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Habitat Mapping and Quality Assessment of NATURA 2000 Heathland Using Airborne Imaging Spectroscopy

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Abstract: Appropriate management of (semi-)natural areas requires detailed knowledge of the ecosystems present and their status. Remote sensing can provide a systematic, synoptic view at regular time intervals, and is therefore often suggested as a powerful tool to assist with the mapping and monitoring of protected habitats and vegetation. In this study, we present a multi-step mapping framework that enables detailed NATURA 2000 (N2000) heathland habitat patch mapping and the assessment of their conservation status at patch level. The method comprises three consecutive steps: (1) a hierarchical land/vegetation type (LVT) classification using airborne AHS imaging spectroscopy and field reference data; (2) a spatial re-classification to convert the LVT map to a patch map based on life forms; and (3) identification of the N2000 habitat type and conservation status parameters for each of the patches. Based on a multivariate analysis of 1325 vegetation reference plots acquired in 2006–2007, 24 LVT classes were identified that were considered relevant for the assessment of heathland conservation status. These labelled data were then used as ground reference for the supervised classification of the AHS image data to an LVT classification map, using Linear Discriminant Analysis in combination with Sequential-Floating-Forward-Search feature selection. Overall classification accuracies for the LVT mapping varied from 83% to 92% (Kappa $\approx$ 0.82–0.91), depending on the level of detail in the hierarchical classification. After converting the LVT map to a N2000 habitat type patch map, an overall accuracy of 89% was obtained. By combining the N2000 habitat type patch map with the LVT map, two important conservation status parameters were directly deduced per patch: tree and shrub cover, and grass cover, showing a strong similarity to an independent dataset with estimates made in the field in 2009. The results of this study indicate the potential of imaging spectroscopy for detailed heathland habitat characterization of N2000 sites in a way that matches the current field-based workflows of the user.

Keywords: hyperspectral; habitat mapping; species mapping; NATURA 2000; heathland; conservation status; classification; *Calluna vulgaris*; tree encroachment; grass encroachment

1. Introduction

In Europe, the main regulations for biodiversity protection are found in the Habitats Directive (HabDir) [1] and the Birds Directive [2], which provide the legal basis for the NATURA 2000 network (N2000). Among the various commitments imposed by these legal initiatives on European Union (EU) member states, are (1) the set-up of monitoring systems to keep track of the '*conservation status*' of protected habitats and species present in the EU member states; and (2) the 6-yearly reporting to the European Commission on the '*conservation status*' of these habitats and species [3]. In practice, these commitments imply that EU member states are in need of accurate, simple and repeatable methods for habitat and species monitoring and surveillance. These habitat and species assessments require detailed, reliable and up-to-date habitat distribution maps, stretching further than merely attributing a given vegetation patch to a habitat type, but also giving indications on its quality. The first implementations of the HabDir however revealed a great lack of knowledge on habitat distribution in many member states [4]. An easily operated, economically priced and as far as possible automated method is hence desired to meet these requirements [5,6].

European heathlands used to extend over several millions of hectares, but the overall decline in traditional agricultural land use practices in heathlands (sheep and cattle herding, sod cutting, controlled burning, etc.) have resulted in a strong decrease in the total heathland area over the last centuries. The decline of traditional agricultural practices has led to decreased nutrient removal, and atmospheric nitrogen deposition remains one of the major threats to heathlands. The nitrogen deposition is causing grass and tree encroachment of the heathlands, resulting in a decline in ericoid heathland species [7–9]. An effective monitoring of heathland areas hence remains necessary to identify such vegetation disturbances, and allow timely management interventions. With heathlands becoming increasingly fragmented, they are now highly valued for biodiversity conservation and as natural and cultural heritage [10,11]. Their formal protection in the EU is now being safeguarded under the HabDir [1]. As part of their protection, member states need to report on their conservation status, i.e., the actual area, the range, the habitat quality and the future prospects for each habitat type. Various definitions of habitat quality exist [12]. In this paper, we use habitat quality as one aspect of a habitat's conservation status, referring to its structure and ecological functioning. Depending on the habitat type, it is for example assessed in terms of species richness and composition, growth form complexity, and presence of invasive species.

Imaging spectroscopy (IS) or hyperspectral imaging, with the ability to collect information at a high spectral resolution using contiguous spectral bands, each with a narrow spectral range, is known to be capable of fairly accurate identification of different species [13]. IS can even be used to produce highly accurate species-level vegetation maps in highly complex grasslands with fine-scale mosaics of different vegetation types [14]. Imaging spectroscopy also provides opportunities for habitat quality and degradation assessment [15], e.g., by mapping of invasive species [16,17] or encroachment of undesired species [18], prediction of species richness measures [19], and mapping of plant functional types [20,21].

Despite the high number of studies that have been performed on using remote sensing for biodiversity assessments, relatively few efforts have been made to specifically map N2000 habitat types with remote sensing, and/or specifically assess N2000 habitat quality or conservation status. Until recently, the vast majority of studies focussed on the mapping of land cover categories, but there are difficulties in determining how land cover categories correspond to N2000 habitats [15]. Some studies have however been performed that specifically focus on a certain aspect of N2000 habitat assessments. Knowledge-based approaches, combined with object-based analysis of Quickbird imagery, have been used to map N2000 forest and heathland habitat types, and evaluate broad aspects of habitat quality by mapping the presence of certain relevant vegetation and land cover classes present in the habitat [6]. More recently, a number of different approaches have also been considered: applying a one-class classifier to multi-seasonal RapidEye imagery to delineate and classify four N2000 habitat types, which were scattered across a complex landscape of different vegetation types [22]; an investigation of the potential of both IS and (simulated) multispectral images to model three N2000 mire habitat types, as well as their floristic composition [23]; the use of Airborne Laser Scanning to assess the conservation status of N2000 grassland habitats [24]; and combining multispectral and laser scanning data to assess the conservation status of Mediterranean forests [25].

For heathlands specifically, the use of IS for N2000 mapping and monitoring has recently received attention by a number of studies. Subpixel unmixing combined with decision tree classification using IS data has been shown to be capable of mapping *Calluna vulgaris* age structures [26]. Small-scale N2000 habitat quality indicators (e.g., the age classes of *Calluna vulgaris*, and the presence of key species) were predicted using coarse-scale indicators, mapped with IS (e.g., occurrence of grass encroachment) [27]. Spectral unmixing of IS data has also been used to quantify grass encroachment at the patch level [28]. Floristic gradients in an ordination space were used to model habitat type occurrence probabilities, as well as habitat conservation status [29]. Except for the latter, all of these studies have in common that they only focus on a specific aspect, e.g., habitat type classification or assessment of certain habitat quality parameters, but not cover the full set of requirements needed for the reporting under the HabDir, i.e., both delineation and determination of habitats, as well as assessing the conservation status.

The objective of this study is to demonstrate the potential of IS in combination with ecological knowledge to both delineate and discern detailed (even $\leq$0.1 ha) N2000 heathland habitat patches, including valuable quality-indicating characteristics within each of the patches (e.g., tree and grass cover) in a way that matches the current field-based workflows of the user, and produces maps and statistics that are familiar in both scale and content to local and national N2000 managers. We presented an earlier version of this method, as well as preliminary results, in the conference proceedings of [30].

2. Materials and Methods

2.1. Study Area

The study area 'Kalmthoutse Heide' is located in the north of Belgium (51.40°N, 04.42°E) (Figure 1), on the drainage divide between the rivers Scheldt and Meuse, and hosts forests, heathlands and grasslands on mostly sandy, acidic soils of aeolian origin. Its central heathland area is almost 1000 ha and contains a mixture of wet and dry heath, inland sand dunes and water bodies [31]. An overview of the N2000 habitat types that are well represented in the area is given in Table 1. The site has been protected as a nature reserve since 1968 and has been part of the N2000 network of protected areas under the HabDir since 1996 (site BE2100015).

As a result of its vicinity to the city and harbour of Antwerp, and despite its protected status, the area is affected by anthropogenic influences such as eutrophication, intense recreation, and desiccation resulting from drinking water extraction [10]. Although dedicated management has been implemented since the 1970s, atmospheric nitrogen deposition has accelerated the colonisation of sand dunes by the alien invasive moss species *Campylopus introflexus* (heath star moss). It has also led to an increased dominance of *Molinia caerulea* (purple moorgrass) in wet and dry heaths, at the expense of other typical species, causing a decline in biodiversity. *Molinia caerulea* is a native species typical of heathlands, but under circumstances of increased nutrient availability (e.g., from air pollution or uncontrolled burning), it responds more rapidly with increased growth and outcompetes other typical heathland species. In recent years, some intensive and uncontrolled wildfires have destroyed nearly one-third of the area's heaths, which were rapidly colonized by *Molinia caerulea* afterwards [32].

