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The Habitat Map of Switzerland: A Remote Sensing, Composite Approach for a High Spatial and Thematic Resolution Product

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Abstract: Habitat maps at high thematic and spatial resolution and broad extents are fundamental tools for biodiversity conservation, the planning of ecological networks and the management of ecosystem services. To derive a habitat map for Switzerland, we used a composite methodology bringing together the best available spatial data and distribution models. The approach relies on the segmentation and classification of high spatial resolution (1 m) aerial imagery. Land cover data, as well as habitat and species distribution models built on Earth observation data from Sentinel 1 and 2, Landsat, Planetscope and LiDAR, inform the rule-based classification to habitats defined by the hierarchical Swiss Habitat Typology (TypoCH). A total of 84 habitats in 32 groups and 9 overarching classes are mapped in a spatially explicit manner across Switzerland. Validation and plausibility analysis with four independent datasets show that the mapping is broadly plausible, with good accuracy for most habitats, although with lower performance for fine-scale and linear habitats, habitats with restricted geographical distributions and those predominantly characterised by understorey species, especially forest habitats. The resulting map is a vector dataset available for interactive viewing and download from open EnviDat data sharing platform. The methodology is semi-automated to allow for updates over time.

Keywords: habitats; vegetation communities; modelling; national; segmentation; classification; forests; grasslands; wetlands; cropland

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1. Introduction

The characterisation of habitats is important for biodiversity conservation and management, since organisms are adapted to specific site conditions [1]. The classification of environments into defined habitats provides a reference system for data collected in the field and facilitates cross-comparisons between surveys. Moreover, maps differentiating habitat types are a fundamental tool in analyses of ecological networks, planning for ecological connectivity, conservation planning and the management of ecosystem services [2,3]. In this context, it is important that habitat maps are available at high spatial and thematic resolution and broad extents [4].

Nationwide or continental land use land cover (LULC) inventories and/or mapping are available for many countries, including Switzerland—for example, the Swiss land use statistics [5] or CORINE land cover [6]. However, the mapping of vegetation communities, biotopes or habitats has a different focus and serves a different purpose. The European Environment Agency [7] defines habitats as "a place where plants or animals normally live, characterised primarily by its physical features (topography, plant or animal physiognomy, soil characteristics, climate, water quality etc.) and secondarily by the species of plants and animals that live there". While land cover maps distinguish the physical cover of the land, such as buildings, water bodies, grasslands, broadleaf and coniferous forests, habitat typologies and maps attempt to discriminate phytosociological units or vegetation communities.

Remote sensing data have long been essential for modern LULC mapping purposes at extents from national [8,9] to continental [6] and global scales [10,11]. Rapid developments in remote

sensing data and processing technology have resulted in the availability of data of increasingly high spatial, temporal and spectral resolution, which offers new opportunities to differentiate habitat types beyond land cover classes at fine spatial and thematic resolutions [12,13]. Indeed, while there are limited examples of high resolution nationwide habitat mapping, existing products often use machine learning approaches to classify either high/moderate spatial resolution or high temporal resolution remote sensing data into habitat types. For example, Sentinel 1 and/or 2 imagery was applied for the Living England habitat map [14] and Scotland's high resolution habitat map [15], while a combination of SPOT, Indian Remote Sensing, Landsat-5, RapidEye and Disaster Monitoring Constellation satellite images as well as aerial photography was used for county-wide habitat mapping in Norfolk, UK [16]. Natura 2000 habitat types were mapped nationwide for Germany with MODIS imagery [17], and WorldView2/3 imagery was used to develop the Hong Kong habitat map [18]. In contrast, distribution modelling approaches based on topographical, climate, geological and land use predictors rather than remote sensing information have been successfully applied in Norway and Britain [19,20]. These maps differentiate a limited number of habitat types/classes, e.g., 17 classes for England [14], 18 for Germany [17], 31 for Norway [19] and 21 for Hong Kong [18], and either have higher uncertainty/less detail around areas with finely resolved habitat mosaics (i.e., in urban areas, [14]) or incorporate higher resolution ancillary data in a composite approach [18].

In Switzerland, the most commonly used habitat classification is the hierarchical Swiss Habitat Typology (also known as TypoCH), where the first level of the hierarchy (habitat classes) is differentiated largely based on physical features, and the second (habitat groups) and third/fourth (habitat types) levels are defined by phytosociology and the presence of character and other indicator species [21]. Although the TypoCH typology is specific to Switzerland, it is translated into the pan-European classification system EUNIS [21]. While habitat mapping according to TypoCH exists for regional areas (e.g., for the Canton of Geneva [22]), a spatially explicit distribution map of habitats across Switzerland had not been developed before now. In the most recent OECD environmental performance review for Switzerland [23], the development of a national habitat map is proposed as one of the necessary next steps to achieve biodiversity management goals. Mapping ecosystems and their services, including the distribution of habitats, is also a priority of the EU Biodiversity strategy [24].

In this context, this work aims to develop the first national map of the current distribution of TypoCH habitat types, in a spatially explicit manner, across Switzerland. We aimed to map to at least the second (habitat group) and, where possible, the third level (habitat types) of the hierarchy, and finally mapped 84 individual habitats. Similar to the approaches of [14,16], we use an image segmentation and object classification approach. To achieve high thematic resolution, we use a composite approach where the best available nationwide data are incorporated (i.e., datasets including species and habitat distribution models derived from Earth observation data).

