Masterarbeit im Studiengang Environmental Management

Degradation, succession, and regeneration processes in the raised bog *Königsmoor*

Classification of vegetation indicators with UAV data

vorgelegt von

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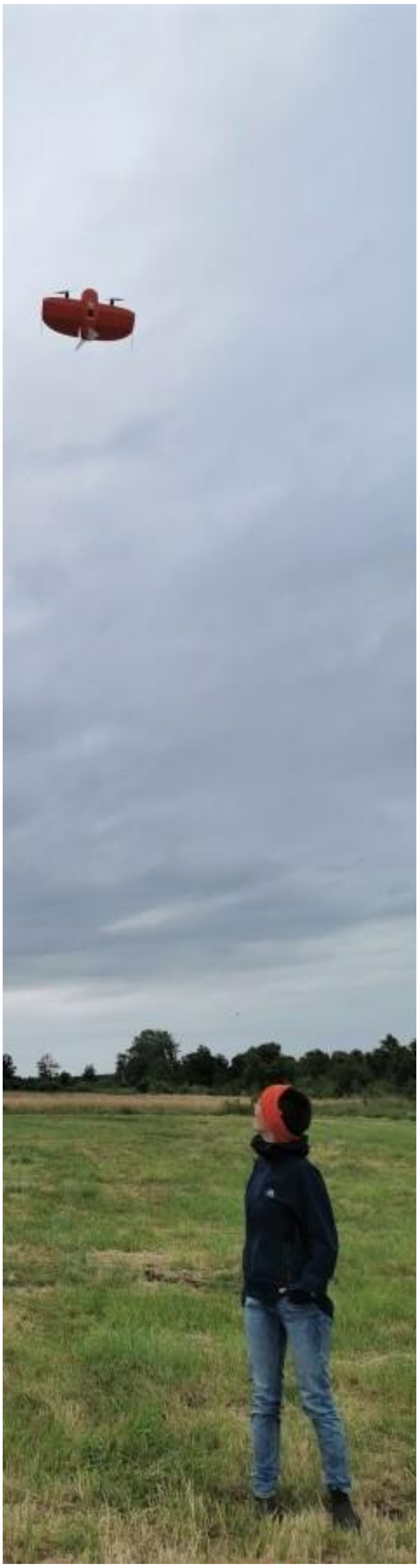

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Abbreviations

AGL	Above Ground Level
CHM	Canopy Height Model
CIR	Color Infrared
DSM	Digital Surface Model
DTM	Digital Terrain Model
ETS	Eider-Treene-Sorge
EU	European Union
FFH	Flora Fauna Habitat
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSD	Ground Sample Distance
LWIR	Longwave Infrared
NDRE	Normalized Difference Red Edge Index
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared
OA	Overall Accuracy
PA	Producer's Accuracy
PPK	Post-Processed Kinematic
RENDVI2	Red Edge Normalized Difference Vegetation Index
RGB	Red, Green, Blue
RINEX	Receiver Independent Exchange Format
SH	Schleswig-Holstein
SNSH	Stiftung Naturschutz Schleswig-Holstein
SPA	Special Protection Area
UA	User's Accuracy
UAV	Unmanned Aerial Vehicles
VI	Vegetation Indices

Abstract

Raised bogs in Schleswig-Holstein have a long history of transformations. Their vegetation has been impacted by melioration processes, peat cutting and conservation measures within the last centuries - vegetation composition and - patterns result from these influences. By developing an indicator set using mainly vascular plant species and associations as an indicator for degradation, succession, and regeneration this thesis aims to complement the existing knowledge of the condition of the raised bog *Königsmoor* in Schleswig-Holstein (Germany). Therefore, on an area of 337 ha data has been collected using an UAV equipped with a multispectral camera. The 5 spectral bands of the camera, calculated vegetation indices and the calculated CHM, together with the mapping of vegetation coverage of 13 plots, form the data basis of this work. In an iterative process 10 400 reference points have been set for 18 species and three plant associations by localizing them in the fields and on the high resolution orthophotos. A Random Forest classifier was trained to perform an automatic classification resulting in a classification- and a health condition map of the *Königsmoor* with different stages of degradation, succession, and regeneration. The critical discussion of the results reveals that, even though the validation shows overall very good results of 89.6 % OA, single classes are overestimated or underestimated. Limitations are mainly resulting of the inadequate distribution of reference points over the entire area and in consequence an overfitted classifier. Degrading areas show very good results, although for heathland areas this only applies to the immediate vicinity of the reference points. Even structures on the smallest scale, indicated by plant species adapted to small gradients of moisture, can be detected from the UAV data. For the grassland and succession areas good results can be achieved, especially with regards to succession stages and its structural changes or usage of an area. Vegetation cover of rewetted areas is difficult to capture by the classifier. The study concludes that if area and research question are wisely matched and selected, UAV can make an impressive contribution to the classification of vegetation and monitoring processes in the *Western Königsmoor*. The method is capable to draw conclusions on the condition of the ecosystem in terms of degradation, succession, and regeneration processes. It can therefore be the starting point for the development of a practicable tool to enable the monitoring of sensitive FFH-areas demanded by the EU, helping to advance the future of bog protection in Schleswig-Holstein.

1 Introduction

In the beginning of the 19^{th} century, 10 % of Schleswig-Holstein (SH) has been covered with mires (LLUR, 2015: 7). Since then, fens and raised bogs have been subject to different transformation processes as lowering water levels by draining, melioration and peat cutting.

Raised bogs are a characteristic landscape type of the Geest region in SH. They form habitats for several highly adapted and protected species of flora and fauna, cushion water balance after heavy rain fall events and, if intact, contribute to natural climate protection due to their carbon storage capacity (LLUR, 2015: 33 ff., 61 ff., 78 ff.). Efforts to protect these sensible habitats have been made since the 1970's and especially in the last decades it has been tried do stop degradation of these through conservation measures and rewetting (ibid.: 27).

The vegetation of this special, water-rich and nutrient-poor habitat type depends strongly on its former use, in terms of agricultural use and of protection measures alike (Irmler et al., 1998: 168). The bog`s water balance and its nutrient input influences its vegetation (Müller-Kroehling et al., 2019: 264–269; Steiner, 2005: 36–38) so that a large-scale vegetation analysis allows conclusions to be drawn on the functionality of protection measures as rewetting, or different degrees of degradation.

In the *Königsmoor* of SH regular monitoring of vegetation development in areas where measures have been applied is necessary to verify their success (Ausgleichsagentur Schleswig-Holstein GmbH, n.d.: 24). In this context, in inaccessible terrain such as raised bogs (being at the same time sensitive to tread (Manderbach, 2020)), the use of unmanned aerial vehicles (UAV) could make a significant contribution to the recording of various parameters of nature conservation interest (Hecke et al., 2018: 429-436).

This thesis aims to show possibilities and limits of the use of UAV for the classification of vegetation and monitoring of measures in the *Western Königsmoor*. Vegetation can be a depiction of a development which is not directly accessible. The vegetation indicator is easy to interpret, reacts sensitive to management or changes in conditions and the use of UAV aerial images data promises good data availability. With regards to possibilities for monitoring approaches it shall be reviewed whether the classification method is suitable to give conclusions about the degree of regeneration or stage of degradation of sub-areas, based on the plant species and associations distinguished, following the leading questions:

- To what extent can the use of UAV contribute to the classification of vegetation and monitoring processes in the *Western Königsmoor*?
- Is the method capable to capture the reflectance values of the species relevant for assessing the condition of this ecosystem in terms of degradation, succession, and regeneration stages?
- What are weaknesses and limitations of this method and is it practicable in the future of bog protection in SH?

To answer these questions, an area of the size of 337 ha including different combinations of rewetted areas, protection status, biotope types (for example extensive used permanent grassland, fallow land, heathland) and cultivation history was studied. Vegetation cover of 13 plots was estimated and their plant associations were determined. Training data for the following automatic classification was generated either of dominant vegetation stands, or, in cases of a heterogeneous vegetation cover, of random chosen points within the association. In total 10 400 reference points (training data points and validation points) were set for 23 classes, which were assumed to indicate degradation, succession, and regeneration processes.

In a second step the area was flown by an UAV (WingtraOne, Switzerland) equipped with a multispectral camera (MicaSense Altum, USA) and a high resolution red, green, blue (RGB) camera (Sony QX1 Professional, Japan). Thereby data of six reflectance bands was collected. Vegetation indices (VI) and a canopy heights model (CHM) were calculated and the training data points were used for a pixel-based input data generation. This input data was used as training data for the Random Forest machine learning algorithm to classify the vegetation of the entire 337 ha. The final result shows a map of the different degradation, succession, and regeneration stages of the *Western Königsmoor*.

In this thesis the study area is described with regards to its special- and historical context (Chapter 2.1 and Chapter 2.2); including the transformation and protection measures applied. Chapter 2.3 gives a detailed overview on the sub-areas and their background. An introductory description of the vegetation of a raised bog is given in Chapter 2.4. Applied methods, in terms of the vegetation survey (Chapter 3.1) and the UAV data collection and post processing (Chapter 3.3), follow. Results are subdivided in the description of the vegetation cover per plot, leading to the generation of input data in form of reference points (Chapter 4.1) and actual results of the automatic vegetation classification and their precursors (Chapter 4.2). The input data is described including their spectral signature per class (species or association). Furthermore the validation is presented in from of a confusion matrix, the classification results are presented in line with the input data for four selected areas and a health map is presented, giving an overview on the conditions of the bog. The results are discussed in detail in Chapter 5, mentioning the limitations of the applied method, the classification results of the individual classes, their function as indicators for the assessment of the succession, degradation, and regeneration stages and the resulting conflicts in the management of the area. In Chapter 6 conclusions concerning the three leading questions are drawn.

2 Context and embedding of the study area

2.1 Special context – formation and location of the raised bog

The study area of this thesis on possible use of UAV for vegetation classification and monitoring processes is the northwestern part of the *Königsmoor*, a rainwater fed raised bog in SH. The bog is located in the 160 000 ha large *Eider-Treene-Sorge* (ETS) lowland, a region on the *Geest*, a moraine landscape formed by periglacial processes (Liedtke and Marcinek 1995: 305; Stewig, 1978: 28, as cited in Mansfeldt, 2003: 9). The bog has formed on the outwash plains of the lower *Geest.* Its development is attributable to glacial sands deposited in the lowlands of the Weichselian- and Saale glaciation by meltwater outwash (ibid; MELUR, 2016: 7). The former expansion of wetlands in this area can be recognized in the representation of the peaty mineral soil expansion[1] (Figure 1). This covers soils in which within the uppermost 40 cm a horizon of at least 10 cm thickness with a minimum of 15 % humus occurs (LLUR, 2020). The peaty mineral soil expansion indicates the existence of former mires, covered by other landscape types now. The percentage of peatland in SH is, with almost 10 %, the third highest of all federal states in Germany (Schütrumpf, 1956, as cited in LLUR, 2015: 16). The major share of these areas is located on the Geest (Burbaum, 2014, as cited in LLUR, 2015: 18; MELUR, 2016: 7; Succow and Jeschke, 1990: 128).

Raised bogs, which are exclusively rainwater fed and therefore very poor in nutrients, made originally up for 46 000 ha, while fens, which have access to ground or surface water and are therefore nutrient-richer, covered about 130 000 ha (Dierßen, Gesellschaft für Schleswig-Holsteinische Geschichte, 2020). Within the 19th century, 3 000 km^2 of mires in SH have been transformed into cultivated agricultural land, a process which was ongoing until the middle of the 20th century (ibid.). Today all mires in SH have been influenced by humans during the last centuries. 35 600 ha are mapped as mire biotopes, with 30% of them categorized as degraded (MELUR, 2011: 7). As a consequence of draining the mires, the typical vegetation is vanished, invasive species are colonizing the habitats and the former peat accumulating soils are degraded (LLUR, 2015: 143).

Before melioration, the area of the ETS lowland was an ample region of mires, their remains are now scattered in a loose network. This larger setting of wetlands, bogs and grassland forms the region with the existing mire complexes of *Königsmoor, Prinzenmoore, Hartshoper Moor, Dellstedter Moor, Südermoor, Tielener Moor, Alte Sorge Schleife* and *Tetenhusener Moor* as characterizing marks of the landscape (Staatskanzlei SH, 2016) (Figure 1).

[1] German: "*Anmoorkulisse*" according to DGLG (Dauergrünlanderhaltungsgesetz, § 3, VII) (Landesregierung Schleswig-Holstein, 2013)

The *Königsmoor*, in which the study area is embedded, has a size of 1 500 ha (Overbeck 1976, as cited in MELUR, 2016: 8). Bordered by the Sorge in the northwest and northeast, the *Königsmoor* lies within the three communities of C*hristiansholm* in the west, *Königshügel* in the northeast and *Friedrichsholm* in the south. The *Hohner Lake* borders the area to the south, while in the east the raised bog turns into a bog forest and runs in front of the L29 in the *Julianen plain*. As already mentioned, it is part of a complex of raised bogs, fens and other wetland type surrounding the area.

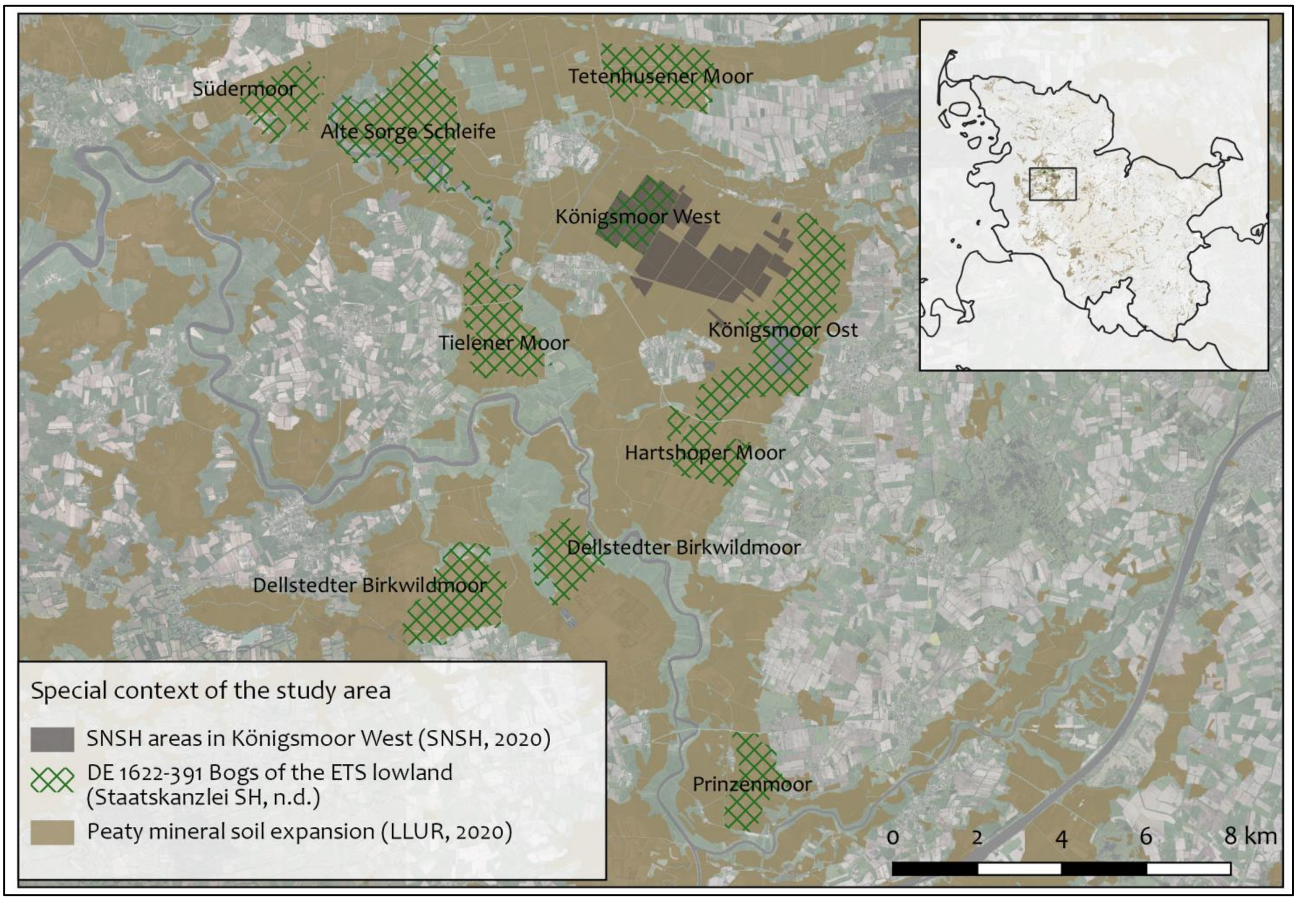

Figure 1 Overview on the special context of the *Königsmoor*, in which the study area is embedded. Bogs of the ETS lowland, the peaty mineral soil expansion and areas owned by the foundation for nature protection SH (SNSH) within the *Königsmoor West*.

2.2 Historical context and management practices

Over time, peatlands in Germany were affected by several attempts of transforming, using raw material and later protecting the habitat. The following embedding in the respective context helps to build a better understanding of processes in the *Königsmoor.*

2.2.1 Transformations of wetland systems

Different drivers of transformation showed large effects on former wetland systems in SH. Lowering water levels, melioration processes, intensification and peat cutting influenced large areas and led to a loss in bogs, fens and other wetlands (LLUR, 2015: 24-26; Succow and Jeschke, 1990: 204 ff., 228 ff.).

In this chapter general drivers of transformation processes on a regional scale are described and related to the concrete influences that were exerted on the study area within the *Königsmoor*, since a deep understanding of these extrinsic processes helps to interpret vegetation patterns on the aerial image data (Hecke et al., 2018: 429-436).

Lowering water levels by drainage

In the 17th century new and effective drainage techniques as dikes and bailing mills were introduced by Dutchmen who settled in the area of *Friedrichstadt* to introduce their know-how on water management in SH (Dierßen, Gesellschaft für Schleswig-Holsteinische Geschichte, 2020). But only the straightening and development of rivers in the 20th century rapidly advanced the drainage of large areas of land, enabling the agricultural use of wetlands on a larger scale (ibid). In the context of land consolidation, drainage was further intensified from 1954-1979 (Minister für Ernährung, Landwirtschaft und Forsten des Landes Schleswig-Holstein, 1980: 32 ff.). Water management was installed to achieve prevention of flood damage and elimination of 'natural disadvantages' for soil and plants, to enable agriculture intensification with a focus on a more economic use of the area (ibid.). The water level, formerly just a few centimeter under floor, was depressed intensely on farmland, since earlier mowing was possible due to fertilization, but wet, not load-bearing soils made farming with bigger agricultural equipment impossible (Drescher et al., 2018: 20 ff.). Raised bogs were either drained directly to use them as agricultural land or by peripheral drainage systems, which have a negative impact on the groundwater dome, whose base is hence lowered. In every case the bog surface slowly dries out (Steiner, 2005: 37).

Grassland areas of the *Königsmoor* were drained through ditches and drains in the mid-18th century and, in a second attempt, in the early 20th century in order to use them as agricultural grassland (Christiansen, 2012: 109–124). From 1915 the land has been cultivated through the 'state mire administration Christiansholm'. Vegetation has been cut, ditches were deepened and drains laid, fertilizer was applied and efficient grassland seed was sown on the former raised bog area (ibid.). From 1922 onwards, huge drainage ditches were created to drain the bog and enable further steps towards fertility and soil improvement[2] (Christiansen, 2012: 109–124; MELUR, 2016: 11).

Melioration of mires

Melioration processes aim to improve fertility and soil structure through removal of vegetation, mixing of formerly drained peat soils with sand, fertilization and deep ploughing of the soil (Gesellschaft für Schleswig-Holsteinische Geschichte, 2020a). The aim of the melioration, which is only possible on the drained areas, is to use them as meadow or agricultural land. Both practices lead

[2] "Improvement" in this chapter should be understood in the sense of agricultural economic improvement

to a compaction of the soil and to a distribution of nutrients (Steiner, 2005: 36). While grazing redistributes nutrients, the use as agricultural land requires fertilizations, since the nutrients of the peaty soil are not sufficient to guarantee a long-term management. This in turn results in a change in vegetation and thus a change in water requirements (ibid.).

In the *Königsmoor* ploughing followed the systematic draining of the area. The soil was limed and heavily fertilized to enable cultivation. After this preparation of the soil, grain was sown and later the land was used for grassland farming. By sowing highly efficient grassland species the use for permanent grazing was enabled (MELUR, 2016: 11).

Peat cutting

Peat cutting was one main reasons for the transformation and draining of mires (Dierßen, Gesellschaft für Schleswig-Holsteinische Geschichte, 2020). The peat was mainly used for heating, either directly by households of the area or by selling the peat as wood substitute to nearby settlements (Lorenzen-Schmidt and Pelc, 2006, as cited in Gesellschaft für Schleswig-Holsteinische Geschichte, 2020b). The conditions for peat cutting include groundwater lowering - it leads to compaction, erosion and oxidative processes (Steiner, 2005: 37).

In the *Königsmoor* the extracted peat was a by-product of the cultivation process. Peat cutting was only applied on a small scale level, to supply energy to the inhabitants of the area (MELUR, 2016: 12). In some sub-areas (where the bog was rewetted in 2015 / 16 (Figure 3)), peat has never been cut (Planungsbüro Mordhorst Bretschneider GmbH, 2014, as cited in Ausgleichsagentur Schleswig-Holstein GmbH, n.d.: 9). Traditional peat cutting on a smaller scale, as applied in the *Königsmoor,* causes much less damage than industrial peat cutting and enables chances for regeneration (Steiner, 2005: 37). As a consequence of bog subsidence areas under cultivation, which were subject to drainage, aeration and oxidation processes, are lower in altitude than unused areas or those left abandoned after peat cutting (MELUR, 2016: 9). They form pedestals where most valuable vegetation structures of typically upland moorland vegetation can be found (ibid.: 2016, 9).

Eutrophication

Eutrophication is affecting water and soil quality alike. The high amount of nutrients distributed as fertilizers on agriculture areas is transported in rural areas by water bodies or the atmosphere (Sutton et al., 2011: 271 ff., 289 ff.). Critical loads for sensitive ecosystems, as raised bogs located in an agricultural surrounding, are considerably exceeded (Mohr et al., 2015: 1-83). Especially nutrient poor areas, as raised bogs or heathlands, suffer of an increased nutrient input (Sutton, 2011: 466 ff.). Accelerated succession on dry areas and fast overgrowth of lower vegetation stands are the consequences. Species adapted to the nutrient poor habitats vanish, either because they cannot compete or are directly affected, as *Sphagnum species* (Gunnarsson,2002; Bragazza and Limpens 2004, Malmer et al. 2003, as cited in Sutton, 2011: 476).

These processes affect areas on a large scale, so that effects of the surrounding agricultural land on the *Königsmoor,* especially against the backdrop of the atmospheric nutrient load in northern Germany (Sutton et al., 2011: 329 ff.), must be assumed, even if no specific investigations of nitrogen depositions of this raised bog are available.

2.2.2 Protection status and management

Large parts of the ETS lowland are part of the European Union (EU) Natura 2000 network. In the year 2000 the special protection area (SPA) 'Eider-Treene-Sorge lowland' (DE 1622-493) was announced for the protection of birds and in 2007 the Flora-Fauna-Habitat (FFH) -area 'Bogs of the Eider-Treene-Sorge lowland' (DE 1622-391) has been added (MELUR, 2016: 5) (compare Figure 1). Almost all land owned by the foundation within the *Königsmoor* belongs to the SPA. Furthermore, two parts of the *Königsmoor*, the western (204 ha) and eastern (291 ha) part, are declared as FFH-areas (MELUR, 2018: 6, 2016: 5); they belong to the interconnected system already described and presented in Figure 1. Additionally, areas of the *Königsmoor* are to a large extend declared as 'Protected Biotopes by Law' (§ 30 Bundesnaturschutzgesetz) and some are declared as 'Area for Protection as Nature Conservation Area'. The area is furthermore categorized as 'Protected Landscape Area of the ETS lowland', as 'Focus Area for the Biotope Network System', and as 'Landscape Protection Area'. The adjoining river *Sorge* is announced as an 'Important Interconnection Axis of the System of Protected Areas and Biotopes'. The most important protection categories to which the area is subject and the areas owned by the foundation are shown in Figure 2.

The area is to a large extent owned by the Foundation for Nature Conservation Schleswig-Holstein (Stiftung Naturschutz Schleswig-Holstein, SNSH) and the extensive use with grassland management and without fertilization, as practiced, is mainly possible due to the ownership and activities of the foundation (Ausgleichsagentur Schleswig-Holstein GmbH, 2017). In addition to this management practices in the years 2012-13, 2015-16 and 2018 measures to enable a regeneration of the raise bog were applied. Embankments have been built and ditches were closed to rewet the peat soil and allow a growth of typical bog vegetation in these areas (Chapter 2.3, Figure 3). The soil used for the construction of the embankments was obtained by a shallow excavation inside of the polders (ibid.). The goal of the undertaken rewetting measures is to reduce climate gas emission by stopping degradation process driven by former water management. This leads to a reduction of greenhouse gas emissions, as due to stopping degradation processes of peat moss-rich raised bog and fenland vegetation the emission of the area is reduced by 55 % per year (ibid.). Within the project period of 50 years 39 520 t CO_2 equivalents will be saved (ibid.). Groundwater level in the area has been raised from 30 - 70 cm under floor up to just a few cm under floor in summer (ibid.).

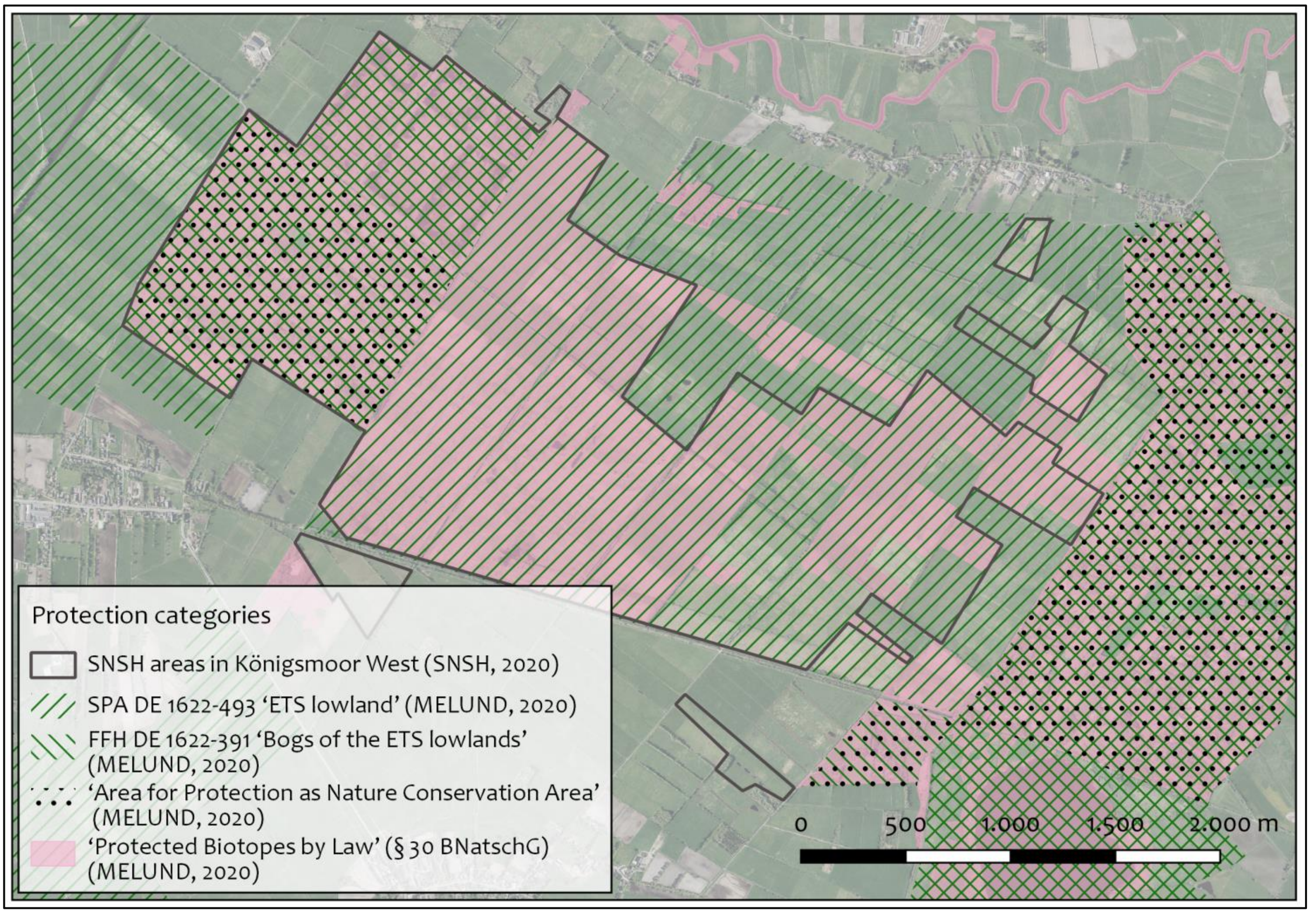

Figure 2 Different protection categories: SPA, the two FFH-areas in *Königsmoor West* and *-East*, areas which are in the process of being protected as Nature Conservation Areas and protected biotopes (MELUND, 2020). Landscape protection categories and biotope network categories are not represented in this map.

2.3 Study area with sub-areas

The study area has a size of 337 ha and is owned by the SNSH. Some sub-areas are farmed, if cultivated at all, in accordance with the principles of nature conservation. Parts of the raised bog are subject to different natural protection systems (Chapter 2.2.2, Figure 2); others have been rewetted or were subject to rural peat cutting. Yet others have been cultivated in different periods in which the cultivation of the *Königsmoor* was advanced, most recently between 1915 and 1936 (Figure 3) (Christiansen, 2012: 109–124). Due to the different prerequisites for vegetation development, which result from these different management forms or conservation forms, the study area is divided further into three sub-areas (Figure 3). As the vegetation patterns are developing in dependence on former management or disturbance (Dierßen & Dierßen, 2001: 82; Irmler et al., 1998: 154 ff.; Tiemeyer et al., 2017: 150 ff.), different challenges and results for the classification of vegetation are expected in the different sub-areas. Table 1 summarizes the various influences which have affected the sub-areas.

Sub-area 1 – Rewetted area 2015 / 16, cultivated from 1915-1936, FFH-area
Sub-area 1 is in the northwest of the *Königsmoor,* within the setting of SPA and FFH-area. The area is divided in sub-area 1a and 1b (Figure 3). It has been cultivated between 1915 and 1936 according to Christiansen (2012: 109–124); a previous cultivation attempt in the 18th century cannot be excluded either. The area has never been subject to peat cutting (Planungsbüro Mordhorst Bretschneider GmbH, 2014, as cited in Ausgleichsagentur Schleswig-Holstein GmbH, n.d.: 9). The 68.7 ha large sub-area is most influenced by protection measures; it has been rewetted in 2015 / 16 by the Compensation Agency (Ausgleichsagentur), a subsidiary of the SNSH. By building embankments of an earth-peat mixture, five polders have been created which are preventing the run-off of precipitation (Ausgleichsagentur Schleswig-Holstein GmbH, n.d.: 11). Unlike in sub-area 3a and 3b, topsoil was used to build the embankments (personal communication Walter, 18.08.2020). Therefore, a larger surface area has been used and simultaneously exposed larger areas of slightly decomposed white peat, which are poorer in nutrients and support the reintroduction of peat mosses (ibid).

The area is classified as 'bog regeneration area, wet, poor in vegetation' in the mapping of biotope types in SH. The buffer zone around the polders created is classified as 'degenerated bog areas of other characteristics' (LANIS SH & LLUR, 2018),(Figure 4). Both types are associated with the habitat type 7120 and 7140. The rewetted area is expected to show a young, productive vegetation pattern due to the large disturbance caused by the removal of the topsoil and change in water regime.

Sub-area 2- No rewetting measures applied, no cultivation from 1915-1936, FFH-area
Sub-area 2 is located in the west of the *Königsmoor*, within the boundaries of SPA and FFH-area. The area is divided in sub-area 2a-c (Figure 3). It is furthermore classified as 'Area for Protection as Nature Conservation Area' (Figure 2) and has not been cultivated between 1915 and 1936 (Christiansen, 2012: 109–124). It is situated within the borders of the colony to the mire and heath colonization of 1760 (LLUR and Planungsbüro Mordhorst Bretschneider GmbH, 2015), so that a former attempt of colonization is possible. The 130.6 ha large sub-area has not been subject to rewetting measures (rewetting measures are in planning process, personal communication SNSH (2020)). Parts of the sub-area include the already mentioned pedestals in the landscape (Chapter 2.2.1), where unused or abandoned areas were to a lesser extent subject to bog subsidence (MELUR, 2016: 9) and vegetation structures of typically raised bog vegetation are left. Marks of rural peat cutting can be found in the area 2b. Vegetation in this area is more diverse in comparison to the other sub-areas due to its management background and advancing degradation, including heathlands, *Molinia* grasslands and birch forests.

In the biotope mapping, the area has been classified as various types of degraded raised bog, raised bog in regeneration, as heathland, as shrubs, grassland and others (LANIS SH & LLUR, 2018), (Figure 4).