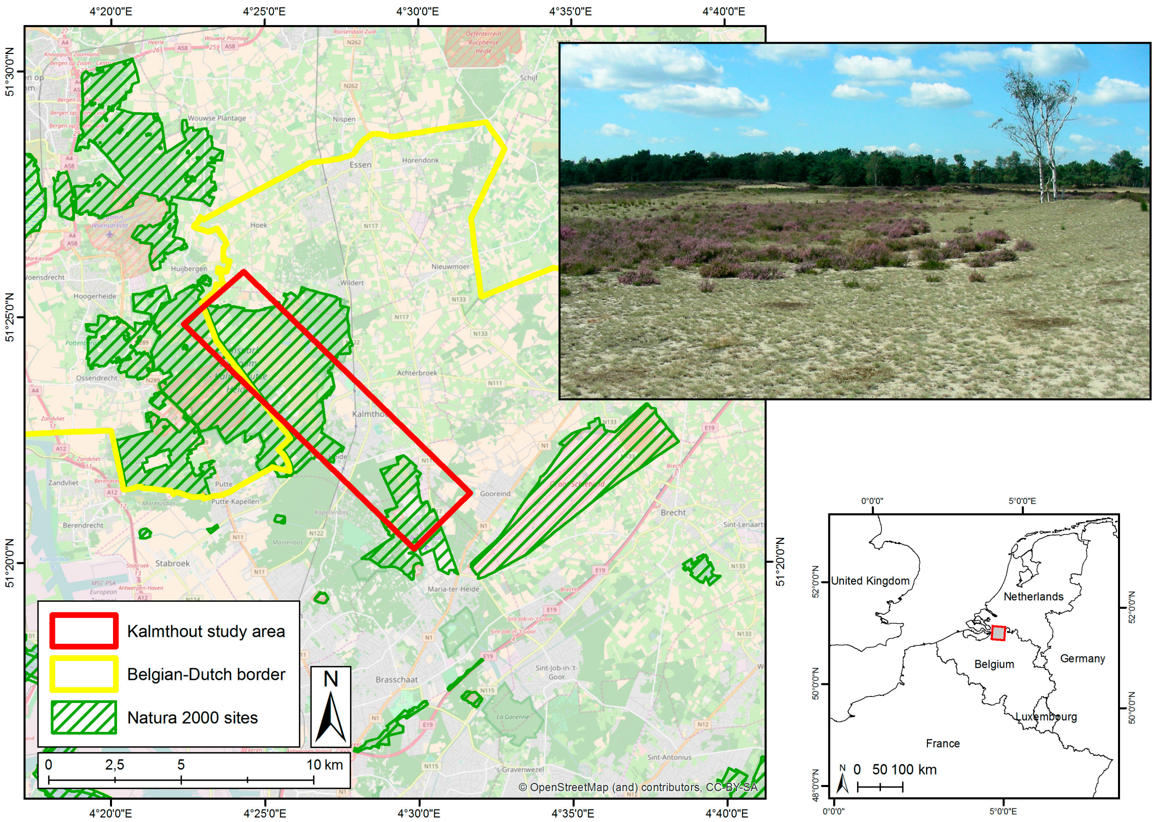


Figure 1. Location and illustration of the study area 'Kalmthoutse Heide' in the north of Belgium. Base map © OpenStreetMap contributors (www.openstreetmap.org/copyright). The inset shows an inland dune with *Corynephorus canescens*—habitat type 2330 (foreground and right) and a dry sand heath with *Calluna vulgaris*—habitat type 2310 (centre to left). Figure modified from [30].

Table 1. Overview of the NATURA 2000 habitat types that are well represented in the 'Kalmthoutse Heide' study area.

Habitats Directive Habitat Code	Habitat Type	Areal Cover (Hectare) [33]
2310	Dry sand heaths with *Calluna* and *Genista*	ca. 250 ha
2330	Inland dunes with open *Corynephorus* and *Agrostis* grasslands	ca. 40 ha
4010	Northern Atlantic wet heaths with *Erica tetralix*	ca. 450 ha
4030	European dry heaths	ca. 60 ha

2.2. Datasets

2.2.1. Ground Reference Data

An extensive field reference dataset was acquired in June–September 2007, i.e., in the same vegetation season as the IS data acquired for this study. Circles of 10 m diameter that represented homogeneous examples of one of the predefined LVT classes (see Section 2.4) were selected in the field as reference plots. Centre points of plot circles were located using Real-Time Kinematic (RTK) GPS, with positional accuracies up to a few centimetres. Data collection was based on the BioHab-methodology [34,35], and included cover of plant life forms (i.e., trees and shrubs, dwarf shrubs, forbs, grass-like species and mosses) and of dominant species, as well as environmental and management information and N2000 habitat type. Vegetation cover was consistently estimated as seen from above, thus adding up to 100%, to resemble a remote sensor's viewpoint. A total of 694 reference plots were collected in the field in 2007. Another 146 plots of dry, wet and *Molinia* heathland that were collected in June 2006 were added, after verification in the field that they were still valid. Additionally, 485 reference plots of easily recognizable classes were taken from orthophoto-interpretation, supported by terrain knowledge. This specifically provided additional reference plots for bare sand, arable fields, agricultural grasslands, *Juncus effusus* swards and unvegetated water bodies, raising the original total reference plot size in the LVT dataset to 1325 plots.

In 2009, a second, independent dataset was collected, containing conservation status data (landscape structure, presence of key species and the amount of grass and tree cover) of 938 random habitat patches. These data were used to validate the conservation status assessments (see Section 2.8.) More details on the conservation status indicators and the field methods can be found in [27].

2.2.2. Imaging Spectroscopy Data

On 2 June 2007, Airborne Hyperspectral line-Scanner radiometer (AHS-160) images of the 'Kalmthoutse Heide' study area were acquired. The AHS sensor, equipped with 63 spectral bands in the visual and near-infrared spectral domain (400 to 2500 nm), was mounted on a CASA C-212 airplane operated by INTA. Six image strips were acquired with a spatial resolution of 2.4 by 2.4 m. Geometric and atmospheric corrections were performed using VITO's in-house Central Data Processing Centre [36]. Previous validation tests on airborne IS data, acquired in similar conditions, have shown the geometric accuracy to be sub-pixel [37]. Atmospheric corrections were based on Modtran 4. After corrections, the six images were mosaicked into one image product. To further reduce the atmospheric influence on reflectance values caused by off-nadir viewing, pixels with the smallest view zenith angle were used in overlapping areas. Further details about the imagery can be found in [26,30].

2.3. Method Overview

Direct mapping of heathland habitat using remote sensing is hampered by the intrinsic properties of high intra-variability, i.e., high heterogeneity in species composition within a habitat type, and low inter-variability, i.e., the occurrence of the same species in multiple habitat types. To circumvent these difficulties, the method we developed is based on breaking down habitats into a number of hierarchical LVT classes that: (i) are related to the dominant species present; (ii) incorporate parameters suitable for habitat quality assessment; and (iii) enable the subsequent reconstruction of habitats using the classes' spatial composition. By doing so, we exploit the inherent properties of heathland habitats in a three-step indirect method that enables habitat quantity and quality mapping at patch level (patches down to 400 m^2). In the first step, a four-level hierarchical supervised classification of airborne imaging spectroscopy data is performed, resulting in LVT maps with increasing detail. In the second step, the Level-4 LVT classification map is converted into a N2000 habitat type patch map, based on the local spatial composition of the LVT classes. To do so, a set of rules is used that relate the LVT classes to life forms, General Habitat Categories and N2000 classes. In the final step, the Level-4 LVT and the General Habitat Categories patch map are combined to derive conservation status indicator maps of habitat quality per patch (e.g., tree and grass cover). The independent dataset, acquired in 2009, is then used to validate the obtained conservation status indicator results. Figure 2 gives a schematic overview of the method. In the following sections, each step of the method is explained in detail.

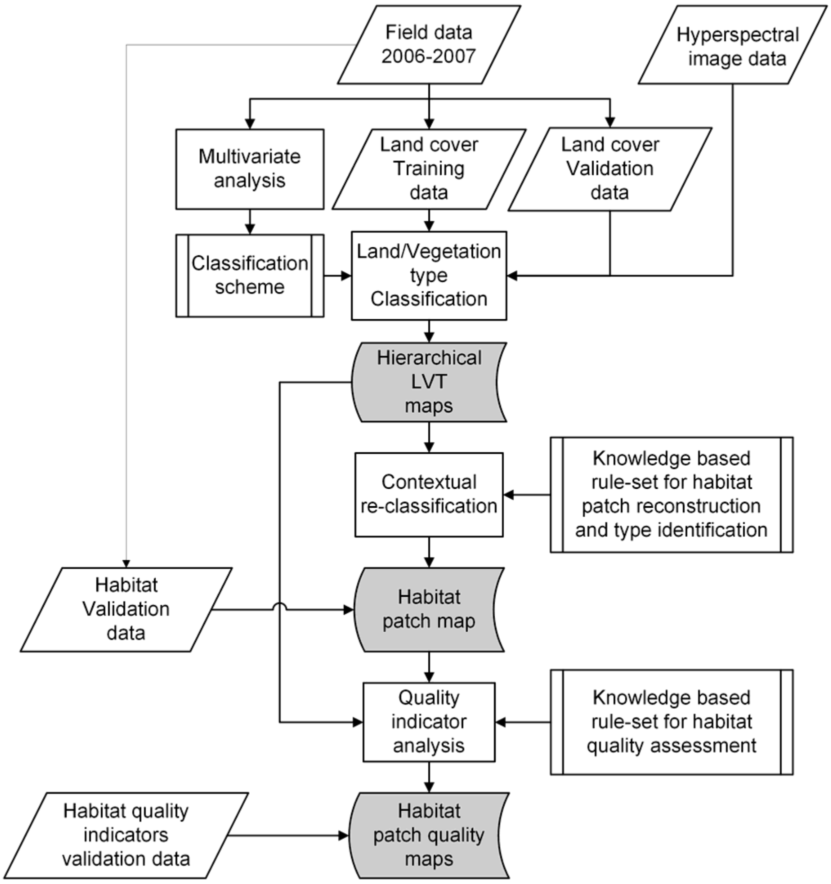


Figure 2. Methodological flowchart: parallelograms represent data input, rectangles with double-lined vertical borders are knowledge-based inputs, rectangles with single-lined borders are data analysis processes, and grey shapes are map results.

