based monitoring will be critical for accounting systems that measure environmental changes in an explicit geo-spatial manner, e.g., the UN ecosystem accounting framework (SEEA EA) and the EU LULUCF Regulation.

A critical element of peatland monitoring is the appropriate definition and delineation of the geographic extent of the peatland as a physical and functional entity. SEPLA adapted the Checks by Monitoring (CbM) concepts to provide a methodology for the identification of a relevant spatial perimeter (feature of interest) through processes of standardized semantic assessment and spatial integration of the national datasets.

The proposed peatland monitoring technical framework addresses the peatland complexity by breaking down issues into manageable components that were individually tested, and by prioritizing their processing according to a site's information needs. It also helps to disentangle the peatland's natural variability from effects of management practices.

SEPLA investigated several promising satellite sensors and satellite-based techniques on their ability to provide information on peatland status and evolution, as well as on the suitability for mapping peat soils. No single method offered a panacea, and the more effective candidate solutions for an individual peatland classification and delineation should be evaluated on a case-by-case basis. Any resulting selection will be more performant in combination with other EO solutions. Ground data are always needed to calibrate and validate those EO methods; products provided by the Copernicus Land Monitoring Services can offer valuable ancillary information.

Where most of the events and processes on peatlands are driven by farming activities, synergy with the current agricultural monitoring systems of CAP is obvious. Thanks to their tiered and modular design, parcel-based CbM-implementations can be tailored and adapted to country-specific peatland policies.

The objective of this project was to describe the concept of and outline common elements in a prototype for a peatland monitoring system. An operational and workable implementation based on that prototype should be individually developed to accommodate local needs and specificities.

The project interacted with 60 experts, covering a broad range of competencies and affiliations, although most experts operated at the national rather than local level. The experts appreciated the pragmatic solutions and collaborative approach during the project's webinar.

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List of abbreviations and definitions

CAP	Common Agricultural Policy
CbM	Checks by Monitoring
CLMS	Copernicus Land Monitoring Services
EEA	European Environment Agency
DEM	Digital Elevation Model
EC	European Commission
EO	Earth Observation
EU	European Union
GAEC	(Standards for) Good agricultural and environmental condition of land
GHG	Green House Gases
GSAA	Geospatial Aid Application
GTCAP	Guidance and Tools for CAP
GWT	Ground water table level
IACS	Integrated Administration and Control System
IPCC	Intergovernmental Panel on Climate Change
JRC	Directorate-General Joint Research Centre of the European Commission
LCML	Land Cover Meta Language
LPIS	Land parcel Identification System
LULUCF	Land use, land-use change and forestry
LUML	Land Use Meta Language
MMU	Minimum Mapping Unit
MS	Member State
NDVI	Normalised Difference Vegetation Index
WDWI	Normalised Difference Water Index
PA	Paying Agency
PPI	Pland Phenology Index
RMSE	Root Mean Square Error
RS	Remote Sensing
SEEA EA	System of Environmental-Economic Accounting— Ecosystem Accounting
SEPLA	Satellite based mapping and monitoring of European peatland and wetland for LULUCF and agriculture
SOC	Soil organic carbon content
UML	Unified Modelling Language
VPP	Vegetation Phenology and Productivity

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