Sub-area 3- Rewetted area 2012 / 13, partly cultivated from 1915-1936, no FFH-area

Sub-area 3 is comparable in terms of protection measures and cultivation attempts with sub-area 1. It is located at the southern border of the *Königsmoor*, close to the community *Christiansholm.* The area is divided in sub-area 3a and 3b (Figure 3). The 137.7 ha large sub-area lies within the setting of SPA but outside of the announced FFH-area *Königsmoor West*. It has been almost entirely cultivated between 1915 and 1936 (except from its southeastern tip), according to (Christiansen, 2012: 109–124). As in the other sub-areas, previous cultivation attempts in the 18th century cannot be excluded. Peat cutting was, if applied at all, only applied as rural peat cutting for self-sufficiency (ibid.). The rewetting measures applied differ slightly from the ones described in sub-area 1: The measures in this part have been implemented earlier, which is why the vegetation on the embankments and the vegetation development within the rewetted areas is in a different stage of development (personal communication SNSH, 22.06.2020). The polders are smaller in size since the surface relief is steeper (personal communication Walter, 18.08.2020). Especially in the area that has been rewetted in 2012 there were strong height differences at a small distance (ibid). In addition to this, the method has changed slightly (ibid). In 2012 / 13 black peat material for the embankments has been extracted from small, deep extraction holes from a depth of 1.5 - 2.5 m (ibid).

The area is (as in sub-area 1) classified as 'bog regeneration area, wet, poor in vegetation' in the mapping of biotope types in SH; the buffer zone around the polders created is classified as 'degenerated bog areas of other characteristics' (LANIS SH & LLUR, 2018), (Figure 4). Both types are associated with the habitat type 7120 and 7140.

Table 1 Overview of the various influences that have affected the sub-areas

	Sub-area 1	**Sub-area 2**	**Sub-area 3**
Rewetting	2015 / 16	-	2012 / 13
Cultivation 1915-36	yes	-	partly
Cultivation 18th century	unknown	unknown	unknown
FFH-area	yes	yes	-
Rural peat cutting	no	yes	unknown
Mapped biotope types[3] (LANIS SH & LLUR, 2018)	MRj, MDy	MDb, MDg, MDm, MRb, MRg, MRm, MRs, MRy, MHy, HGm, HGx, HGy, GYf, GYj, GYn, GYy, Gay, GNa, GNm, NSs, RHr, SVg, SVo, SVs, SVt, FLa, AAe	MRj, MDy

[3] All abbreviations are listed in the appendix in Table 5 with the official German designation of the biotope types and their translations.

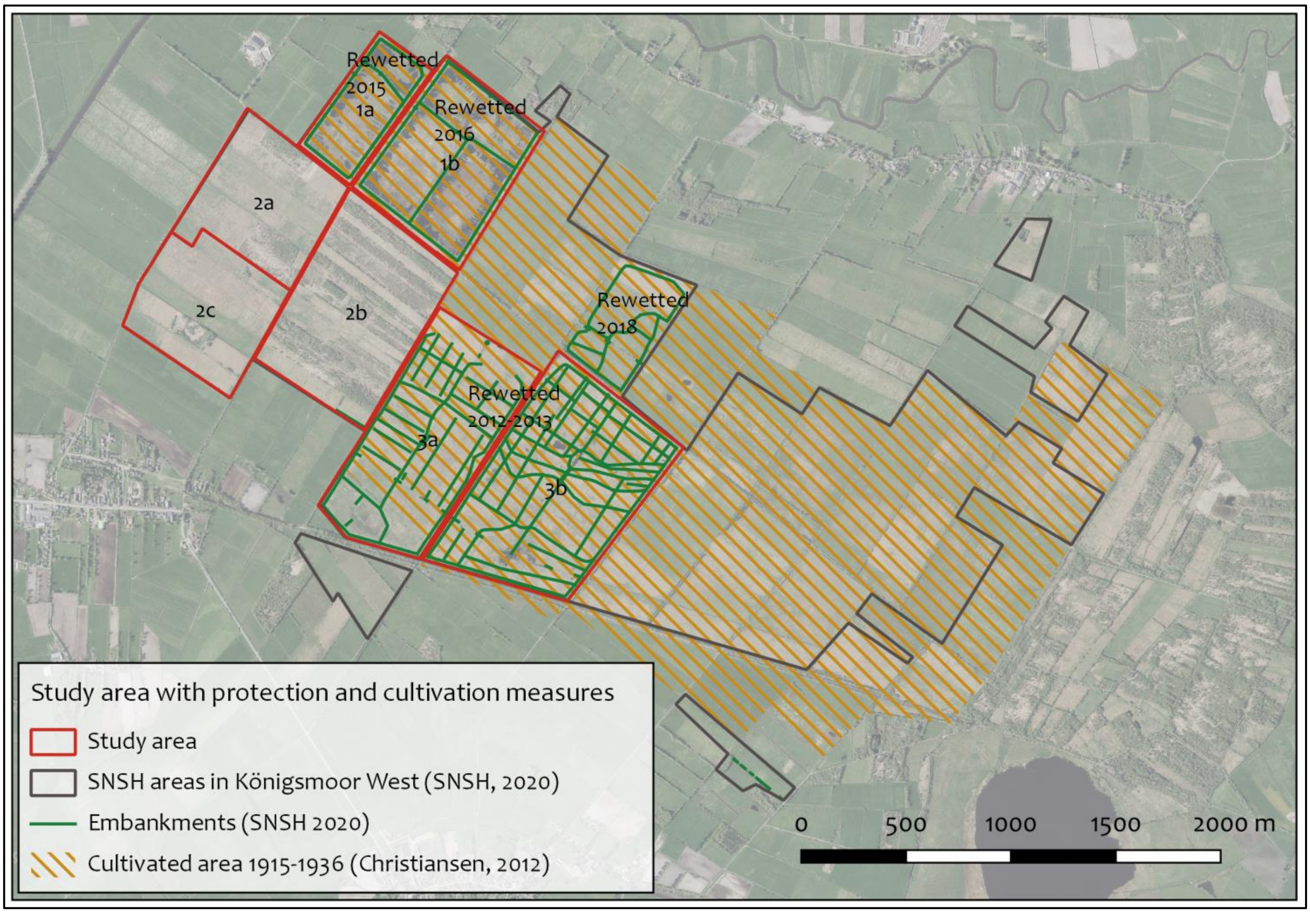

Figure 3 The study area with its sub-areas 1, 2 and 3 within their location in the *Königsmoor* area, the FFH-area and the area cultivated between 1915 and 1936. The further division into 1a, 1b, 2a, 2b, 2c, 3a and 3b is not subject to any selected criteria and should allow a detailed description of the results.

2.4 Vegetation in the *Königsmoor*

The development of a raised bog's flora is highly adapted to its nutrient and oxygen poor, wet habitat (Dierßen & Dierßen, 2001: 60 ff., 74 ff.; Irmler et al.: 121 ff., 1998; LLUR, 2015: 35) and depends on abiotic location factors as well as former management (Tiemeyer et al., 2017: 150 ff.). Moisture-determining factors as water levels and soil hydrological parameters have, together with chemical factors as nutrient availability and pH value, decisive influence on the vegetation development (ibid). The use of an area, former or current, can affect the composition of vegetation indirectly (by changing the mentioned factors) or directly through management practices (ibid.). These characteristics make vegetation an adequate indicator for the condition of a raised bog – its health state. All components affected are concentrated in one synoptically value (vegetation) which is verifiable and depicts (indicates) the state of the system that is too large and impassable to be directly accessible. The indicator is interpretable, reacts sensitive to management or changes in conditions and data availability is good due to the use of UAV. The indicator provides therefore aggregated information on the state of the management progress and highlights the difference between the existing state and the aspired target state of the raised bogs condition.[4] In awareness of the current scientific discourse on the term ecosystem health and its use, this thesis refers to the term as a balance between adaptability and robustness (Ramírez-Carrillo et al., 2018: 4 ff.).

In intact raised bogs, which cannot be found in SH any longer, the treeless vegetation is characterized by peat mosses, *Sphagnum* (Vitt and Slack, 1984, as cited in Bönsel and Sonneck, 2012: 504). The moss, which is optimally adapted to wet, acidic and nutrient-poor conditions, even intensifies the conditions it requires by storing water in its cells and lowering the pH value of the environment during the absorption of cations and by releasing hydrogen ions (Andrus, 1986, as cited in LLUR, 2015: 35). Dead parts of the plant, which cannot be decomposed under the oxygen-poor conditions, accumulate to a peat layer and thus form the raised bog body (Strack and Price, 2009, as cited in Bönsel and Sonneck, 2012: 504; Dierßen & Dierßen, 2001: 9 ff.)

As the natural vegetation of raised bogs consists of a few adapted specialists, species richness in this ecosystem is more indicative of disturbance through anthropogenic management, than of an healthy ecosystem (Manderbach, 2020). Due to the transformation processes described in Chapter 2.2.1 and interferences caused by the rewetting measures, different vegetation compositions are expected in the *Königsmoor,* which are reflecting the former use or measures applied.

Succession and degradation processes in raised bogs follow a typical sequence of dominating plant species (Schrautzer and Jensen, 1999, as cited in Dierßen & Dierßen, 2001: 162 ff.; Irmler et al., 1998: 21 ff.). The initial species dominate due to an advantage by changed conditions and in turn change the abiotic conditions of the habitat and make it accessible to species that were not adapted to the pristine conditions to the same extent (Dierßen & Dierßen, 2001: 66 ff.; Irmler et al., 1998: 141).

Primary open raised bog areas with hummocks and hollows

Sphagnum growth, which is highly sensible to low water levels and eutrophication (Sutton, 2011: 476; Irmler et al., 1998: 23, 141), is the driver for the growth of raised bogs (Dierßen & Dierßen, 2001: 9; Irmler et al., 1998: 16; LLUR, 2015: 35). When *sphagnum* begins to vanish due to lowering of water levels, the raised bog stops growing and degradation can be noted; vegetation expands that previously depended on areas slightly higher in altitude (Irmler et al., 1998: 21 ff.).

[4] General functions and definitions of indicators are adopted from Wiggering and Müller (2003: 10 ff.) and the EEA (2005: 10).

- **First degradation stage (degradation stage I)** - Wet heathland-hummock associations of raised bogs: wet heathlands with *Erica tetralix* and *Sphagnum* species are described as part of the primary open raised bog with intact hydrology, which occur in SH only in rural peat cutting- or rewetted areas as a secondary form (LLUR, 2015: 38). Irmler et al. (1998: 21 ff.) categorize the vegetation type of dominating dwarf shrubs as the first degradation stage after the *Sphagnum* species start to vanish. Peat hummocks, areas slightly higher in altitude, have been built over decades by hummock-forming peat mosses (Irmler et al., 1998: 18). Dwarf shrub species, as *Andromeda polifolia,* expands from the edges of these hummocks since the species is optimally adapted to a nutrient poor, humid surrounding, due to its shallow roots (Dierßen & Dierßen, 2001: 61). *Erica tetralix* is spreading and the hummocks offer habitat for taller dwarf shrubs as *Empetrum nigrum* and *Calluna vulgaris* (Dierßen & Dierßen, 2001: 109). Irmler et al. (1998: 23) conclude that this initiates the degradation of the raised bog.
- **Second degradation stage (degradation stage II)** - *Molinia caerulea*: Further drainage leads to dominant stands of *Molinia caerulea*, single *Betula* plants already establish on higher hummocks (Irmler et al., 1998: 22).
- **Third degradation stage (degradation stage III)** - *Betula*: In this stage, a closed birch forest of *Betula pubescens* and *Betula pendula* has developed on the former raised bog (Irmler et al., 1998: 22). *Molinia caerulea* often forms the herb layer (Lindner-Effland, 2020: 53).

The first two stages represent transitional stages between the initial raised bog vegetation and the birch forests. The forest mires can be considered as a resilient stage of vegetation if the water level does not decrease significantly (Ellenberg et al., 2010: 457) or rewetting measures are taken (Müller-Kroehling et al., 2019: 264–269). Forest mires also develop on abandoned wet grasslands (Ellenberg et al., 2010: 457), which is why these two habitat types are still closely intertwined (Breuer et al., 2007, as cited in LLUR, 2015: 36).

Secondary raised bog areas with cultivated grassland

On secondary raised bog areas, which have been developed on peat soil through the described melioration, a similar process of succession stages takes place if the grassland lies idle. Depending on the period since when the area is not subject to mowing or grazing any longer, different stages of succession can be derived (Schrautzer and Jensen 1999, as cited in Dierßen & Dierßen, 2001: 162 ff.). Schrautzer and Jensen (1999) describe four stages of succession: multiple species are dispersed on the recently abandoned area in the first stage, followed by a second stage where plants reproducing trough clonal multiplication are in dominance, and in a third stage a dominance of tall growing plants that have been migrated and are often perennial occurs. These are then, only if the topsoil is disturbed, replaced by a more resilient stage of woodland (Schrautzer and Jensen, 1999, as cited in Dierßen & Dierßen, 2001: 162 ff.). In this thesis only three stages of successions are in focus:

- **Species rich grassland / First succession stage (succession stage I)**: In line with the described stage, a state where multiple species are dispersed on the recently abandoned area. In the early fallow years first structural changes in the species composition are visible(Dierschke and Briemle, 2008: 176 ff.). In terms of species richness this stage is described as biological valuable (ibid.: 176 ff.).
- **Second succession stage (succession stage II):** Megaphorbs with communities of tall growing, perennial species develop. This species habits lead to shadowing of the herb layer and a development of a microclimate if their litter from biomass of the previous year is not decomposed completely (Dierschke and Briemle, 2008: 177). Some sedges and rushes built very high and dense litter layers (ibid.: 174).
- **Third succession stage (succession stage III)**: This stage covers woodlands consisting of *Betula spec., Salix spec.* and *Myrica gale.* Within this stage different phases are described in the literature, but since they only play a minor role in this thesis, woody plants, pre-forest stages and forest stages are combined as one (Dierschke and Briemle, 2008: 177).

Rewetted areas

The rewetted areas are expected to show an initially swamp vegetation with reeds, sedges and rushes (Ausgleichsagentur Schleswig-Holstein GmbH, 2017: 16 ff.). Two predictions of the vegetation development after rewetting the area have been made; one for the first period, 1-30 years after implementing the measures, and one for the second period, 31-50 years after implementation (ibid.: 16 ff.).

- **Disturbed areas / embankments:** The prediction for the first period expects a development of hydrophilic tall herb fringe communities directly on the embankments (ibid.: 16).
- **First regeneration stage (regeneration stage I):** In the ditches and on the areas, where the topsoil has been removed, flooded reed beds are expected to grow (ibid.: 16). In the polder the growth of wet tall sedge communities and flooded reed beds and a development of peat forming plants is expected (ibid.: 16).
- **Second regeneration stage (regeneration stage II):** After 30 years the vegetation is expected to have changed into a vast extend of transition mires with peat forming communities of S*phagnum* moss with reed beds only to be found in the deeper ditches (ibid.: 17).

3 Method

The first part of this chapter describes the development of a set of indicators to depict changed conditions in the *Königsmoor.* The indicators are species or associations that have been derived from the vegetation description of degradation-, succession- and regeneration stages in Chapter 2.4. In the second sub-chapter the vegetation survey, whose results are used as input for the automatic vegetation classification, is described. Therefore, 13 plots were selected and their vegetation cover was mapped. The vegetation was then digitalized and exactly spatially related to the aerial image data (orthophotos), to be further used as training and validation data for the Random Forest classifier. The data collection of the orthophotos, the multispectral data and the calculation of the indices, as well as post processing of the aerial images is explained in the final sub-chapters.

3.1 Definition of an indicator set

Chapter 2.4 summarizes the different stages of degradation on primary raised bog areas, succession stages on secondary raised bog areas, and regeneration on rewetted areas, whereby its characterizing vegetation indicates these processes. To depict the health state of the raised bog later, the interpretation of the indicators in terms of conditions is necessary. To serve as adequate vegetation indicators, the species must fulfill several requirements: they must depict the systems state. The described classification in degradation-, succession-, and regeneration stage is a guiding principle. To assure the data availability, they must be detectable by the UAV and, since the focus of this thesis is on vascular plants, most defined indicators belong to the vascular plants.

The first indicator forms an exception: For hollows of primary open raised bog areas, peat accumulating *Sphagnum species* have been identified as an indicator for intact raised bogs (Dierßen & Dierßen, 2001: 84; Irmler et al., 1998: 15-18). Intact raised bog patches are within the study area of the *Königsmoor* only expectable in rewetted areas of regeneration stage II. Species of dwarf shrub heathlands, as for example *Erica tetralix,* serve as indicator for the first degradation stage of the raised bog, while *Molinia caerulea* has been identified as an indicator for the second degradation stage (Dierßen & Dierßen, 2001: 85; Irmler et al., 1998: 22, 141). *Betula pubescens* and shrubs as *Myrica gale* serve as an indicator for the final degradation stage, the mire forest (ibid.). On the fallow land, the identification of indicators of succession stages is slightly more difficult, since species presence highly depends on the agricultural practices applied, seeding used before and species growing in the edges of the meadows (Dierschke and Briemle, 2008: 170). For wet grassland, *Carex* species and *Calamagrostis canescens* can be used as indicators (Dierßen & Dierßen, 2001: 67; Dierschke and Briemle, 2008: 170), but also grassland types which are categorized in LANIS SH & LLUR (2018) to define mesophile grassland in SH (as *Festuca rubra* and *Agrostis capillaris)* serve as indicators for the first stage of succession in this thesis. *Holcus lanatus* serves as indicator for succession stage I (invasion by grasses on fresh soils (Dierschke and Briemle, 2008: 170)). An indicator for succession stage II can be a dense, old grown stand of *Juncus spec*. or perennial plants as *Cirsium spec*. and *Rubus* *spec.* (Dierschke and Briemle, 2008: 170). As succession stage III and degradation stage III are difficult to distinguish, *Betula spec.* serves as an indicator for both (Dierßen & Dierßen, 2001: 163; Irmler et al., 1998: 22, 141; Dierschke and Briemle, 2008: 173). Disturbed areas are indicated by plants of edge communities with an Ellenberg-Nitrogen value > 7 as *Urtica dioica* or *Galeopsis tetrahit* (Dierschke and Briemle, 2008: 170; Ellenberg et al., 1992, as cited in Zillgen, 2020). The first regeneration stage, at which water is still present in the ditches, tall sedges and reed beds, is indicated through *Typha latifolia* (Dierßen & Dierßen, 2001: 85) and *Phalaris arundinacea* (Dierschke and Briemle, 2008: 170). Regeneration stage II is, as already mentioned, indicated by *Sphagnum spec.*

Table 2 Degradation, succession, and regeneration stages on different areas assigned to characterized habitats or species.

Site	Indicandum	Indicators	Assigned Plots
Open raised bog areas with hummocks and hollows	Intact raised bog area	*Sphagnum spec.*	-
	Degradation stage I	*Erica tetralix, Empetrum nigrum, Narthecium ossifragum*	7
	Degradation stage II	*Molinia caerulea*	6
	Degradation stage III	*Betula spec., Myrica gale*	4, 8
Secondary raised bog areas (cultivated)	(Wet) grassland	*Carex spec., Calamagrostis canescens, Festuca rubra, Agrostis capillaris, Holcus lanatus*	9, 10
	Succession stage I		
	Succession stage II	*Cirsium spec., Juncus effusus, Rubus spec.*	5, 11
	Succession stage III	*Betula spec.*	4
Rewetted areas	Disturbed areas	*Urtica dioica, Galeopsis tetrahit*	1, 12
	Regeneration stage I	*Typha latifolia, Phalaris arundinacea*	2, 3
	Regeneration stage II	*Sphagnum spec.*	13

It is important to note that the species which are now identified as indicators have been identified in an iterative process in the field. For other areas the species could be different.

3.2 Vegetation survey

The aim of the vegetation survey was a recording of representative plant associations of different stages of succession, degradation, and regeneration. To facilitate the subsequent analysis of the data mainly dominant, uniform stands have been mapped, but also plots with a heterogeneous species composition that are assumed to be identifiable on the aerial image data were recorded. The recording of this data should help to enable an exact location of the plants on the orthophotos to locate the reference points.

13 plots were selected representing different stages of degradation, succession, and regeneration and their indicating vegetation patterns. The plots are located on different biotope types and have been selected for their ability to represent a broad variety of typical plant communities that can be expected in these German raised bog habitats that have been subject of disturbance and usage for many centuries. One plot has the approximate size of 4 m². If dominant vegetation stands were present, the plot was placed in the dominant patch; if more than one plant was dominating a stand, the plots center has been placed at the border of the two dominant patches. Some species outside the plot were included in Table 6, appendix if they characterize the surrounding area and / or are defined species of the indicator set.

Figure 4 shows the location of the selected plots and allows an allocation within the biotope types (LANIS SH & LLUR, 2018). The vegetation survey of these plots has been carried out on June 22-24, 2020, on July 03, 2020 and August 02, 2020. Species within the plots were mapped and their share on the total vegetation cover estimated according to Braun-Blanquet (1964). The cover is noted as an estimated respective degree of species coverage of every species, given as a cover from <1 % to 100 %. If a species is dominating a plot, the probability that the digitized points hit pixels representing the reflectance spectrum of the species is very high. For dominant species which cover more than 75 % of a plot's vegetation the reference points were set to represent the dominant species. For other plots with a heterogeneous species composition it is assumed that the digitized points represent the spectrum of the plant association assigned. Therefore this thesis' vegetation description is based on the classical plant sociology, described for the habitats of raised bogs and grassland in Dierschke and Briemle (2008); Dierßen (1982); Dierßen & Dierßen (2001); Ellenberg et al. (2010, 1992) and Lindner-Effland (2020). Associations were determined by the vegetation cover of the species composition (Chapter 4).

Table 6, appendix, lists the plant species mapped per plot and its vegetation cover. The table furthermore indicates if a dominant species or the assigned association is used to set reference points and how many reference points were set per plot and species or association. Figure 12 gives an impression of the plots.

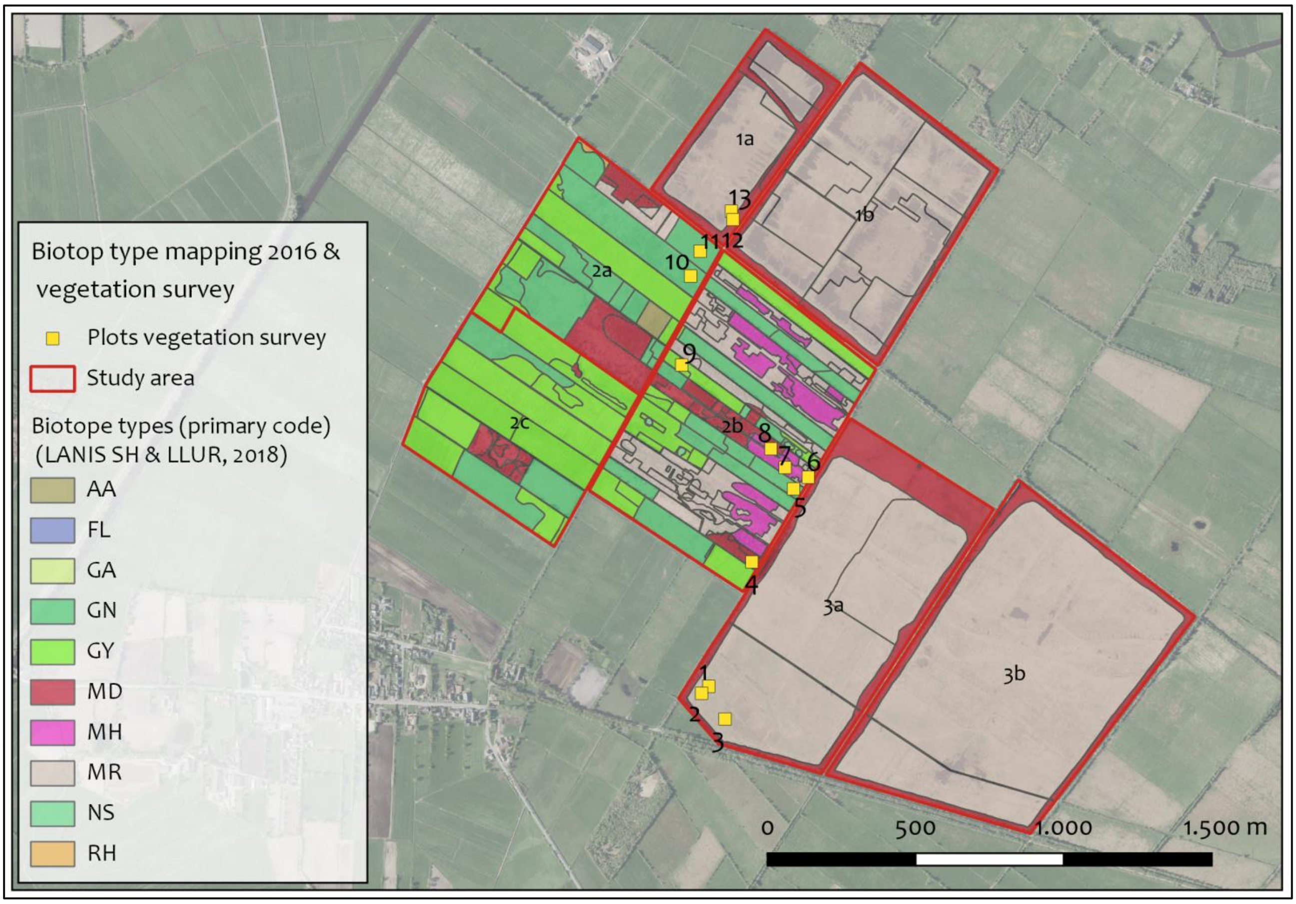

Figure 4 Biotope type mapping 2016 (LANIS SH & LLUR, 2018) and the 13 selected plots within the study area.

3.3 Data collection

To collect multispectral data and create RGB orthophotos, the study area was flown by the UAV WingtraOne in two steps. On the first flight the UAV was equipped with the multispectral camera MicaSense Altum and on the second flight with a Sony QX1 Professional (Table 3).

The first survey was conducted on July 03, 2020. Due to the weather conditions the flight over sub-area 3b needed to be completed on July 14, 2020. The flight route of the WingtraOne was planned with the software WingtraPilot 1.9 setting the flight altitude at 80 m height.[5] The software allows to place transects in the study area, depending on parameters such as flight direction, lateral overlap and frontal overlap, all being adjustable. Due to the flight altitude, the frontal overlap was set to 70 %, which does not impact transects but the number of images recorded. The lateral overlap was also set to 70 %. A high frontal overlap leads to a reliable reconstruction of the orthophotos. Recommendations for a frontal overlap range between 70 % (WingtraAG, 2020a) and 85 % (for the

[5] For general information on the drone see (WingtraAG, n.d.)

classification of dense vegetation) (2020Pix4D SA, 2020a). Since frontal overlap is limited by flight speed, height and trigger time, the maximum frontal overlap achievable in this thesis is 70 %.[6]

During the first survey, the UAV was equipped with the multispectral camera MicaSense Altum, an integrated radiometric thermal camera, producing thermal and multispectral data (MicaSense.Inc, 2020a). Including the thermal band, the MicaSense Altum captures six bands - red, green, blue, red edge, near-infrared and thermal (ibid.). The wavelength and the ground sample distance (GSD) on 80 m above ground level (AGL) covered by each band are summarized in Table 3. It is important to note that the GSD of the thermal sensor is much higher and therefore much coarser than the GSD of the multispectral sensor. The light conditions are recorded before each take-off and after each landing. All image data are automatically subjected to irradiation correction.

Table 3 Altum Sensor specifications, for more information visit the website MicaSense.Inc (2020a)

Camera	Band	Wavelength (nm center)	Bandwidth (nm)	Ground sample distance (GSD)
Multispectral camera MicaSense Altum, 8 mm lens	blue	475	32	3.4 cm / 80 m AGL
	green	560	27	3.4 cm / 80 m AGL
	red	668	16	3.4 cm / 80 m AGL
	red edge	717	12	3.4 cm / 80 m AGL
	Near-infrared (NIR)	842	57	3.4 cm / 80 m AGL
	Longwave infrared (LWIR), thermal infrared	8-14 um	-	54 cm / 80 m AGL

On July 13, 2020 the data of the whole study area could be collected on a second flight using the camera Sony QX1 Professional, 20 mm lens. The flight route was also created with the software WingtraPilot, setting the flight altitude to 97 m resulting in a GSD of 2 cm. The lateral overlap for this flight was 80 %, while the frontal overlap was only 65 %. The selected overlap is very small but had to be chosen because of the high spatial resolution. The combination of WingtraOne and Sony QX1 Professional allows the application of a Post-Processed Kinematic (PPK) module. PPK permits the correction of Global Positioning System (GPS) data in post-processing, obtaining absolute accuracy up to 3 cm in x, y and up to 3 cm in z (WingtraAG, 2020b). In order to apply the correction, a reference point was recorded with the Stonex°S900T Global Navigation Satellite System (GNSS) receiver using AgCelNet for Real Time Kinematic data. The Stonex°S900T continued recording GPS positions during

[6] Flight height was limited to 100 m due to the nearby airport Hohn

the entire survey to produce receiver independent exchange format (RINEX) data for the post-processing.

3.4 Post processing, vegetation indices and Random Forest

The orthomosaic of the RGB data, the canopy height model (CHM), the false color composite (color infrared, CIR) as well as the Vegetation indices (VI) were calculated with the software Pix4D mapper (2020Pix4D SA, 2020) and further processed in Q-GIS version 3.14 (QGIS, 2020).

Beyer & Grenzdörfer (2018: 531) identified the digital surface model (DSM) in their study on the classification of vegetation types on peatlands as the most important variable for their classification method. As this thesis uses a method very similar to the one described in Beyer & Grenzdörfer (2018: 524 ff.), the DSM, representing the topography with all elevations of the area, is an important input for the algorithm. It is constructed as a vertical array of elevation by automatically extracted algorithms, representing the surface of all objects (including vegetation) on the area (MicaSense.Inc, 2020b). Beyer & Grenzdörfer (2018: 525) used the DSM under the assumption that the mire landscape is so flat that vegetation height can be determined. As the study area *Königsmoor* contains some differences in terrain height, the Digital terrain model (DTM, representing bare ground surface) was additionally subtracted from the DSM to get the CHM. The CHM represents the distance between the ground and the top of the objects above the ground and is used in this study as an input. Especially the identification of tall vegetation stands as *Typha latifolia* and *Betula pubescens* are expected to profit of this variable. The false color composite CIR is useful to identify water bodies, soil and plant health (MicaSense.Inc, 2020b). It gives a first impression on possible response of the NIR band, as it combines NIR, red, and green bands.
The VI used in this study are based on strong signals in the NIR and red edge spectrum. The relevance of the bands was assessed by comparing the spectral signature of the classes (Chapter 4.2.1, Figure 5). The vegetation-specific reflectance properties for each VI are presented in Table 4. Next to the DSM Beyer & Grenzdörfer (2018: 531) identified thermal data, Red Edge Normalized Difference Vegetation Index (reNDVI2) and Normalized Difference Vegetation Index (NDVI) as the most relevant bands and VI to classify bog vegetation. The thermal band was not used in this study due to its very high GSD. The commonly used NDVI (Beyer & Grenzdörfer, 2018: 525; Lehmann et al., 2016: 7; Michez et al., 2016: 146; Bhatnagar et al., 2020: 4) is a normalized version of the Difference Vegetation Index introduced by Tucker 1979 (Schurawa, 2018: 14). The NDVI has its strength in capturing differences in above-ground biomass and canopy density variations in early stage of development (MicaSense.Inc, 2020b). In addition to the NDVI, the two red edge based VI Normalized Difference Red Edge Index (NDRE) and the Red Edge Normalized Difference Vegetation Index 2 (reNDRE2) are included in the study. The NDRE is an adjustment of the NDVI, where the red band is replaced by the red edge band (Gitelson and Merzlyak, 1994; Barnes et al., 2000, as cited in Schnurawa, 2018: 14). It captures the chlorophyll content in leaves and thus the variability in the leaf area (MicaSense.Inc, 2020b). A mask

was used for the VI to cover plants only. The significance of the VI was, similar to the bands, assessed by comparing the spectral signature of the different classes (Chapter 4.2.1, Figure 5).

Table 4 Calculation of the VI as proceeded with the software Pix4Dmapper (Pix4D, 2020)

Vegetation Index	Calculation
NDVI Normalized Difference Vegetation Index	(NIR – red) / (NIR + red)
NDRE Normalized Difference Red Edge	(NIR – red edge) / (NIR + red edge)
reNDVI2 Red Edge Normalized Difference Vegetation Index 2	(red edge – red) / (red edge + red)

The reference points of the selected species and associations were set with the Q-GIS version 3.4.14 ‘Points within boundaries’ tool. The exact amount of points per species or association and their allocation within the plots is described in Chapter 4.1. For two species (*Narthecium ossifragum* and *Galeopsis tetrahit*) the availability of identifiable areas was limited and did not allow a sampling of sufficient reference points. For those two species the minimum of 500 training data points were not applied. In total 10 400 reference points were set for 23 classes to ensure a significant training and validation of the classifier. A partially automatic classification of vegetation types was then carried out using the training data as input. The reference points of the defined vegetation classes are partly used as training data and partly as validation data.

75 % of the reference data points were used to train the Random Forest classifier. Therefore, the reflectance values of the spectral bands (Table 3 with exception of the thermal band) and the values for each VI and the CHM were extracted and used as input parameters, resulting in a total of nine input features (R, G, B, red edge, NIR, NDVI, NDRE, reNDVI2, and CHM). The remaining 25 % of reference points were used for validation. Random Forest is a non-parametric machine learning algorithm developed by Breiman (2001: 5-32). The ensemble learning algorithm is composed of the combination of independent decision trees (in this study 200 trees were used). The algorithm is based on the assumption that individual trees are producing errors that are not reflected by the majority of the trees decision (Schnurawa, 2018: 16). In this application a majority vote is used to create the final classification result. To achieve this, random subsets of training data generate the input data, which is then used to train the classifier. Due to the random choice, it might be that parts of the training data are used several times while others are not included in the process, leading to an increased stability of the classifiers (Schnurawa, 2018: 15). The output is a final prediction that is returning a predicted pixel level class, identified by majority vote (ibid.). The Random Forest package in the open source software R, version 3.5.1 was implemented by Liaw and Wiener using the Fortran script of Breiman (2001: 5-31) (Schnurawa, 2018: 16). For this thesis, the package was imbedded into a script which is based on Schnurawa's (2018) classification script and is similar in methodology to the approach published by Beyer & Grenzdörfer (2018: 526).