2.4. Design of a Dedicated Hierarchical LVT Classification Scheme

N2000 heathland habitats do not consist of homogeneous vegetation patches of a single or a few dominant species. Instead, most habitats are intricate mixtures of different LVTs. Dry sand heaths with *Calluna* and *Genista* (habitat code 2310) for example, naturally consist of tufts of heather (*Calluna vulgaris*), mosses, lichens and grasses, and small patches of bare sand. In most cases, the observed LVT pattern in a habitat patch, i.e., presence/absence and relative abundance of certain species, is the result of internal dynamics and external influences acting on the habitat patch. Therefore, the observed LVT pattern can also be used to assess the ecological quality of that patch. While some LVTs are indicative of a good habitat quality, others reflect pressures with a negative impact on habitat quality. Several European Union member states have made use of this inherent complexity of habitats to draw up evaluation frameworks for the assessment of the quality of habitat patches in the field [38–41]. For dry sand heaths with *Calluna* and *Genista* for example, positive indicators are the presence of bare sand and patches of mosses and lichens, whereas encroachment by grasses, especially *Molinia caerulea*, and trees are considered negative indicators.

To raise the chances of successful IS-based habitat mapping, the classification scheme should be based on habitat characteristics with a strong influence on the spectral signature (e.g., dominant species, plant architecture). Therefore, the list of habitats present in the study area was translated into a provisional list of LVT classes, which can be thought of as a typology of spatial units of homogeneous structure and plant species dominance (Figure 3). For habitat 2330, for example, we distinguished bare sand, fixed sand (three types) and trees (*Pinus sylvestris*, *Betula* sp.) as possible LVT classes that make up the habitat. Habitat definitions [42–44] and quality indicators [39,45] served as input for this translation. The field vegetation survey data, recorded in 2006–2007, were first analysed using two contrasting techniques of multivariate analysis: (1) TWINSPAN (a divisive method; [46]) and (2) Ward's clustering with Euclidean distance measure (an agglomerative method; [47]). The outcome of both methods was then compared and outliers were removed from the dataset to assure that remaining clusters were robust and homogeneous in plot composition. Each of the retained clusters was consequently interpreted and matched with a LVT class from the provisional list. Some of these predefined classes turned out not to be present in sufficient amount or in sufficiently large patches (with respect to the pixel size of the IS data used; see Section 2.2.2) in the study area, and were therefore removed from the list (e.g., *Rhynchosporion* vegetations). This led to a final list of LVT classes, as shown in the right column of Figure 3. In a final step, the LVT classes were arranged in a four-level hierarchical classification system, based on similarity of plant life forms (Level 1, 2) or dominant species (Level 3, 4) present. We applied extra thresholds of vegetation cover to ensure that all reference plots in a class would represent a typical spectral signature of that class (e.g., >60% cover of *Calluna vulgaris* for class '*Calluna*-dominated heathland'). The total number of reference points that eventually remained for use in the next steps was 938. The final classification scheme is given in Table 2.

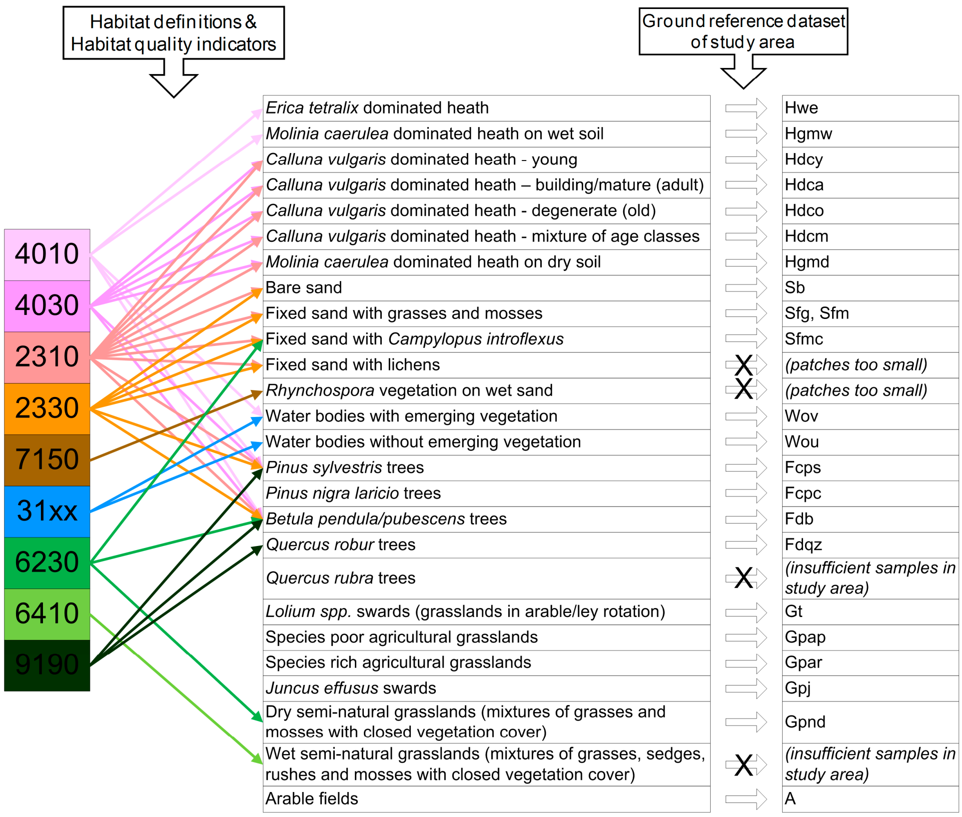


Figure 3. Translation of habitat types to land/vegetation type classes to serve the classification. For each of the habitats (defined by their respective code on the left), a specific colour is used to enable easy visualization of the LVT classes the habitat consists of (middle: full name description; right: codes used in this study).

Table 2. Land/vegetation type classification scheme.

Level 1		Level 2		Level 3		Level 4	
H	Heathland	Hd	Dry heathland	Hdc	*Calluna*-dominated heathland	Hdcy	*Calluna*-stand of predominantly young age
						Hdca	*Calluna*-stand of predominantly adult age
						Hdco	*Calluna*-stand of predominantly old age (open)
						Hdcm	*Calluna*-stand of 2 or 3 mixed age classes
		Hw	Wet heathland	Hwe	*Erica*-dominated heathland	Hwe-	*Erica*-dominated heathland
		Hg	Grass-encroached heathland	Hgm	*Molinia*-dominated heathland	Hgmd	*Molinia*-stand on dry soil
						Hgmw	*Molinia*-stand on moist (wet) soil
G	Grassland	Gt	Temporary grassland	Gt-	Temporary grassland	Gt–	Temporary grassland
		Gp	Permanent grassland	Gpa	Permanent grassland in intensive agricultural use	Gpap	Species-poor permanent agricultural grassland
						Gpar	Species-rich permanent agricultural grassland
				Gpn	Permanent grassland with semi-natural vegetation	Gpnd	Dry semi-natural permanent grassland
				Gpj	*Juncus effusus*-dominated grassland	Gpj-	*Juncus effusus*-dominated grassland
F	Forest	Fc	Coniferous forest	Fcp	Pine (*Pinus* sp.) forest	Fcpc	Corsican pine (*Pinus nigra laricio*)
						Fcps	Scots pine (*Pinus sylvestris*)
		Fd	Deciduous forest	Fdb	Birch (*Betula* sp.) forest	Fdb-	Birch (*Betula pendula/pubescens*)
				Fdq	Oak (*Quercus* sp.) forest	Fdqz	Pedunculate oak (*Quercus robur*)
S	Sand dune	Sb	Bare sand	Sb-	Bare sand	Sb–	Bare sand
		Sf	Fixed sand dune	Sfg	Sand dune with grasses as important fixators	Sfgm	Sand dune fixed by grasses and mosses
				Sfm	Sand dune with mosses as dominating fixators	Sfmc	Fixed sand dune with predominantly *Campylopus introflexus*
						Sfmp	Fixed sand dune with predominantly *Polytrichum piliferum*
W	Water body	Wo	Oligotrophic water body	Wov	Shallow, vegetated oligotrophic water body (banks of pools)	Wov-	Shallow, vegetated oligotrophic water body (banks of pools)
				Wou	Unvegetated (deep) oligotrophic water (centre of pools)	Wou-	Unvegetated (deep) oligotrophic water (centre of pools)
A	Arable fields	Ac	Arable field with crop	Acm	Arable field—maize	Acm-	Arable field—maize
				Aco	Arable field—other crops	Aco-	Arable field—other crops

2.5. Land/Vegetation Type Classification

LVT classifications were performed using Linear Discriminant Analysis (LDA) [48] in combination with a Sequential-Floating-Forward-Search (SFFS) [49] feature selection algorithm. We used a one-against-one approach which implies that for each pixel-spectrum all possible pairs of output classes are compared, resulting in C(C-1)/2 classifiers, where C is the number of classes. The finally assigned LVT class is then decided through a maximum-probability decision rule. The SFFS feature selection was used to extract the spectral band combination that led to the highest accuracies. The field dataset of 2006–2007 was used for training and validating the classification using leave-one-out cross-validation (LOOC). Classifications were first performed on each of the four levels separately to gain insight into the performance and accuracies at each level, to identify the best-performing spectral bands for each 1–1 class combination at all levels, and to set the baseline for comparison with a hierarchical approach. To investigate the effect of using the hierarchy of the classification scheme in the LVT classification, the classifier was implemented hierarchically. For example, if a sample is classified as Forest at Level 1, it can only be classified as *Deciduous forest* or *Coniferous forest* at Level 2. To train the LDA classifier at each node in the classification scheme, the same features for each 1–1 class combination were used as were previously selected in the non-hierarchical approach, but only those samples were used that were correctly classified at the previous level. Given the LOOC, the sample that was the test sample at a certain iteration, was also excluded from the training set at this iteration. On the one hand, this hierarchical approach has the advantage that confusion with similar classes at a certain level that have a different parent class is reduced. On the other hand, errors that occur at a certain level are continuously carried to more detailed levels. The results of the LVT classifications are discussed in Section 3.1. An analysis of the selected features to differentiate each 1–1 class combination is considered to be out of the scope of this paper.