2. Materials and Methods

2.1. Habitat Typology

The Swiss habitat typology (TypoCH) is widely used to define habitat types within Switzerland and is the basis for the national Red List of Habitats [25]. The typology is hierarchical, defining first 9 habitat classes (1st level), largely corresponding to land cover types. These classes are 1, Non-marine water bodies; 2, Banks, shores and wetlands; 3, Glaciers, rocks, screes and gravel; 4, Grasslands; 5, Woodland edges, tall herb communities, shrubs; 6, Forests; 7, Pioneer vegetation of disturbed areas (ruderal vegetation); 8, Plantations and cropland; 9, Built habitats. These habitat classes are subdivided into 39 habitat groups (2nd level) and then further partitioned into habitat types (3rd and 4th levels). The habitat types are defined by character and other indicator species and typically correspond to phytosociological alliances.

2.2. Overview Methodology

The overall approach to developing the Habitat Map of Switzerland is image object segmentation and classification in the software eCognition Developer v10.1, Trimble Germany GmbH: Munich, Germany (Figure 1). The base data are 1-m resolution airborne ortho-imagery (R,G,B and near-infrared (NIR) bands) from the years 2017–2019, which is segmented into image objects. Habitat types are assigned to the segments in a rule-based approach informed by the best available spatial data per habitat type, including habitat and species distribution models, the vegetation height model (VHM) and land cover data from the open access 2020 topographic landscape model (TLM) [26]. All input data and models have high spatial resolution (1–25 m) and assigning habitats to segments rather than pixels minimises any potential issues associated with resolution disparities. To avoid heterogeneity in input quality, only datasets and outputs from habitat and species distribution models that are available Swiss-wide are used. Once each image segment has been assigned a habitat type (or group in some cases), segments are dissolved according to habitat type. Then, the segments are exported in vector format to ArcGIS for smoothing and cleaning. Finally, the dataset is overlaid with fine-scale features from the 2020 TLM, e.g., roads, buildings, railways.

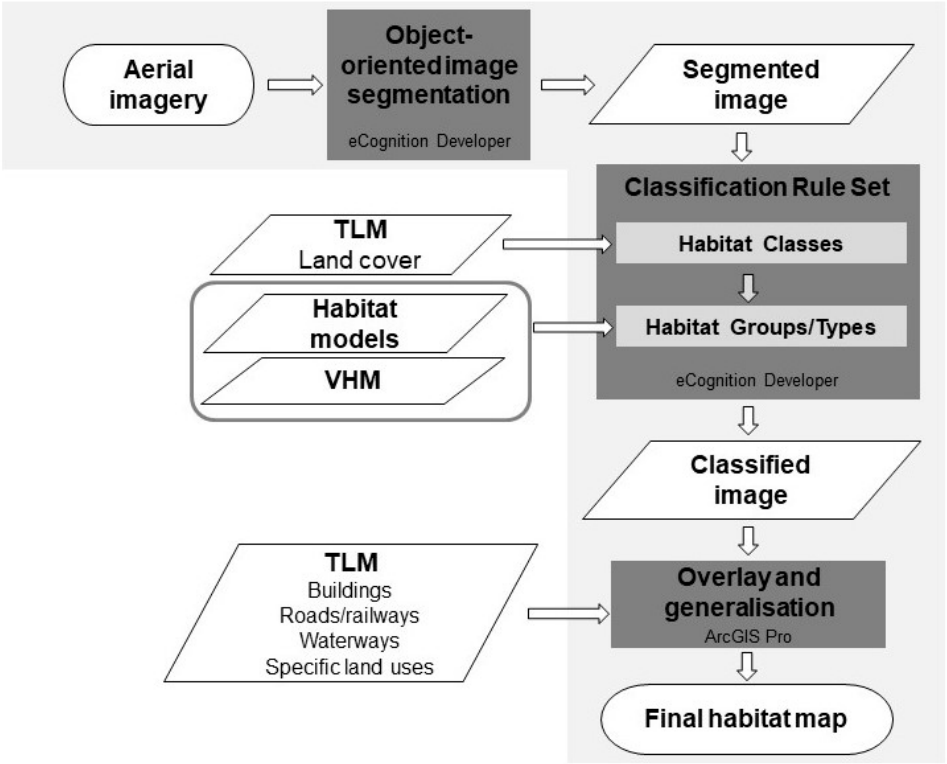


Figure 1. Workflow for the development of the Habitat Map of Switzerland. Aerial imagery is segmented within the eCognition Developer software, and image segments are classified into habitat types informed by habitat and species distribution models, the vegetation height model (VHM) and topographic landscape model (TLM) land cover data. The classified images are exported in vector format and overlaid with small-scale features from the TLM, generalised and merged in ArcGIS to form the final habitat map.

2.3. Imagery

Stereo imagery is captured with the Leica Geosystems (Heerbrugg, Switzerland) ADS100 sensor (Pushbroom scanning) across Switzerland by swisstopo on a systematic ongoing cycle (3 yearly updates, 6 yearly leaf-on) [27]. The 2017–2020 imagery used here has spectral bands R,G,B and near-infrared and was resampled to 1 m resolution. It is also the base data for the derivation of the photogrammetric 1 m Swiss VHM [28].

2.4. Habitat Distribution Data

The distribution of each habitat type was defined based on the best available data per habitat group, with four source types: (1) the TLM Landcover; (2) habitat distribution models specifically targeting TypoCH habitat types; (3) a combination of existing species distribution models; (4) classification by rule set. The data source type used for each habitat group is given in Table 1.