25 % of the reference points serve as validation data (a total of 125 points for all classes, except from 50 for *Narthecium ossifragum* and *Galeopsis tetrahit* respectively). A confusion matrix provides a table comparing the predicted classes with the validation data. To analyze the statistical validation a confusion matrix was calculated with the Random Forest package in R Studio. It helps to analyze the Total-, User's- and Producer's Accuracy and reflects the quality of classification. The final confusion matrix is presented in Chapter 4.2. The underlying assumption of the matrix is that each pixel can be associated to a single class. It gives information on Overall Accuracy (OA) and per Class Accuracy, the error of commission- and omission of each class and their complements, the User's- and Producer's Accuracy (UA and PA) (Schnurawa, 2018: 17 ff.; Humboldt State University, 2019). The UA shows the maps reliability, hence how often a class on the map is actually be present as a validation point of this class on the raised bog (ibid). It shows the ratio of the total number of correct classifications and the total classifications as this species (ibid). For example, out of ten *Juncus effusus* validation points eight have been referenced correctly but four others that belong to the *Molinia caerulea* class are as well classified as *Juncus effusus* (10 / 14 = 0.57). PA is the number of a species in the bog that has been correctly represented on the classified map. This value shows the ratio of validation points classified correctly, divided by the total number of validation points in a certain class (ibid). For example eight *Juncus effusus* points of ten are correctly classified (8 / 10 = 0.8). The corresponding error of omission shows how many reference points were erroneously assigned to the class (ibid.). An error of omission in one class is necessarily an error of commission in another class (Humboldt State University, 2019; Strahler, 2006, as cited in Schnurawa, 2018: 17) [7].

[7] For more detailed information on converting the confusion matrix into a probability confusion matrix or estimating the area for the defined classes see Olofsson et al., 2014, as cited in Schnurawa (2018: 17 ff.).

4 Results

4.1 Generation of input data from plant associations and species

The following chapter describes the species and their vegetation cover mapped within the 13 plots in a floristic-inductive approach based on vascular plants. The species of one plot were assigned to different classes, orders, alliances and associations. The descriptions of the different habitats of raised bogs and grassland in Dierschke and Briemle (2008); Dierßen (1982); Dierßen & Dierßen (2001); Ellenberg et al. (2010, 1992) and Lindner-Effland (2020) have been used to set the vegetation of the *Königsmoor* in context of its plant classes and / or –associations. For some areas, which were subject to changed conditions as rewetting or land left fallow, the classification process was challenging due to the dynamic pioneer vegetation mapped. Therefore, for single plots transition forms of associations are assigned.

In general, raised bogs in SH inhabit four plant classes (Dierßen & Dierßen, 2001: 87; LLUR, 2015: 35):

- ***Scheuchzerio-Caricetea nigrae*** – a fen and raised bog class which is dominated by sedges on oligo- to mesotrophic sites with constant high water levels (ibid.)
- ***Phragmiti-Magnocaricetea*** – reeds and tall sedge reed beds which are very productive classes, partly flooded, in nutrient rich siltation zones (ibid.)
- ***Oxycocco-Sphagnetea*** – heathlands on raised bogs, located on ombrotrophic to oligotrophic sites dominated by dwarf shrubs on dry or wet soil (ibid.)
- ***Alnetea*** – shrub trees at nutrient-rich, temporarily flooded sites (ibid.).

In addition to this, this thesis discusses secondary raised bog areas which have been cultivated in the described melioration process (Chapter 2.2.1).

- ***Vaccinio-Piceetea*** – a forest stage of high resilience (if water levels do not change significantly), developed on mineralized soils (ibid.)
- ***Molinio-Arrhenatheretea*** – different types of grasslands and their succession stages (ibid.).

Furthermore, disturbed areas where topsoil was (re-)moved to implement rewetting measures are expected to be covered by nutrient indicating plants categorized as an edge community with an Ellenberg-indicator for N >7 (Ellenberg et al., 1992, as cited in Zillgen, 2020).

The plots are described in order of the classes they belong to. A brief introduction of the plots location and the plants mapped within the plots is followed by a description of the association they were categorized in. Finally, each section mentions the reference points set in the area around this plot for different species. Figure 4 gives an orientation where the plots are, Figure 12 shows pictures of the plots (or overview pictures of the area) and Table 6 lists the species found.

4.1.1 Hybrid of *Scheuchzerio-Caricetea nigrae* and *Molinio-Arrhenatheretea*

Plot 13

The plot is in sub-area 1a, which has been rewetted in 2015. The plot lies within a hollow where topsoil was removed on a large area to build the surrounding embankments. It showed very young and heterogeneous vegetation with 35 % covered by *Juncus effusus* and *Rumex spec.* respectively and 20 % covered by *Sphagnum spec.*. *Carex acuta* was present with 3 %, *Typha latifolia* with 5 %, *Juncus articulatus* with 1 % and single species of *Persicaria spec.* could be noted.

Due to its location and history of conservation measures applied, the process of vegetation inhabiting the area is according to Ellenberg et al. (2010: 479) described as a 'primary autogenous succession', whereby the seeds that are already present in the soil play a major role in its development. Since the seed bank situation plays such an important role in the species composition, it does not allow a clear assignment in this plot. The pioneer community is on the one hand influenced by its former *Calthion* history, on the other it might be in a transition process to the *Scheuchzerio-Caricetea nigrae*, still dominated by ruderal vegetation. Furthermore, deficits in the determination of *Sphagnum* species make complicate a clear assignment. The link between former species compositions and their presence in rewetted areas is discussed in Chapter 5.

As *Sphagnum spec.* species are used as an indicator for regeneration stage II, 300 reference points for young *Sphagnum spec.* mosses were set to complete the reference data of Plot 5. Furthermore 500 reference points have been identified in this plot for young *Juncus effusus* to make a comparison with Plot 5 possible and to use them as an indicator of succession.

4.1.2 *Phragmiti-Magnocaricetea*

Order: *Phragmitetalia*, Alliance: *Phragmition*, Association: *Typhetum latifoliae*

Plot 2

The plot is located within sub-area 3a, close to a flooded ditch. It shows a heterogeneous vegetation cover with a few species in dominant stands. *Typha latifolia* accounts with 40 % for the major share of the vegetation cover, *Carex acuta* makes up for 30 % of the plot`s vegetation, *Juncus effusus and Salix spec.* for approximately 10 % respectively and *Carex disticha* shows a cover of approximately 5 %. *Carex hirsuta* and *Agrostis canina* are present with 2 % respectively and single specimen of *Alopecurus pratensis* and *Ranunculus repens* were found. The assigned association is categorized following Naturschutzbund Burgenland (2015); Soó ex Eggler, 1933, as cited in Info Flora, 2020.

Between the aquatic plant societies and the landward following large sedge societies, *Phragmition* societies are located in the siltation zone of lakes or ponds (Naturschutzbund Burgenland, 2015). The dominance of *Typha latifolia*, in combination with different *Carex* species, shows that this plot experienced a strong disturbance due to the rewetting and the soil removal. After the rewetting *Typha* species have an advantage on the flooded soft soil compared to *Phragmites australis,* a species that is usually dominating this communities of reeds, due to their fast reproduction with seeds (Ellenberg et al., 2010: 504).

Typha latifolia serves as indicator species for regeneration stage I and can in general be used to identify flooded areas as ditches. 500 reference data points were set around this plot to identify the species on the orthophotos.

4.1.3 *Oxycocco-Sphagnetea*

Order: *Erico-Sphagnetalia*, Alliance: *Oxycocco-Ericion tetralicis*, Association: *Erico-Sphagnetum magellanici*, Sub-association *Empetrum nigrum* and *Narthecium ossifragum*

Plot 7

The plot is located within sub-area 2b on the mentioned pedestals in the bog. The plot shows narrow dry ditches that may be remnants of a preparatory work of rural peat cutting. The resulting small scale profile is reflected in the plant communities present. The plot shows a vegetation cover dominated by *Empetrum nigrum (*60 %) accompanied by *Narthecium ossifragum* (20 %) in the deeper hollows and *Erica tetralix* (20 %) growing in between*. Molinia caerulea* covers approximately 5 % of the plots foreland, followed by *Andromeda polifolia, Sphagnum* patches, *Calluna vulgaris* and *Festuca rubra.* Single species of *Epilobium palustre, Vaccinium oxycoccos, Eriophorum angustifolium* and very young individuals of *Betula pubescens* were noted. In line with Lindner-Effland (2020: 45 ff.) the characterizing climate zone taxa, as *Empetrum nigrum* and *Narthecium ossifragum,* are used to define the plant association. The assigned association is categorized following Dierßen & Dierßen (2001: 114) and Lindner-Effland (2020: 45 ff.).

Within the study area 2b, the *Erico-Sphagnetum* can be found on pedestals of the raised bog area, where the bog has not been subject to cultivation-initiated subsidence. The *Sphagnum* species are still strongly represented, although the subsoil was very dry during the vegetation survey. Within the plant association *Empetrum nigrum* together with *Erica tetralix* takes up a large part of the area. *Empetrum nigrum* is thereby located on higher hummocks than *Erica tetralix* (Dierßen & Dierßen, 2001: 85)*. Andromeda polifolia* is located on the edges of the hummocks, since it is capable to accept more humid surroundings due to its shallow roots (Dierßen & Dierßen, 2001: 61, 67). According to Lindner-Effland (2020: 47)*,* this characteristic can be mainly found in northwestern Schleswig-Holstein. The insular occurrences of *Narthecium ossifragum* were found in lower areas of the heathland, within the described ditches and hollows. This characteristic is the most clear Atlantic sub-association of *Erico-Sphagnetum* (Lindner-Effland, 2020: 47). The question if the small scale structure and the observed reflectance in the vegetation can be identified from the UAV data or whether only a general identification of the association is possible will be discussed in Chapter 5.

For the indicator species *Narthecium ossifragum* 200 reference data points were set since the allocation was limited, since patches of the species were difficult to locate exactly on the orthophotos. For the second indicator species of degradation stage I, *Erica tetralix,* 500 reference data points were set and 500 were set as random reference data points for the association *Erico-Sphagnetum*. No reference data points for *Empetrum Nigrum* were set, since it was not identifiable clearly on the orthophotos.

Plot 6

This plot is in the same area as Plot 7, but on the outer edges of the heathland. The heathland is completely framed by a vegetation similar to the one described in this chapter. The plot showed a vegetation cover dominated by *Molinia caerulea* (90 %) and *Betula pubescens (< 10 %),* overgrown *Sphagnum* could be noted to a small extend and single species of *Dryopteris carthusiana, Erica tetralix* and *Calluna vulgaris* were mapped. The assigned association is categorized following Lindner-Effland (2020: 49).

The homogenous plot is categorized as a degradation stage of the described association of *Erico-Sphagnetum* that occurs on drained bogs or raised bog areas which have been subject to peat cutting (Lindner-Effland, 2020: 47). They can be found on minerotrophic raised bog edge areas (Dierßen & Dierßen, 2001: 114), where unsteady water levels and soil aeration led to mineralization (Eigner and Schmatzler, 1991, as cited in Lindner-Effland, 2020: 47). *Molinia caerulea* and *Myricetum gale* built typical contact associations to *Erico-Sphagnetum* (Dierßen & Dierßen, 2001: 114,126). Phosphate and other nutrient inputs lead to an increase in *Molinia caerulea* compared to *Erica tetralix,* especially in combination with low water levels (Dierßen & Dierßen, 2001: 115).

Since *Molinia caerulea* is an indicator species of degradation stage II, 500 reference data points were set to identify the species of this plot.

4.1.4 *Alnetea-glutinosae*

Order: *Alnetalia-glutinosae*, Alliance: *Salicion-cinereae*, Association: *Myricetum gale*

Plot 8

The plot is also located within sub-area 2b, close to Plot 7. The immediate surrounding of the plot was comparable with Plot 6. It showed a vegetation cover dominated by *Myrica gale* (90 %) and *Betula pubescens (< 10 %), Molinia caerulea* and *Calluna vulgaris* made up for 1 % each in the herb layer. Overgrown *Sphagnum* could be noted as single species; others have been *Erica tetralix* and *Narthecium ossifragum*. The assigned association is categorized following Dierßen & Dierßen (2001: 126) and Lindner-Effland (2020: 52).

Species-poor, dense bushes of *Myrica gale* are, as already mentioned, also a contact association of *Erico-Sphagnetum* and of *Vaccinio-Betuletum* (Dierßen & Dierßen, 2001: 126). Other species in this association are rare, which is partly because it inhabits already species rare areas, with a *Molinia caerulea* dominance (Lindner-Effland, 2020: 52). Growing on edge areas of raised bogs or secondary in rural peat cutting areas, its occurrence is linked to high water levels (Dierßen & Dierßen, 2001: 126) and accordingly lower peat hummocks (Dierßen & Dierßen, 2001: 86).

For the indicator species of degradation stage III, *Myrica gale*, 500 reference data points were set around and within this plot.

4.1.5 *Vaccinio-Piceetea*

Order: *Cladonio-Vaccinetalia*, Alliance: *Phyllodoco-Vaccinion*, Association: *Betuletum pubescentis*

Plot 4

The plot is located within sub-area 2b, within an open birch forest. The area is surrounded by a small ditch, indicating that it has been drained. The plot shows vegetation coverage of approximately 100 % *Betula pubescens* in the tree layer. The herb layer was dominated by *Molinia caerulea* (> 70 %), *Dryopteris carthusiana* made up 5 % and mosses 1 %. Other species noted were young individuals of *Sorbus aucuparia, Picea abies* and *Rubus* spec. The assigned association is categorized following Dierßen & Dierßen, (2001: 123) and Lindner-Effland, (2020: 53).

Betula pubescens, the characterizing species of this association, is a degradation indicator. Its distribution, triggered by low water levels, is further intensified trough eutrophication (Irmler et al., 1998: 141). The trees shade light demanding species and intensify the lowering of water levels through the evapotranspiration and a resulting higher water demand (Dierßen & Dierßen, 2001: 123; Irmler et al., 1998: 34; Müller-Kroehling et al., 2019: 264–269). The ground vegetation finally dies due to leaf fall and coverage (ibid.). At the same time, *Betuletum pubescens* can often be noted as the final succession stage of fallow land (Breuer et al., 2007, as cited in LLUR, 2015: 37), on which the marsh forests developed as terminal vegetation stages. The plant association of *Betuletum pubescentis* is not only a resilient stage of vegetation if the water level does not decrease or increase (Ellenberg et al., 2010: 457; Müller-Kroehling et al., 2019: 264–269), it also leads to a complete disappearance of the typical species composition of the raised bog (LLUR, 2015: 39).

Around and within the plot, 500 reference data points were set to identify *Betula pubescens* as an indicator for degradation stage III and succession stage III. It is to mention that the herb layer cannot be identified by UAV data for this association, depending on the structure of the canopy.

4.1.6 *Molinio-Arrhenatheretea*

Order: *Potentillo-Polygonetalia*, Alliance: *Potentillion-Anserinae*, Association: *Ranunculo-Alopecuretum geniculati*

Plot 3

The plot is in sub-area 3a in close distance to Plot 2, in the center of one of the polders build to rewet the area. It shows a vegetation cover strongly dominated by *Persicaria spec.* (60 %). *Agrostis stolonifera* accounts for the second largest vegetation cover with 30 %. *Juncus effusus* and *Potentilla anserina* were present with 3-4 % respectively, *Alopecurus geniculatus* with 1 % and a single specimen of *Deschampsia cespitosa* was found. The assigned association is categorized following Dierschke and Briemle, (2008: 109 -110).

The plot is in the rewetted area and the vegetation indicates that this part is exposed to frequently changing water levels and is flooded during heavy rain periods. The flooded area is directly connected to Plot 2 which describes the ditch vegetation of the area. The fluctuation in the species composition is assumed to be high (Dierschke and Briemle, 2008: 109) and it cannot be ruled out that the former vegetation is represented due to seeds present in the soil.

500 reference data points were set for the association of *Ranunculo-Alopecuretum geniculati* in Plot 3, as no spatially locatable, indicating species could be isolated to indicate regeneration stage I.

Plot 9 and 10

Hybrid of: Order: *Molinietalia caeruleae*, Alliance: *Calthion palustris* and *Caricetum acutae*[8] (Class: *Phragmiti-Magnocaricetea*, Order: *Phragmitetalia*, Alliance: *Caricion elatae*)

Plot 9 is in sub-area 2b, Plot 10 in 2a, they are separated by a path crossing the bog. They both show very heterogeneous meadow vegetation and are both left as fallow land since 2015 (personal communication SNSH, 03.08.2020). They are framed by ditches. Plot 9 is surrounded by birches and shrubs, while Plot 10 is surrounded by other meadows.

Plot 9 showed heterogeneous vegetation coverage of 19 species. *Juncus effusus* (20 %), *Carex acuta* (15 %) and *Linaria vulgaris* (25 %) made up the largest share, followed by *Holcus lanatus* (15 %), *Anthoxanthum odoratum* (5 %), *Festuca rubra* (5 %), *Stellaria graminea* (3 %), *Carex disticha* (2 %). *Cirsium palustre*, *Agrostis capillaris*, *Lotus pedunculatus*, *Rumex acetosa*, *Deschampsia cespitosa*,

[8] also *Caricetum gracilis*

Epilobium palustre, *Dryopteris carthusiana*, *Ranunculus acris* and *Elymus repens* were estimated to cover 1 % respectively and single specimen of *Cirsium oleraceum* and *Cerastium fontanum* were found.

Plot 10 showed similar heterogeneous vegetation coverage of 14 different species, with a higher share of *Carex* species. *Festuca rubra* (30 %), *Carex acuta* (20 %), *Anthoxanthum odoratum* (20 %) and *Juncus effusus* (10 %) accounts for the largest share, followed by *Phalaris arundinacea (5 %), Rumex acetosa* (5 %), *Holcus lanatus* (5 %), *Festuca arundinacea* (< 5 %) and a *Carex* species that could not be species-specific identified (Carex spec. (3 %)). *Galium palustre, Cerastium fontanum* and *Potentilla anserina* made up for 1 % of the vegetation coverage and single species of *Carex nigra* and mosses were found.

The assigned association is categorized following Ellenberg et al. (2010: 986); Dierschke and Briemle (2008: 111 ff.) and Dierßen & Dierßen (2001: 120) but it is to be noted that the assignments due to advanced succession and former usage is variable.

The two plots showed a highly divers species spectrum, as it is typical for fallow land which has only recently fallen into disuse (Dierschke and Briemle, 2008: 169-170, 176 ff.). If the stabilizing factor *usage* lapses, the occurrence of plant colonies growing in herds increases and a small scale mosaic of species pattern develops in the first years of succession (ibid.: 169). Depending on the initial situation of the area an invasion of herbs or grasses occurs (ibid.: 169-170). Despite their former use, the areas are dominated by groundwater-indicating species (Dierßen & Dierßen, 2001: 127). Sedges dominate the moistest patches in raised bogs (Dierßen & Dierßen, 2001: 67). The dominance of these species group partially allows an assignment to the large grown sedges (here, *Caricetum gracilis*, (Ellenberg et al., 2010: 506, 986)). The *Caricetum gracilis* occurs on acidic soil and builds large patches of even lawn, tolerating a high degree of moisture (ibid.: 506-508). The dominance of *Carex acuta* can be often found on areas in the northern German lowlands on ruderalized former agricultural marginal land which was left fallow (Dierßen & Dierßen, 2001: 120). Plot 10 showed a higher degree of different sedges and patches of *Phalaris arundinacea,* compared to Plot 9.

In Plot 9, 500 reference data points were set as random reference data point for the alliance *Calthion palustris*, 200 to identify *Cirsium palustre,* 300 for *Holcus lanatus* and 500 for *Agrostis capillaris*. In Plot 10, 500 reference data points were set for *Carex acuta*, 450 for *Phalaris arundinacea* and 500 for the alliance on Plot 10. The 1 000 points set to represent the alliance are supposed to be very similar in their reflectance.

Plot 11

Hybrid of Order: *Molinietalia caeruleae*, Alliance: *Calthion palustris*, Association: *Angelico-Cirsietum palustris* and *Calamagrostietum canescentis* (Class: *Phragmiti-Magnocaricetea*, Order: *Magnocaricetalia*, Alliance: *Magnocaricion elatae*)

Plot 11 is on a neighboring site of Plot 10, but in contrast has been lying fallow since 2002 (personal communication SNSH, 03.08.2020). The vegetation cover of Plot 11 is dominated by *Calamagrostis canescens* (50 %) followed by *Cirsium palustre* (20 %) and *Juncus effusus (15 %). Rumex acetosa, Dryopteris carthusiana* and *Lotus pedunculatus* were present with approximately 5 % respectively and one specimen of *Epilobium palustre* was found. The assigned association is categorized following Ellenberg et al. (2010: 986); Dierschke and Briemle (2008: 111 ff.) and Info Flora (2020b) but it is to be noted that the assignment is variable due to advanced succession and former usage. *Cirsium palustre* is underrepresented in the plot compared to the area, as well as *Rumex acetosa.*

Plot 11 is inhabited by tall growing plant, which are stronger competitors, indicating an advanced succession (Dierschke and Briemle, 2008: 169). The described small scale structured mosaic in the first succession stage gives way in favor of dominance of single species. In general, the area is species-poor compared to Plot 9 and 10. A change in species composition has already taken place, towards a loss of less competitive species. This can be seen in the dominance of *Calamagrostis canescens* in the plot which is only representative for the edges of the area. The dominance of this species is typical for drained and proportionately nutrient rich areas as a results of a follow up community of sedge stands (Dierßen & Dierßen, 2001: 123). *Rubus spec.* is spreading from the edges, which is why *Rubus spec.* has been mapped as reference data points for succession stage II on the area. The species was not present in the plot directly.

150 reference data points were set to represent *Calamagrostis canescens*, to complete reference data in Plot 5. To indicate succession stage II, 300 reference data points were set for *Cirsium palustre,* completing Plot 9 and 500 were set for *Rubus spec.*

Plot 5

Order: *Molinietalia caeruleae*, Alliance: *Molinion caerulea*, Association: *Junco-Molinietum*

The plot is located within sub-area 2b, on an open area surrounded by birch trees. The area is slightly lower in altitude than its surroundings. The vegetation cover is dominated by *Juncus effusus* to 80 % with *Calamagrostis canescens* (< 20 %) as second most represented species. *Deschampsia cespitosa* was represented within the plot with approximately 1 %. Single specimen of *Carex rostrate*, *Sphagnum spec*. and young individuals of *Betula pubescens* were found.

A loose assignment to the association *Junco-Molinietum* following Dierschke and Briemle (2008: 122) and Lindner-Effland (2020: 39 ff.) is possible. Dierßen & Dierßen (2001: 131) describe the vegetation as a 'floristically weakly differentiated wet grassland'.

The association describes fallow land that was disturbed by livestock treads and eutrophication. As *Juncus effusus* builds very high and dense litter layers (Dierschke and Briemle, 2008: 174), it leads to shadowing of the herb layer and a development of a moist microclimate.

Since the species was identified as an indicator for succession stage II 500 reference data points were set to represent *Juncus effusus* which might be different from younger *Juncus effusus* patches (compare Plot 13). 350 were set for *Calamagrostis canescens* and 200 for *Sphagnum spec.* patches (also here, these points might differ from the ones in Plot 13 due to over-aging).

Plot 1 and 12

Order: *Molinietalia caeruleae*, Alliance: Filipendulion, Association: Filipendulo Geranietum

Both plots are located on the embankments; Plot 1 is in sub-area 3a, where the embankments have been built from 2012-2013 and Plot 12 in sub-area 1a, where rewetting measures took place in 2015. The embankments differ in material, as for the ones in Plot 1 peat of deeper layers was used and for the ones in Plot 12 surface peat was used.

Plot 1 showed a vegetation cover strongly dominated by *Urtica dioica* (90 %). *Galium aparine*, *Cirsium arvense* and *Deschampsia cespitosa* cover < 5 % respectively. Less than one percent of the area was covered by mosses, *Phalaris arundinacea* and *Elymus repens* and single specimen of *Cirsium oleraceum*, *Dactylis glomerata, Arctium minus* and *Epilobium palustre* were found.

Plot 12 shows a dominance of *Galeopsis tetrahit* with 60 % and *Holcus lanatus* patches with coverage of 30 %. *Cirsium palustre* was present with < 5 % and *Rumex acetosa* accounts for 5 %. *Agrostis capillaris, Juncus effusus* and *Persicaria spec.* were present with 1 % and single specimen of *Galium palustre* and *Rumex crispus* were found. The assigned association has been categorized following Dierßen & Dierßen (2001: 130).

A dominance of the edge community species *Urtica dioica* and *Galeopsis tetrahit* (Dierschke and Briemle, 2008: 170) is described if mineralization of the soil is high and the soil is rich in nutrients (Dierßen & Dierßen, 2001: 130). The plots are located on the embankments which are built in the course of the rewetting measures. They are generally dominated by shrub trees as *Betula pubescens* or *Salix spec.*, or nitrophilous plants as *Urtica dioica* or *Galeopsis tetrahit.* These plant communities indicate topsoil disturbance (Ellenberg et al., 2010: 221) and a strong availability of nutrients due to the degrading peat (since it is not water-saturated in this state). Secondary locations of the associations can be fallow land of former *Calthion* meadows, where tall growing, persistent species as *Cirsium oleraceum* are still present (Dierßen & Dierßen, 2001: 130).

To indicate disturbed areas, 500 reference data points were set for *Urtica dioica* in Plot 1. 50 reference data points were set for *Phalaris arundinacea*, which was growing on the side of the embankment outside the plot to complete the data in Plot 10. In Plot 12, 200 reference data points were set to represent *Holcus lanatus* (to complement the reference data of Plot 9) and 200 were set for *Galeopsis tetrahit* as an indicator of disturbed areas.

4.2 Interim evaluation, validation, and vegetation classification with Random Forest

The indicators of Table 2 are reflected in the reference data points for species and associations and build the classes used for the classification of vegetation in the entire study area. A comparison of the reflection values of all bands, VI and CHM of the 23 classes results in a box plot graph which is presented in Chapter 4.2.1. The independent validation of the classification is described in the second sub-chapter with the help of the confusion matrix (Figure 6). In order to enable a more detailed representation of input layers and results of the entire study area, four representative areas have been selected that inhabit the six plant classes that have been presented in Chapter 4.1. Representative for the input data, selected images of the RGB, the false color composite CIR, the DSM (as basis of calculation of the CHM) and the reNDVI2 (representative for the VI), are attached in the appendix (Figure 17 - Figure 20, Figure 22 - Figure 25, Figure 27 - Figure 30 and Figure 32 – Figure 35). There will only be a brief description of these datasets to give an insight in the input layers used for classification. The maps of the classification results of these areas (Figure 7, Figure 8, Figure 9 and Figure 10) are presented and described in Chapter 4.2.2 and are additionally attached in the appendix to enable a comparison between results and input data. The last sub-chapter describes a simple reclassification to present the health conditions of the ecosystem in a map (Figure 11).

4.2.1 Spectral signature and presentation of the input parameters

To answer the question to what extent the use of UAV can contribute to the classification of vegetation and monitoring processes in the *Western Königsmoor* an analysis of the input data is necessary.

Figure 5A shows the spectral signature (reflectance values) for all 23 classes of the multispectral bands of the camera (red, green, blue, red edge, and NIR). In general, the reflectance values can be better distinguished in the wavelength spectrum of red edge and NIR bands than within the blue, red and green wavelength spectrum. The boxplots indicate that the reflecting signals in the red edge and NIR spectrum are of greater relevance for the classification of vegetation. Therefore, as already mentioned, VI have been chosen whose calculations are based on these bands. Figure 5B shows the values of the selected VI (NDRE, NDVI and reNDVI2). They display different spectra, even if the overall pattern among them appears similar. Figure 5C and D show the height values (in m) for the classes as shown in the CHM. As already mentioned, the CHM represents the distance between the ground and the top of the objects above the ground, thus the height of the vegetation is represented. Figure 5C shows that the classes *Betula pubescens* and *Water* differ clearly in their signature from the other classes, which is why they were excluded in Figure 5D to enable a detailed view on the differences in reflection values of the remaining classes. While *Betula pubescens* differs significantly in height from the other classes, water shows such high values in the CHM because the computation of the DSM over water surface is often dominated by artefacts due its smooth surface and the resulting low number of key points. Although the model does not give us realistic heights for the *Water* class, the high value here allows a good determination of the water areas.

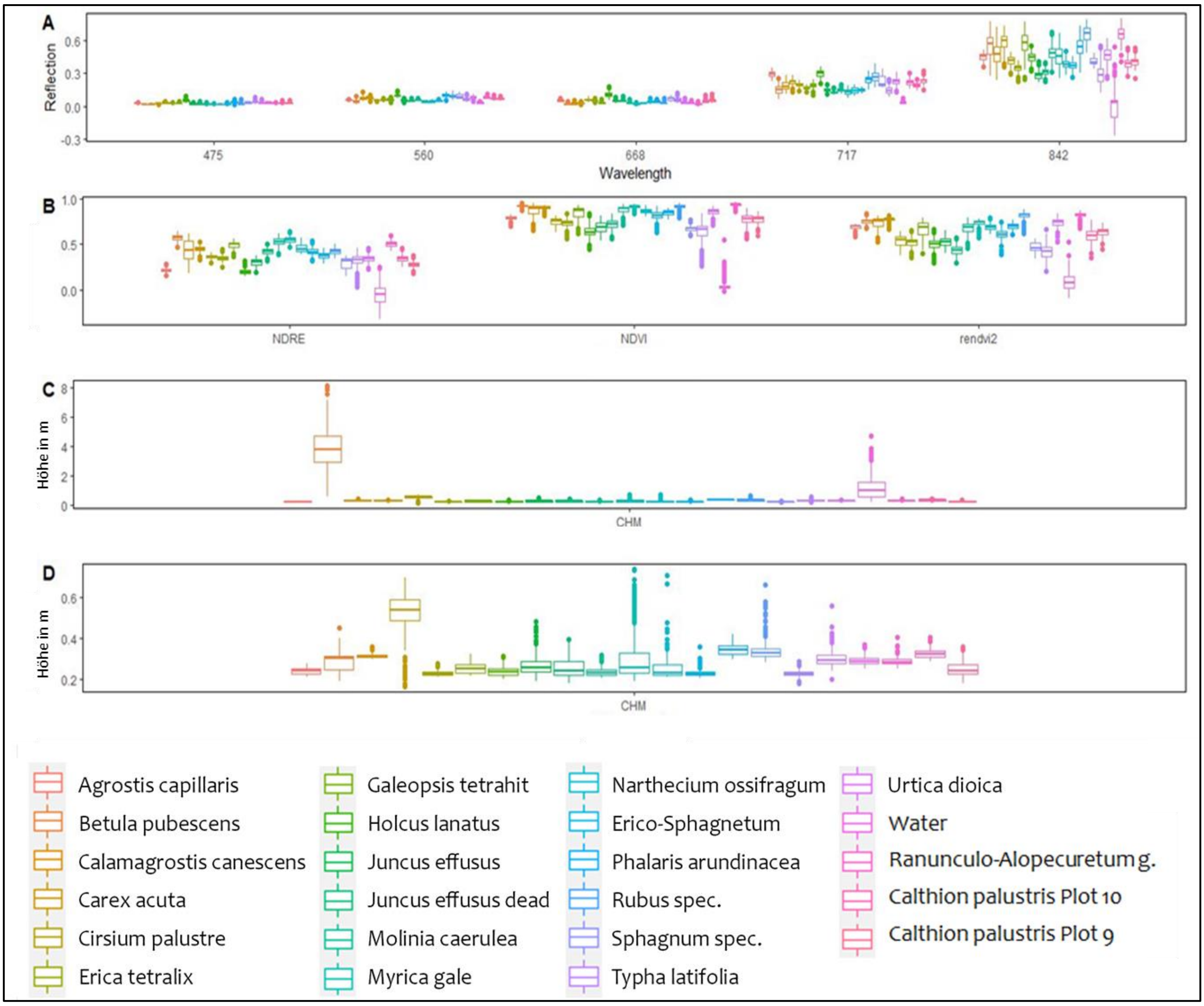

Figure 5 A: reflection values of the 23 classes in different wavelengths from left to right: blue, green, red, red edge and NIR, B: reflection values of the 23 classes in different VI (NDRE, NDVI, reNDVI2) C: height values of 23 classes in CHM, D: height values of 21 classes (*Betula pubescens* and *Water* excluded.) The y-axis is scaled differently for A, B, C and D.

Figure 17 - Figure 20, Figure 22 - Figure 25, Figure 27 - Figure 30 and Figure 32 - Figure 35, appendix show a selection of representatives of the input parameters[9] used for the classification. This selection of input parameters is briefly described in this chapter to ensure an understanding of the input data. Every DSM picture can be set into context by looking at Figure 15, where the elevation classes of the entire study area are presented.