2.6. Habitat Patch Mapping

The classification scheme was designed in such a way that the list of N2000 habitats present in the study area is translated into a list of LVT classes that can be classified using the spectral information of the IS data (see Section 2.4). These LVT classes can conversely be interpreted as spatial units which can serve to construct habitat patches. Certain LVT classes can however occur in several habitat types, hampering a straightforward re-classification from LVT classes into a habitat map. For example, trees (LVT classes Fcpc, Fcps, Fdb-, Fdqz) can occur in almost all habitat types. When they form large, contiguous patches, they are part of a forest habitat, while smaller patches or individual pixels of these LVTs are simply a part of the surrounding open habitat. Incorporating the context in the reclassification process is therefore essential for identifying the most plausible habitat type.

To solve this issue, we split the mapping of habitat patches into two stages, the first one aiming to delineate patches, and the second one serving to assign a habitat type label to each patch (see Section 2.7). This method mimics the mapping approach used by field mappers (e.g., [50]): they first delineate 'uniform' habitat patches and then identify the habitat type based on the species that are present. For the first stage, to delineate patches, we defined a number of rule sets that are used to: translate the LVT classes to life form compositions [51] (Table 3); and determine a General Habitat Category [52,53] based on the life forms present in a local spatial window. Grouping of adjacent pixels with the same General Habitat Category then delivers the desired patches (polygons). This method is an adaptation of the BioHab/EBONE methodology [35] that is designed for consistent mapping of habitat patches in the field. To determine the General Habitat Category for each pixel and surroundings, a spatial kernel of 5 $\times$ 5 pixels was run over the image, for which the composition of LVT classes was determined (adding up to 100%). This local composition is then translated into life form composition using Table 4. This table accounts for the typical composition of the LVTs in terms of life forms. For example, *Calluna*-stands of predominantly adult age typically contain about 80% of evergreen low shrubs (LPH_EVR; here: *Calluna vulgaris*), 10% of grasses (CHE) and 10% of mosses (CRY). Older *Calluna*-stands typically have a lower cover of *Calluna vulgaris* (60% LPH_EVR), but a higher cover of mosses (30% CRY). Using the definitions and rules in Table 5, the General Habitat Category is then determined based on the life form composition, and assigned to the central pixel of the spatial kernel. Running this over the complete image, results in a new map of General Habitat Category classes. This map was vectorised for further use, and determined the shape of each of the habitat patches. The steps from LVT classes to General Habitat Categories via life form compositions proved necessary to help the reclassification process group LVT classes that naturally occur together in habitat patches. If omitted, the reclassification process based on a moving window would yield unexpected results: the moving window approach would inevitably combine LVT classes of neighbouring, but unrelated habitat patches, leading to combinations of LVT classes that do not correspond to the expert descriptions of any habitat type.

Table 3. Description of the most abundant life forms in the 'Kalmthoutse Heide' study site (adapted from [52]).

Super-Category	Life Form	Full Name	Explanation/Examples
SPV		Sparsely vegetated	Less than 30% vegetation cover
	AQU	Aquatic	Permanent water bodies
	TER	Terrestrial	Bare ground (sand)
CUL		Cultivated	Cultivated land
	CRO	Herbaceous crops	e.g., Maize
HER		Herbaceous	Non-woody vegetation
	HEL	Helophytes	Plants that grow in waterlogged conditions e.g., *Juncus effusus*
	LHE	Leafy hemicryptophytes	Biannual or perennial broadleaved herbaceous plant species ('forbs')
	CHE	Caespitose hemicryptophytes	Perennial monocotyledonous grasses, sedges and rushes e.g., *Molinia caerulea*
	CRY	Cryptogams	Bryophytes and lichens e.g., *Campylopus introflexus*
TRS		Trees and shrubs	Woody vegetation
	SCH/EVR	Shrubby chamaephytes (evergreen)	Undershrubs with height 5 to 30 cm. e.g., *Erica tetralix*, young *Calluna vulgaris*
	LPH/EVR	Low phanerophytes (evergreen)	Low shrubs, buds between 30 and 60 cm. e.g., adult *Calluna vulgaris*
	FPH/CON	Forest phanerophytes (coniferous)	Coniferous trees between 5 and 40 m. e.g., *Pinus sylvestris*
	FPH/DEC	Forest phanerophytes (winter deciduous)	Broadleaved, winter deciduous trees between 5 and 40 m. e.g., *Quercus robur*

Table 4. Rule set to convert the land/vegetation type (LVT) classes to life form compositions (%). Rows represent the LVT classes (see Table 2), and columns represent life forms (see Table 3).

	CRO	FPH_CON	FPH_DEC	LPH_EVR	SCH_EVR	CHE	CRY	HEL	TER	AQU	LHE
Acm_	100										
Aco_	100										
Fcpc		50				50					
Fcps		50				50					
Fdb_			70			30					
Fdqz			100								
Gpap						80					20
Gpar						50					50
Gpj_						50		50			
Gpnd						50	50				
Gt__	100										
Hdca				80		10	10				
Hdcm				80		10	10				
Hdco				60		10	30				
Hdcy				80		10	10				
Hgmd						100					
Hgmw						100					
Hwe_					50	50					
Sb__									100		
Sfgm						10	60		30		
Sfmc							80		20		
Sfmp							80		20		
Wou_										100	
Wov_								30		70	

Table 5. Definitions and rule set used to convert life forms to General Habitat Categories (GHC).

Definitions									
	SPV	=	AQU	+	TER				
	FPH	=	FPH_CON	+	FPH_DEC				
	TRS	=	FPH_CON	+	FPH_DEC	+	LPH_EVR	+	SCH_EVR
	HER	=	HEL	+	LHE	+	CHE	+	CRY

Life Form	**Rule**	**General Habitat Category (GHC)** [1]	**Rule**
CRO × 100	>50	Unspecified	
SPV × 100	>=30	Highest (e.g., AQU, TER)	$\frac{Highest \times 100}{(Highest+2nd\ Highest)} \geq 70$
		Highest_2ndHighest (e.g., AQU/TER, TER/AQU)	$\frac{Highest \times 100}{(Highest+2nd\ Highest)} < 70$
TRS × 100	>=30	FirstNonZero_Highest (e.g., FPH_CON)	$\frac{Highest \times 100}{(Highest+2nd\ Highest)} \geq 70$
		FirstNonZero_ HighestNonZero/2ndHighestNonZero (DEC, EVR, CON) (e.g., FPH_DEC/CON)	$\frac{Highest \times 100}{(Highest+2nd\ Highest)} < 70$
$\frac{HEL \times 100}{(CHE+CRY+HEL+LHE)}$	>=30	Unspecified	
$\frac{HEL \times 100}{(CHE+CRY+HEL+LHE)}$	<30	Highest (e.g., CHE, CRY)	$\frac{Highest \times 100}{(Highest+2nd\ Highest)} \geq 70$
		Highest_2ndHighest (e.g., CHE/LHE)	$\frac{Highest \times 100}{(Highest+2nd\ Highest)} < 70$

[1] Legend to the GHCs: Highest: The life form with the highest proportion in the kernel becomes the GHC for the central pixel. Highest_2ndHighest: The GHC of the central pixel is a combination of the two life forms with highest proportions in the kernel (with order being of relevance, e.g., AQU/TER is different from TER/AQU). FirstNonZero: In the TRS subcategory, life forms growing higher take precedence over lower life forms, thus FPH > LPH > SCH. The first life form in this order that is not zero becomes the GHC for the central pixel. Highest vs. HighestNonZero/2ndHighestNonZero: In the TRS subcategory, life forms are always accompanied by a leaf type qualifier (DEC, CON, EVR). This can be either one such qualifier (e.g., FPH_DEC for a deciduous forest) or a combination of two qualifiers accompanying a single life form (e.g., FPH_DEC/CON for a mixed forest with a (slight) dominance of deciduous over coniferous trees).

2.7. Habitat Type Identification

The previous step resulted in a map with delineated habitat patches, but the patches did not yet have a N2000 habitat type assigned to them. To achieve this, an additional rule set was defined that characterizes each habitat using percentage ranges of LVT compositions. (Note that General Habitat Categories (see Section 2.6) were not further used for N2000 habitat type identification, since there is not a one-to-one correspondence between the typologies.) Using the descriptions of habitats in [42,44,54], we identified which LVT classes (regardless of their hierarchical level) could occur in each habitat type, and what the minimal and maximal expected percentage of occurrence within a habitat patch were. A patch was only assigned to a habitat class when its LVT composition specifically fell into the percentage ranges of that habitat. If it did not fit any of the percentage ranges, the patch was considered not a N2000 habitat. Table 6 illustrates the rules to translate the LVT map to a N2000 habitat map. As a result of the high variability within each habitat, these translation rules had to be further refined to first separate degraded (tree and grass-encroached) habitat occurrences. The full table of LVT to N2000 habitat translation rules is available in the Supplementary Material of the paper. The resulting habitat type maps were evaluated using the habitat types noted in the field for each plot.