Table 1. TypoCH habitat groups at the second level and the method used to determine their distribution. Method types are (1) the TLM Landcover; (2) habitat distribution models targeting specifically TypoCH habitat types; (3) combination of existing species distribution models; and (4) classification by rule set. Habitats highlighted in light grey were modelled to the 3rd level with the same methodology as indicated in the column 'Source (Method)'. Habitats in italics and with a '9' indicated in the Methods column were not modelled in version 1 of the habitat map. The source for validation data is indicated in the final column as detailed in the original publications [29–32]: the Swiss land use statistics (SLUS) [5], Delarze distribution maps [21], manual aerial image interpretation (AII), SwissFungi field observation (SF) [33] or not validated due to lack of data (NV).

TypoCH	Class	Group	TypoCH Name	Source (Method)	Validation Source
1	1	-	Non-marine water bodies	1	SLUS
1.1	1	11	Standing fresh water	1	SLUS
1.2	1	12	Running water	1	SLUS
1.3	*1*	*13*	*Springs*	*9*	*NA*
1.4	*1*	*14*	*Underground waters*	*9*	*NA*
2	2	-	Banks, shores and wetlands	1	[21,29]
2.0	*2*	*20*	*Artificial banks*	*1*	*NA*
2.1	2	21	Bank and shore vegetation	1	[21,29]
2.2	2	22	Fens and transition mires	2	[21,29]
2.3	2	23	Wet meadows	2	[21,29]
2.4	2	24	Raised bogs	2	[21,29]
2.5	*2*	*25*	*Temporarily flooded annual vegetation*	*9*	*NA*
3	3	-	Glaciers, rocks, screes and gravel	1	SLUS
3.1	3	31	Glaciers, permanent ice and snow	1	SLUS
3.2	3	32	Alluvial deposits and moraines	1	SLUS, AII
3.3	3	33	Screes	1	SLUS, AII
3.4	3	34	Cliffs and exposed rocks	1	SLUS, AII
3.5	*3*	*35*	*Caves*	*9*	*NA*
4	4	4	Grasslands	2	[21,29]
4.0	4	40	Re-seeded and heavily fertilised grasslands (re-seeded grasslands)	2	[21,29]
4.1	4	41	Pioneer vegetation on rocky surfaces	4	SLUS, [21]
4.2	4	42	Dry grasslands	2	[21,29]
4.3	4	43	Nutrient-poor alpine and subalpine grasslands (alpine/subalpine grasslands)	2	[21,29]
4.4	4	44	Snowbed communities	2	NV
4.5	4	45	Nutrient-rich pastures and meadows	2	[21,29]
4.6	*4*	*46*	*Fallow grasslands*	*9*	*NA*
5	5	-	Woodland edges, tall herb communities, shrubs	1	[21,30], AII
5.1	*5*	*51*	*Herbaceous fringes*	*9*	*NA*
5.2	5	52	Forest clearings	4	AII
5.3	5	53	Shrubs, bushes, hedges	1	[21,30], AII
5.4	5	54	Dry dwarf shrub heaths	2	[30], AII

Table 1. *Cont.*

TypoCH	Class	Group	TypoCH Name	Source (Method)	Validation Source
6	6	-	Forests	1	[21,31,33]
6.0	6	60	Plantations and trees outside forest	4	[21,31,33]
6.1	6	61	Swamp forests	3	[21,31,33]
6.2	6	62	Beech forests	3	[21,31,33]
6.3	6	63	Other deciduous forests	3	[21,31,33]
6.4	6	64	Thermophilic pine forests	3	[21,31,33]
6.5	6	65	Bog forests	3	[21,31,33]
6.6	6	66	High-altitude coniferous forests	3	[21,31,33]
7	7	-	Pioneer vegetation of disturbed areas (ruderal vegetation)	4	NV
7.1	7	71	Trampled and ruderal areas	4	NV
7.2	*7*	*72*	*Anthropogenic rocky habitats*	*9*	*NA*
8	8	-	Plantations and cropland	2	[32], SLUS
8.1	8	81	Tree nurseries, orchards, vineyards	1	[32], SLUS
8.2	8	82	Cropland	2	[21,32], SLUS
9	9	-	Built habitats	1	SLUS
9.1	*9*	*91*	*Dumps*	*9*	*NA*
9.2	9	92	Buildings	1	SLUS
9.3	9	93	Transport routes	1	SLUS
9.4	9	94	Sealed sports grounds, car parks, etc.	1	SLUS

2.4.1. Swisstopo TLM

The topographic landscape model (TLM) of Switzerland is an open access detailed vector dataset that provides information on land cover at high spatial resolution interpreted from aerial imagery by swisstopo [26]. The TLM is subset into different sub-datasets, of which the following have been incorporated into the Habitat Map of Switzerland: linear features of roads and paths, public transport and hydrography; and spatially explicit features of buildings, land cover and 'area', which includes specific-use sites in the categories of transport, recreation and commercial activity. The 2020 TLM Landcover dataset is used to identify certain habitat classes and groups (see Tables 1–3) and as an initial classification into broad habitat classes before further classification into habitat types. TLM Landcover identifies the following classes: rock surfaces, loose rock surfaces, boulders, running water, shrub forest, gravel, loose gravel, glaciers, standing water, wetlands, forests, open forest, other wooded areas and snow fields [26]. Grassland and agricultural land cover are not defined within the TLM and instead fall into the remaining 'open spaces'. Linear features were buffered by a distance of half the width of the feature, which is given in the metadata of the TLM dataset. No width is defined for hydrological linear features, which are buffered by a constant 1 m. TLM area features are directly incorporated into the habitat map. The TypoCH habitat types assigned to each of the TLM linear and area features given in Table 2.