Figure 17 shows the RGB of area 2b (heathland vegetation) and the reference data points set in the areas around Plot 6 (*Molinia caerulea*), Plot 7 (*Erico-Sphagnetum*) and Plot 8 (*Myrica gale*). Figure 18 shows the false color composite CIR. Visual analyses indicates that the classes of *Molinia caerulea*, *Betula pubescens* and different forms of dwarf shrubs might differ in their spectral reflectance of the infrared band. Figure 19 shows the DSM where *Betula pubescens* clearly differs in altitude (more than 2.5 m above sea level) from the heathland pedestal. *Myrica gale* seems to create specific values here as well that are differentiable from the ones of *Betula pubescens*. Furthermore, linear diagonal structures can be guessed in the DSM. They reflect the small scale ditch structure and the general slope of the terrain towards the ridge of the area. The VI reNDVI2 is presented for this area in Figure 20.

Figure 22 shows the RGB of area 2a, *Calthion* meadows. These meadows are abandoned since five years (meadow around Plot 10) and since eight years (meadow around Plot 11, in this picture series located in the north) (personal communication SNSH, 03.08.2020). The reference data points set in the areas around Plot 10 are presented. Figure 23 shows the false color composite CIR. Visual analyses indicated that the classes *Carex spec*., *Cirsium palustre* and *Holcus lanatus* differ in their spectral reflection values of the infrared band. Figure 24 shows the DSM where the *Carex spec.* patches (0 m above sea level) and *Cirsium palustre* plants (0.5 m above sea level) are clearly higher than the other parts of this area. The VI reNDVI2 is presented for this area in Figure 25.

Figure 27 shows the RGB of area 1a, rewetted in 2015, and the reference data points set in the areas around Plot 12 (embankment) and Plot 13 (rewetting area). Figure 28 shows the false color composite CIR. Visual analysis indicates that the classes on the embankments as well as *Sphagnum spec.* are identifiable through the infrared band. Figure 29 shows the DSM where the embankments are, with 0.5 m above sea level, clearly higher than the deepest part of this area which is at a level of approximately - 1 m. A difference in vegetation pattern cannot be indicated from the DSM in this area because the vegetation is very flat. The VI reNDVI2 is presented for this area in Figure 30.

[9] The input data (bands, VI and CHM) are represented by showing the RGB and false color composite, as well as one picture of the VI reNDVI2 and the DSM as explained in Chapter 4.2.

Figure 32 shows the RGB of area 3a, rewetted in 2012, and the reference data points set in the areas around Plot 2 (ditches) and Plot 3 (rewetting area). Figure 33 shows the false color composite CIR. Visual analyses indicated that *Typha latifolia* and *Holcus lanatus* differ in the reflectance values of the infrared band. Figure 34 shows the DSM where *Salix* species growing close to the ditches are identifiable (2.5 m) as well as *Phalaris arundinacea* (1.5 – 2 m) and a rather diffuse picture of ditches appears (0.5 -1 m). The VI reNDVI2 is presented for this area in Figure 35.

4.2.2 Confusion Matrix and data modification

The confusion matrix helps, as explained in chapter 3.4, to analyses the errors and accuracies of the classes and gives the overall accuracy of the vegetation classification approach by using 25 % of the reference data as validation data. Correctly classified data is shown in the diagonal of the matrix. The vertical and horizontals represent false classification.

In this chapter the final confusion matrix is presented (Figure 6). With the first classification an overall accuracy of 81 % was reached, after which the reference data has been adjusted. After a first analysis of the box plots and the confusion matrix, the following adjustments were made:

- Inclusion of 500 additional reference data points for water bodies
- Relocation of the *Holcus lanatus* reference data (example see appendix, Figure 13)
- Relocation of the *Sphagnum spec*. reference data.

For the second classification (before including the VI in the classification procedure) an OA of 86.3 % was reached. The final OA indicates that the average accuracy, with which a class is correctly identified, lies at 89.6 %. It is to be noted and discussed in detail in Chapter 5 if these results can be realistic with regards to overfitting the model. Furthermore, visual comparisons of the RGB images, the achieved results and the selected reference data help to interpret the results. Class specific User’s- and Producer's Accuracy values are given in percent for each class, while the OA shows the total of validation points correctly assigned. Most classes have a total number of validation points of 125 (only *Galeopsis tetrahit* and *Narthecium ossifragum* have only 50 validation points respectively). Values in the last row indicate if the model overestimates (more than 125 / 50) or underestimates the classes (less than 125 / 50). It shows total validation points assigned to the class. The lowest UA and PA values are highlighted yellow, so are the classes with which others have been confused (pale red background).

	A.c.	B.p	C.c.	C.a.	C.p	E.t.	G.t.	H.l.	J.e.	J.e.d.	M.c.	M.g.	N.o.	E-S	P.a.	R.	S.	T.l	U.d.	W.	R-A.g.	C.p.10	C.p.9	UA	Total
Agrostis capillaris (A.c)	116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	93%	125
Betula pubescens (B.p.)	0	125	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100%	125
Calamagrostis canescens (C.c.)	0	0	97	4	0	1	2	0	0	3	3	0	0	9	1	0	0	0	0	0	4	1	0	78%	125
Carex acuta (C.a.)	0	0	6	97	0	0	0	0	0	0	1	0	1	0	0	8	0	0	5	0	5	2	0	78%	125
Cirsium palustre (C.p.)	0	0	0	0	108	5	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	9	0	86%	125
Erica tetralix (E.t.)	0	0	0	0	0	105	0	0	5	0	0	0	0	9	0	0	3	2	0	0	0	1	0	84%	125
Galeopsis tetrahit (G.t.)	0	0	0	0	0	2	42	0	1	1	1	0	0	2	0	0	0	0	0	0	1	0	0	84%	50
Holcus lanatus (H.l.)	0	0	0	0	0	0	0	123	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	98%	125
Juncus effusus (J.e.)	0	0	0	0	0	3	0	0	116	0	0	0	0	3	0	0	0	0	0	0	0	3	0	93%	125
Juncus effusus dead (J.e.d)	0	0	0	0	0	0	0	0	0	125	0	0	0	0	0	0	0	0	0	0	0	0	0	100%	125
Molinia caerulea (M.c.)	0	0	1	0	0	0	1	0	0	0	123	0	0	0	0	0	0	0	0	0	0	0	0	98%	125
Myrica gale (M.g.)	0	0	0	0	0	0	1	0	0	1	0	116	4	3	0	0	0	0	0	0	0	0	0	93%	125
Narthecium ossifragum (N.o.)	0	0	0	0	0	0	0	0	0	0	0	0	47	3	0	0	0	0	0	0	0	0	0	94%	50
Erico-Sphagnetum (E-S)	0	0	1	0	0	3	1	0	1	0	1	0	6	112	0	0	0	0	0	0	0	0	0	90%	125
Phalaris arundinacea (P.a.)	0	0	0	2	0	0	0	0	0	0	0	0	0	0	122	0	0	0	0	0	0	1	0	98%	125
Rubus spec.(R.)	0	0	1	17	0	0	0	0	0	0	0	0	0	0	5	101	0	1	0	0	0	0	0	81%	125
Sphagnum spec. (S.)	0	0	1	0	0	0	0	37	1	0	0	0	0	0	0	0	56	0	6	0	0	0	24	45%	125
Typha latifolia (T.l.)	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	122	0	0	0	0	0	98%	125
Urtica dioica (U.d.)	0	0	5	2	0	0	0	1	2	0	0	0	0	0	5	0	0	1	105	0	0	2	2	84%	125
Water (W.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	121	0	0	0	100%	121
Ranunculo-Alopecuretum geniculati (R-A.g.)	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**0**	0	0	0	0	0	124	0	0	99%	125
Calthion palustris Plot 10 (C.p.10)	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	122	0	98%	125
Calthion palustris Plot 9 (C.p.9)	1	0	0	0	0	1	0	6	0	0	0	0	0	1	0	0	0	0	0	0	0	2	114	91%	125
PA	99%	100%	86%	78%	100%	88%	89%	73%	92%	95%	95%	100%	81%	78%	90%	93%	95%	97%	91%	100%	93%	84%	77%	**OA:**	
Total	117	125	113	125	108	120	47	169	126	131	129	116	58	143	135	109	59	126	116	121	134	145	149	**89,6%**	

Figure 6 Confusion matrix with Overall Accuracy, Producer's Accuracy and User's Accuracy values

4.2.3 Classification results

The results presented in the following sub-chapters form the basis to answer the question if the method is capable to capture the reflectance values of the species, which are relevant for assessing the condition of this ecosystem in terms of degradation, succession, and regeneration.

Figure 7 shows the classification results for area 2b (heathland vegetation). The figure is shown again in the appendix (Figure 21) to allow a visual comparison with the input data. The classification shows small scale structures, like the linear structures classified as *Narthecium ossifragum* and *Erico-Sphagnetum*. *Erica tetralix* is classified to larger areas. The class of *Molinia caerulea* is assigned to pixels in a linear diagonal structure. Also *Betula spec*. and *Myrica gale,* which completely frame the area, are classified by the model.

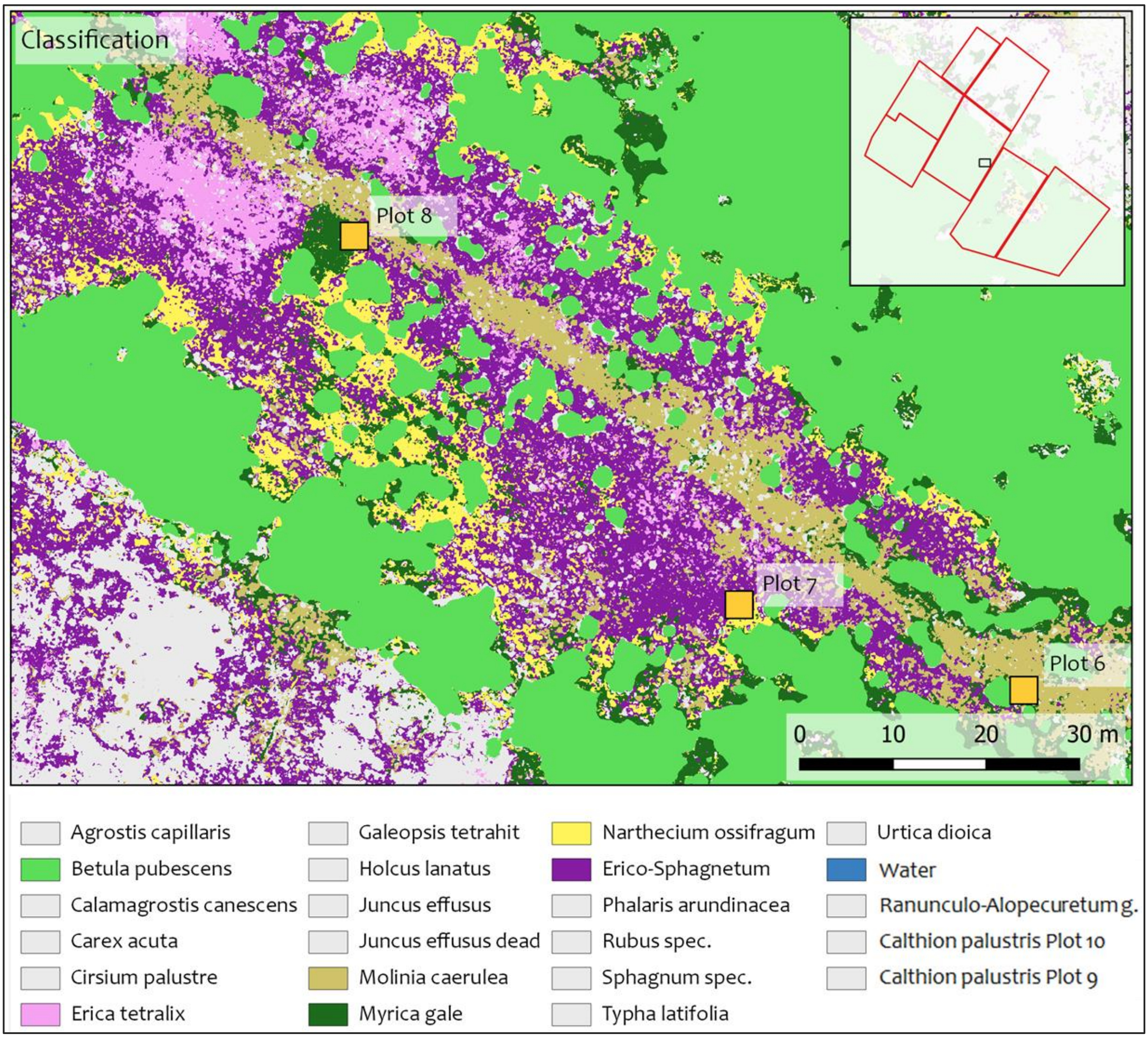

Figure 7 Classification, area 2b. Only classes essential for the area are shown in color on the map.

Figure 8 shows the classification results for area 2a, *Calthion* meadows. The figure is shown again in the appendix (Figure 26) to allow a visual comparison with the input data. *Carex spec.* and *Calamagrostis canescens* are assigned by the model to circular structures, while the alliance *Calthion palustris* covers most of the covers most of the diagonally delimited area. The appearance of *Juncus effusus* and *Cirsium palustre* are assigned mainly to pixels in the northern area. Small patches of *Holcus lanatus* are registered and represented by the model within areas covered by the class *Calthion palustris.*

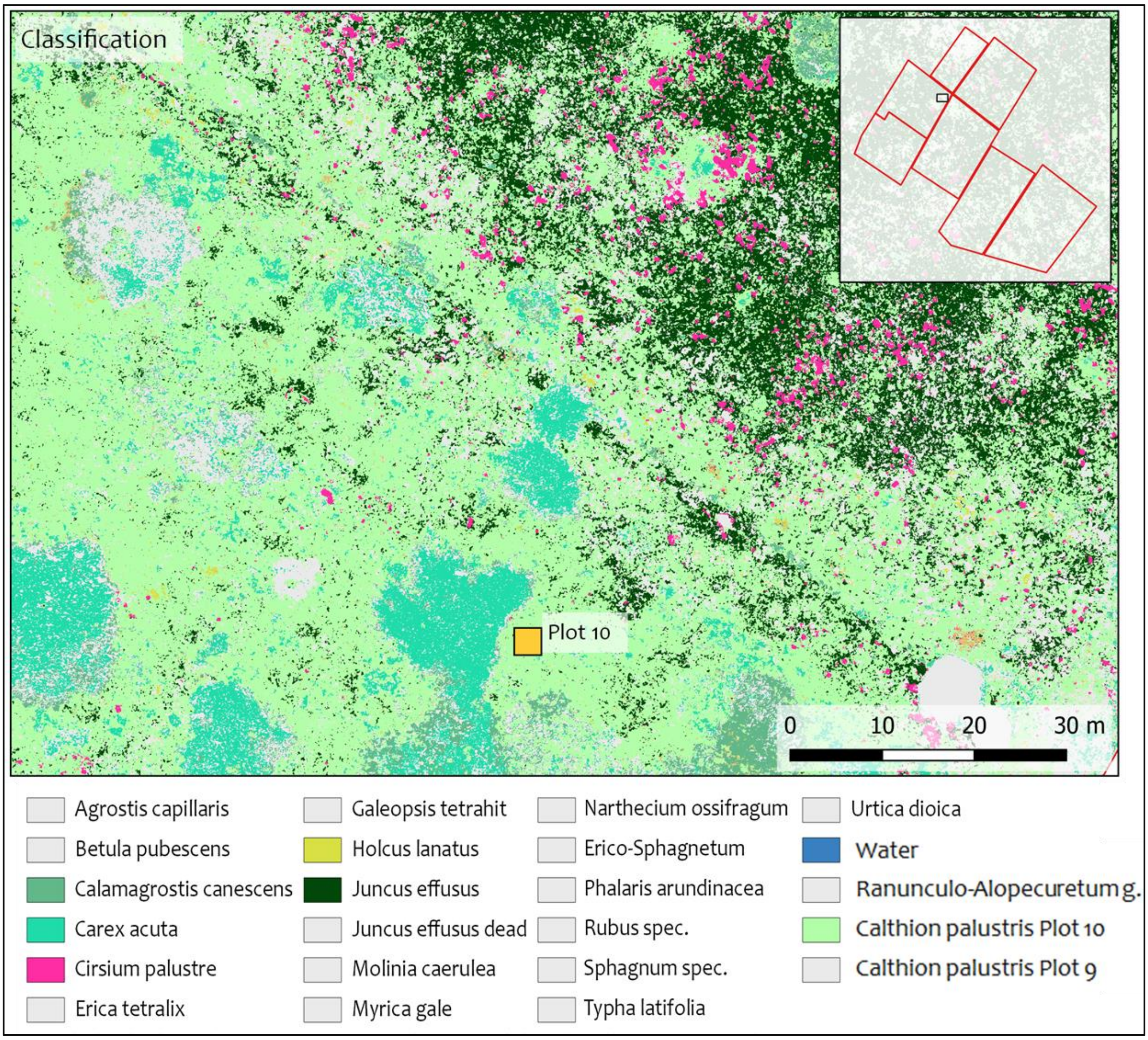

Figure 8 Classification, area 2a. Only classes essential for the area are shown in color on the map.

Figure 9 shows the classification results for area 1a, rewetted in 2015. The figure is shown again in the appendix (Figure 31) to allow a visual comparison with the input data. Large scale structures (as the embankments) show a different vegetation cover from the rewetted areas. *Juncus effusus* shows patterns around the open water areas. *Sphagnum spec.* is reproduced by the classification within the rewetted areas, but also on the embankments. *Typha latifolia* was classified by the model in large parts of this area too. The distribution of *Holcus lanatus*, *Galeopsis tetrahit* and patterns of *Urtica dioica* are classified on the embankments and in the case of *Urtica dioica* within the rewetted area.

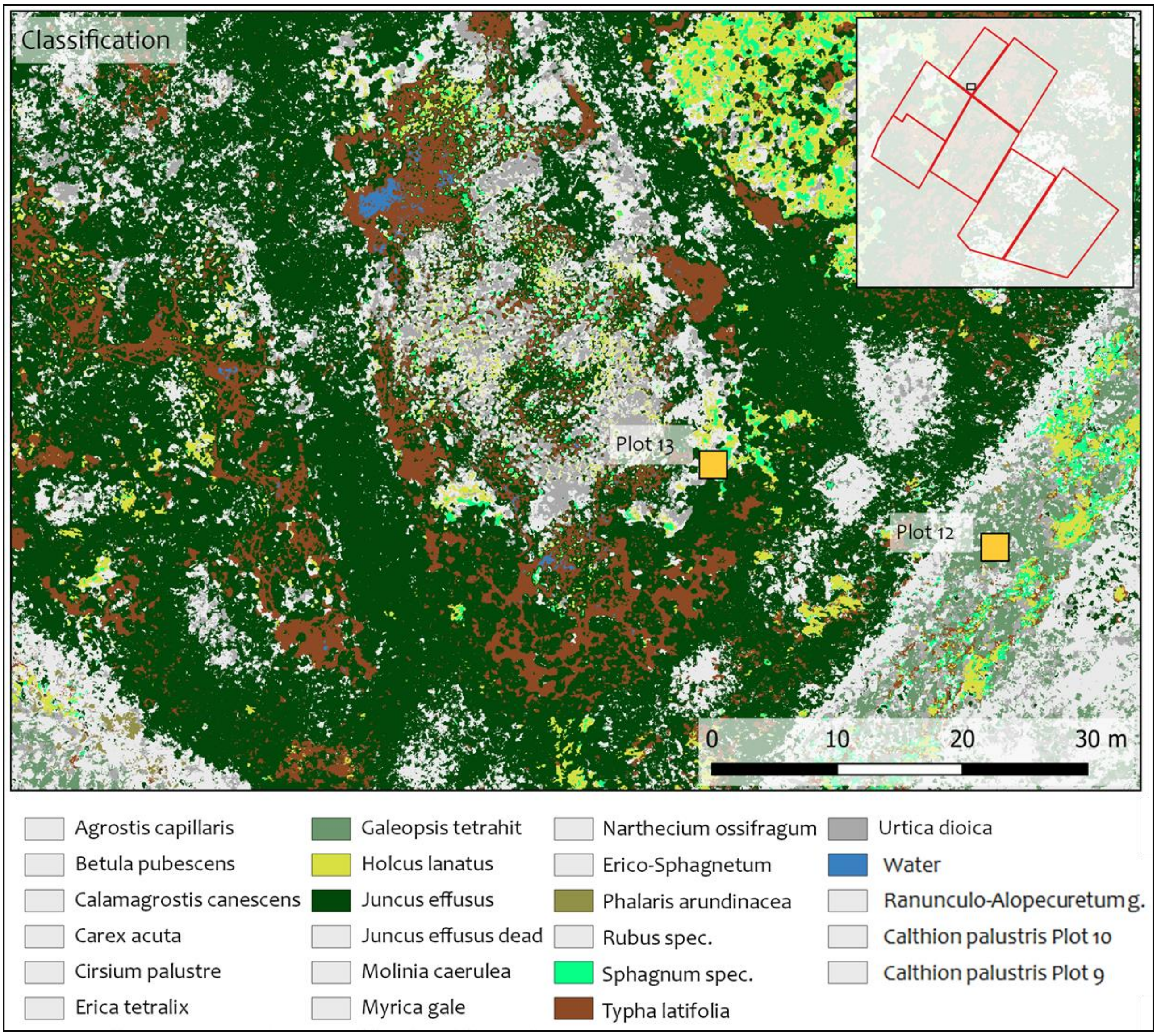

Figure 9 Classification, area 1a. Only classes essential for the area are shown in color on the map.

Figure 10 shows the classification results for area 3a, rewetted in 2012. The figure is shown again in the appendix (Figure 36) to allow a visual comparison with the input data. The association of *Ranunculo-Alopecuretum geniculati* is assigned by the model to a large area. The vegetation cover of the embankments is assigned to the classes *Urtica dioica* and *Holcus lanatus,* while *Betula pubescens* and *Typha latifolia* cover areas close to the ditch. Open water areas of the ditch are partly represented in the classification. *Phalaris arundinacea* is assigned by the model mainly to the outline of bigger circular structures.

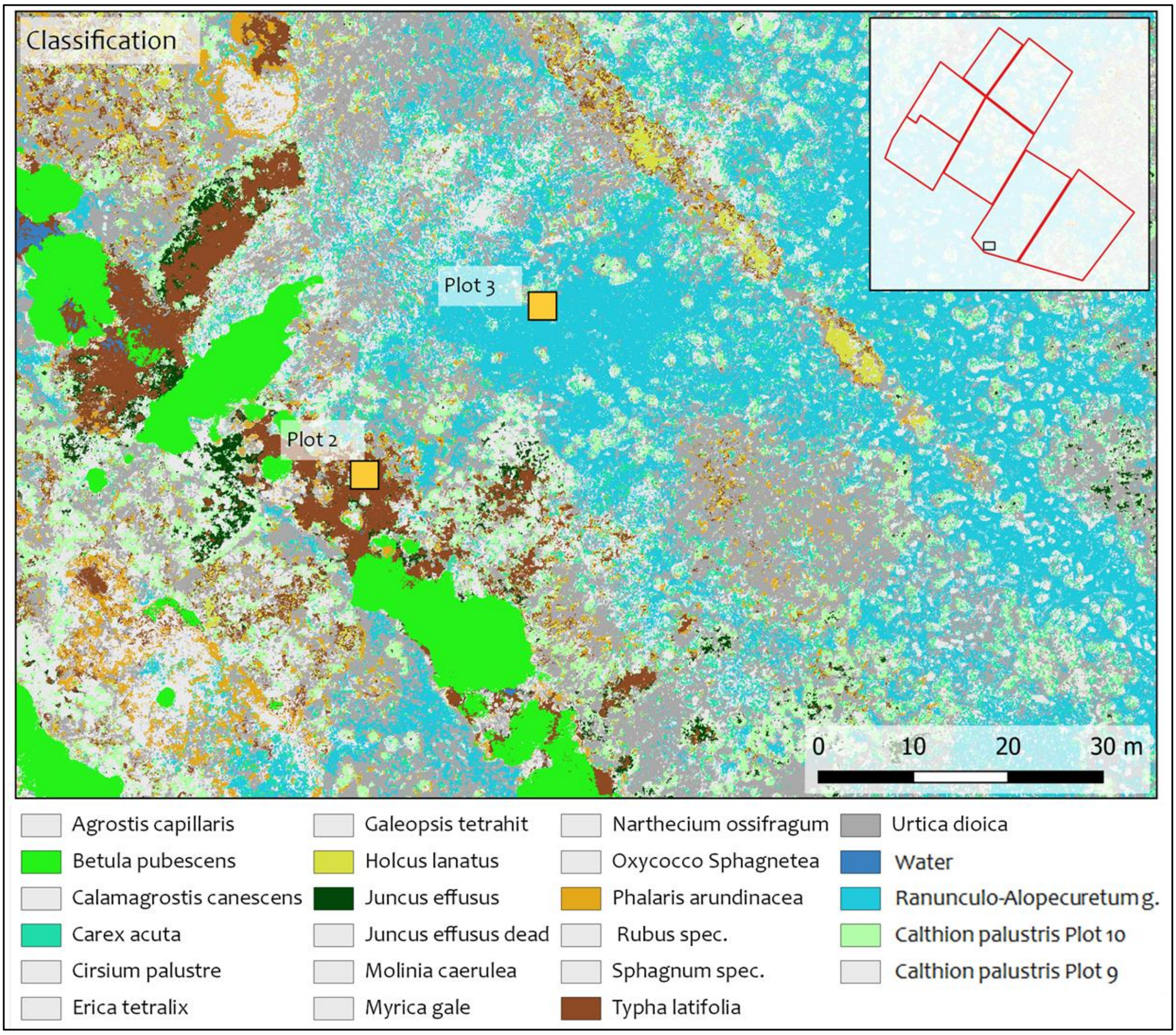

Figure 10 Classification, area 3a. Only classes essential for the area are shown in color on the map.

4.2.5 Reclassification

With the help of the extensive classification a holistic picture of the state of the raised bogs *Königsmoor* should be provided. Therefore, the classified vegetation areas were reclassified to correspond to the stages degradation, succession, and regeneration. Therefore, all indicators of Table 2 belonging to one stage are combined. The resulting classes are regeneration stage I and II, degradation stage I, II and III, grassland / succession stage I, succession stage II and III and disturbed areas, whereby degradation stage III and succession stage III are the same class. Figure 11 shows the conditions and ecosystem health based on the classification of the indicators assigned to different stages of degradation, succession, and regeneration. Despite possible errors (both in the clarity of the indicators and in the method of pixel-based classification, discussed in Chapter 5) some patterns are clearly identifiable. The results indicate strong degradation patterns in area 2a, 2b and 2c, closely intertwined with areas of degradation stage I and II and grassland / succession stage I. Furthermore, degradation stage III is assigned to many of the embankments in area 3a and 3b. Grassland / succession stage I and II are the classes covering in general most of the area, while regeneration stages I and II are limited to rather small areas. They are most extensive in area 1a, 2c and 3b.

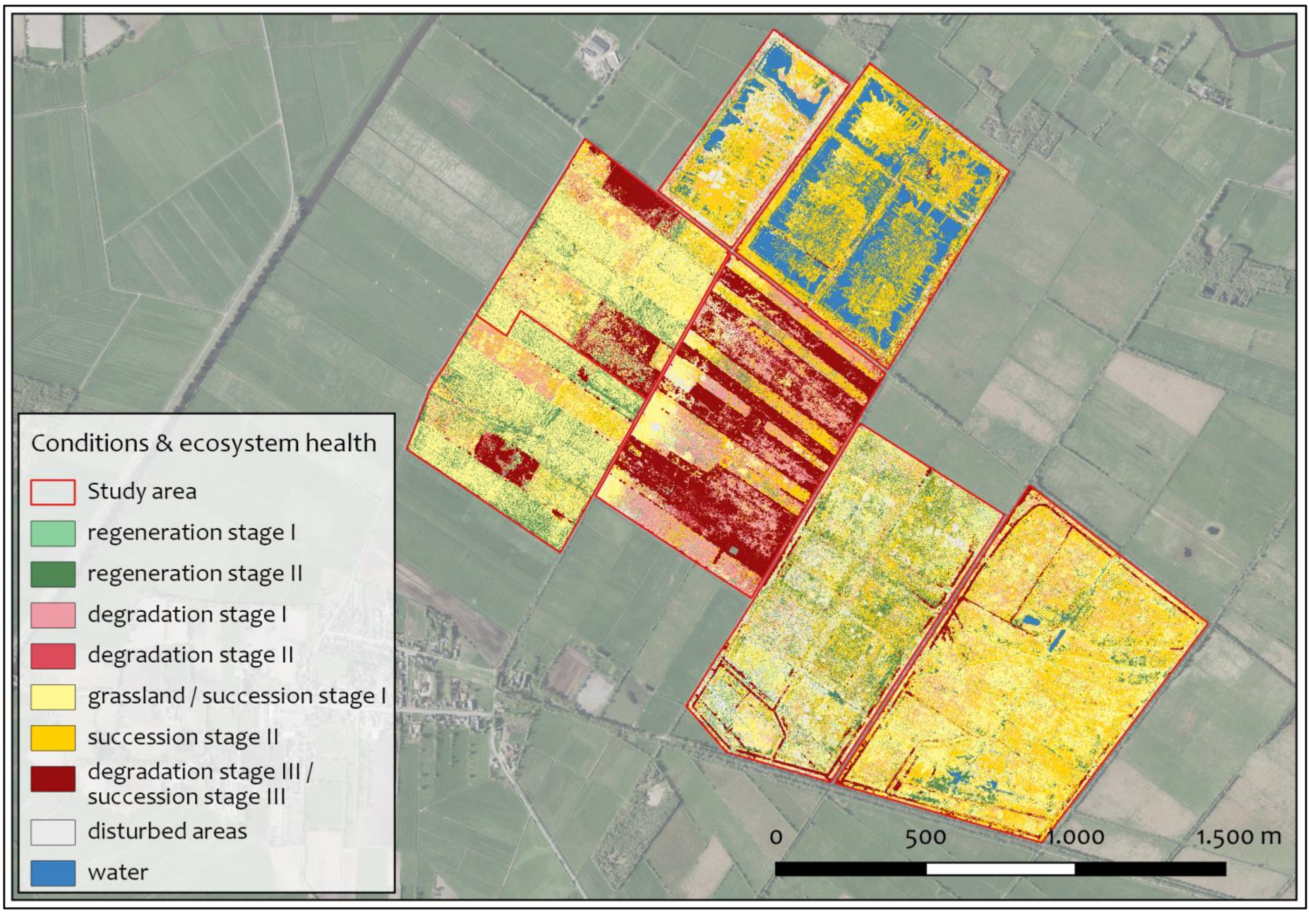

Figure 11 Conditions and ecosystem health in the raised bog *Königsmoor*, presentation based on classification results of the indicators forming the different stages of degradation, succession, and regeneration. Different stages and their indicators are explained in detail in Chapter 2.4 and Chapter 3.1.

5 Discussion

"In the ecological scope, the scientific community is very enthusiastic about the use of the UAS[10]*, proclaiming the dawn of drone ecology (Kohand Wich 2012) and that the UAS will revolutionize spatial ecology (Anderson & Gaston 2013)"* (Michez et al., 2016).

Different studies show that UAV data can make a significant contribution to gain data of the flora of raised bogs (Hecke et al., 2018: 431 ff.; Beyer & Grenzdörfer, 2018: 527 ff.; Kalacska et al., 2013: 6502 ff.; Kohv et al., 2017: 424 ff.). Methodological research on the most efficient VI (Beyer & Grenzdörfer, 2018: 525 ff.; Schnurawa, 2018: 18 ff.) and on different approaches like the use of different data sets (satellite data or UAV data (Bhatnagar et al., 2020: 3; Bhatnagar et al., 2020a: 4)), different evaluation approaches (spectral- or object-based analysis (Beyer & Grenzdörfer, 2018: 525 ff.; Michez et al., 2016: 11)), videography (Kalacska et al., 2013: 6503 ff.) and image segmentation (Bhatnagar et al., 2020a: 4) have been developed and examined in their functionality in the research area of classification.

Issues of papers with a non-methodological approach, if focusing on peatland, are often connected to climate gas emission (Kalacska et al., 2013: 6502 ff.; Lehmann et al., 2016: 2 ff.) and are in many cases focusing on very intact, remote forms of the habitat (Canada (Kalacska et al., 2013: 6502 ff..); Estonia (Kohv et al., 2017: 424 ff.), Patagonia (Lehmann et al., 2016: 3)). In contrast, this thesis focuses on German raised bogs, remnants in the landscape, which have been subject to several attempts of usage, melioration, or protection processes. Research on health conditions connected to the classification approaches are present for example for riparian forests (Michez et al., 2016: 14 ff.) where defoliation symptoms of alder trees were recorded. Barbedo (2019: 3 ff.) reviewed the use of UAV for monitoring and assessing plant stresses (water stress, nutrient disorders, and diseases) with a focus on agricultural field crops. This thesis presents an approach to assess health condition of an entire ecosystem by using several plant species as indicators. The scientific community assumes that the use of UAV data can make a decisive and necessary contribution to the assessment of health of ecosystems. The method and vegetation classification described in this thesis should be, as proposed in Bhatnagar et al. (2020: 12), the starting point for implementations in practice in SH. It might be applied, for example, with regards to the task of the FFH-monitoring required by the EU. A monitoring is required because the conservation objectives of FFH-areas are to be specific, measurable, realistic, consistent and comprehensive to enable the EU to consider the prohibition of deterioration (European Commission, 2019). This is, according to the size and sensitivity of some areas, a task that presently is associated with high costs and a great deal of effort that could not be

[10] UAS = Unmanned aerial systems, synonym for unmanned aerial vehicles

handled as the letter of formal notice from the EU Commission shows. In this letter the EU announces an infringement proceeding to Germany because of inadequate definitions of conservation targets (European Commission, 2019). To serve as a basis for this implementation in practice, this chapter analyzes possible sources of error in the research design, addresses the weaknesses of the method and points out possible improvements to enable an analyzation of the results.