As a worked example, say a patch has an areal composition (in terms of corresponding pixels with assigned LVT class) of 70% H (i.c. Hd: 20%; Hw: 30%; Hgmw: 20%), 10% S (i.c. Sfgm), 10% G (i.c. Gpj), 5% F (i.c. Fd) and 5% W (i.c. Wov). The percentage covers of H, Hd, Hw and Hgmw are all within the ranges of habitats 2310, 4010 and 4030. Habitat 2330 is excluded because H has more than 50% coverage. Furthermore, the covers of S, Gpj, F and W also comply with the named three habitats. The lower-level LVT classes, Sfgm, Fd and Wov, are of no relevance here for the identification. Ultimately, we can decide that the patch is of habitat type 4010 because Hw − Hd is positive (30 − 20 = 10). Had there been more Hd than Hw (i.e., Hw − Hd = negative), then we would have had to conclude that the patch was either 2310 or 4030, and in this particular case we would have needed additional information (e.g., soil or geomorphology data) to distinguish these two habitat types.

Table 6. Rule set illustrating the relation between land/vegetation type (LVT) classes and N2000 habitat types. Rows consists of LVT classes, columns define the N2000 habitat types. Numbers represent expected cover ranges (in %) in a patch (unless otherwise indicated).

Habitat	2310	2330	4010	4030
H	30–100	0–50	70–100	50–100
Hd	0–100	0–50	0–50	0–100
Hw	0–50	0–10	0–100	0–50
Hg	0–50	0–50	0–50	0–50
Hgmw	0–30	0–10	0–50	0–30
Hgmd	0–50	0–50	0–30	0–50
S	0–70	0–100	0–10	0–30
G	0–70	0–100	0–10	0–30
Gpnd	0–70	0–100	0–10	0–30
Gpj	0–10	0–10	0–10	0–10
Gpa	0–10	0–10	0–10	0–10
Gt	0–10	0–10	0–10	0–10
S + Gpnd	0–70	50–100	0–10	0–30
F	0–30	0–15	0–30	0–30
W	0–10	0–10	0–30	0–10
A	0–10	0–10	0–10	0–10
Hw − Hd	negative	negative	positive	negative
minimum patch size (m^2)	400	400	400	400

2.8. Assessment of Habitat Quality

Assessing the quality of natural habitats is complex and not without discussion [55]. Rules for assessing the quality of N2000 habitats (such as in [38,40,41,45]) are however mainly based on three sets of characteristics. A first group are indicators related to the specific structural characteristics of habitats. For example, the occurrence of different age classes of *Calluna vulgaris* is typical for a well-developed dry heathland [26]. Second, indicators of the more general pressures on natural ecosystems are considered (e.g., grass and tree encroachment for open ecosystems). The third important characteristic is the number and cover of key species.

To illustrate the potential of IS for the derivation of certain habitat quality parameters, we combined the information from the habitat patch map (output from 2.7) with the LVT maps (output from 2.5) to derive the tree and grass coverage per patch. Tree or grass coverage is defined as the percentage of trees (F class) or grass (Hgm class) cover within a habitat patch. To validate the amount of cover obtained with the IS method, we compared the mapped percentage of tree and *Molinia* coverage (the F and Hgm classes, respectively) with cover estimates made in the field, using a set of habitat polygons delineated in the field in 2009.

2.9. Method Implementation

All analyses for this study were performed using our own code implementations in Matlab R2014a. For the feature selection and classification of the LVT classes, we additionally made use of the PRTools 4.2 package [56]. Our code can be shared upon e-mail request to the corresponding author.

3. Results

3.1. Land/Vegetation Type Classification Results

LVT classifications produced four LVT classification maps at four different levels of detail (Level 1: lowest detail; Level 4: highest detail). Classifications were first performed on each level separately, i.e., independent of the other levels, to gain insight into the performance at each level. Subsequently, the hierarchical nature of the classification scheme was exploited to further improve classification results. A true colour representation of a study area extract and the corresponding level-4 classification result are shown in Figure 4. Table 7 summarizes the overall accuracies (OA) and Kappa (KHAT) for all levels of LVT detail, both when performed separately and when exploiting the hierarchical nature of the classification scheme.

Table 7. Overview of overall classification accuracies (OA in %) and Kappa indices at all hierarchical LVT class levels, without and with exploiting the hierarchical nature of the classification scheme. All accuracy measures were calculated using leave-one-out cross-validation.

Level	Number of Classes	Non-Hierarchical		Hierarchical L1 → L4		Hierarchical L2 → L4	
		OA (%)	Kappa	OA (%)	Kappa	OA (%)	Kappa
1	6	93.82	0.93	93.82	0.93	-	-
2	11	91.68	0.91	90.19	0.89	91.68	0.91
3	17	88.17	0.87	87.10	0.86	88.59	0.88
4	24	81.77	0.80	81.24	0.80	82.84	0.82

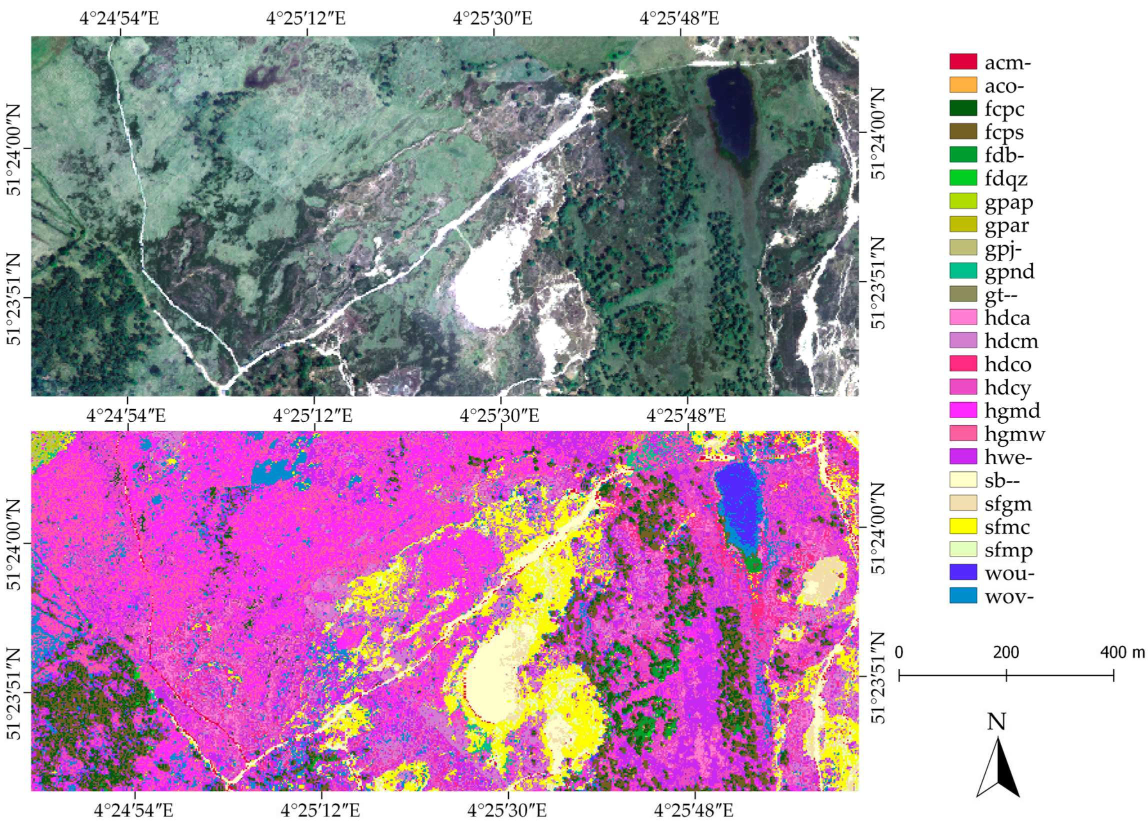


Figure 4. True colour extract of the study area (**top**), and land/vegetation type (LVT) classification result at Level 4 of the same extract, consisting of 24 classes (**bottom**). Full names of the Level 4 classes can be found in Table 2. The LVT classification maps for Level 2 to 4 of the whole study area are provided in the supplementary material.

Without incorporating the hierarchical information in the classification scheme, OA (and KHAT) were already high at all levels, ranging from 81.8% (0.80) at Level 4 up to 93.8% (0.93) at Level 1. Using the full hierarchical nature of the classification scheme from Level 1 down to Level 4 slightly negatively influenced OA (and KHAT) for the more detailed Levels 2 to 4. With differences of 1.5%, 1.1% and 0.5% in OA at Levels 2, 3 and 4, respectively, the gap between the non-hierarchical and the full hierarchical implementation narrows with the increase in class number and detail. On the one hand, these results indicate that the LVT classification algorithm appears to adapt well to increasing levels of complexity. On the other hand, it also suggests that including the hierarchical information becomes increasingly important with increasing levels of detail. The step from Level 1 to 2 in the full hierarchical implementation resulted in the biggest decrease of OA (and KHAT), meaning there is avoidable confusion introduced between classes at L1 that is carried throughout the hierarchy. At Level 1, the LVT classes are still very broad, e.g., Grassland (G), Heathland (H), and Water Bodies (W). At Level 2, we introduce some important distinctions that are likely to cause confusions at Level 1, e.g., the Grass-encroached heathland (Hg) class, which belongs to the Heathland (H) class at Level 1, and is likely to cause confusion with the Grassland (G) class. Another example is the Wet heathland (Hw) class, also belonging to the Heathland (H) class at Level 1, and likely to cause some confusion with the Water bodies (W) class. Taking this into account, we also explored the hierarchy effect from Level 2 to 4. Doing so resulted in a slight increase in OA (and KHAT) for Level 3 and 4, 88.6% and 82.8%, respectively. With differences in OA of 0.4% and 1.1% at Level 3 and 4, respectively, these results show that a hierarchical implementation can benefit LVT map accuracy. Consequently, the maps produced with the hierarchical LVT classification of Level 2 to 4 (not level 1) were used for further analysis. Level 2 to 4 LVT classification maps for the entire study area are available in the Supplementary Materials.