2.4.2. Habitat Distribution Models

Habitat distribution modelling approaches were used to identify habitat types within the classes 2, Banks, shores and wetlands, 4, Grasslands, 5, Woodland edges, tall herb communities, shrubs and 8, Permanent crops.

Before modelling grassland and wetland habitat types, a random forest modelling approach was used to differentiate cropland (TypoCH group 8.2) from permanent grassland [29]. Areas of known non-crop or grassland (e.g., forest, settlements, glaciers) were excluded using the TLM landcover data and the VHM with height greater than 3 m. Multi-year (2017–2019) growing-season spectral indices including normalised difference vegetation index (NDVI) derived from Sentinel 2 satellite imagery, as well as terrain indices, were used as predictors for this crop vs. permanent grassland model. Parcel-based training data were derived from landholder reporting. The mapping was conducted within the Google Earth Engine using a random forest classifier. The classifier was trained separately for lowland areas and the Alps. Further details are available in [32].

Table 2. TLM data included in the habitat map with source sub-dataset and translation to TypoCH. The dataset TLM Landcover (original name: BODENBEDECKUNG) is used in an initial coarse eCognition classification. Asterisked * classes are then further classified using the methodological approaches 2, 3 or 4 detailed in Table 1. All other TLM datasets indicated in the table are incorporated as an overlay, after eCognition processing, using the software ArcGIS Pro v2.7.1. The field object code (original name: OBJEKTART) shows the TLM object class from the original TLM sub-dataset [26]. NDVI is the normalised difference vegetation index calculated from the 1m aerial imagery.

TLM Dataset	Original Object Code	Description of TLM Class	TypoCH	TypoCH Name
TLM landcover	1 *	Rock surfaces	3.4	Cliffs and exposed rocks
TLM landcover	2 *	Loose rock	3.3	Screes
TLM landcover	3 *	Boulders	3.3	Screes
TLM landcover	4 *	Boulders, loose	3.3	Screes
TLM landcover	5	Running water	1.2	Running water
TLM landcover	6	Shrub forest	5.3	Shrubs, bushes, hedges
TLM landcover	7 *	Loose rock	3.3	Screes
TLM landcover	8 *	Loose rock, loose	3.3	Screes
TLM landcover	9	Glaciers	3.1	Glaciers, permanent ice and snow
TLM landcover	10	Standing water	1.1	Standing fresh water
TLM landcover	11 *	Wetlands	2	Wetlands
TLM landcover	12 *	Forest	6	Forests
TLM landcover	13 *	Open forest	6	Forests
TLM landcover	14 *	Wooded area with VHM > 3m, VHM < 3m	6.0.0, 5.3	Trees outside forest, shrubs, bushes, hedges
TLM roads and paths	all	with surface type ('Belagsart') = 100	9.3.2	Sealed roads
TLM roads and paths	all	with surface type ('Belagsart') = 200	9.3.3	Unsurfaced track, lane
TLM railways	all	Railways	9.3.4	Railway
TLM building footprints	all excluding 16	Buildings	9.2	Building
TLM sports facilities	0 (with mean NDVI < 0.1)	Sports field	9.4	Sealed sports ground, car park, etc.
TLM sports facilities	1 (with mean NDVI > 0.1)	Sports field	4.0.2	Artificial lawns; sport and urban areas
TLM dams and weirs	0	Dam wall	9	Built habitats
TLM dams and weirs	1	Dam	9	Built habitats
TLM dams and weirs	2	Water basins	1.1	Standing water
TLM dams and weirs	3	Weir	9	Built habitats
TLM transport facilities	2	Grass piste	4.0.2	Artificial lawns; sport and urban areas
TLM transport facilities	3	Hard surface piste	9.3.2	Sealed roads
TLM transport facilities	4	Platforms	9.3	Transport routes
TLM transport facilities	5	Tarmac grass	4.0.2	Artificial lawns; sport and urban areas
TLM transport facilities	6	Tarmac hard surface	9.3.2	Sealed roads
TLM transport facilities	7	Lock (canal)	1.2	Running water
TLM special use areas	3	Tree nursery	8.1	Tree nurseries, orchards, vineyards
TLM special use areas	9	Waste incineration area	9	Built habitats
TLM special use areas	15	Orchards	8.1	Tree nurseries, orchards, vineyards
TLM special use areas	17	Vineyards	8.1.6	Vineyards
TLM special use areas	18	Allotment gardens	8.2.3	Root crops, gardens
TLM special use areas	23	Substation area	9.2	Building
TLM special use areas	5	Public car park	9.4	Sealed sports ground, car park, etc.
TLM special use areas	All others not included			
TLM traffic areas	10	Private car park	9.4	Sealed sports ground, car park, etc.
TLM traffic areas	All others not included			
TLM recreation areas	Not included			

Table 3. Classification rules for habitats that are defined through a rule set.