Operational recommendations and methodological weaknesses

Within area 1a and 2a the data of the red edge band shows an artefact that could not be removed or improved manually (Figure 38). It can be assumed that the artefact might be a calculation mistake occurred during the post processing with Pix4Dmapper, but since the data processing binds a lot of computing capacity, a repetition within this project was not possible. An effect of the classification results in these areas is strongly reflected for some species in the results. This is mainly due to the fact that the red edge band is not only included as itself in the classification, but is reflected in the red edge supported VI (NDRE and reNDVI2). It is therefore represented threefold. The classification results of every species are discussed at a later stage in this chapter. Beyer and Grenzdörfer (2018: 531) showed that for their study area the reNDVI2 was of greater relevance than the other VI. This is not reflected clearly in the boxplot results (Figure 5). To verify this statement for this study, additional analyses would be necessary. Also, it is important to note that due to a problem with the memory card (while flying the same area) a narrow strip of data (approximately 3 m at the furthest point and with interruptions 300 m long) could not be included in the study. This is visual in the dataset but does not pose a problem for the further processing or interpretation of the data.

For defining the reference data points, a minimum distance between each reference data point is recommended for further studies. Keeping a minimum distance is a recommendation derived from McCoy (2005), as cited in Schnurawa (2018: 13), to avoid the reference points to have the same spectral reflectance value. It is calculated by $A = P (1 + 2L)$, P being the ground sampling distance and L the pixel positional accuracy of geometric registration (Rodriguez-Galiano, 2011, as cited in Schnurawa, 2018: 14). Not considering this minimum distance between training data points is one reason why the results indicated an overfitting of the model by using the training data. The other reason is that the reference data points for the entire area have only been taken at one (maximum two) plot per species. The high OA, UA and PA values show, in comparison with a view on wider areas where the vegetation can be determined of the RGB, biotope type mappings (compare Figure 37) or from the vegetation survey that the model is misclassifying large areas in some classes, without reflecting this in high errors of omission and commission. The results indicate furthermore that the classification draws the most realistic picture in the areas where the reference data points were recorded. This discrepancy in good OA, UA and PA values with, at the same time, partly unrealistic classifications in the larger areas is possible since the reference data points per species have been only taken in one specific patch of the wide terrain – which might represent the reflectance values of the species here, but does not match them in another area. The already mentioned artefact in the red edge band amplifies this error, because reference points taken here do not correspond to the spectral signature of the same class in other regions (this becomes evident by comparing the distribution of *Calthion palustris* Plot 9 and 10 in Figure 14 where the reference points have been collected insight (Plot 9) and outside (Plot 10) of the affected area). The collection of a wider range, in number and area, of reference data (and hence training data) generously distributed over the entire study area would probably lead to a significant improvement of the classification results and draw a more realistic picture. The very good results which are presented in the confusion matrix (Figure 6) can therefore only in parts be relied on. They are interpreted very strictly in the following discussion considering the distribution of species and associations in the whole area. The following interpretation of vegetation patterns must be read in the light of these methodological insecurities.

If these adjustments of the method would lead to significant lower OA (and PA or UA) values, additional benefit of using an object-based classification could be considered. Object-based classifications are mentioned in some studies (Michez et al., 2016: 11; Lehmann et al., 2016: 6 ff.) as an important parameter to classify vegetation. Also, the results of this thesis do suggest a significant improvement for some classes (*Carex acuta, Calamagrostis canescens* and *Phalaris arundinacea*, Chapter 4.2.3) through the additional use of an object-based classification. Hecke et al. (2018) presents four different drivers of the development of vegetation patterns: the intrinsic patterns of specific species (for example *Molinia caerulea* growing in tufts), patterns developed due to site conditions (for example zoning due to availability of nutrients or water), extrinsic patterns (for example marks of former cultivation attempts) and random patterns (for example the wildlife traces etc.). Due to the history of the study area and choice of method of this thesis, the vegetation patterns are mainly representing patterns developed through site conditions and extrinsic patterns. By including the object-based approach, a wider range of drivers for plant classification could be displayed.

Degrading areas: Classification, patterns in health map and conclusions for protection measures

Degradation stage I is indicated by the species *Erica tetralix* (PA 88 %, UA 84 %) and *Narthecium ossifragum* (PA 81 %, UA 94%) and the association *Erico-Sphagnetum* (PA 78 %, UA 90 %). The results indicate that *Narthecium ossifragum* is slightly overestimated, as it probably is assigned to pixels where *Empetrum nigrum* grows which is not assigned to any class. For the association *Erico-Sphagnetum* a strong overestimation is indicated in the results. The overestimation of the area of heathland is confirmed in Figure 37, as a comparison of the classification results with the biotope type mapping results of 2016 shows. It seems to be especially unrealistic for sub-area 2a and 2c where grassland is expected. In these areas the erroneous assignment of this class is possibly related to the error in the red edge band (Figure 38). For rewetted areas as 1a, 1b, 3a and 3b (Figure 3) an occurrence would be possible and cannot be excluded, but seems rather overestimated, especially when compared to the experience in the *Dosenmoor*, where the reintroduction of the *Ericaceae* is described as a long process (Irmler et al., 1998: 170). Since *Narthecium ossifragum* and *Erica tetralix* are defined as single classes but are also species occurring in the *Erico-Sphagnetum*, a high probability of confusion in these classes cannot be ruled out and becomes present in the PA of *Erico-Sphagnetum* and the misclassification of nine validation points as *Erica tetralix* and three as *Narthecium ossifragum.* In terms of future studies, it is recommended to adapt the classes, resulting in a clear classification in which duplications of single species and associations are excluded.

Degradation stage II is represented by the species *Molinia caerulea.* Its PA and UA values are with 95 % and 98 % also extraordinarily good. According to the classification (Figure 14), the shrub is hardly ever found in the rewetted areas but is found on scrubby grassland and, above all, as edge structure of the heath areas. The restrained occurrence of *Molinia caerulea* in the rewetted areas is surprising and is described differently in Irmler et al. (1998: 169) for the *Dosenmoor* in SH.

Degradation stage III is defined by *Betula pubescens* and *Myrica gale. Betula pubescens* has an UA value of 100 %, which means that every validation point was correctly classified. *Myrica gale* reaches a PA value of 100 % and an UA value of 93 %. Species of degradation stage II and III show realistic pattern in their overall distribution (Figure 14). For *Betula pubescens* and *Myrica gale,* which frame the area, it is to be noted that the herb layer of a dense stand of *Betula pubescens* cannot be identified under the leaf canopy.

The overall very realistic distribution picture (Figure 7) close to the reference points leads to the conclusion that for the degrading areas very good results can be achieved, although for degradation stage I this only applies to the immediate vicinity of these points.

The comparison of corresponding classes in Figure 14 with the DSM (Figure 15) shows that the assumption of the spread of *Erico-Sphagnetum* on pedestals of the raised bog area, where the bog has not been subject to cultivation-initiated subsidence, can be confirmed. The heavy use of most bogs in SH then explains why the plant association of *Erico-Sphagnetum* is only to be found in small scale secondary areas (Lindner-Effland, 2020: 47). Furthermore Figure 7 shows that the classification of small scale structures, like the linear structures remaining from the preparations for peat cutting (Chapter 4.1.3, Plot 7), can be derived from the observed spectral signature of the vegetation. The gradient from the deeper areas to areas slightly higher in altitude is generally represented in the result. Deeper areas, occurring in the area in linear patterns with a distance of approximately one meter, are visual in the classification since *Narthecium ossifragum* populates the deeper grooves, alternating with the association that settles on the higher ridges. Further up, the association *Erico-Sphagnetum* alternates in the same pattern with *Erica tetralix* which also covers larger areas here. The band of *Molinia caerulea,* crossing the heath on the highest ridge area, is clearly identifiable. *Molinia caerulea* shows the stronger drying and mineralization of the substrates, since this species prefers drier locations (Lindner-Effland, 2020: 45). The increased hummocks indicate a stronger maturation of the area (ibid.). The results show that even structures on the smallest scale, indicated by plant species adapted to small gradients of moisture, can be detected from the UAV data.

Referring to Figure 11, in areas characterized as degradation stage I bog vegetation still occurs, but the areas are endangered due to drainage and already too dry to provide a habitat for raised bog fauna on the long term. Figure 11 shows that the three degradation stages grow closely intertwined, as they prepare the habitat for each other and thus replace themselves on the surfaces. The distribution of stage III (Figure 11) shows that it occurs in linear structures between areas which are categorized as grassland or heathland. The indicator plant *Betula spec.* is, if managed by removal without simultaneously rewetting an area, hard to reduce. At least for one of the line shaped areas this former management is documented and can be seen as the main reason for this pattern (personal communication Walter, 18.08.2020).

In terms of protection it can be concluded that even though a vast majority of area 2b shows original vegetation of raised bogs, protection measures should not target this area only as a refuge for its flora. Especially with regards to the long-term protection of these species which cannot be guaranteed here. A complete rewetting of the entire area, as planned by SNSH, would in the near term destroy plant communities in this area, but would on the long run create a habitat in which they could redevelop and are not endangered due to low water levels. The solution of this conflict between long-term protection measures and protected biotopes (§30 Bundesnaturschutzgesetz) is a matter for consideration and cannot be facilitated by the method presented in this thesis.

Grassland and its succession areas: Classification, patterns in health map and conclusions for protection measures

Succession stage I is indicated by the species *Carex acuta* (PA 78 %, UA 78 %), *Calamagrostis canescens* (PA 86 %, UA 78 %), *Agrostis capillaris* (PA 99 %, UA 93 %), and *Holcus lanatus* (PA 73 %, UA 98 %) and the alliance *Calthion palustris Plot 9 and 10* (PA 77 %, UA 91 % and PA 84 %, UA 98 %).

Pixels classified as *Carex acuta* are often confused by the algorithm with the class *Rubus spec.* (Figure 6). Also the differentiation of the classifier between *Calamagrostis canescens*, *Urtica dioica* and *Ranunculo-Alopecuretum geniculati* and *Carex acuta* probably contains errors. Figure 8 indicates that this class would benefit from an additional object-based approach, since it has a clearly recognizable round structure which is at times only recognized in their outlines. The overall distribution (Figure 14) supports the thesis that the classification of single species in the vicinity of the recorded reference points is much better than in other areas. *Calamagrostis canescens* does not seem to have a particularly clear signal and is often confused with various other classes (Figure 6) The class seems to be underestimated while its distribution in the area looks realistic (Figure 14). In contrast, the distribution of *Agrostis capillaris* (Figure 14) is limited to the flight area where the artefact in the red edge band was recognized which is due to the fact that the reference points of *Agrostis capillaris* were included within this area (in Plot 9). This class cannot be used for further interpretations. *Holcus lanatus* is strongly overestimated to the disadvantage of *Sphagnum spec*. (Figure 6, Figure 14). Since *Holcus lanatus* is defined as a single class, but can also occur naturally in *Calthion* meadows, a high probability of confusion in these classes was expected. Areas recently mowed have been misclassified to large parts as *Holcus lanatus*, resulting in the linear distribution pattern in Figure 14. Small patches of *Holcus lanatus* within the *Calthion* class are represented by the classifier, which shows that a classification is partly possible even though a species is at the same time part of an association. The confusion with *Sphagnum spec.* could be tried to be ruled out in further studies by using additional VI with good results for *Sphagnum spec.* classification. The alliance *Calthion palustris* is well reproduced by the model. The overall distribution (Figure 14) of this class reproduces the error in the red edge band mentioned above. Since reference points for this class have been taken inside (Plot 9) and outside (Plot 10) of the affected area, a realistic picture of distribution emerges by combining the classes as one.

Succession stage II is represented by the species *Cirsium palustre* (PA 100 %, UA 86 %)*, Juncus spec.* (PA 92 %, UA 93 %)*, Juncus spec. dead* (PA 95 %, UA 100 %) and *Rubus spec.* (PA 93 %, UA 81 %).

The distribution of *Cirsium palustre* in area 2a (Figure 8) gives a very realistic picture of the actual distribution patterns but partly the class appears overestimated (area 1b, Figure 14). At this point it should be mentioned that the results from area 1b are partly strongly influenced by the faulty red edge band (Figure 38), so they will not be included in the discussion of single classes. This is especially evident in *Cirsium palustre* and *Rubus spec.*. The distribution of *Juncus effusus* and *Juncus dead* indicate that the special signal of the dead parts of the plant does not influence the pattern significantly, so that the overall distribution is basically fragmented (as explained for *Calthion palustris*) in two areas, one where *Juncus effusus* reference points have been taken and one where the reference points for the class of the dead plants were taken (Figure 14). *Rubus spec.* seems to be, according to the confusion matrix, underestimated in favor of *Carex acuta.* Its distribution in edge areas is very realistically reflected by the classification model, while the patch in area 3b (Figure 14) is a misclassification. The area is densely covered with a pioneer plant species in a former area covered with surface water. Degradation stage III and succession stage III are indicated by *Betula pubescens*, which has already been discussed.

The results show that although some species are subject to severe misclassifications, the different fallow stages are reproduced in the results (Figure 8 and Figure 39). The results indicate that if the stabilizing factor *usage* lapses, the occurrence of plant colonies growing in herds increases (Dierschke and Briemle, 2008: 169). The small scale mosaic of species pattern, which develops in the first years of succession (ibid.: 169), is reflected when comparing meadows under cultivation with abandoned ones (Figure 39). An invasion of herbs or grasses on these areas (ibid.: 169-170) is reflected in the UAV data. If a differentiation between grassland which is still farmed and abandoned grassland in its first succession stage is possible at any time cannot be derived from the results, as the areas under cultivation have just been mowed in the time of data collection. It is impressive that the classification allows exact conclusions, even about the type of use. Although the SNSH only mentioned areas that were mowed, grazed or where both types of use were present, the results allow the conclusion that one area was mowed (at least this year) only in parts (the north-west), while the south-east has probably not been used or was used for grazing only (Figure 40). Nevertheless, areas under cultivation were misclassified as *Holcus lanatus* and *Typha latifolia,* probably representing *Lolium perenne* and bare soil, neither of which were provided with an own class. Also areas dominated by groundwater-indicating species (Dierßen & Dierßen, 2001: 127) such as sedges can be identified from the data. The results give reason to assume that the soil moisture of an area can be distinguished by the classification of individual species. A further insight from the classification results in the *Calthion* meadows is that edge communities as *Rubus spec.* and their spreading can be monitored. Since the shrub species *Rubus spec*. is very tolerant in pH value, but does not tolerate wet ground (Ellenberg et al., 2010: 134), even a gradient of soil moisture from the outside to the inside of these areas might be derived from the results.

The, in large parts, realistic distribution patterns (Figure 8 and Figure 14) lead to the conclusion that for the grassland and succession areas good results can be achieved, especially with regards to succession stages and its structural changes or usage of an area.

Figure 11 shows that areas with succession stage III and meadows are growing, as described in literature, closely intertwined (Breuer et al., 2007, as cited in LLUR, 2015: 36). Areas of succession stage I and II, whereby stage II is dominated by the presence of *Juncus effusus*, show distribution patterns that can be compared with the usage maps of SNSH (Figure 40). The rewetted areas (1 and 3) are covered to a large extend with succession stage II, mainly due to the presence of *Juncus effusus*. Succession stage I mainly occurs within the areas 2a and b, which is reasonable since the land in this area was cultivated until recently or is still being cultivated.

Deriving protective measures for the grassland and its succession stage involves conflicts. Mesophile grassland (or species rich grassland) is defined as a protected biotope type (§ 30 Bundesnaturschutzgesetz) and is of great importance for meadow birds. Birds, as the Northern lapwing (*Vanellus vanellus*) or the Black-tailed godwit (*Limosa limosa*), are one of the declared protection targets of the SPA *Königsmoor West* (MELUR, 2018). By rewetting this habitat, the needed structures will be lost for many of these species, but serve as a habitat for other species typical for raised bog fauna (for example Common curlew (*Numenius arquata*) and Great bittern (*Botaurus stellaris*)).

Regeneration and vegetation development in rewetted and disturbed areas: Classification, patterns in health map and conclusions for protection measures

Disturbed areas are indicated by the species *Urtica dioica* (PA 91 %, UA 84 %) and *Galeopsis tetrahit* (PA 89 %, UA 84 %).

Even though the confusion matrix indicates a slight underestimation for *Urtica dioica,* on the entire study area the class shows a rather overestimated distribution pattern (Figure 14) (as described for heathland vegetation). It seems realistic that the embankments and the rewetted areas are heavily covered with *Urtica dioica*, while the growth in area 2b is due to the erroneous red edge band. The distribution patterns of *Galeopsis tetrahit* (Figure 14) seem to display their coverage on the embankments very well (especially in area 1a and b), while their diffuse occurrence in grassland areas (2a and c) is possible but not verifiable.

Regeneration stage I is represented by the species *Typha latifolia* (PA 97 %, UA 98 %) and *Phalaris arundinacea* (PA 90 %, UA 98 %) and the association *Ranunculo-Alopecuretum geniculati* (PA 93 %, UA 99 %). The confusion matrix does not indicate an overestimation of *Typha latifolia* but, looking at the distribution patterns of Figure 14 the class seems enormously overestimated especially in area 2. This is partly due to the misclassification of bare soil as *Typha latifolia*. The distribution in the rewetted areas seems in parts strongly overestimated (Figure 14 and Figure 9). In the area where reference points were taken, the classification achieves very good results (Figure 10). The overall results for *Phalaris arundinacea* are very realistic, even though the class seems little overestimated in the distribution results of area 2c, but its occurrence cannot be excluded here (Figure 14). The results of Figure 10 indicate that this class would profit of an additional object-based approach, since only outlines of patches are classified correctly. The association of *Ranunculo-Alopecuretum geniculati* obtains very good results with reliable distribution patterns (Figure 10 and Figure 14), even though the distribution for this class probably shows much better results in the vicinity of the recorded reference points than for the whole area.

Regeneration stage II is based on the species *Sphagnum spec.* (PA 95 %, UA 45 %). *Sphagnum spec.* obtains the lowest PA and UA, comparing all species and associations of the confusion matrix. With regards to the already discussed discrepancy in distribution patterns and results in the confusion matrix for other species, it is to be assumed that the classification results for this species can only be trusted to a very limited extent. The confusion matrix indicates that the class is mostly confused with *Holcus lanatus* and the alliance of *Calthion palustris.* Especially the confusion with the spectral reflectance of *Holcus lanatus* leads to a misclassification of pixels as *Sphagnum spec.* on the embankments (Figure 9). The distribution in area 2a seems overestimated but is, due to the occurrence of old *Sphagnum* spec. patches in this uncultivated area not completely unrealistic (Figure 14). The distribution in area 3a is very interesting and would, if the result could be fully trusted, prove the success of irrigation in this area. A fast development of loose patches of *Sphagnum fallax* and

Sphagnum cuspidatum has been described for rewetted areas in the *Dosenmoor*, SH (Irmler et al., 1998: 169).

Figure 9 indicates that *Juncus effusus* shows reasonable patterns, while open water areas are poorly reproduced in this part of the study area compared to other parts. *Sphagnum spec.* seems to be strongly overestimated, especially on the embankments. Also *Typha latifolia* was classified by the classifier in large parts of this area, but hardly ever occurred here, so a strong overestimation must be assumed. At the same time the distribution of *Holcus lanatus* and *Galeopsis tetrahit* looks reasonable, even though patches within the rewetted area classified as *Holcus lanatus* can only be partially correct, confusion with dead *Juncus effusus* is assumed here. While the patterns of *Urtica dioica* look reasonable on the embankments, the pixels in the wet area were wrongly classified as *Urtica dioica* due to the missing class of *Rumex spec*. The large number of grey pixels shows that this area is not well captured in the results since only the colored classes are expected. Even the surface water areas, which are very well reflected in other parts of the study area, could not be classified here. This error could be fixed in future studies by using a 'plant only' mask using VI. Figure 10 shows that large scale structures are well reflected in the classification. The association of *Ranunculo-Alopecuretum geniculati*, the embankment covered with *Urtica dioica*, *Holcus lanatus,* and *Betula pubescens* as well as areas close to the ditch covered with *Typha latifolia* show reasonable results. Open water areas are partly represented in the classification. It is to be noted that due to absence of a class for *Salix spec.* these were covered as *Betula spec.*. For *Phalaris arundinacea* the model seems to capture only parts of the patterns. Overall the vegetation cover of the rewetted areas seems to be difficult to capture for the model. According to Ellenberg et al. (2010: 479) the process of vegetation inhabiting young areas is described as a 'primary autogenous succession' whereby the seedbanks in the soil have a strong influence in the vegetation development of the areas. The link between former species compositions and their presence in rewetted areas could not be confirmed by the analysis of the spatial intersection of a map of area 1 with a vegetation map before rewetting (Figure 41) and the classification results (Figure 16). The results indicate that rewetted parts have experienced a strong distribution, either by the dominance of *Urtica dioica* or by the occurrence of *Typha latifolia,* which often inhabits disturbed soil due to the access to nutrients.

The, in large parts, realistic distribution patterns (Figure 9, Figure 10 and Figure 14) of the indicator species of disturbed areas lead to the conclusion that for the embankments realistic results can be drawn (admitting that *Betula spec.* is covering large parts and *Salix spec*. is not reproduced). The result shows furthermore that the overall fauna of recently rewetted areas can only be insufficiently classified, while areas which have been rewetted a longer time ago show a more realistic pattern.

Even though the classification of the indicators for regeneration stage I and II in Figure 11 are, as discussed, to be interpreted with caution, clear signs of the indicandum regeneration stage I and II are reflected in the rewetted areas 1 and 3. Assuming that the classification of the relevant classes is trustworthy to a certain extent, this shows that the rewetting areas are in a regenerating process.

Patterns of regeneration stage II in area 2b are realistic due to the occurrence of old *Sphagnum spec.* patches. This shows that the use of indicators can sometimes lead to wrong derivations if they are not explicit. *Sphagnum spec.* patches in this area do not indicate regeneration, but the occurrence of a formerly intact raised bog fauna. The classification of regeneration stage I and II in area 2a and c is most likely due to errors in the classification.

Conceivably, a clear definition of vegetation types (as described in the literature of the classical plant sociology) for the areas that have been rewetted is not possible, since such stages of high disturbance do usually not occur in natural raised bogs. One conclusion of this thesis is that in some locations rewetted bogs no longer form the classic vegetation types, but do nevertheless still perform valuable functions as CO_2 storage and contribute to biodiversity conservation.

6 Conclusion

Several studies have shown that in inaccessible, sensitive terrain (such as raised bogs) the usage of UAV can make a significant contribution to gain data of the flora and indicate the condition of the habitat. This thesis tried to link species classification by using drone data with the health conditions of the raised bog *Königsmoor* via plant indictors. The aim was to achieve and interpret minimal invasively collected data of a large area in order to generate a practical and efficient approach for the monitoring of FFH-areas. The leading questions of the study were thereby answered as follows:

- To what extent can the use of UAV contribute to the classification of vegetation and monitoring processes in the *Western Königsmoor*?

This thesis shows that by using UAV data an area of 337 ha can be covered and analyzed with some limitations. The results show, apart from one species, very good classification accuracies, even though they vary strongly in reliability for the different classes concerning their distribution over the whole area. This leads to the conclusion that a stronger focus on individual species or habitats would, with a few exceptions, lead to better classifications. By taking the reference points of the admired species within the areas of one flight sector (or various points per species distributed over the entire study area), errors in confusing spectral reflectance can be minimized. This thesis shows that next to single species (growing in patches), which can be identified by the combined method of an exact localization in the field and the localization on the collected high resolution data, also associations are well reflected. In summary, it can be said that the classes representing species, associations or alliances of the grassland and the heathland areas achieved better results than the rewetted areas. Depending on the aim of a possible monitoring the method is capable to contribute, for example, to a monitoring of the spread of certain species or to the status of surface water areas.

- Is the method capable to capture the reflectance values of the species relevant for assessing the condition of this ecosystem in terms of degradation, succession, and regeneration stages?

The results indicate that the identification of small scale structures and key-indicator species can help to interpret former cultivation forms and inform about the health conditions and the expected development of the area. Although the classification is incorrect in detail in some areas, interpretations about, for example, the (former) use of certain areas can be made without doubt. Based on classification results, the results for degradation- and succession stages are more reliable than those in the regeneration stages. By changing or adapting the indicators, the determination of areas of degradation, areas in succession or in regeneration could be improved or adjusted to more specific future research.

- What are weaknesses and limits of this method and is it practicable in the future of bog protection in SH?

Limitations of the method can be divided into practical limitations and limits of interpretation and derivation for further measures. Limitations in practice are for example the time period during which biotopes can be flown by UAV. This should be as exact as possible to the vegetation period of the most important indicator species to be recognized and must also be based on permits and possible closed periods (for example disturbance of breeding birds). The size of the area is limiting because first the difficulty of handling the data increases and second the error rate (reference data and their deviating spectral values in different flights) rises with larger areas. Indicators are a factor of uncertainty in the conclusions that can be drawn from them about the indicandum. Therefore, the derivation of recommendations for action is limited. Arguments for certain measures cannot be based exclusively on this method and so conflicts between different objects of protection cannot be solved based on these arguments. Although an attempt has been made to evaluate the health of the ecosystem *Königsmoor*, a clear evaluation is difficult and in the field of tension of different protection goals. For example heath is protected as such, but in this thesis it is already classified as degradation stage - other areas play an important role for the protection of meadow birds but are not necessarily designated as primary raised bog habitat.

Concluding, it has to be noted that the feasibility (with regards to financial and time efficiency for possible users) has been a main issue of this study. The aim was to investigate limits and possibilities of UAV data to assess the state of a raised bogs ecosystem. Using UAV is cheaper, faster, less disturbing and covering larger areas than a monitoring by a biological expert in the field. On the other hand it will never achieve the same degree of accuracy and reliability that can be decisive for the derivation of measures. This discrepancy leads to the conclusion that to reach comprehensive results the combination of these two methods is addressed and recommended.

7 Literature

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8 Appendix

Table 5 Biotope type mapping, abbreviations, official German designation and translation

Abbreviations	Official German designation	Translation
MRj	Moorregenerationsbereich, nass, vegetationsarm	Bog regeneration area, wet, poor in vegetation
MRb	Moorregenerationsbereich mit Moorbirken, torfmoosreich	Bog regeneration area with birch, peat moss rich
MRg	Moorregenerationsbereich mit Gagelgebüsch, torfmoosreich	Bog regeneration area with gale, peat moss rich
MRm	Moorregenerationsbereich mit Pfeifengras, torfmoosreich	Bog regeneration area with purple moor grass, peat moss rich
MRs	Moorregenerationsbereich mit Moorvegetation, torfmoosreich	Bog regeneration area with bog vegetation, peat moss rich
MRy	Sonstiger Moorregenerationsbereich	Other bog regeneration area
MDy	Degenerierte Moorflächen anderer Ausprägung	Degenerated bog areas of other characteristics
MDb	Trockener, sekundärer Moorwald	Dry, secondary bog forest
MDg	Degenerierte Moorfläche mit Gagelgebüsch	Degenerated bog area with gale
MDm	Degenerierte Moorfläche mit Pfeifengras	Degenerated bog area with purple moor grass
MHy	Sonstige Moorheide	Other bog heathland
HGm	Feldgehölze mit mittlerem Nadelgehölzanteil	Field shrubs with a medium proportion of conifers
HGx	Feldgehölze aus nicht heimischen Arten	Field shrubs of non-native species
HGy	Sonstige Feldgehölze	other field shrubs
GYf	Artenarmes bis mäßig artenreiches Feuchtgrünland	Species-poor to moderately species-rich wet grassland
GYj	Artenarmes bis mäßig artenreiches Grünland mit Flatterbinsen - Dominanzbeständen	Species-poor to moderately species-rich grassland with common rush dominance
GYn	Artenarmer bis mäßig artenreicher Flutrasen	Species-poor to moderately species-rich flood grassland
GYy	Mäßig artenreiches Wirtschaftsgrünland	Moderately species-rich farmed grassland
Gay	Artenarmes Wirtschaftsgrünland	Species-poor farmed grassland
GNa	Nährstoff und basenarmes Nassgrünland	Nutrient and base-poor wet grassland
GNm	Mäßig nährstoffreiches Nassgrünland	Moderately nutrient-rich wet grassland
NSs	Großseggenried	Large sedge reeds
RHr	Brombeerflur	Blackberry
SVg	Straßenbegleitgrün mit Gebüsch	Roadside with bushes,
SVo	Straßenbegleitgrün ohne Gehölz	Roadside without trees and shrubs
SVs	Vollversiegelte Verkehrsfläche	Sealed traffic area
SVt	Teilversiegelte Verkehrsfläche	Partially sealed traffic area

FLa	Naturnahes, lineares Gewässer mit Stillgewässercharakter	Near-natural, linear water body with still water character
AAe	Extensivacker	Extensive farmland

Table 6 Species list and location, Vegetation mapping 22-24.06.2020, the species presented in bold, red letters are dominant species, assumed to be represented by the digitized points and the spectrum of the pixels. Plots with a grey background show associations, which are assumed to have a species rich composition and can only be represented as whole associations, not single species. The Vegetation cover is given as r = < 1 %, + = 1 %, I = 5 %, II = 25 %, III = 50 %, IV = 75 %, and V = 100 %

Plot Class, Order, Alliance, Association	**Species**	**Vegetation cover**	**Digitized points**
1 Disturbed area, embankments *Molinio-Arrhenatheretea* *Molinietalia caeruleae* *Filipendulion* *Filipendulo Geranietum*	*Cirsium arvense*	II	
	Cirsium oleraceum	r	
	Urtica dioica	**V**	**500**
	Deschampsia cespitosa	I	
	Moss	+	
	Phalaris arundinacea	**+**	**50**
	Galium aparine	I	
	Elymus repens	+	
	Dactylis glomerata	+	
	Epilobium palustre	r	
	Arctium minus	r	
2 Rewetted area *Phragmiti-Magnocaricetea* *Phragmitetalia* *Phragmition* *Typhetum latifoliae*	*Alopecurus pratensis*	r	
	Carex acuta	III	
	Carex disticha	II	
	Carex hirsuta	I	
	Juncus effusus	II	
	Typha latifolia	**III**	**500**
	Agrostis canina	I	
	Ranunculus repens	r	
	Salix spec.	II	
3 Wet, flooded grassland *Molinio-Arrhenatheretea* *Potentillo-Polygonetalia* *Potentillion-Anserinae* *Ranunculo-Alopecuretum geniculati*	*Agrostis stolonifera*	III	500
	Alopecurus geniculatus	+	
	Deschampsia cespitosa	r	
	Persicaria spec.	IV	
	Potentilla anserina	I	
	Juncus effusus	I	
4 Mire forest *Vaccinio-Piceetea* *Cladonio-Vaccinetalia*	***Betula pubescens***	**V (tree layer)**	**500**
	Molinia caerulea	IV	
	Dryopteris carthusiana	I	
	Moss	+	

Plot Class, Order, Alliance, Association	**Species**	**Vegetation cover**	**Digitized points**
Phyllodoco-Vaccinion *Betuletum pubescentis*	*Sorbus aucuparia*	r	
	Picea abies	r	
	Rubus spec.	r	
5 Grassland *Molinio-Arrhenatheretea* *Molinietalia caeruleae* *Molinion caerulea* *Junco-Molinietum*	***Calamagrostis canescens***	**III**	**350**
	Carex rostrata	r	
	Juncus effusus	**V**	**500**
	Sphagnum spec.	r	**200**
	Betula pubescens	r	
	Deschampsia cespitosa	+	
6 Heathland edge area *Degradation stage of* *Oxycocco-Sphagnetea* *Erico-Sphagnetalia,* *Oxycocco-Ericion tetralicis* *Erico-Sphagnetum magellanici*	***Molinia caerulea***	**V**	**500**
	Betula pubescens	II	
	Dryopteris carthusiana	r	
	Erica tetralix	r	
	Calluna vulgaris	r	
	Sphagnum spec.	+	
7 Dwarf shrub heathland *Oxycocco-Sphagnetea* *Erico-Sphagnetalia* *Oxycocco-Ericion tetralicis* *Erico-Sphagnetum magellanici* *Empetrum nigrum* *Narthecium ossifragum*	***Narthecium ossifragum***	**II**	**200**
	Erica tetralix	**II**	**500**
	Andromeda polifolia	+	500
	Empetrum nigrum	IV	
	Eriophorum angustifolium	r	
	Sphagnum spec.	+	
	Molinia caerulea	I	
	Betula pubescens	r	
	Calluna vulgaris	+	
	Festuca rubra	I	
	Epilobium palustre	r	
	Vaccinium oxycoccos	r	
8 Heathland edge area *Alnatea-glutinosae* *Alnetalia-glutinosae* *Salicion-cinereae* *Myricetum gale*	***Myrica gale***	**V**	**500**
	Betula pubescens	II	
	Molinia caerulea	I	
	Calluna vulgaris	I	
	Narthecium ossifragum	r	
	Erica tetralix	r	
	Sphagnum	r	
9 Wet grassland *Molinio-Arrhenatheretea*	***Cirsium palustre***	**+**	**200**
	Holcus lanatus	**II**	**300**
	Agrostis capillaris	**+**	**500**