In Table 8, an overview is provided of the User's and Producer's accuracies (UA and PA) per LVT class for Level 2 to 4, using the chosen classification implementation. The confusion matrix of the Level 4 classification is shown in Table 9. At Level 2, UA and PA for all classes are higher than 84% and 77%, respectively. At Level 3, 14 of the 17 classes still have UA > 76% and PA > 71%, with the majority >80% for both accuracies. The LVT classes Gpa and Gpj have UA of 63% and 55%, and PA of 60% and 33%, respectively. Aco has a PA $\approx$ 54%. Two of the three LVT classes that suffer from higher confusion, i.e., Gpa and Aco, are agricultural types, and hence of less importance for the heathland core area. At the most detailed level of LVT mapping, the majority of classes again shows UA and PA of >70%. Most of the classes that score below 70% are actually child classes of the classes that were already suffering from confusion at Level 3. A continuous trend over all levels, is that particularly the classes that have a lower amount of training spectra, are likely to show some confusion.

Of particular interest in terms of conservation status assessment, is the relatively low success in mapping the different *Calluna* heather age classes Hdca, Hdcm, Hdco and Hdcy. Confusion does arise between the age classes, but given the low amount of training spectra for each class, and the existence of the mixed-age Hdcm class, these results are not surprising. In a parallel study, we applied a different strategy to improve the separation between these classes, using spectral unmixing techniques to characterize the *Calluna* heath age classes, taking into account their specific morphological characteristics [26]. Given this study, conservation status assessment using *Calluna* heather age classes is not treated further in this study.

The high accuracy results demonstrate that overall a robust LVT map can be obtained for further processing to habitat maps, and that even specific habitat quality-indicating classes can be mapped with moderate to high accuracy.

Table 8. Overview of user's and producer's accuracies per class for Levels 2 to 4, using the hierarchical implementation from Level 2 to 4.

Level 2				Level 3				Level 4			
Class	**# of Reference Plots**	**UA**	**PA**	**Class**	**# of Reference Plots**	**UA**	**PA**	**Class**	**# of Reference Plots**	**UA**	**PA**
Ac	133	96.77	90.23	Acm	98	87.62	93.88	Acm-	98	87.62	93.88
				Aco	35	100.00	54.29	Aco-	35	100.00	54.29
Fc	97	93.75	92.78	Fcp	97	93.75	92.78	Fcpc	44	70.21	75.00
								Fcps	53	79.59	73.58
Fd	80	93.90	96.25	Fdb	32	90.63	90.63	Fdb-	32	90.63	90.63
				Fdq	48	94.00	97.92	Fdqz	48	94.00	97.92
Gp	66	91.07	77.27	Gpa	25	62.50	60.00	Gpap	12	50.00	41.67
								Gpar	13	35.71	38.46
				Gpj	18	54.55	33.33	Gpj-	18	54.55	33.33
				Gpn	23	90.48	82.61	Gpnd	23	90.48	82.61
Gt	97	94.90	95.88	Gt-	97	94.90	95.88	Gt–	97	94.90	95.88
Hd	84	85.39	90.48	Hdc	84	85.39	90.48	Hdca	28	68.97	71.43
								Hdcm	23	60.00	65.22
								Hdco	8	44.44	50.00
								Hdcy	25	65.38	68.00
Hg	25	85.19	92.00	Hgm	25	85.19	92.00	Hgmd	15	68.75	73.33
								Hgmw	10	72.73	80.00
Hw	88	84.09	84.09	Hwe	88	84.09	84.09	Hwe-	88	84.09	84.09
Sb	104	96.08	94.23	Sb-	104	96.08	94.23	Sb–	104	96.08	94.23
Sf	62	89.39	95.16	Sfg	14	76.92	71.43	Sfgm	14	76.92	71.43
				Sfm	48	86.79	95.83	Sfmc	40	77.08	92.50
								Sfmp	8	40.00	25.00
Wo	102	90.00	97.06	Wou	45	84.62	97.78	Wou-	45	84.62	97.78
				Wov	57	86.21	87.72	Wov-	57	86.21	87.72
Total:	938			Total:	938			Total:	938		

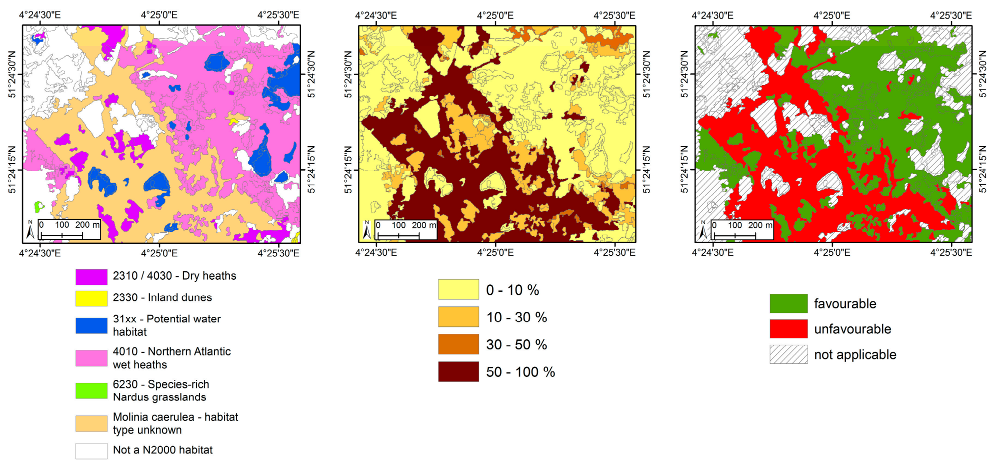
Table 9. Confusion matrix of the Level 4 land/vegetation type classification, using the hierarchical implementation from Level 2 to 4.

Reference Data	Classified Data																									
	Acm-	**Aco-**	**Fcpc**	**Fcps**	**Fdb-**	**Fdqz**	**Gpap**	**Gpar**	**Gpj-**	**Gpnd**	**Gt–**	**Hdca**	**Hdcm**	**Hdco**	**Hdcy**	**Hgmd**	**Hgmw**	**Hwe-**	**Sb–**	**Sfgm**	**Sfmc**	**Sfmp**	**Wou-**	**Wov-**	**Total**	**PA**
Acm-	92	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0	0	0	1	1	98	93.88
Aco-	9	19	1	0	0	3	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	35	54.29
Fcpc	0	0	33	8	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	44	75.00
Fcps	0	0	10	39	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	53	73.58
Fdb-	0	0	3	0	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	90.63
Fdqz	0	0	0	0	1	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	97.92
Gpap	0	0	0	0	0	0	5	2	0	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	12	41.67
Gpar	0	0	0	0	1	0	3	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	38.46
Gpj-	0	0	0	1	0	0	1	4	6	0	0	0	0	0	0	0	0	1	0	0	2	0	0	3	18	33.33
Gpnd	0	0	0	0	0	0	1	0	0	19	0	0	0	0	1	0	0	1	0	1	0	0	0	0	23	82.61
Gt–	0	0	0	0	0	0	0	2	0	0	93	0	0	0	0	1	0	0	0	0	0	0	1	0	97	95.88
Hdca	0	0	0	0	0	0	0	0	0	0	0	20	5	1	1	0	0	1	0	0	0	0	0	0	28	71.43
Hdcm	0	0	0	0	0	0	0	0	0	0	0	4	15	0	3	0	0	1	0	0	0	0	0	0	23	65.22
Hdco	0	0	0	0	0	0	0	0	0	0	0	0	1	4	0	0	0	1	0	0	1	0	0	1	8	50.00
Hdcy	0	0	0	0	0	0	0	0	1	0	0	2	3	0	17	0	0	2	0	0	0	0	0	0	25	68.00
Hgmd	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	2	1	0	0	0	0	0	1	15	73.33
Hgmw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	8	0	0	0	0	0	0	0	10	80.00
Hwe-	0	0	0	0	0	0	0	0	0	0	0	3	1	3	4	1	0	74	0	0	1	0	0	1	88	84.09
Sb–	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	98	1	1	0	0	0	104	94.23
Sfgm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	10	1	1	0	0	14	71.43
Sfmc	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	37	2	0	0	40	92.50
Sfmp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	2	0	0	8	25.00
Wou-	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	44	0	45	97.78
Wov-	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	5	50	57	87.72
Total	105	19	47	49	32	50	10	14	11	21	98	29	25	9	26	16	11	88	102	13	48	5	52	58		
UA	87.62	100.00	70.21	79.59	90.63	94.00	50.00	35.71	54.55	90.48	94.90	68.97	60.00	44.44	65.38	68.75	72.73	84.09	96.08	76.92	77.08	40.00	84.62	86.21		

3.2. Habitat Type Patch Map Results

Four N2000 habitat types that frequently occur in European heathlands were mapped (Table 1). Figure 5a shows the habitat map re-classification result of the same study area excerpt as in Figure 4. We tested different window sizes (5 × 5, 7 × 7, and 9 × 9) for the delineation of the habitat patches (for the conversion of lifeforms to GHC classes; see Section 2.6), but the resulting habitat maps showed only minor changes with different window sizes. Using a 5 × 5 window is hence preferable as this results in a lower computational load. The habitat patch map consists of 22 classes in total, definitions of all these classes, as well as a habitat map covering the whole study area, are available in the Supplementary Materials. For accuracy assessment purposes, we have taken a subset consisting of the four habitat type classes and a *No N2000 habitat type* class. The *No N2000 habitat type* class groups all patches that do not match the definitions determined for the habitat types, e.g., agricultural area, urban area and walking trails (see Table 6).