TypoCH	Classification Rule
2.1 Banks and shore vegetation	TLM landcover running or standing water with mean NDVI (aerial imagery) > 0.1 and 95th percentile growing season NDVI (Sentinel 2) > 0.1
3.2.1 River gravel banks	TLM landcover loose rock surfaces, boulders, gravel or loose gravel bordering running water
3.2.2 Moraines	TLM landcover loose rock surfaces, boulders, gravel or loose gravel bordering TLM landcover glaciers
4 Grassland	Non-classified areas (non-tree or shrub) within the settlement boundary: 95th percentile of growing season NDVI (Sentinel 2) > 0.3
4.1 Pioneer vegetation on rocky surfaces	TLM landcover rock surfaces with median growing season NDVI (Sentinel 2) > 0.2 and < 0.45
5.2 Forest clearings	TLM landcover forest or open forest with mean VHM 2012 > 3m and mean VHM 2019 < 3 m
5.3.0 Hedges and shrubs outside of shrub forest	No TLM landcover classification with median VHM 2019 > 1.5m and median VHM2019 < 3 m, and mean NDVI (aerial imagery) > 0.2 TLM landcover other wooded areas with mean VHM < 3m
6.0.0 Trees outside forest	No TLM landcover classification with median VHM 2019 > 3 m and mean NDVI (aerial imagery) > 0.2
7.1 Trampled and ruderal areas	Within the settlement boundary: 95th percentile of growing season NDVI (Sentinel 2) < 0.3 Outside the settlement boundary: No classification with median growing season NDVI (Sentinel 2) < 0.2

An ensemble modelling approach [34] combining random forest, boosted regression trees, generalised linear models and general additive models was used to model the distribution of wetland and grassland habitat types within the remaining grassland area (with crop land excluded) to the level of the habitat type (3rd level), and for Dwarf shrub types 5.4.3 (Alpine hairy alpenrose—*Erica* heaths), 5.4.4 Mountain *Juniperus nana* scrub) and 5.4.5 (Alpine rusty alpenrose heaths). Training data samples were compiled from various data sources: for grassland and wetland types, predominantly from Swiss-wide monitoring programs; for dwarf shrubs, from aerial image interpretation. Sentinel 1 backscatter products, various Sentinel 2 growing season indices and image texture as grey-level co-occurrence matrix indices from 2017–2020 imagery, as well as variables describing climate, soil properties and topography, were used as predictors. The maps of the individual grassland and wetland habitat types (except for group 4.4, Snowbed communities) were combined into an overall map differentiating 20 habitat types at a 10 × 10 m resolution using a weighted maximum probability approach. In addition, a probability map was created indicating the weighted median of the predicted probability of occurrence of the most likely grassland or wetland type. Full details can be found in [29].

To avoid an over-estimation of the distribution of snowbed communities (TypoCH group 4.4), the ensemble distribution map for snowbed communities was restricted to areas characterised as featuring long (but not permanent) snow cover. This long snow cover was identified using monthly base maps from cloud-free composites of 3 m spatial resolution PlanetScope data from June 2020 and July 2020. For the extraction of snow, the blue band with a fixed threshold was used. Areas featuring snow cover in June but no snow cover in July and located within the predicted distribution area resulting from the ensemble modelling were considered snowbed communities.

2.4.3. Species Distribution Models

The potential distributions of the 70 most common tree species of Switzerland have been modelled at 25 m resolution within Swiss forest areas by [31] in an ensemble modelling approach (MoGLI project: modelling woody species within the National Forest Inventory (NFI)). The models rely on NFI data from 2009–2017, and use climate, topography and NDVI metrics from the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS)

1985–2015 [35] and forest structure from LiDAR from 2000–2007 as spatial predictors. The resulting distribution maps for each species give a likelihood of occurrence in 3 classes (likely, unsure, unlikely), where the class 'likely' shows where at least 4 (of 5) models from the modelling ensemble predict the occurrence of the species.

For each of the TypoCH forest habitat types at the third level, we identified the character and other indicator species for which a MoGLI model was available. We then combined the relevant distribution models for each habitat type, using only the areas predicted to be 'likely'. The areas where the likely distribution models of all available character and other indicator species intersected one another (see Table S1 for details) defined the distribution of the forest habitat type. One distribution map per forest habitat type at 25 m resolution resulted. In cases where it was not possible to distinguish habitat types through the available species distribution models, we mapped only the forest habitat group.

The distribution models of Rüetschi et al. [30] (10 m resolution) were used to determine the distributions of green alder shrub forest (*Alnus viridis*, TypoCH 5.3.9) and mountain pine shrubs (*Pinus mugo* ssp. *mugo*, TypoCH 5.4). They combined random forest modelling and an active learning approach with training data derived from NFI plot and image interpretation training data, and predictors from the VHM, Sentinel 1 and 2 satellite imagery and topographic data from the 2 m digital terrain model [26], all dating from 2017 to 2019. Full methodological details can be found in [30].

2.4.4. Classification Rules

The habitat types 2.1, Banks and shore vegetation; 3.2.1, River gravel banks; 3.2.2, Moraines; 4.1, Pioneer vegetation of rocky surfaces; 5.2, Forest clearings; 5.3.0, Hedges and shrubs outside of shrub forest; 6.0.0, Trees outside forest; and 7.1, Trampled and ruderal areas are defined using a rule-based approach based on auxiliary datasets but no specific modelling. The classification rules and threshold values for auxiliary datasets were defined in an iterative tuning approach involving the visual inspection of classified aerial imagery in different regions and appropriate adjustment of the thresholds. In addition, we did not apply the wetland and grassland models in urban areas due to very fine-scale habitat mosaics and buildings or infrastructure causing mixed Sentinel 2 pixels. Instead, simple classification rules were applied for grasslands within settlement boundaries, defined with the TLM settlement boundary data for areas with a population greater than 700. The auxiliary datasets are the SwissAlti3D 25m digital terrain model [36], VHMs of 2012 and 2019 [28] and mean and median growing season (March–November) NDVI derived from 4 years (2017–2020) of Sentinel 2 imagery. The classification rules are summarised in Table 3 for the relevant habitat groups and types.