Plot Class, Order, Alliance, Association	**Species**	**Vegetation cover**	**Digitized points**
Molinietalia caeruleae *Calthion palustris* & *Phragmiti-Magnocaricetea* *Phragmitetalia* *Caricion elatae* *Caricetum acutae*	*Anthoxanthum odoratum*	I	500
	Carex acuta	II	
	Carex disticha	I	
	Juncus effusus	II	
	Lotus pedunculatus	+	
	Rumex acetosa	+	
	Stellaria graminea	I	
	Linaria vulgaris	II	
	Festuca rubra	I	
	Deschampsia cespitosa	+	
	Epilobium palustre	+	
	Cirsium oleraceum	r	
	Dryopteris carthusiana	+	
	Ranunculus acris	+	
	Elymus repens	+	
	Cerastium fontanum	r	
10 Wet grassland *Molinio-Arrhenatheretea* *Molinietalia caeruleae* *Calthion palustris* & *Phragmiti-Magnocaricetea* *Phragmitetalia* *Caricion elatae* *Caricetum acutae*	***Carex acuta***	**II**	**500**
	Phalaris arundinacea	**I**	**450**
	Anthoxanthum odoratum	II	500
	Carex nigra	r	
	Carex spec.	I	
	Festuca arundinacea	I	
	Galium palustre	+	
	Juncus effusus	II	
	Rumex acetosa	I	
	Festuca rubra	III	
	Holcus lanatus	I	
	Moss	r	
	Potentilla anserina	+	
	Cerastium fontanum	+	
11 Perennial grassland *Molinio-Arrhenatheretea* *Molinietalia caeruleae* *Calthion palustris* *Angelico-Cirsietum palustris* &	***Calamagrostis canescens***	**III**	**150**
	Cirsium palustre	**II**	**300**
	Juncus effusus	II	
	Rumex acetosa	I	
	Rubus spec.	**I**	**500**
	Dryopteris carthusiana	I	
	Epilobium palustre	r	

Plot Class, Order, Alliance, Association	**Species**	**Vegetation cover**	**Digitized points**
Phragmiti-Magnocaricetea *Magnocaricetalia* *Magnocaricion* *Calamagrostietum canescentis*	*Lotus pedunculatus*	I	
12 Disturbed area, embankments *Molinio-Arrhenatheretea* *Molinietalia caeruleae* *Filipendulion* *Filipendulo Geranietum*	*Cirsium palustre*	I	
	Holcus lanatus	**III**	**200**
	Galeopsis tetrahit	**IV**	**200**
	Galium palustre	r	
	Juncus effusus	I	
	Agrostis capillaris	+	
	Persicaria spec.	+	
	Rumex acetosa	I	
	Rumex crispus	r	
13 Rewetted area *Scheuchzerio-Caricetea nigrae* *& Molinio-Arrhenatheretea*	*Carex acuta*	I	
	Juncus effusus	**III**	**500**
	Sphagnum spec.	**II**	**300**
	Juncus articulatus	+	
	Persicaria spec.	r	
	Rumex spec.	III	
	Typha latifolia	I	

Plot 1

Plot 2

Plot 3

Plot 4

Plot 5

Plot 6

Plot 7

Plot 8

Plot 9

Plot 10

Plot 11

Plot 12

Plot 13

Figure 12 Pictures of the plots (some pictures do not represent the exact location of the plot, but give an area overview)

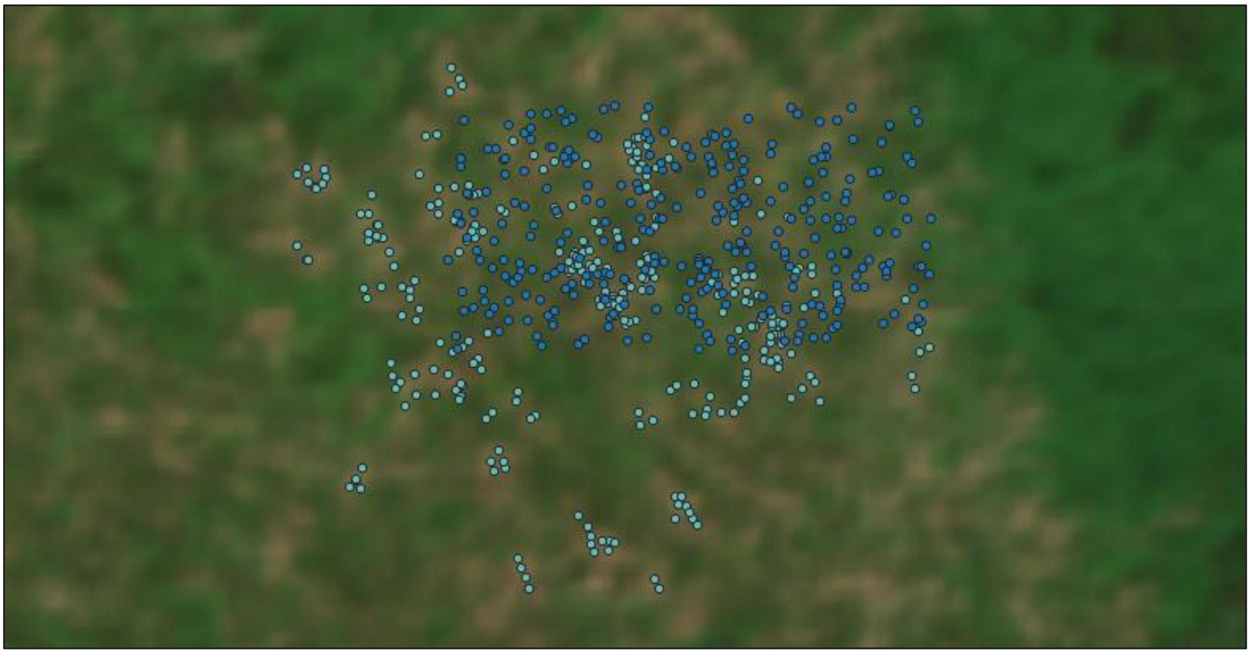


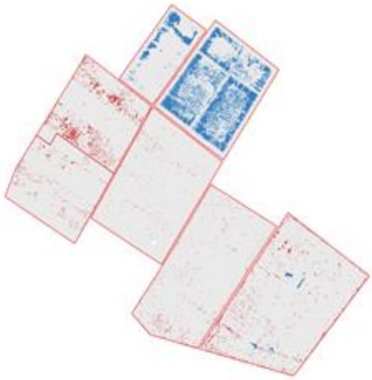
Figure 13 Dark blue represents the old reference data set within a *Holcus lanatus* patch made with the Q-GIS tool 'Points within boundaries' while light blue shows the adjustments made after analyzing high errors in this class in the first Confusion Matrix. The adjustment led to an improvement from 45 % UA to 90 % UA for the class *Holcus lanatus*.

Agrostis capillaris

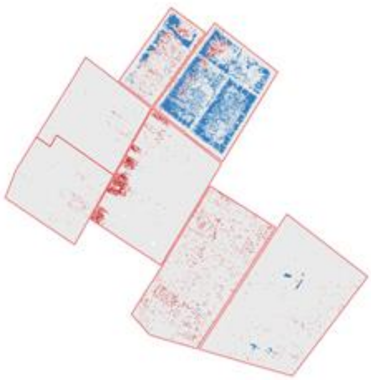
Betula pubescens

Calamagrostis canescens

Carex acuta



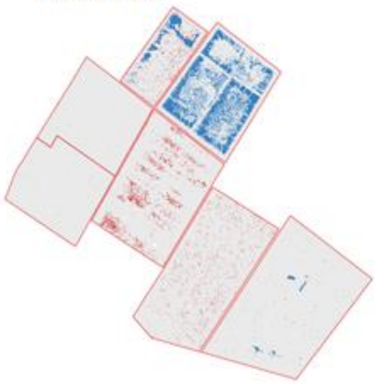
Calthion palustre plot 9



Calthion palustre plot 10

Cirsium palustre

Erica tetralix

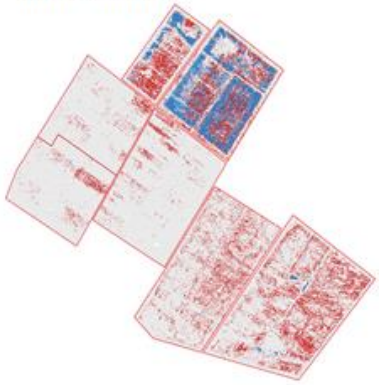


Erico-Sphagnetum

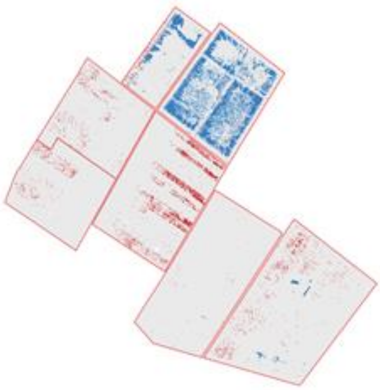
Galeopsis tetrahit

Holcus lanatus

Juncus effusus



Juncus effusus dead



Molinia caerulea

Myrica gale

Narthecium ossifragum

Phalaris arundenacia

Ranunculo-Alopecuretum g.

Figure 14 Presentation of the predicted distribution of the classes within the study area

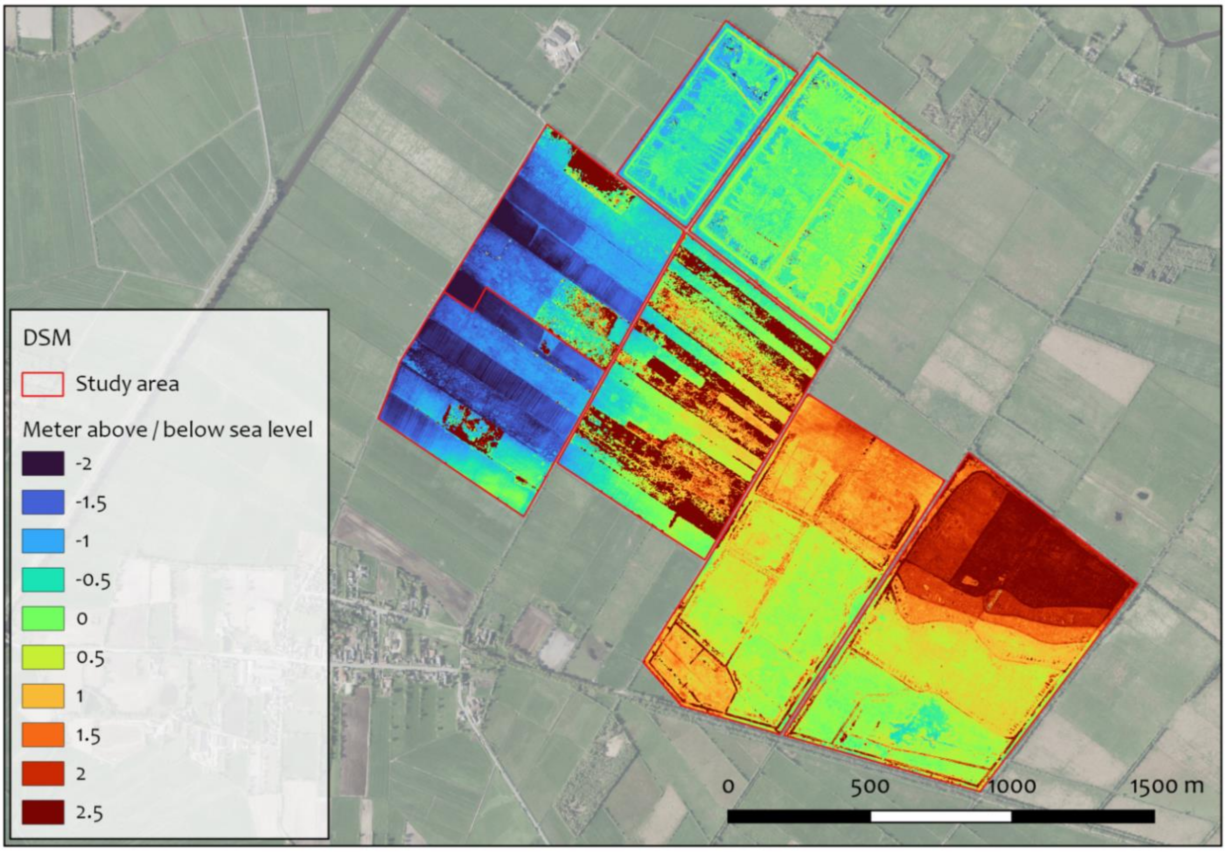


Figure 15 The DSM shows areas above and below sea level in the *Königsmoor*.

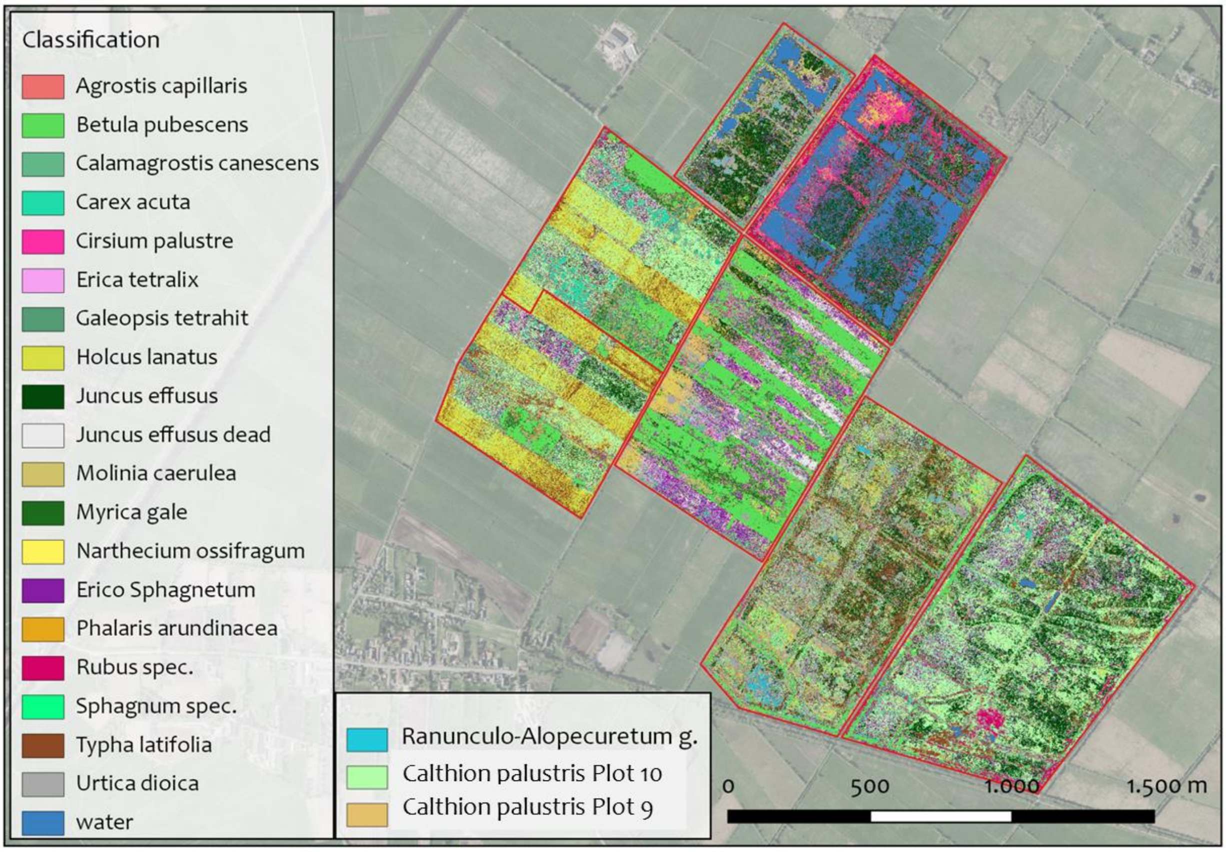


Figure 16 Classification of the entire study area and all 19 classes and 3 different associations/ alliances

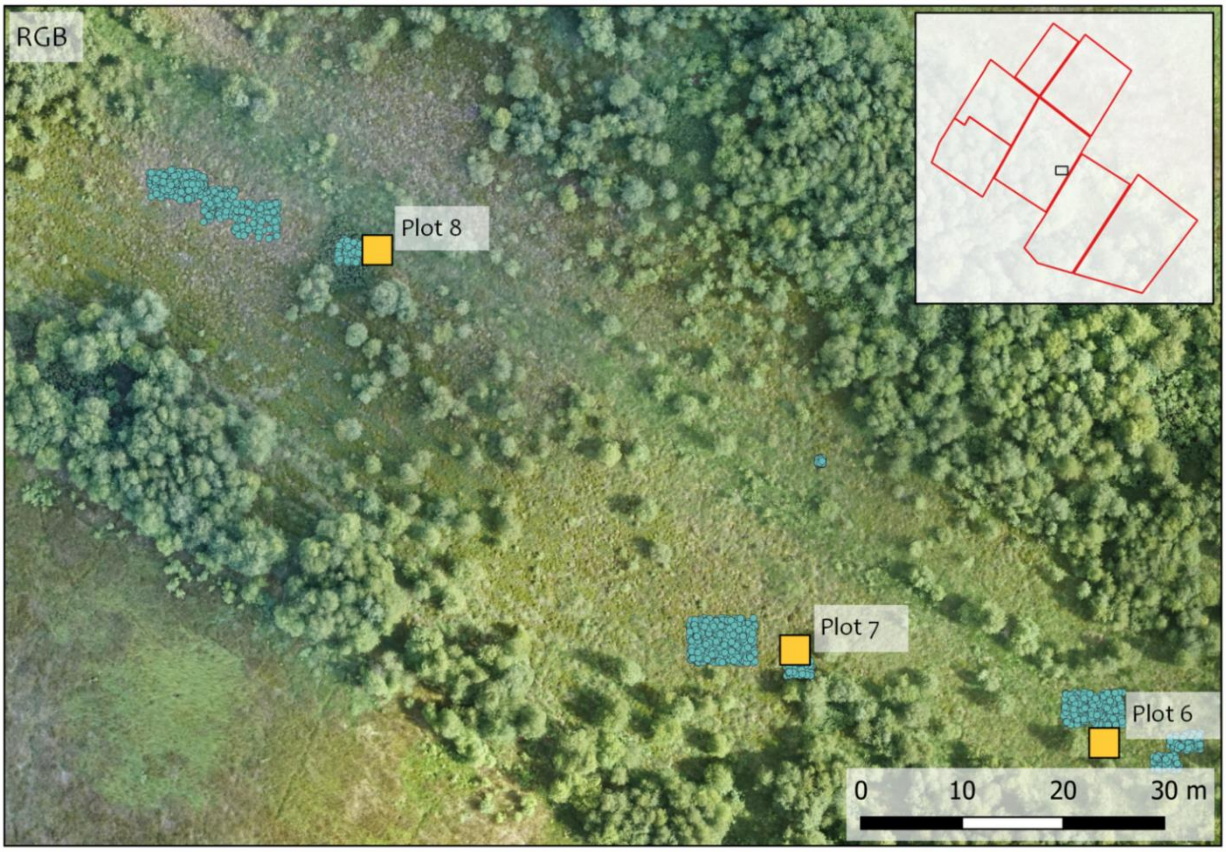


Figure 17 RGB, sub-area 2b, reference data points around plot6 (*Molinia caerulea*), Plot 7 (*Oxycocco-Sphagnetea*) (Chapter 4.1.3) and 8 (*Myricetum Gale*, Chapter 4.1.4), the plant association *Betuletum pubescentis* is also present

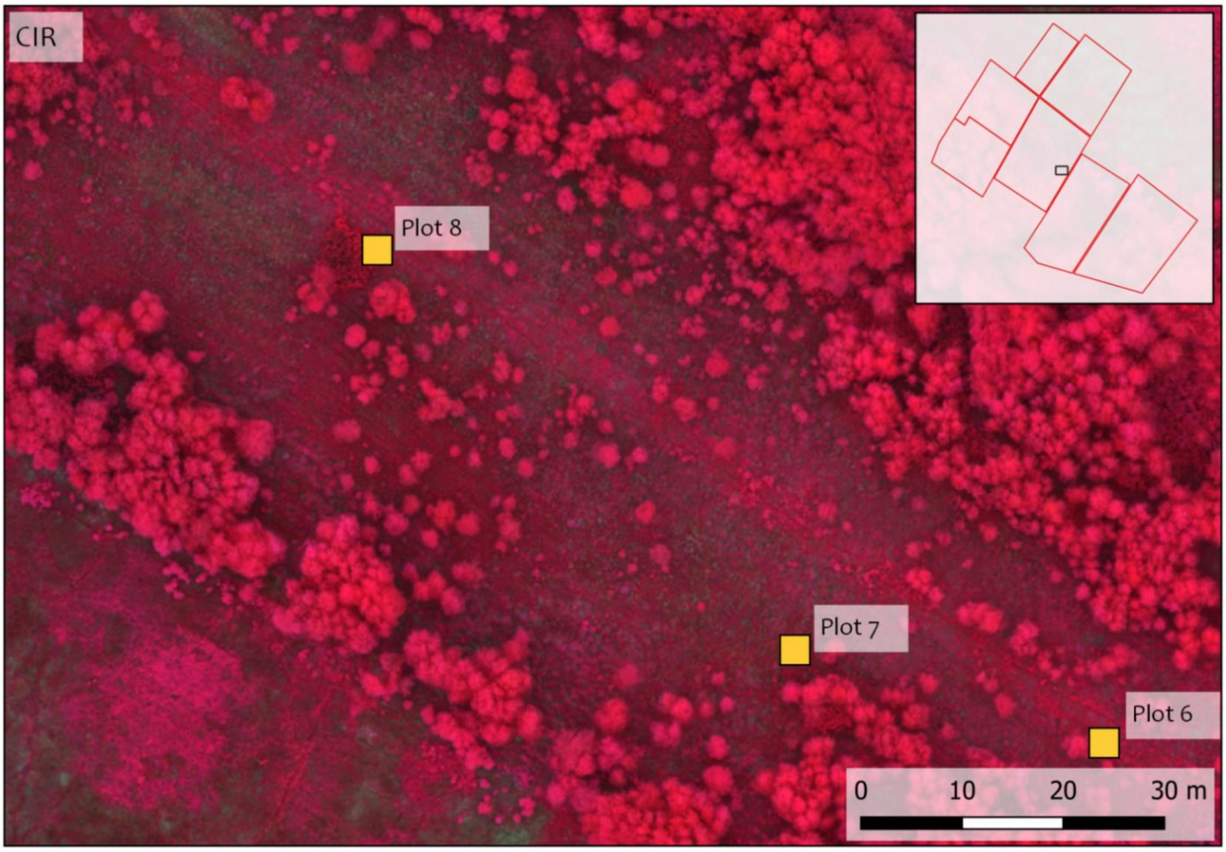


Figure 18 CIR, sub-area 2b with Plot 6, 7 and 8

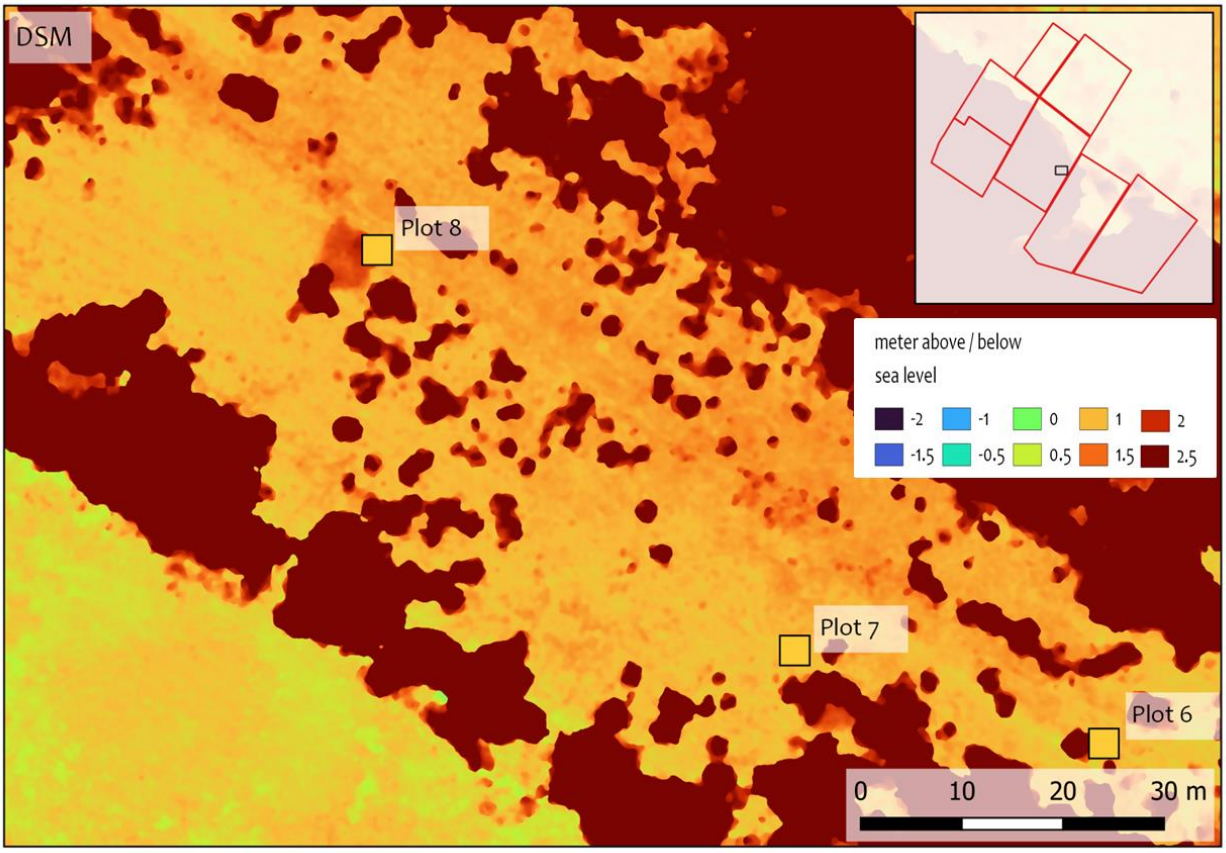


Figure 19 DSM, sub-area 2b with Plot 6, 7 and 8, showing altitude above sea level

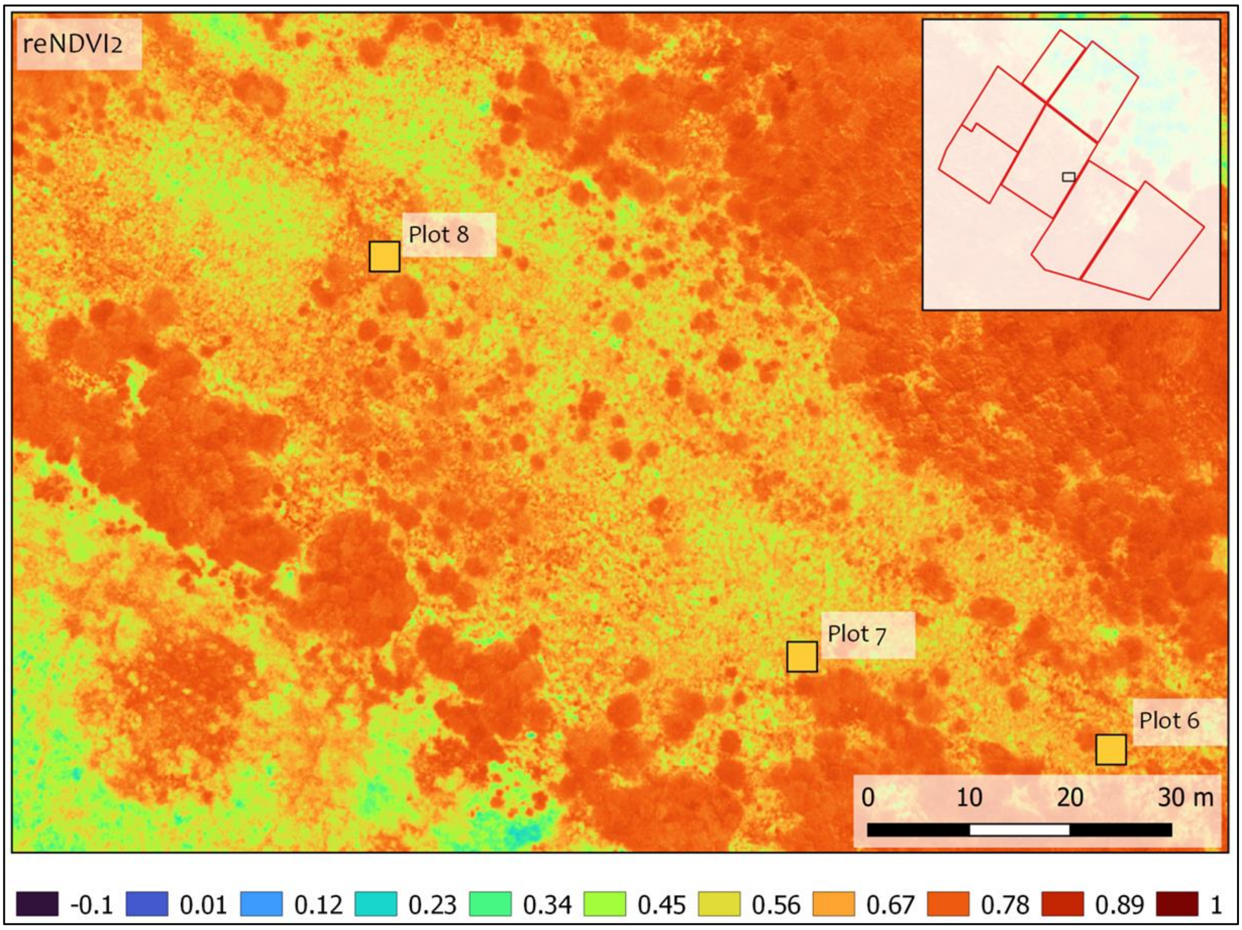


Figure 20 reNDVI2, sub-area 2b with Plot 6, 7 and 8

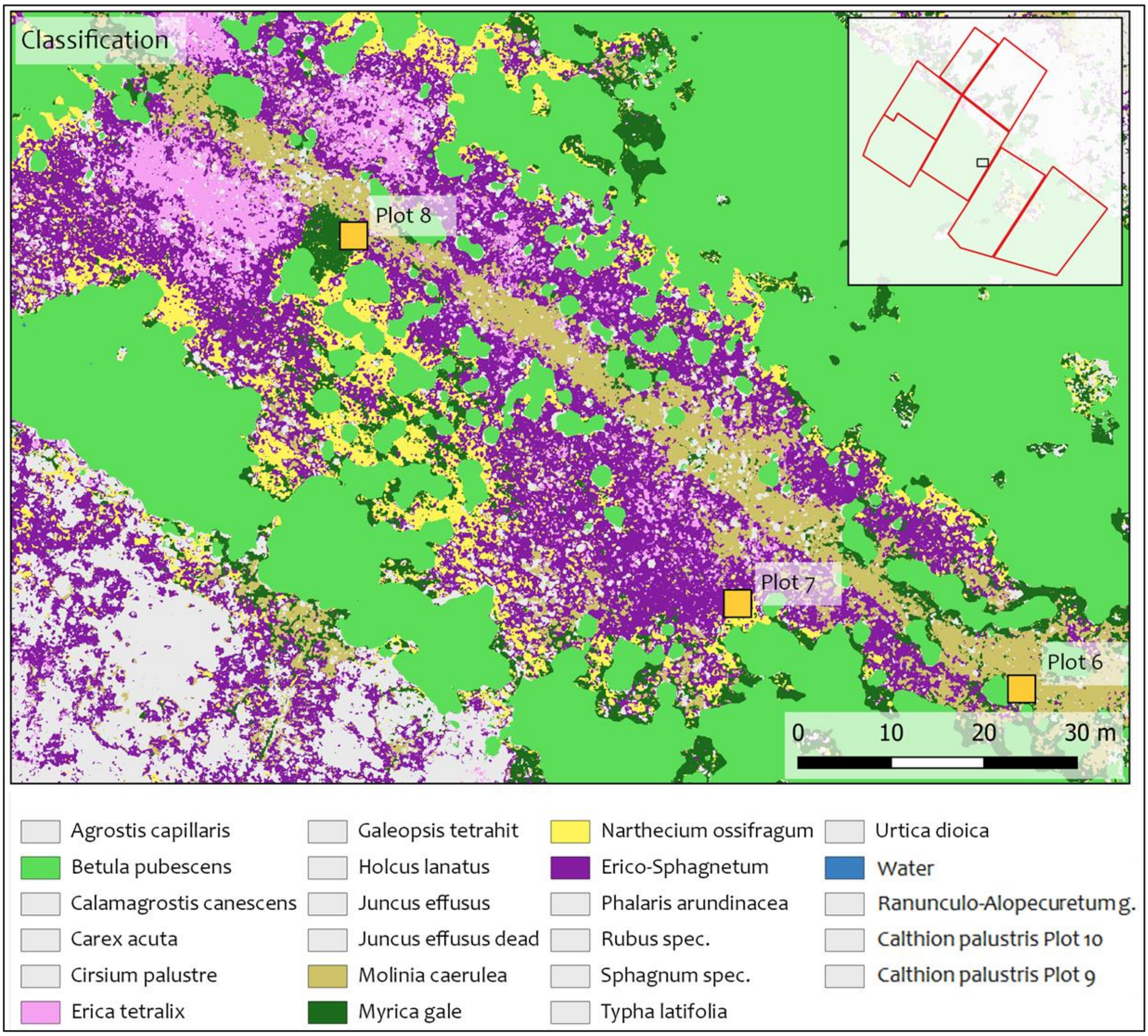


Figure 21 Classification, sub-area 2b with Plot 6, 7 and 8, copy of Figure 7 to enable comparison with input data. Only the classes essential for the area are shown in color on the map.