OA, UA and PA for all habitat types are summarized in Table 10. The obtained OA was 89%. For three of the four mapped habitat types, a PA > 72% and UA > 80% was obtained. Habitat type 4030 showed a lower PA of 54%, with most confusion ending up in the 'No habitat type' class. The UA of habitat type 4030 however equals 100%, so all of the patches that were mapped as 4030 were noted in the field to be this habitat type, but the procedure fails to map all 4030 habitat patches. Habitat type 2310, with a PA of 73% and UA of 69%, seems to confuse most with habitat type 4010. These accuracy numbers were acquired in a slightly different manner than the conventional way, due to fuzziness of the obtained habitat map. As the LVT range composition rules from Table 6 are not fully mutually exclusive, the resulting habitat map can contain multiple possible habitat types for each patch. We opted to give more importance to the habitat definitions given in the literature [42,44,54] than to try to change the habitat composition definitions in such a way that they are mutually exclusive. These habitat definitions are however not fully quantitatively described and can thus be subject to interpretation. Similarly, field interpreters often take note of the several potential types. Taking this into account, we considered the decision of the classification method as being correct, when one of the habitat types the method had assigned the patch to, corresponded to the habitat type noted in the field for that patch. In Figure 5, the patches that were constructed using the method described in Section 2.6 are also depicted. Neighbouring patches can have the same habitat type assigned to them, but each patch is maintained as an entity. As such, it is ensured that the assessment of conservation status parameters can be done at patch level, instead of at a large continuous entity that may have both well-developed and degraded forms of the habitat within it.



(a) (b) (c)

Figure 5. (**a**) Habitat type classification result; (**b**) *Molinia* cover per patch (%); (**c**) conservation status of *Molinia* coverage indicator.

Table 10. Confusion matrix for the mapped heathland habitat types present in the 'Kalmthoutse Heide' study area.

	Mapped						
Field	**No N2000 Habitat**	**2310**	**2330**	**4010**	**4030**	**# of Reference Plots**	**PA (%)**
No N2000 Habitat	542	1	4	3	0	550	**98.55**
2310	3	48	2	13	0	66	**72.73**
2330	24	9	143	1	0	177	**80.79**
4010	6	12	0	81	0	99	**81.82**
4030	15	0	3	3	25	46	**54.35**
# of reference plots	590	70	152	101	25	938	
UA (%)	**91.86**	**68.57**	**94.08**	**80.20**	**100.00**	**OA =**	**89.45%**

3.3. Assessment of Habitat Quality at the Patch Level

Figure 5b,c provide an example of the results obtained by combining the habitat patch map with the LVT Level-4 map to derive conservation status indicator maps. In Figure 5b, *Molinia* cover per patch (in %) is depicted. In Figure 5c, the example is converted to an easily interpretable *favourable/unfavourable* conservation status indicator map, using the terminology of N2000 that terrain managers and monitoring experts are accustomed to. To this end, identical rules are applied as in the field, i.e., for the habitats 2310, 4010 and 4030, the conservation status is unfavourable when *Molinia* covers over 50%, otherwise it is favourable for this indicator. For habitat 2330, the reasoning is identical but the threshold is at 30% *Molinia* cover. To validate the conservation status indicator results, a comparison was made between the percentages of tree and *Molinia* cover estimated by the IS method and those recorded in the field in 2009 (see Section 2.2.1). In Figure 6a,b, the coverage distribution of the ground reference patches and those obtained using the IS method are given for tree and grass encroachment, respectively. Percentages of cover are grouped into six classes (0%, 0–20%, 20%–40%, etc.). In Figure 6c, the difference between the corresponding cover estimates per patch is shown (calculated as the estimate obtained in the field minus the estimate from the IS method).

For tree cover, the observed distribution patterns recorded in the field and with the IS method are highly similar (Figure 6a). The amount of tree cover is low (0–20%) in most of the heathland habitat validation patches. The only difference is found in the 0% class: field observers tend to score the tree encroachment more often as being completely absent. As this is normally easy to assess in the field, this difference between both methods is likely related to the presence of a few misclassified pixels of forest types (e.g., due to shadow). These minor errors, however, rarely lead to big differences. Figure 6c indeed confirms the agreement in estimates in each patch. For 91% of the validation patches, the difference between the field estimate and the IS method is less than 20%. When the conservation status is considered (favourable vs. unfavourable amount of tree encroachment), the overall accuracy is 93%. The distribution pattern of estimates of grass encroachment, i.e., *Molinia*-cover, observed in the field and those obtained with the IS method (Figure 6b), show a larger dissimilarity. There are a lot more patches estimated to have little *Molinia*-cover (0% and 0–20%) according to the IS method. The numbers in the 20%–40% and 40%–60% cover classes are similar, while the cover classes of >60% number only about half the amount found in the field estimates. The latter might be related to an overestimation of the *Molinia*-cover by field observers in the classes with a higher *Molinia*-cover due to the surveyor's oblique view in the field [28]. Figure 6c reveals that only 40% of the difference in estimates per patch is less than 20%. Another 25% of the patches has a cover estimate with the IS method that is 20% to 40% lower than made by visual interpretation in the field (20% to 40% class). The remaining patches have estimates that are >40% lower than those made in the field. These discrepancies between the field estimates and the estimates with IS-based method also impact the conservation status evaluation: when patches are classified as favourable or unfavourable, an overall accuracy of 62% is reached. These results point to either an underestimation of *Molinia*-cover with the IS method, or an overestimation by the field interpreter. On the one hand, field estimates were made using visual interpretation, and are hence inherently subjective, i.e., dependent on the field interpreter [57]. On the other hand, the minimum mapping unit in the LVT classification is equal to the pixel size. Each pixel is assigned to only one of the LVT classes, even though subpixel differences might exist. This means that pixels classified as *Hd* or *Hw* in the LVT classification might contain low amounts of *Molinia* cover, but this is not reflected in the class of the pixel and will not be included in the estimate of the amount of grass encroachment in the habitat patch. Nevertheless, the results indicate a high correlation in *Molinia*-cover estimates between both methods in 60% to 80% of the patches.

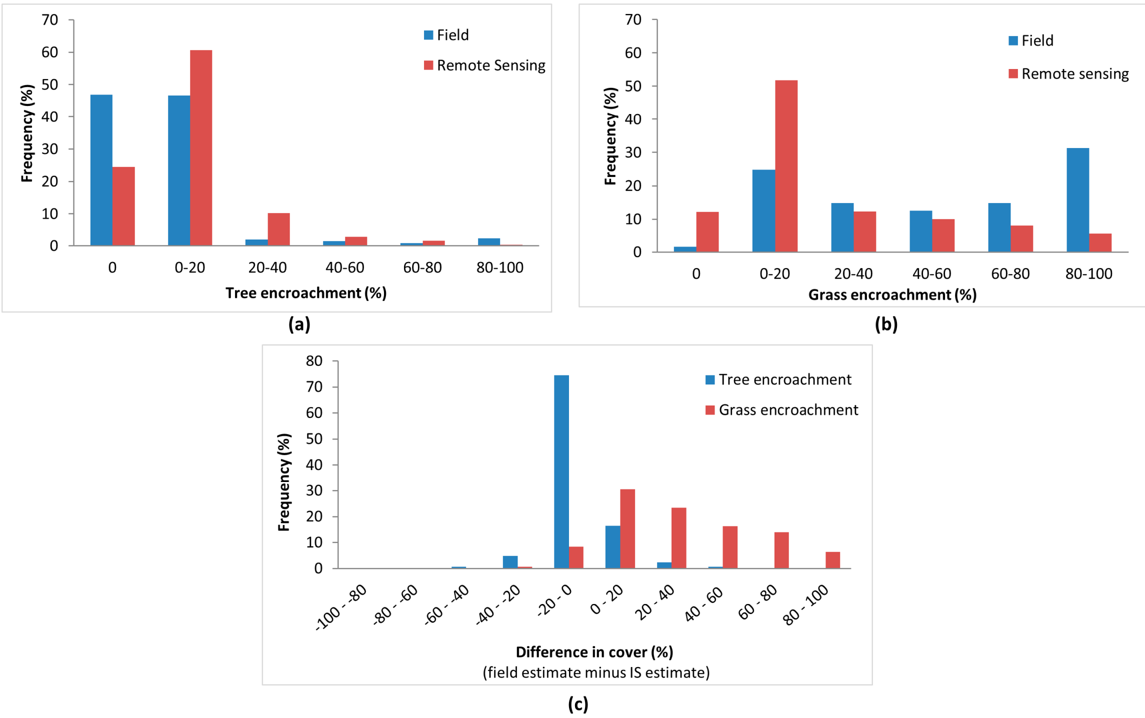


Figure 6. (**a**) Distribution of the tree encroachment estimates in the ground reference and mapped habitat patches; (**b**) distributions of the grass encroachment, i.e., *Molinia* cover, estimates in the ground reference and mapped habitat patches; (**c**) differences between the tree and grass encroachment estimates obtained per patch in the field in 2009, and with the IS-based method. Applicable threshold values for discerning favourable and unfavourable status are: tree encroachment in habitats 2310, 4010 and 4030: 30%; and in habitat 2330: 10%; Grass encroachment, i.e., *Molinia* cover, in habitats 2310, 4010 and 4030: 50%; and in habitat 2330: 30% [45].