2.5. Image Segmentation

Image segmentation was performed using the multiresolution segmentation within eCognition Developer v10.1. The segmentation relied on the 1 m VHM, all 4 bands of the 1 m aerial ortho-imagery, as well as derived indices NDVI ((NIR − Red)/(NIR + Red)) and Normalised Difference Water Index NDWI ((Green − NIR)/(Green + NIR)), and the coarse TLM landcover information. In an iterative tuning approach, the following weights were given to each image band to emphasise segment differentiation by vegetation greenness and height: R = 5; G = 4; B = 3; NIR = 5; NDVI = 12; NDWI = 2; VHM = 10. The scale parameter was set to 50, shape to 0.8 and compactness to 0.2. The area of Switzerland was split into 260 image tiles, each covering the same area as one 1:25,000 mapsheet for the purpose of image segmentation and classification.

2.6. Classification Process

A set of additional raster layers also inform the segment classification: crop, grassland, shrub and forest distribution models and associated probability and cover maps (described further in Section 2.7); the SwissAlti3D digital terrain model and derived slope [37]; median

and 95th percentile of growing season (April–October) NDVI from Sentinel 2 imagery; 2012 VHM and the boundary for TLM settlement areas with a population greater than 700.

Initial classification (also within eCognition Developer v10.1) is to broad land cover classes using TLM landcover, largely corresponding to the TypoCH habitat classes (1st level of the hierarchy); see Table 1 and Section 2.4.1. Each habitat class is then further classified into habitat groups (2nd level) or types (3rd or 4th level). The habitat groups and types sourced from the TLM landcover data are assigned directly to TypoCH habitats (Table 1).

Cropland, grassland and wetland habitats are assigned using the corresponding habitat distribution maps in areas not already assigned to a broad habitat class. In addition, wetland habitat types (TypoCH class 2) can also be assigned to TLM landcover wetland areas. Shrubland types can be assigned to any segment within the modelled shrubland distribution regardless of TLM landcover type.

Each image segment is assigned the habitat type that, according to the distribution model rasters, has the majority cover by area of that segment. Cropland (TypoCH 8.2) and shrubland types (TypoCH 5.3.9, 5.4) are assigned first, followed by the wetland and grassland type assignment (TypoCH classes 2 and 4).

Forest types are classified in the same majority cover manner within the areas that have been identified from TLM landcover data as forest (forests, open forest and other wooded areas with vegetation height greater than 3 m). Swamp forest (TypoCH group 6.1) can also be assigned within TLM wetland areas. In segments with forest cover according to TLM landcover, but for which we do not have sufficient information from the MoGLI species distribution maps to determine a forest habitat type or group, the habitat class '6, Forest' is assigned.

All other habitat types are assigned according to a rule-based allocation as described in Table 3.

A number of habitat types were not included in the habitat map due to limited data availability, the inability to detect these habitats adequately with remote sensing data or the dynamic nature of the habitat type. These were habitats of groups 1.3, Springs; 1.4, Underground water; 2.0, Artificial banks; 3.5, Caves; 7.2, Anthropogenic rocky habitats; 9.1, Dumps; 4.6, Fallow grasslands; and 5.1, Herbaceous fringes.

2.7. Probability and Percentage Cover

The probability of occurrence and percentage cover of an image segment were calculated for habitat types defined by methods 2 and 3 (Table 1). For habitat types determined by the swisstopo TLM dataset (method 1) or rule set classification (method 4), we did not calculate a probability or cover variable. TLM probability of occurrence is unknown but generally assumed to be high, and we do not have adequate validation data to determine the probability of occurrence of the habitat types identified with the rule set (Table 3). The cover variable is not relevant in these cases and can be implicitly inferred to be 100%.

For cropland (group 8.2), wetland and grassland (classes 2 and 4) and shrubs (type 5.3.9 and group 5.4), a probability of occurrence was derived from the outputs of the associated random forest or ensemble models. In each case, a mean probability was calculated for each eCognition segment. These probabilities were reclassified to 3 classes so that probability 0–0.5 = 1, 0.5–0.75 = 2 and greater than 0.75 = 3.

For forest habitat types, a probability raster was derived where probability 3 (high likelihood) was assigned to pixels with the MoGLI distribution for all available character and other indicator species for the habitat type overlap. Probability class 2 was assigned to pixels that were inside the forest area, according to the NFI forest mask [38], but no habitat type could be determined based on the overlap of character and other indicator species. All other pixels were generally outside the forest mask and assigned to the low-probability class (1). Some segments partially outside or neighbouring the forest boundary can still be assigned a forest habitat type within the eCognition classification to overcome mismatches between the defined forest boundary and the VHM and to avoid unclassified areas at

forest edges. Probability for each segment was determined within eCognition by the most commonly occurring probability class (mode) within the segment.

The cover variable was calculated for the same habitat types as the probability variable. For each segment, the percentage area covered by the assigned habitat types was determined from the combined distribution raster map of the relevant habitat class, i.e., wetland (2) and grassland (4), shrub forest (5) and forest (6).