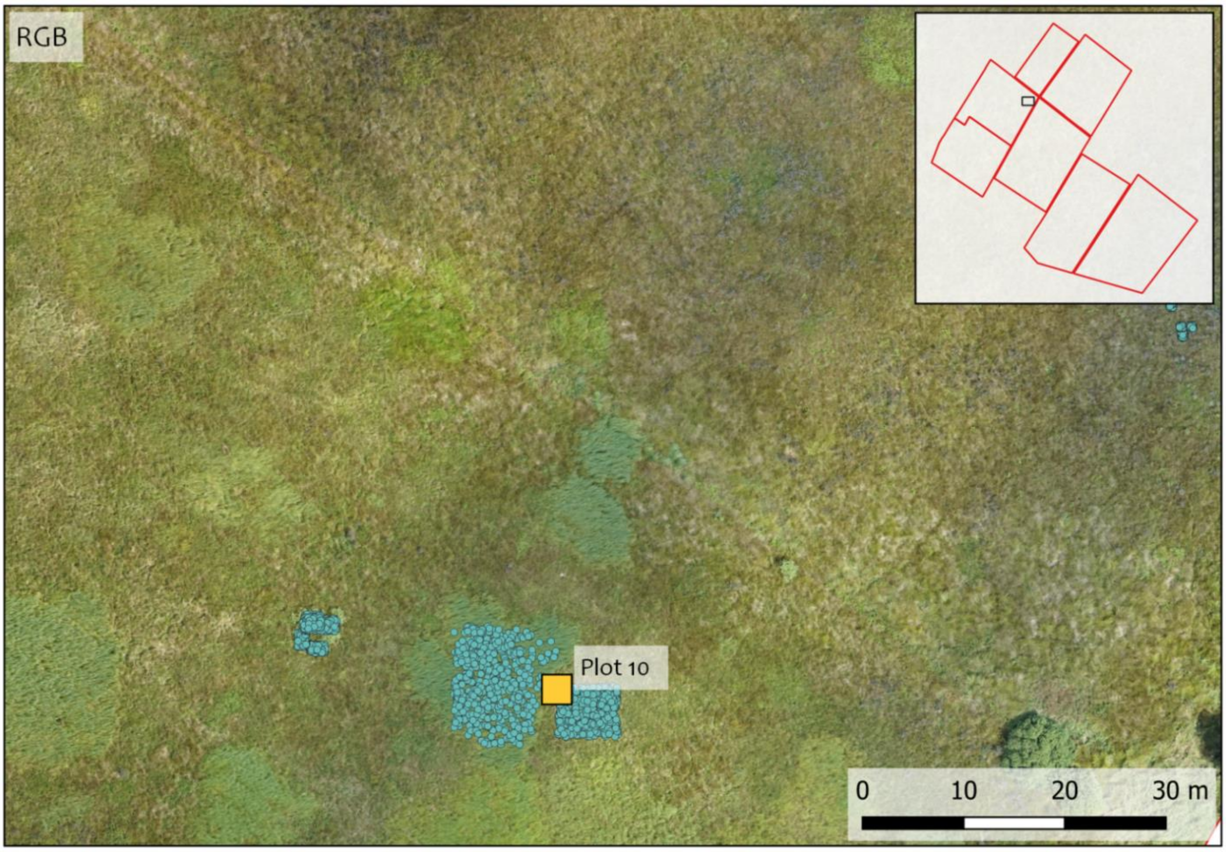


Figure 22 RGB, sub-area 2a, reference data points around Plot 10 (*Calthion palustris* / *Caricetum acutae*, Chapter 4.1.6), the border to the meadow where Plot 11 is locates separates the image diagonally

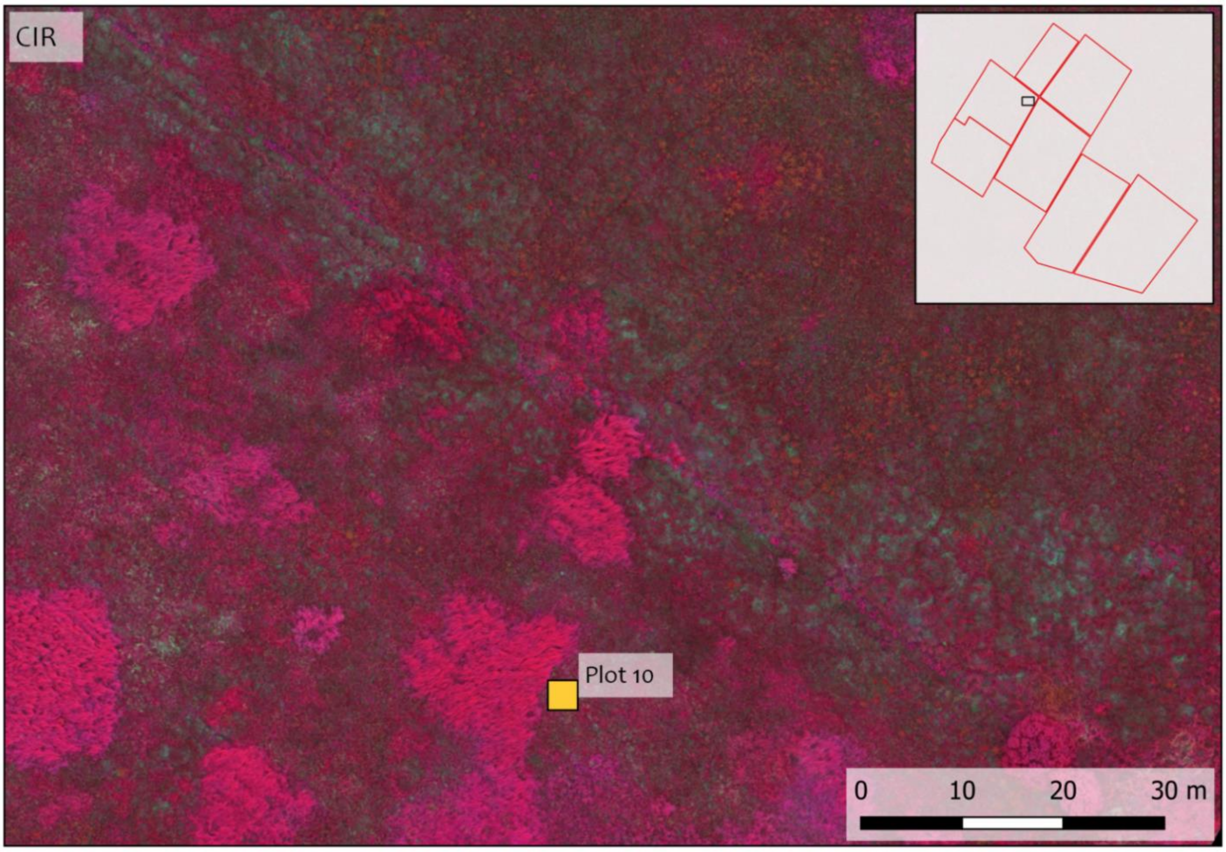


Figure 23 CIR, sub-area 2a with Plot 10

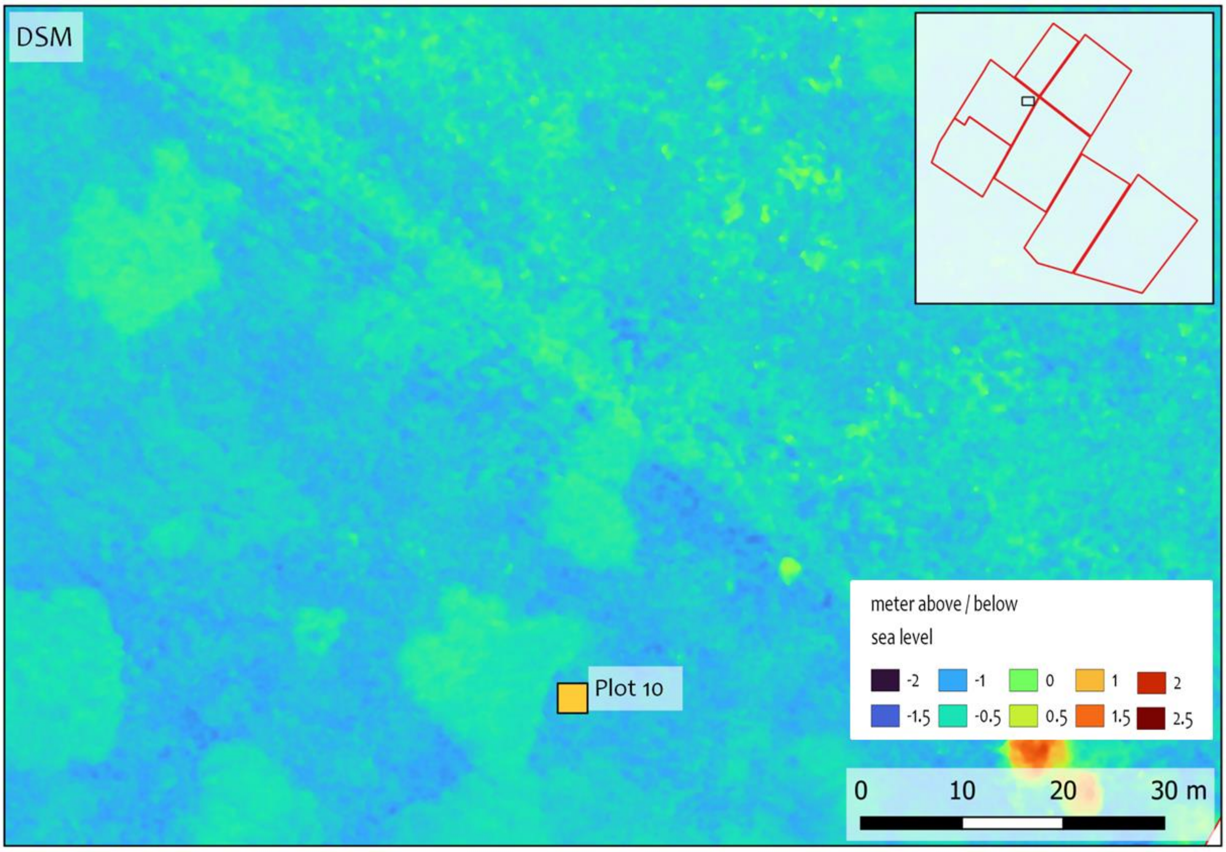


Figure 24 DSM, sub-area 2a with Plot 10, showing altitude above / below sea level

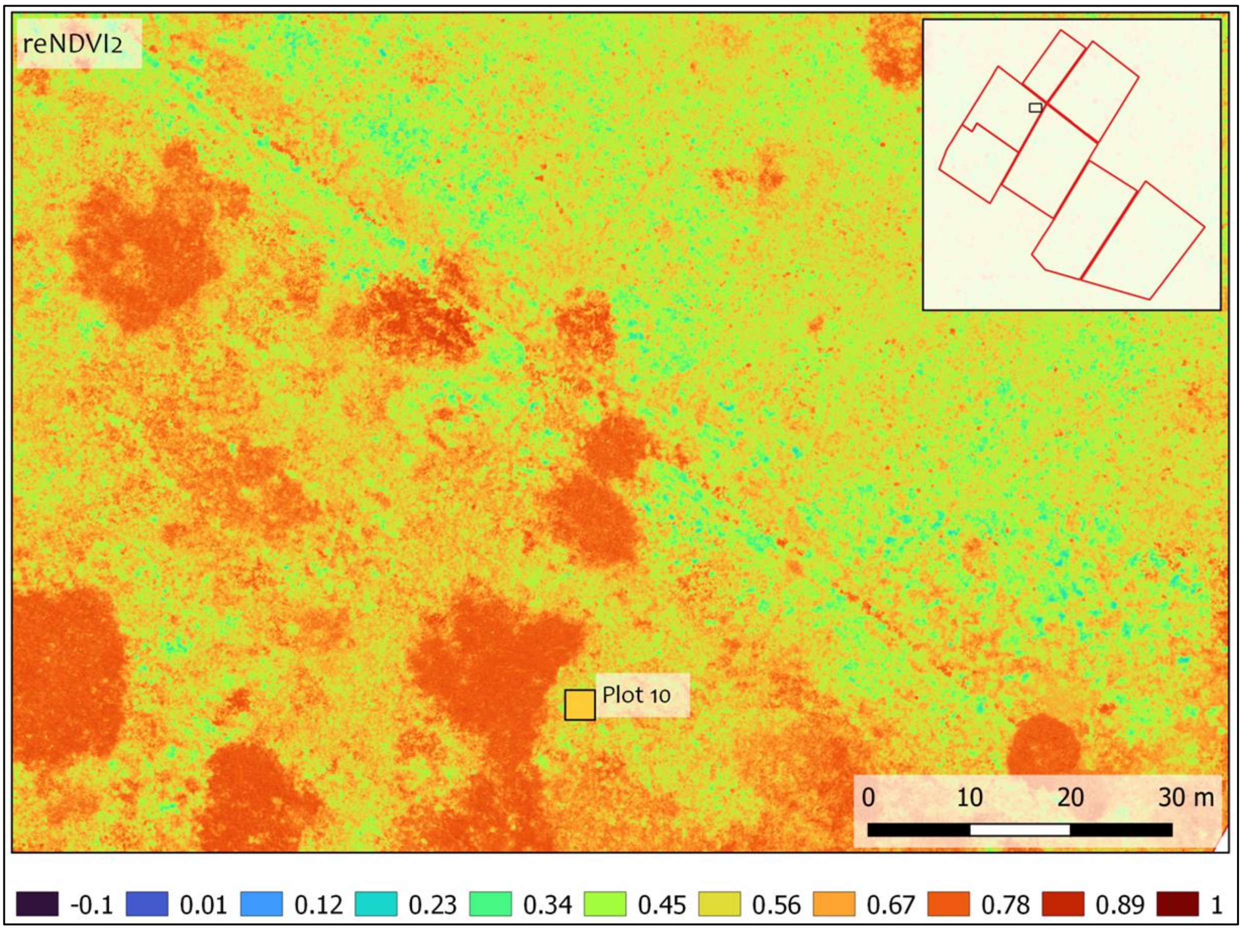


Figure 25 reNDVI2, sub-area 2a with Plot 10

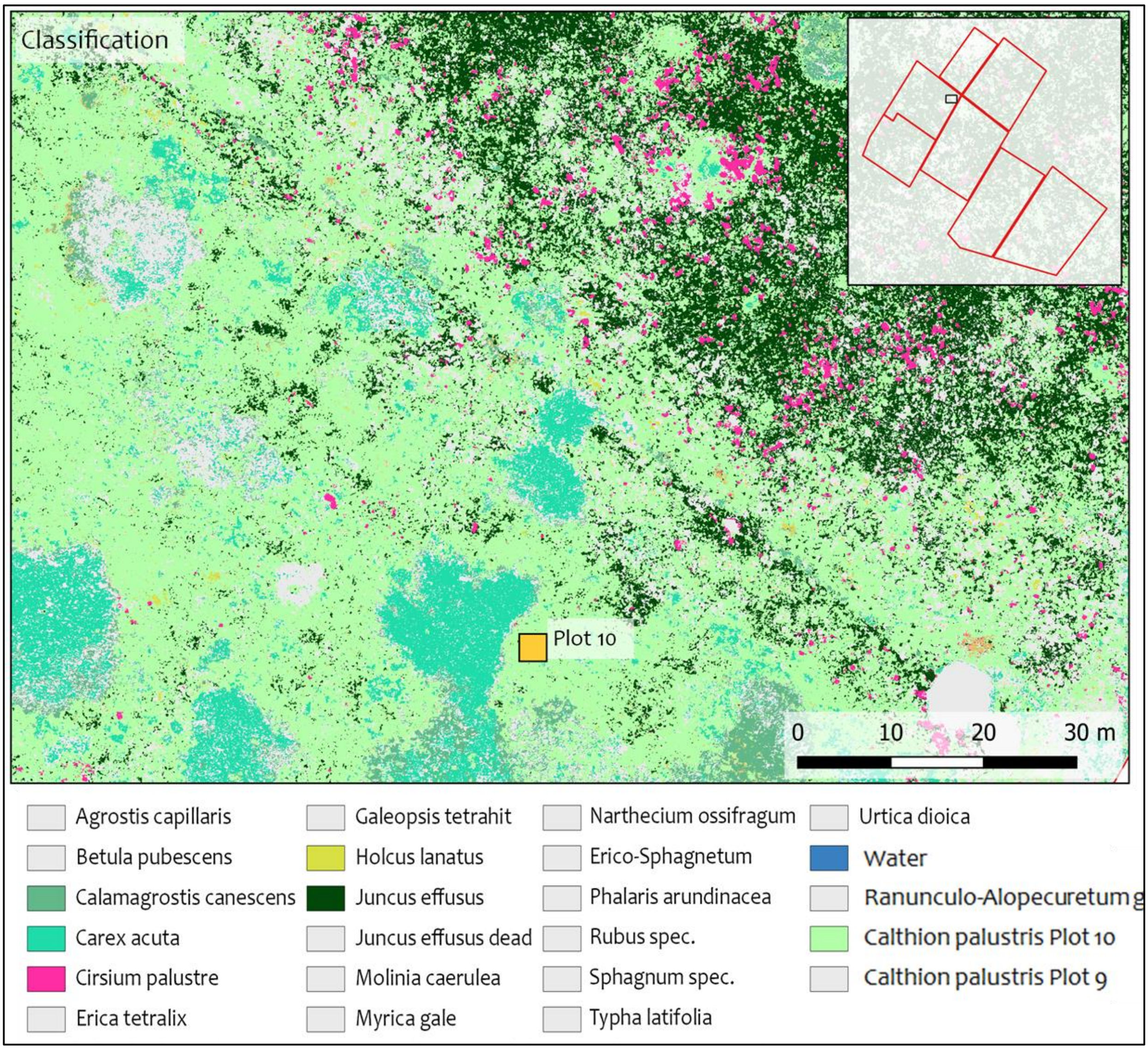


Figure 26 Classification, sub-area 2a with Plot 10, copy of Figure 8 to enable comparison with input data. Only the classes essential for the area are shown in color on the map.

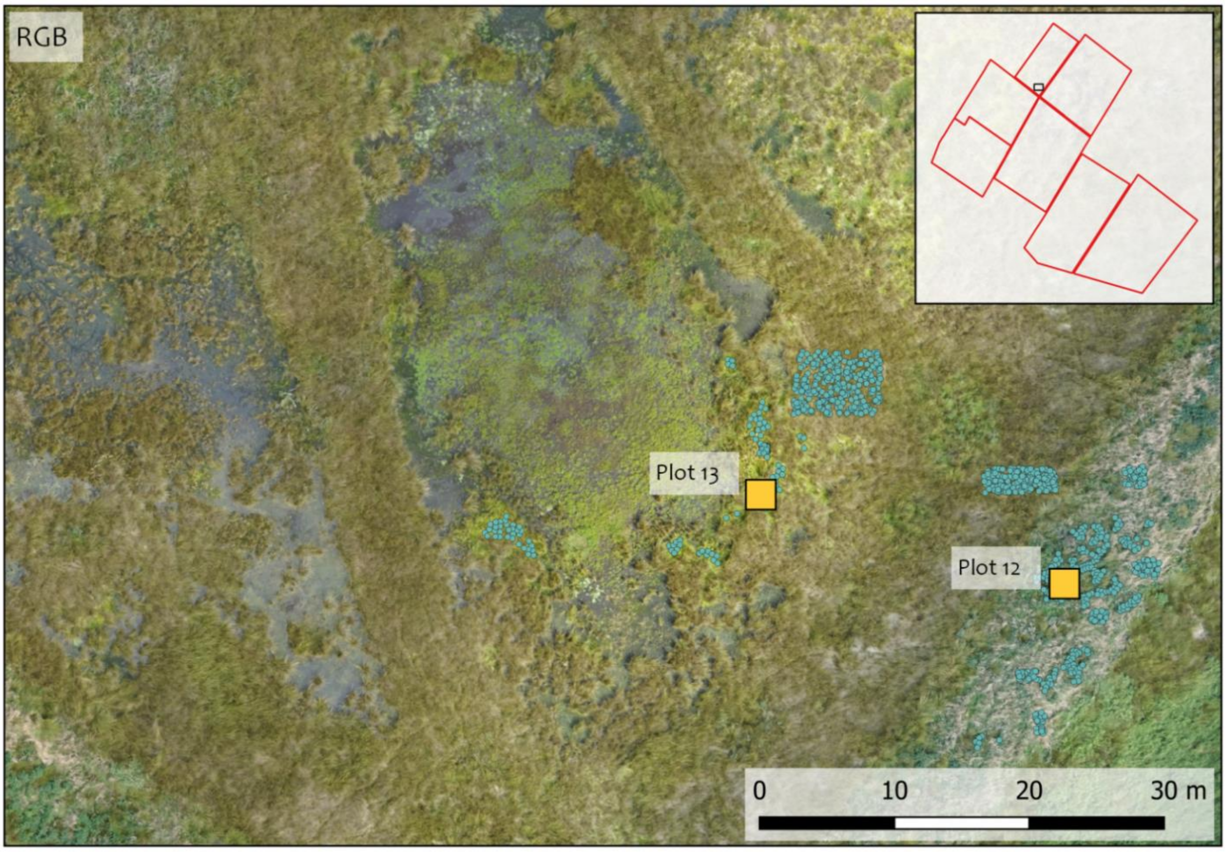


Figure 27 RGB, sub-area 1a, reference data points around plot 12 (embankments, *Filipendulo Geranietum*, Chapter 4.1.6) and 13 (rewetted area, transition to *Scheuchzerio-Caricetea* Chapter 4.1.1)

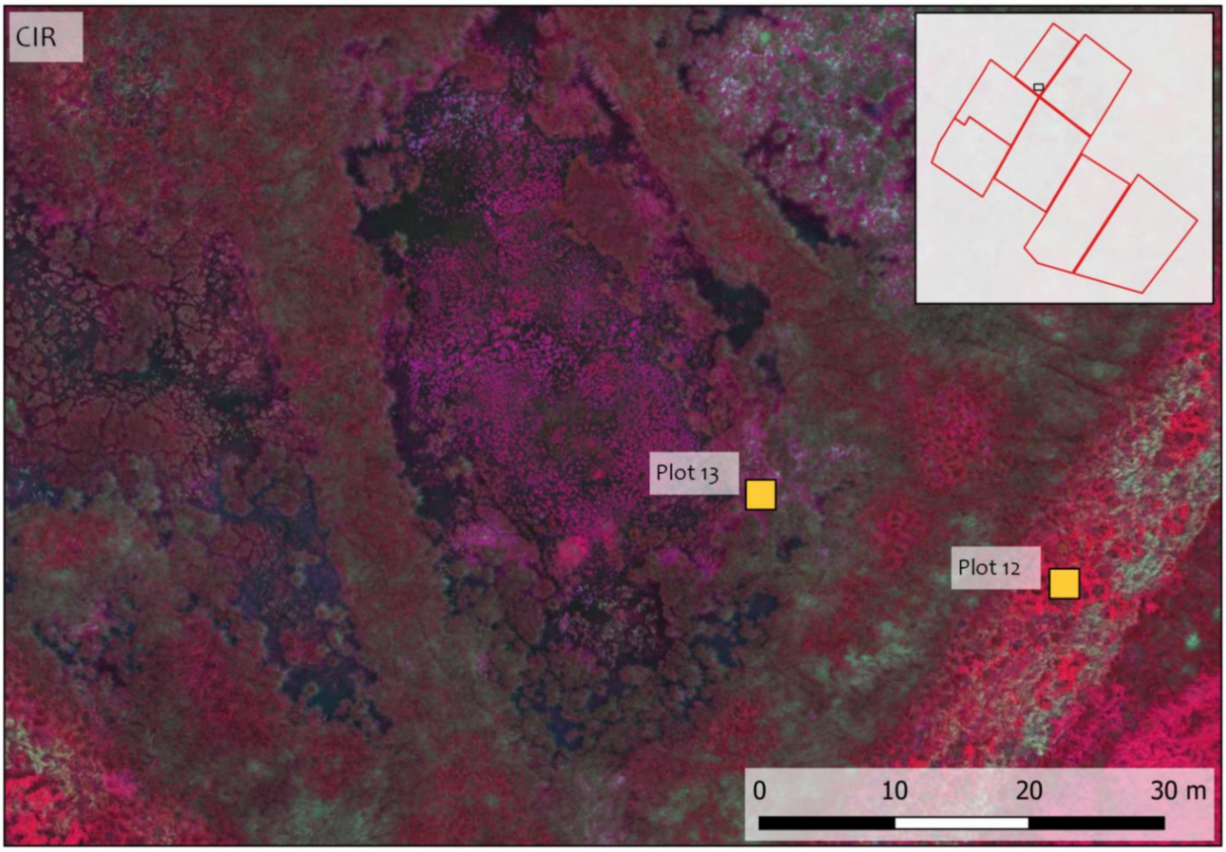


Figure 28 CIR, sub-area 1a with plot 12 and 13

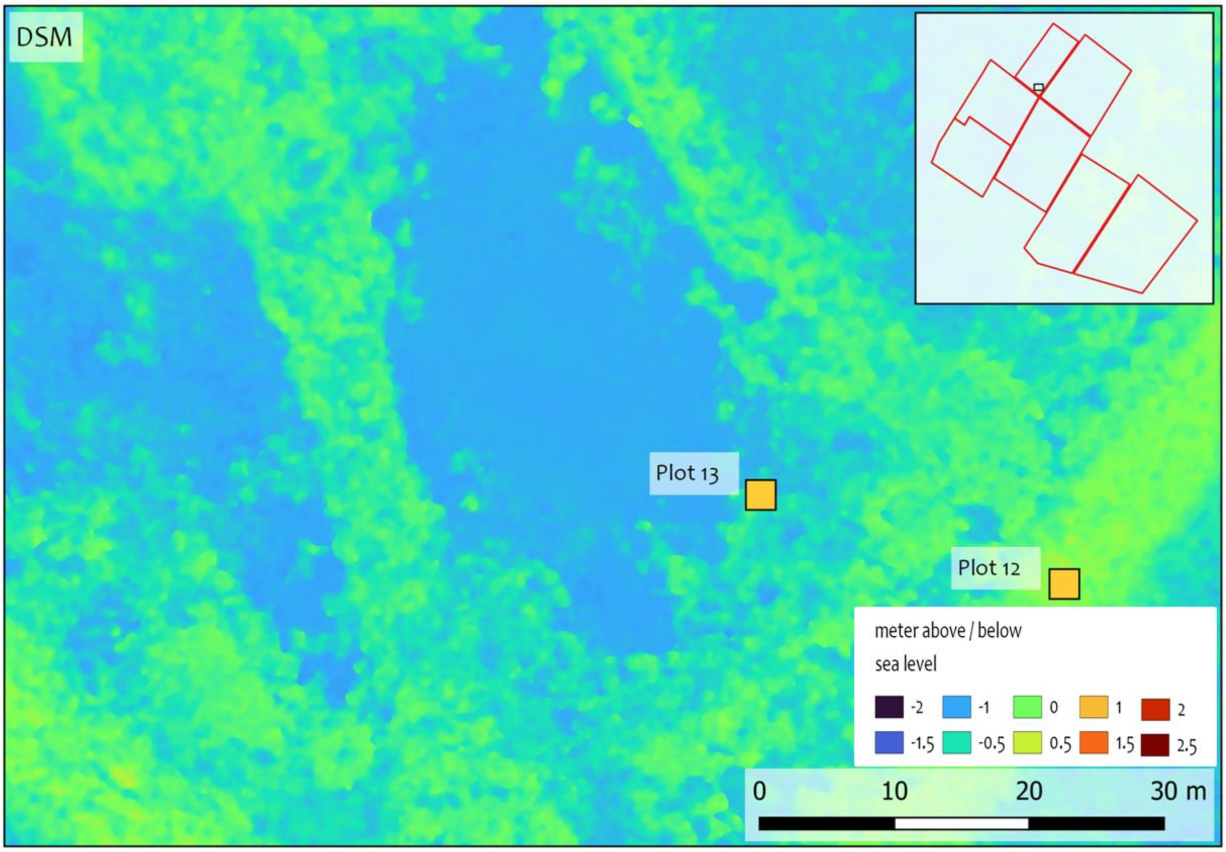


Figure 29 DSM, sub-area 1a with plot 12 and 13, showing altitude above / below sea level

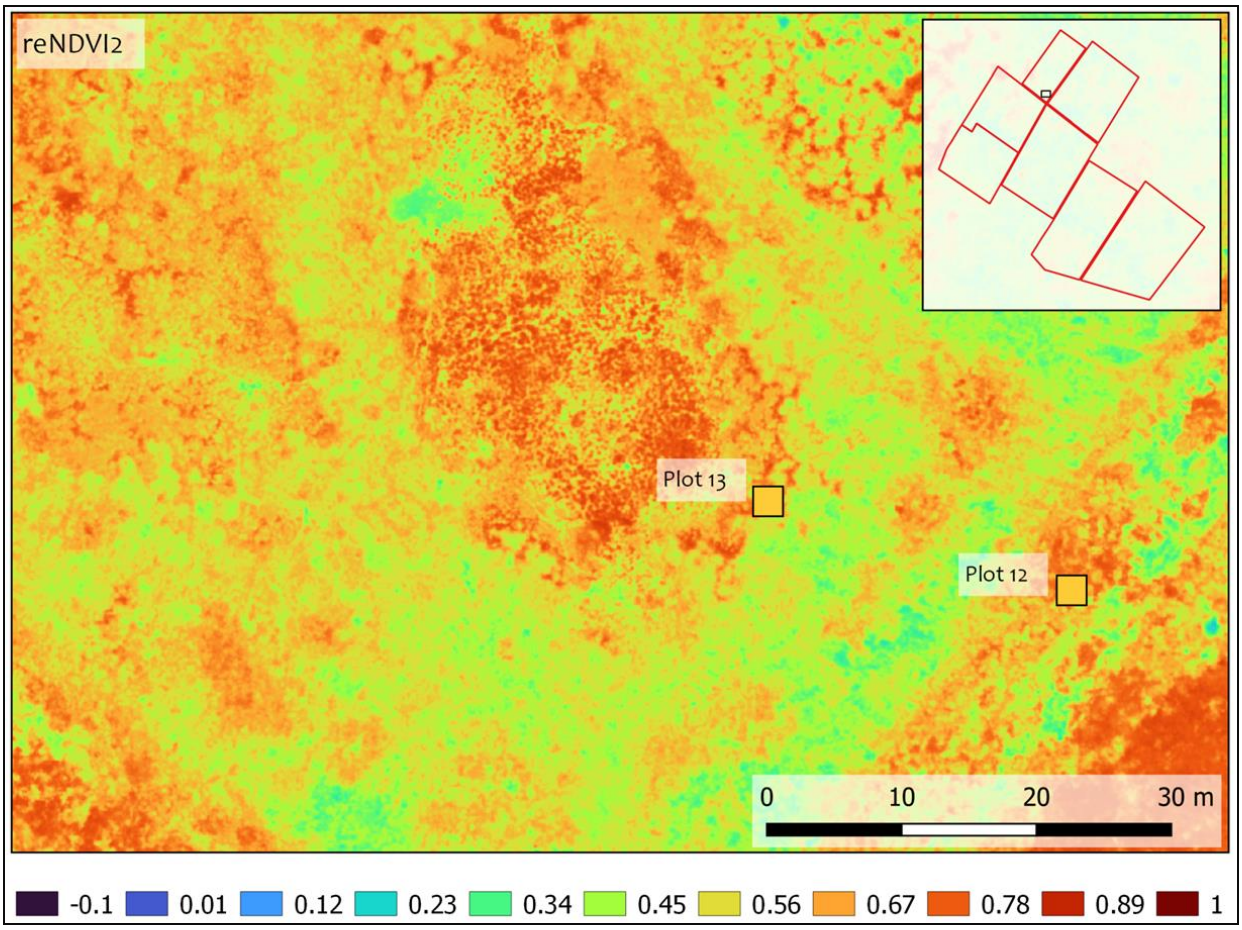


Figure 30 reNDVI2, sub-area 1a with plot 12 and 13

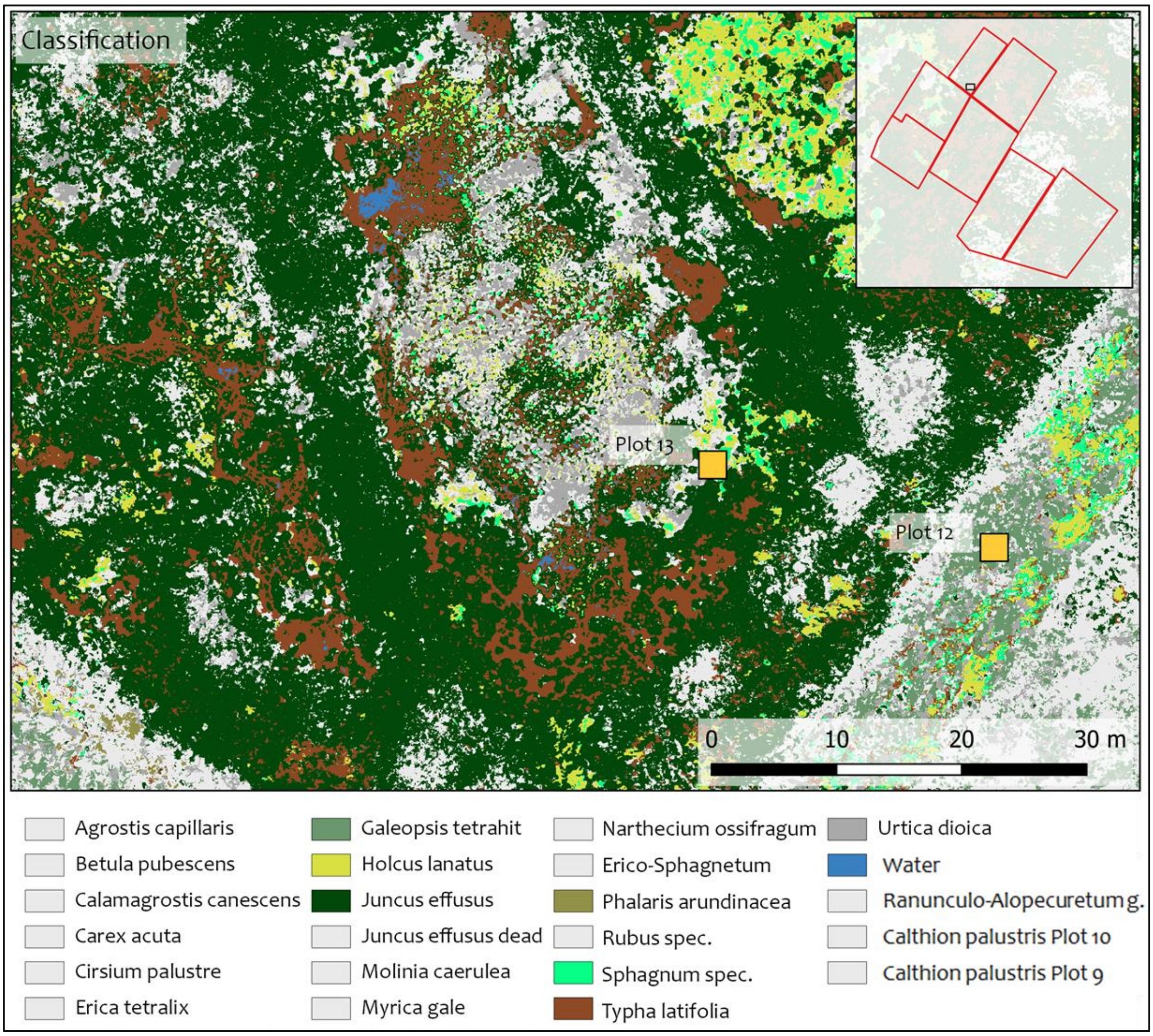


Figure 31 Classification, sub-area 1a with plot 12 and 13, copy of Figure 9 to enable comparison with input data. Only the classes essential for the area are shown in color on the map.