4. Discussion

Different heathland habitat types, despite being to some extent dominated by the same plant species, were successfully discerned, and spatially explicit quality-indicating parameters were mapped at the patch level, such as tree and grass cover. Our results show that using a three-step approach (LVT → habitat patch and type → habitat conservation status) with high spatial resolution IS in a heathland area, can produce both quantitative information on the N2000 habitat types present (e.g., area, extent, and occurrence), as well as flexible habitat conservation status indicators. The applied hierarchical land/vegetation type (LVT) classification scheme and the three-step approach provide the advantage of accurate extraction of habitat classes and conservation status parameters of ecological importance, which typically occur at different spatial scales. Large continuous parts of one habitat type can be mapped, but assessment of conservation status is maintained within smaller patches in the entity. This provides information at various levels of detail which can serve several information and stakeholder needs. For example, statistical and qualitative information (e.g., area per habitat, percentage of patches affected by tree and grass encroachment) can be extracted at the level of the protected site to serve the reporting needs of the HabDir, while more detailed maps can provide a terrain manager with essential spatially explicit information to guide the site management.

In designing our method, we explicitly chose to strive for habitat patch mapping and assessment as is done when mapping in the field. Although a continuous approach (like in [29]) is better at visualizing e.g., transitions between habitats, our three-step approach offers the advantage of producing outputs that look familiar to site managers, and at the same time feed well into the reporting needs of monitoring experts. The LVT classification maps allow for a flexible assessment of patch quality, both in space (e.g., thresholds in bare sand, ericoid cover, or tree and grass encroachment vary between habitat types) and in time (applied thresholds may change in future, and the method allows for re-evaluation of past situations). The main limitation is set by the available spatial resolution: at the present pixel size of 2.4 by 2.4 m^2, we were unable to adequately map fine-scale habitat types (e.g., habitat 7150—*Rhynchosporion*) and conservation status indicators (e.g., presence of key species, *Calluna* age classes, cover of lichens). However, in earlier work [27], we showed that to a certain degree (35%–39%) these fine-scale structures can be modelled from the coarser-scale remotely sensed data. Hence, our method provides a good overview of the site with sufficient detail for many reporting and management needs. When very specific questions about specific locations arise however, additional information in the form of a field visit remains necessary.

In terms of assessing habitat quality at the patch level, it is clear that assessments based on our IS method may differ from field assessments, and that these differences may be smaller or greater depending on the indicator (e.g., OA of tree (93%) versus grass encroachment (62%) in Section 3.3). However, this need not necessarily compromise further use of the IS method for habitat monitoring, reporting and management, for several reasons. First, it is impossible to tell which approach is 'right' and which is 'wrong'. Current field-based assessments also suffer from a great deal of uncertainty due to observer effects in cover estimates [58]. As a result, data that are now used routinely are already partly 'wrong'. Second, assessments are usually based on a threshold cover value (often 10, 30% or 50%). This implies that an erroneous assessment is unlikely for patches where the indicator value deviates far (e.g., 80% or 90%) from that threshold value. Third, assessments of single indicators at single habitat patches are not reported as such to the European Commission, but are further integrated in two different ways. In a first step, the assessments of several indicators (e.g., tree and grass encroachment, key species, and structural complexity) of the same patch are first integrated at the level of the patch, where 'unfavourable' usually takes precedence over 'favourable'. Indicators are known to correlate to a certain degree [27], which means that the likelihood that any single indicator will lead to an erroneous assessment at the patch level is lowered. In a second step, these patch assessments are further integrated–weighted by patch area–to an assessment per habitat at the N2000 site or even the member state level, which is the final assessment that will be reported to the European Commission. A fourth reason why the differences between the field and IS-based habitat quality not necessarily compromise further use of the IS method is that, for management purposes, the interests of the site managers are most of the time not in the binary assessment (favourable–unfavourable) of each patch, but rather in getting insight in the patterns and processes behind it. As a consequence, managers are interested in the relative or even absolute estimates of e.g., tree and grass encroachment, and perhaps more importantly, how these evolve over time. In this context, remote sensing offers the advantage over field work in providing an objective, repeatable method of obtaining estimates, which will ultimately lead to more reliable monitoring of trends over time.

The three-step approach might have additional advantages towards transferability and implementation in other similar habitat areas. While the method has been demonstrated in this study for a number of heathland habitats, other habitat types exist for which similar composition and several quality-indicators could potentially be mapped using the proposed method (e.g., coastal dune habitats). This would at least require an adaptation and re-tuning of the LVT classification and habitat re-classification schemes, but without altering the overall strategy. The method is however not deemed appropriate for habitat types for which the identification or quality depend on the presence of key species in low numbers (e.g., certain grassland habitat types), or structural layers that are not visible from above (e.g., certain forest habitat types). As such, this method contributes to the toolset useful for N2000 habitat mapping using remote sensing, but does not claim to be a one-size-fits-all solution for all N2000 habitat types.

We used IS data with a spatial resolution of about 2.4 m and 63 spectral wavelength bands in the visual and near-infrared spectral domain (400 to 2500 nm) to achieve the necessary thematic detail in the LVT classifications. Such spectrally detailed image data is however not always available, but this does not necessarily mean the method cannot be applied using different image sources (e.g., multispectral data). As the IS data contains sufficient spectral detail to discern the necessary thematic detail, we relied solely on spectral features (i.e., the information in the different wavelength bands), in combination with the hierarchy of the classes, to perform the LVT classifications that result in the first maps that are the basis of the rest of the habitat mapping method. Although sufficient spatial detail, i.e., a spatial resolution roughly <3 m, might be a prerequisite to be able to map the habitat types and conservation status indicators at a similar spatial detail with the method proposed in this study, the necessary thematic detail might be achieved with imagery that has less spectral information by using different information present in these images. One possible approach is to take advantage of multi-temporal or phenological information. Highly accurate tree species classifications have, for example, been achieved in savannah habitats using multi-temporal WorldView-2 imagery (spatial resolution ~= 2m in multispectral mode) [59]. Another approach is to take into account spatial information for the classification, e.g., using object-based analysis (e.g., [60]). As such, we believe the method also has potential to be used with image sources other than IS, given the LVT classifications are properly adjusted to the available image source. Additionally, using a hierarchical approach for the LVT classification also provides opportunities to develop dedicated class splitting methods at each node. In this paper, we actually already do so by using different spectral features for every split, but a variety of approaches could be taken to achieve similar or better results. We have for example shown that discerning the different heather age structures (i.e., the split from Hdc at Level 3 to Hdca, Hdco, Hdcy, and Hdcm at Level 4) could be improved by combining spectral unmixing with a decision tree classifier [26].

The IS data for this study were acquired in the summer of 2007, while the habitat conservation status indicator validation data were acquired in the summer of 2009. As natural changes in heathland habitats are a rather slow process (except for fires), we do not expect the two-year time gap between the 2007 image acquisition and the 2009 conservation status validation dataset to have caused large inaccuracies due to changes in the conservation status indicators during this period. This means that, although field data acquired at comparable times of the image acquisition are preferable, some flexibility is present in the acquisition of field data for similar, naturally slowly changing habitats.

In this study, we used an extensive LVT reference dataset of 1325 plots. However, such a number is often not achievable, especially when considering the routine application of the method. Further research could consider several options to lower the method's dependency on ground reference data, such as the use of spectral libraries [29,61], classifiers that are robust in dealing with small sample sizes [14], or techniques like active learning and domain adaptation [62].

5. Conclusions

Direct heathland habitat mapping using remote sensing is hampered by the high intra-variability of habitat patches, as well as the low inter-variability between different habitat types. This study illustrates a method, using high spatial resolution imaging spectroscopy (IS) data, that actually exploits these inherent characteristics, not only to obtain a habitat distribution map, but also to assess the habitat quality through indicators that monitoring experts are accustomed to. We showed that a land and vegetation type (LVT) classification map, which is typically achievable using IS, can be used to delineate habitat patches, as well as determine the NATURA 2000 (N2000) habitat type. As we were able to achieve high thematic detail in the LVT maps, we were also able to illustrate that the derived habitat patch maps can then again be combined with the LVT maps to derive typical N2000 habitat conservation status indicators. As such, we use IS and field data in combination with knowledge-based rules to produce the full set of information that is necessary to report on a N2000 area under the Habitats Directive.

Given that our method does not require any additional input data (except for knowledge-based rule sets), once LVT maps are achieved with sufficient thematic detail, it has the potential to also be applied successfully using other image sources than IS. If the prerequisite of LVT maps with sufficient thematic and spatial detail can be achieved using other image sources, the method has the potential to be applied more frequently in both time and space for heathland habitats. Applying the method to other similar habitat types, such as coastal dune regions, should in principle also be possible, but will require adaptations and fine-tuning of the knowledge based rule sets.

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