2.8. Vector Update and Cleaning

The raw (unsmoothed) vector segments, with assigned habitat type and the associated probability and cover values, are exported per mapsheet area from eCognition Developer for simplification, cleaning and updating with snowbed habitat areas and small-scale land use features from TLM (Table 2), in ArcGis Pro v2.7.1. In a first step, all polygons are smoothed using the smooth polygon tool with a 40 m PAEK tolerance setting and a shape file with the footprint area of all mapsheets acting as a barrier layer to avoid smoothing of mapsheet corners. Each mapsheet is then updated with the small-scale TLM (Table 2) and snowbed community features (Section 2.4.2) using the ArcGIS Analysis tool 'Update'. The update order was as follows: (1) TLM area data (where TLM transport, recreation and commercial activity areas are pre-merged to one feature dataset); (2) snowbed communities; (3) water courses (smaller linear river features not found in TLM landcover with a constant 1 m buffer); (4) transport routes; (5) buildings.

2.9. Validation

Thorough validation has been carried out for the mapping of grassland and wetland habitat types, shrub forest, forest species and cropland distribution models and is described in the original publications [29–32]. The grassland and wetland type mapping was compared with independent data using confusion matrices, resulting in geometric mean values (squared root of the product of the sensitivity and specificity [39]) of above 0.5 for most types, although the accuracies of several wet grassland types (TypoCH 2.2.1, 2.2.3, and 2.3.1), mountain and subalpine hay meadows and pastures (4.5.2, 4.5.4) and blue moorgrass slopes (4.3.1) were lower [29]. The accuracy of the models used to map green alder shrub forest (*Alnus viridis*, TypoCH 5.3.9) and mountain pine shrubs (*Pinus mugo* ssp. *mugo*, TypoCH 5.4) was measured with 50 cross-validation runs of the metrics F1 score and producer's and user's accuracy, the resulting values of which were almost always greater than 0.93 for all metrics and both shrub forest types [30]. The true skills statistic was used to assess the accuracy of each forest species ensemble model in a 70/30 training/testing data approach, with all species models used for our mapping having a TSS value greater than 0.5 [31]. The cropland model was compared in two strata with three independent datasets and resulting in overall map accuracies between 0.85 and 0.93 [32].

The nation-wide data and distribution models used to develop the Habitat Map of Switzerland are based on the available data from national monitoring and inventory programs. Many of the TypoCH habitat groups and types are defined by the species composition of their vegetation communities, thus requiring field identification and meaning that remote identification through, e.g., image interpretation, is unfeasible. Therefore, the availability of independent Swiss-wide data for the validation of the final mapping at the habitat type or group level is very limited. As such, further validation of the final habitat map was conducted through a multi-dataset approach, with different datasets being relevant for different habitat groups (Table 1). (1) At the Swiss-wide extent, plausibility for the habitat types mapped using species or habitat distribution modelling approaches was tested with comparison to maps of the estimated current distribution of each habitat from [21]. (2) Swiss-wide validation for habitat groups (and some types) that can be determined based on land cover, rather than vegetation community, was conducted with the independent Swiss land use statistics 2013/18 LULC data, which are derived from manual aerial image interpretation [5]. (3) In restricted sample areas, mapping for some habitats was validated with available detailed manual image interpretation data. (4) Forest habitat type mapping

was validated using citizen science reports of TypoCH habitat types for forests, recorded in the SwissFungi database.

2.9.1. Delarze et al. [21] Coarse Distribution Maps

Delarze et al. [21] constructed coarse maps to indicate both potential and current distributions of each habitat type based on recorded field observations of the character and other indicator species of each habitat type (henceforth referred to as 'Delarze maps'). These maps are not spatially explicit and instead determine the likelihood of occurrence of each habitat in each of 625 mapping units into which Switzerland is divided. These broad mapping units were defined based on geographical and topographical criteria [40]. To derive current distribution maps, field observation records are sourced from the literature more recent than 1980 and the databases of Info Flora, the National Data and Information Center on the Swiss Flora. Info Flora is the national platform for the collection of flora occurrence data and includes over 10,000,00 flora records [41]. For each map area, the sum of all records of the relevant character and other indicator species for a given habitat type was calculated. Character species are key species occurring almost exclusively in the respective habitat type, while other indicator species are indicative of the respective habitat type, sometimes dominant, but occurring in other habitat types as well [21]. Character species presences are weighted with the value 1.0 and other indicator species with 0.2. To better represent the current distribution of habitats, the regional conservation status according to the Red List of Species [42] is taken into account through an additional weighting process. Least concerned species were weighted by 1.0, near threatened by 0.95, vulnerable by 0.8, endangered by 0.3 and critically endangered by 0.1. Following the summing of all relevant species for a given habitat type, the resulting value of the most species-rich map area is designated the observed maximum and given a value of 1, and then the values of all mapping areas with character or other indicator species for that habitat type present are scaled between 0 and 1 [21].

This dataset was used to determine the plausibility of our habitat mapping for the habitat types that we mapped using species or habitat distribution modelling approaches: the groups 2, Banks, shores and wetlands; 4, Grasslands; 5, Woodland edges, tall herb communities, shrubs; and 6, Forests. Results for 54 habitat types in these classes were compared to the Delarze maps. The values for each mapping area were re-coded to likely presence or absence: values less than 0.2 likely absent, greater than or equal to 0.2 likely present. The presence or absence of each habitat in each map area according to our generated final habitat map was calculated, and a confusion matrix comparison for each habitat type conducted, calculating accuracy, sensitivity and specificity.