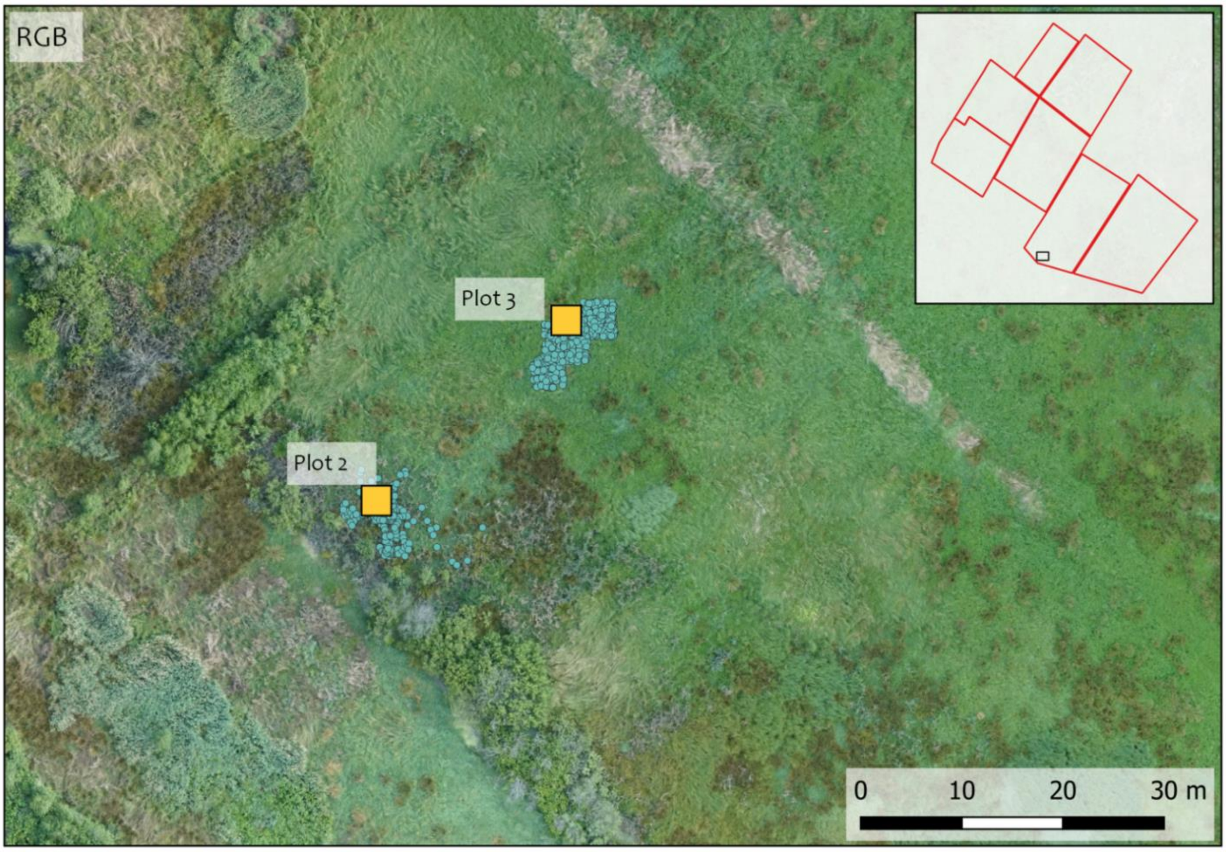


Figure 32 RGB, sub-area 3a, reference data points around Plot 2 (rewetted area with ditches, Chapter 4.1.2 and 3 (rewetted area, *Ranunculo-Alopecuretum geniculati*, Chapter 4.1.6)

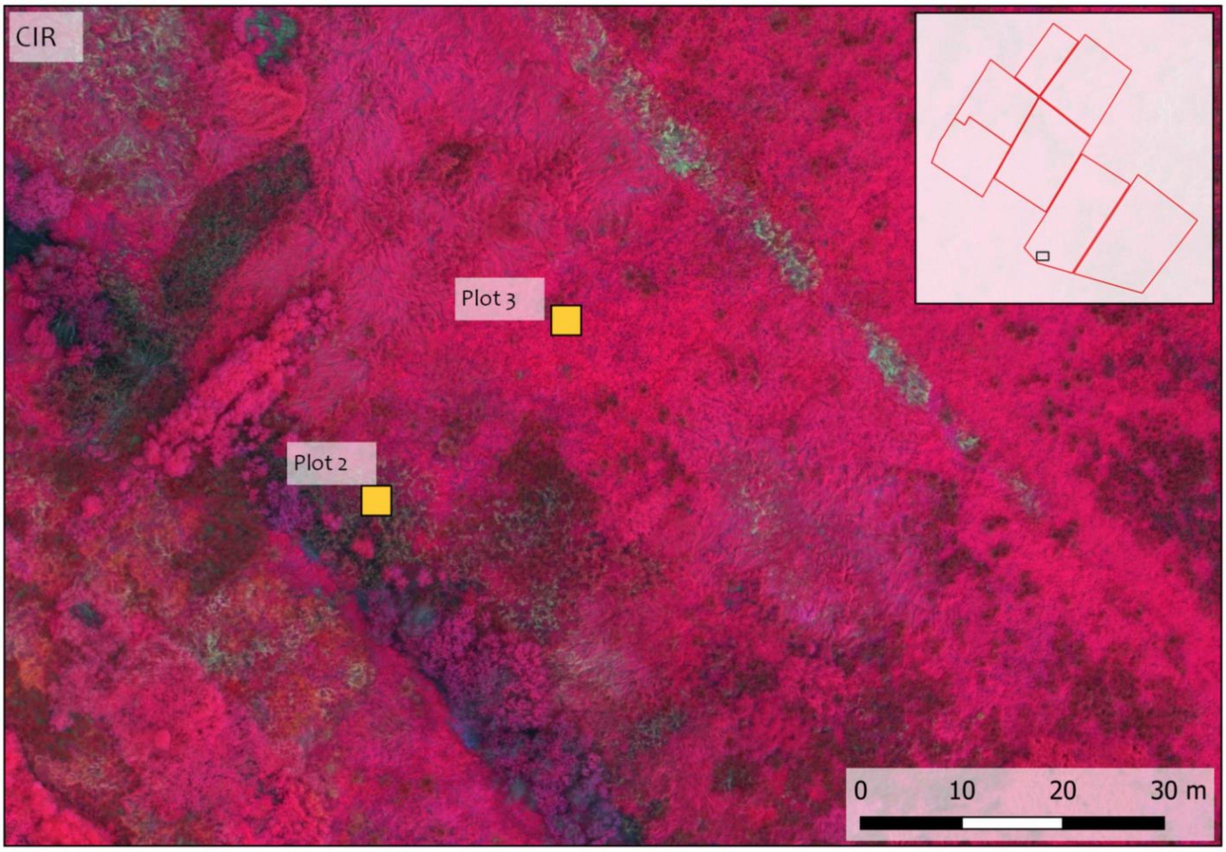


Figure 33 CIR, sub-area 3a with Plot 2 and 3

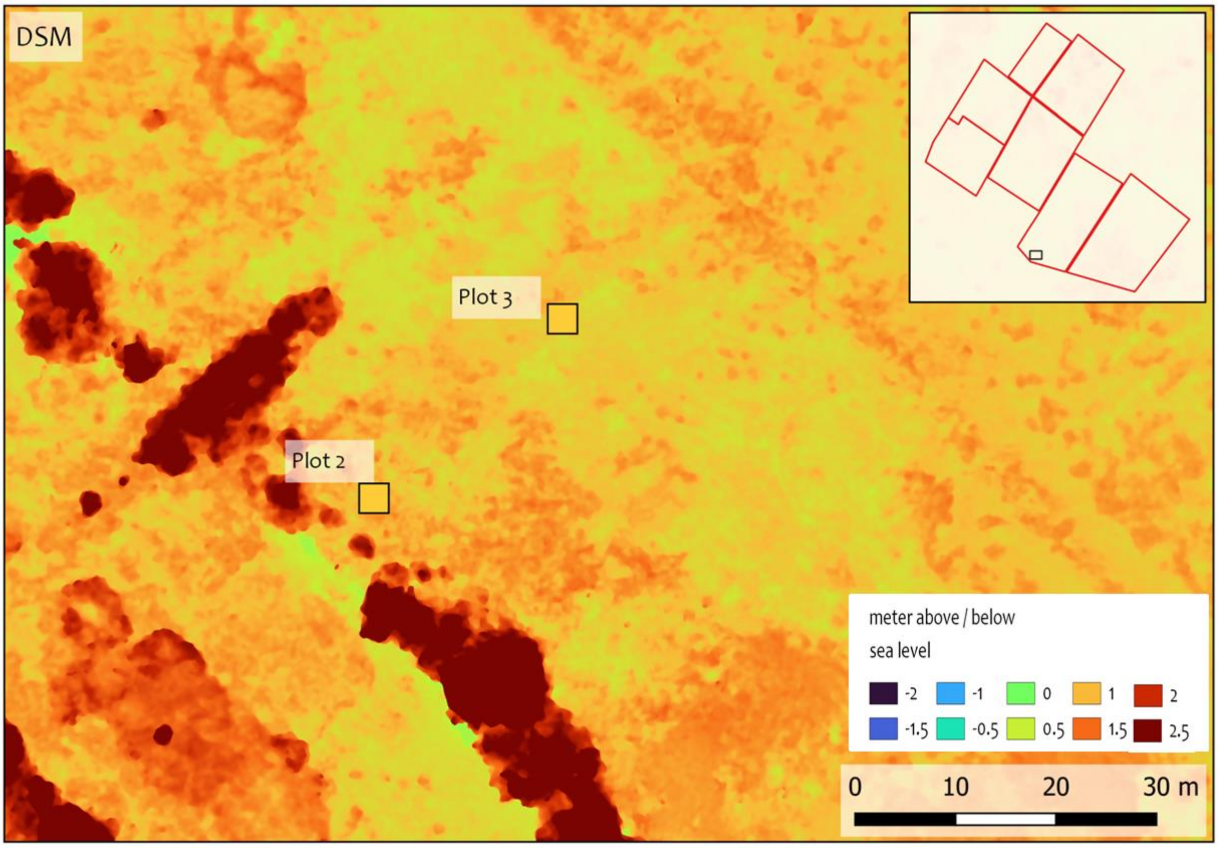


Figure 34 DSM, sub-area 3a with Plot 2 and 3, showing altitude above sea level

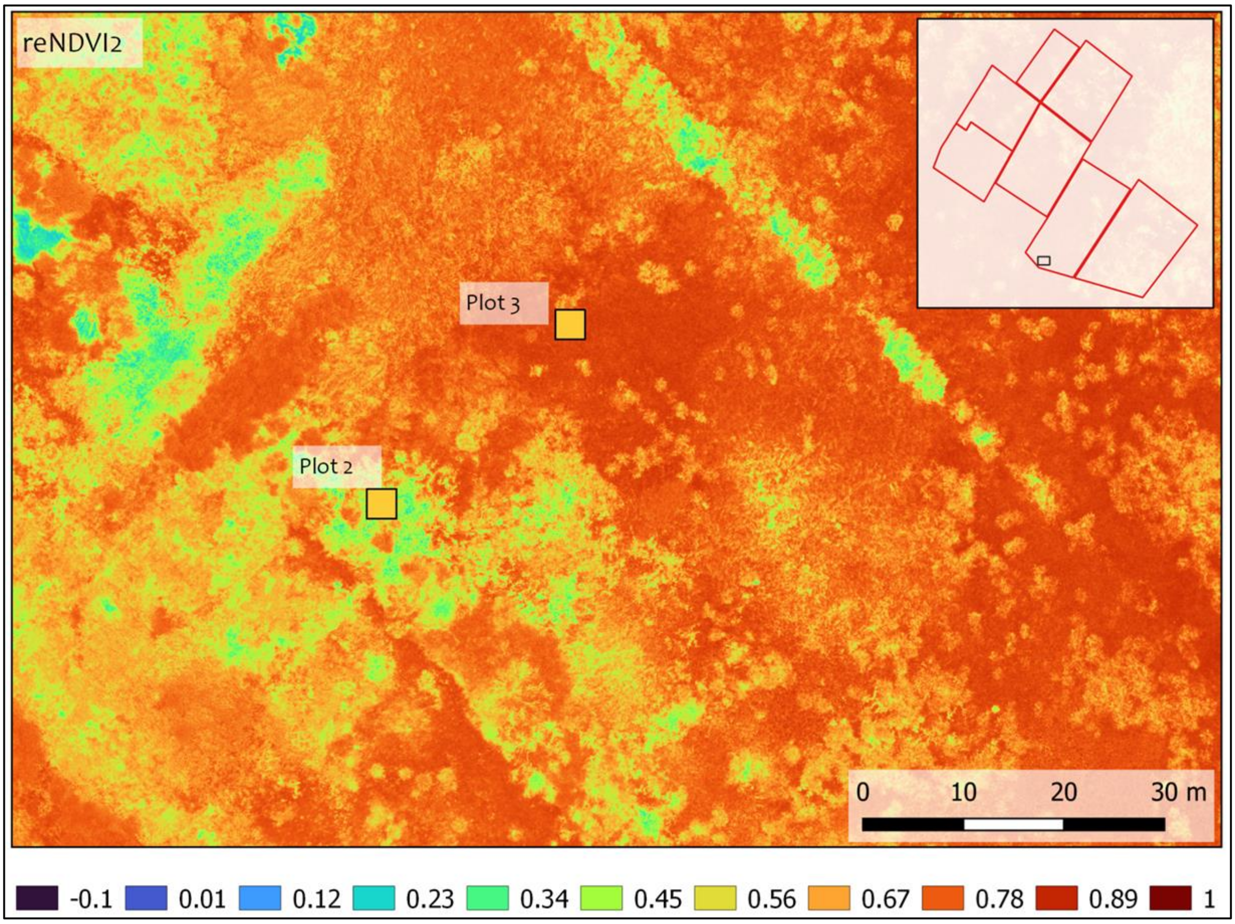


Figure 35 reNDVI2, sub-area 3a with Plot 2 and 3

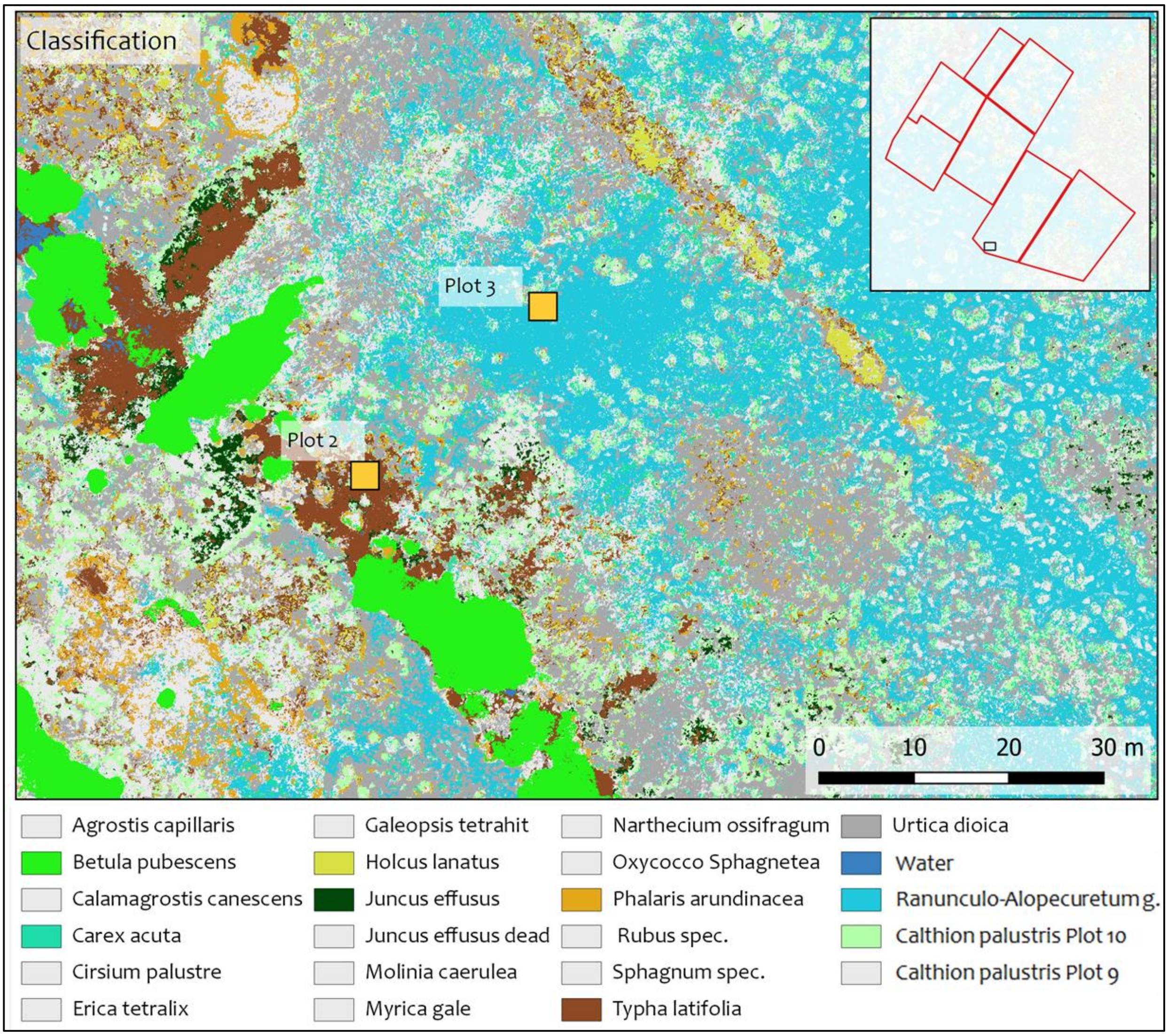


Figure 36 Classification, sub-area 3a with Plot 2 and 3, copy of Figure 10 to enable comparison with input data. Only the classes essential for the area are shown in color on the map.

Figure 37 Comparison between biotope type mapping, 2016 (LANIS SH & LLUR, 2018) MH and MD (bog heathland and degenerated bog area) with the classification results of *Erico-Sphagnetum*, *Erica-tetralix* and *Narthecium ossifragum.*

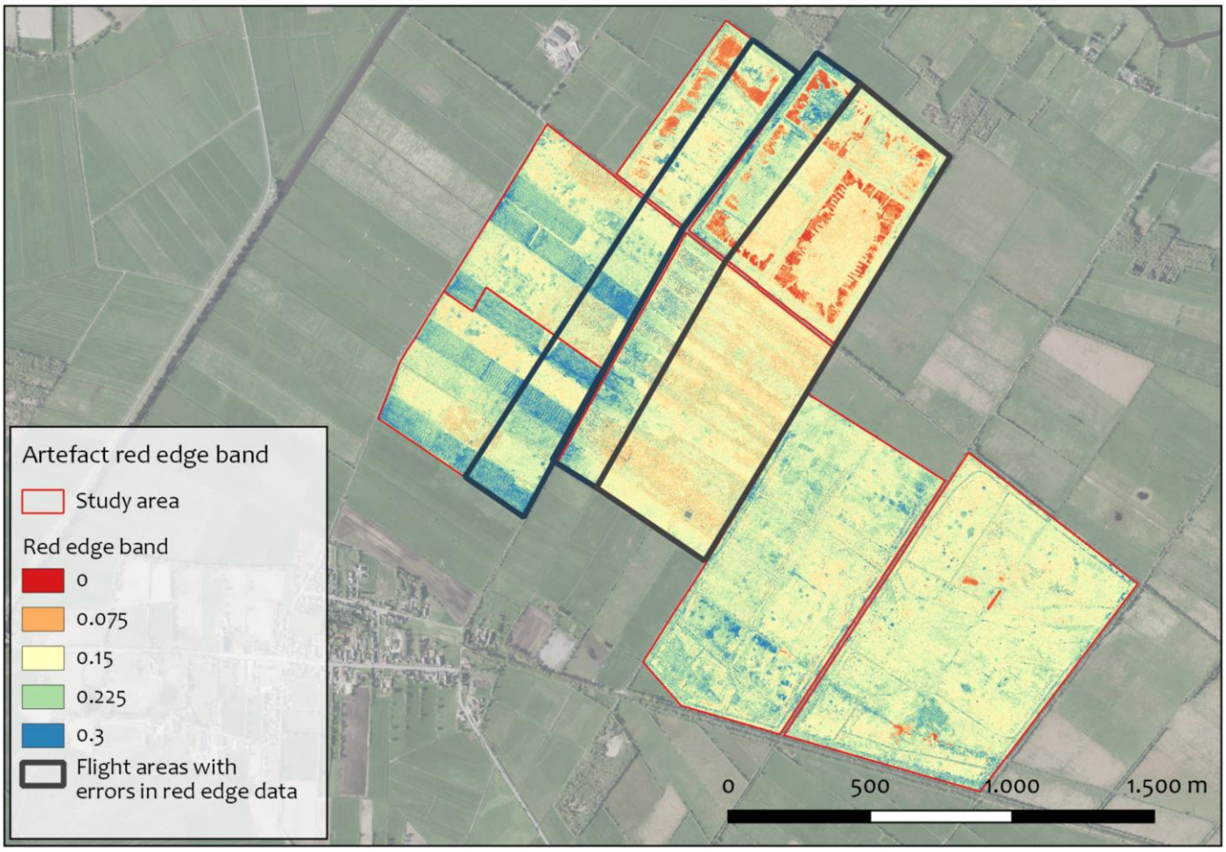


Figure 38 Areas with artefacts in red edge bands corresponding to data processing

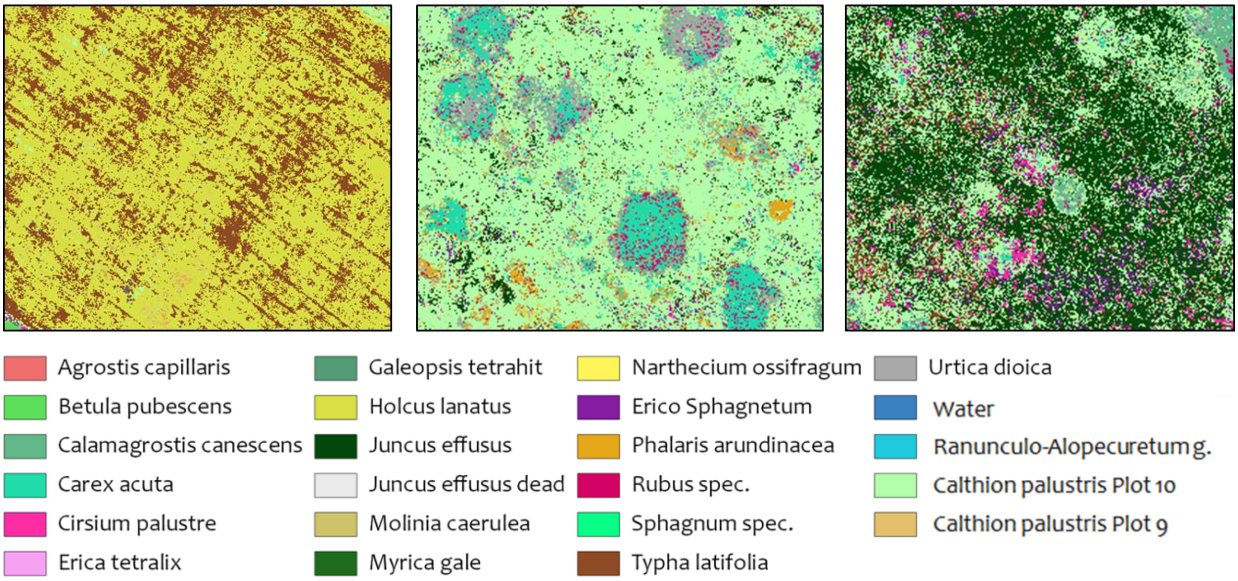


Figure 39 Classification of three areas with different succession stages, from left to right: area still under cultivation (open soil misclassified as *Typha latifolia*), area left fallow since 5 years with a large species spectrum of grasses growing in herds and area left fallow since 8 years with a degreasing species spectrum dominated by tall growing plants.

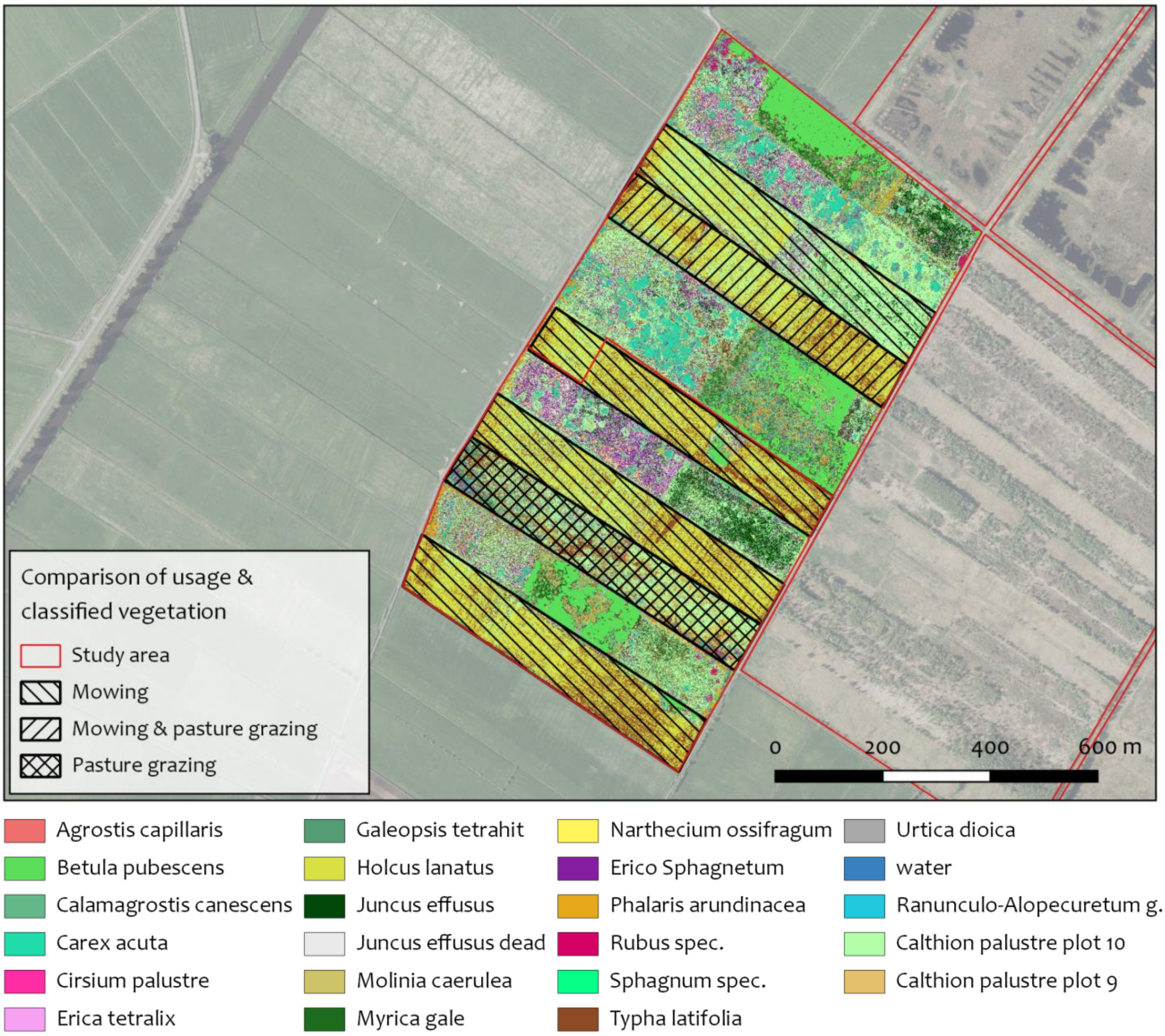


Figure 40 Comparison of classified vegetation in area 2a and c and usage 2015 (personal communication SNSH, 03.08.2020)

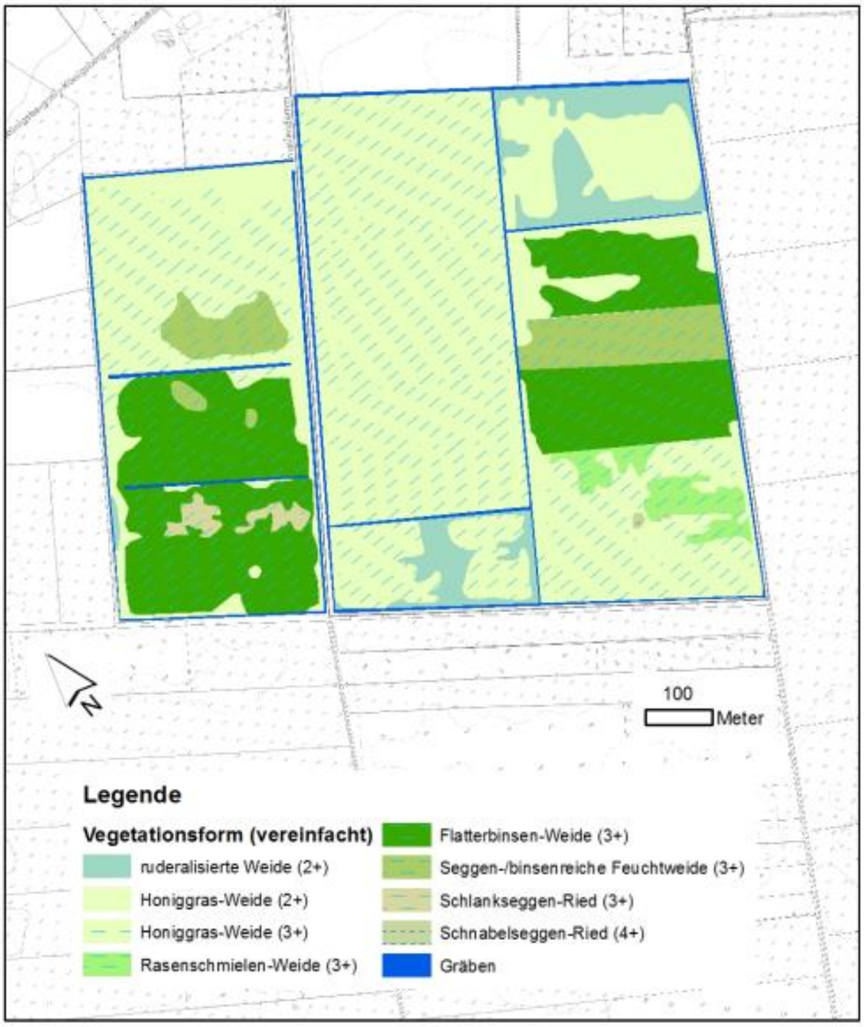


Figure 41 Map of vegetation in area 1a and b, initial state, presentation of Mordhorst Brettschneider GmbH, 2014, as cited in Ausgleichsagentur Schleswig-Holstein GmbH (n.d.).

Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbständig und ohne fremde Hilfe angefertigt und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe.

Die eingereichte schriftliche Fassung der Arbeit entspricht der auf dem elektronischen Speichermedium.

Weiterhin versichere ich, dass diese Arbeit noch nicht als Abschlussarbeit an anderer Stelle vorgelegen hat.

20.01.2021, Anna M. Backes