2.9.2. Swiss Land Use Statistics

The Swiss land use statistics dataset provides sample-based measures of LULC for over 4 million points on a regular 100 m grid across Switzerland [5]. LULC is determined through manual aerial image interpretation of high resolution aerial imagery (10–50 cm spatial resolution depending on year/region) for the point locations in one of 72 categories, in the broad classes of settlement areas, agricultural areas, wooded areas and unproductive areas. The most recently available data cover the period 2013–2018 [5]. These data are independent from the TLM and were used to determine the accuracy of our mapping of the habitats, where they can be defined on the basis of land cover rather than species distributions. This was largely relevant for habitats in the classes 1, Water bodies; 3, Glaciers, rocks, screes and gravel; 8, Plantations and cropland; and 9, Built habitats, but habitats in other classes were also assessed in coarse groupings. It was not possible to reclassify the Swiss land use statistics classes to TypoCH in a mutually exclusive manner, since the land use statistics categories are often relevant to a number of TypoCH habitats. Therefore, accuracy was not determined using a confusion matrix. Instead, the total number of points in each TypoCH habitat was determined, and then the proportion of those points with a matching land use statistics category calculated.

2.9.3. Aerial Image Interpretation

Manual stereo aerial image interpretation and mapping of the 0.10/0.25 m swisstopo ADS100 imagery [27] was previously conducted by a professional image interpreter across 17 of the 260 1:25,000 mapsheet areas of Switzerland and includes southern and northern alpine flanks, west and east central Alps, the Plateau and the Jura. The goal of this work was largely to differentiate the groups 5.2, Forest clearings; 5.3, Shrubs, bushes, hedges; and 5.4, Dry dwarf shrub heaths from each other and from 4, Grasslands, and 6, Forests. In addition, 3.2, Alluvial deposits and moraines, and 4.1, Pioneer vegetation on rocky surfaces, were identified. It was not possible to consistently differentiate wetland, grassland or forest types or groups (further than the habitat class) with image interpretation. Point-based sampling of the habitat map and the image interpretation mapping was conducted on the regular Swiss land use statistics 100 m grid across the extent of the 17 interpreted mapsheet areas. The results were then compared in a confusion matrix for the relevant habitats (Table 1) and the geometric mean (g-mean) values calculated [39].

2.9.4. SwissFungi

SwissFungi is the national data information centre for Swiss fungi, which, among other objectives, maintains a distribution atlas of field observations of fungi species sourced from citizen science [33]. The majority of these records are from forests and many include the TypoCH habitat recorded by the observer. After excluding records older than the year 2000 and those with a location precision worse than 25 m, 10,173 observations within the habitat map forested area remained for validation. There were insufficient data to validate to the level of habitat type, and instead the habitat group classification was validated, again using confusion matrices and g-mean.

3. Results

In total, we were able to map 84 habitat types or groups within the nine overarching classes (Table 4). Since the map is based on current Earth observation data, it represents the current distribution of the habitat types rather than a theoretical or potential distribution that might otherwise be obtained from climate- and topography-based distribution modelling. Figure 2 demonstrates the appearance and detail of the map in three different regions of Switzerland.

Table 4. TypoCH habitat types and groups mapped for the Habitat Map of Switzerland. The Latin name of the habitat type according to Delarze et al. [21] is given where appropriate. The 'Area' column shows the percentage of the entire area of Switzerland covered by each of the 9 habitat classes (highlighted in grey). In addition, for each type or group, the percentage cover of their respective class as well as their total area in hectares is given.

TypoCH	Name	Latin Name	Area	
1	**Non-marine water bodies total**			**4%**
1.1	**Standing fresh water**		**86% (143,621 ha)**	
1.2	**Running water**		**14% (22,580 ha)**	
2	**Banks, shores and wetlands total**			**1.5%**
2.1	**Bank and shore vegetation**		**7% (3100 ha)**	
2.1	Bank and shore vegetation		5% (2954 ha)	
2.1.2.2	Riverbank and terrestrial reeds	*Phalaridion arundinaceae*	2% (1046 ha)	
2.2	**Fens and transition mire**		**40% (25,239 ha)**	
2.2.1	Large sedge communities	*Magnocaricion elatae, Cladietum marisci*	3% (1567 ha)	
2.2.2	Acidic fens	*Caricion fuscae*	9% (5915 ha)	
2.2.3	Calcareous fens	*Caricion davallianae*	28% (17,757 ha)	

Table 4. *Cont.*

TypoCH	Name	Latin Name	Area	
2.3	**Wet meadows total**		**53% (32,574 ha)**	
2.3.1	Purple moorgrass meadows	*Molinion caerulea*	2% (1061 ha)	
2.3.2/3	Nutrient-rich humid meadows (marsh marigold meadow)	*Calthion palustris, Filipendulion ulmariae*	49% (30,526 ha)	
2.4	**Raised bogs total**		**2% (987 ha)**	
2.4.1	Bog hummocks, ridges and lawns	*Sphagnion magellanici*	2% (987 ha)	
3	**Glaciers, rocks, screes and gravel total**			**14%**
3	**Gravel** (not assigned to a group)		**1% (8460 ha)**	
3.1	**Glaciers, permanent ice and snow**		**16% (92,758 ha)**	
3.2	**Alluvial deposits and moraines**		**4% (24,672 ha)**	
3.2.1	River gravel banks		1% (8764 ha)	
3.2.2	Moraines		3% (15,908 ha)	
3.3	**Screes**		**45% (262,491 ha)**	
3.4	**Cliffs and exposed rocks**		**34% (196,354 ha)**	
4	**Grasslands total**			**32.5%**
4	Grasslands		8% (109,488 ha)	
4.0	**Re-seeded grasslands**		**2% (32,536 ha)**	
4.0	Re-seeded and heavily fertilised grasslands		2% (30,209 ha)	
4.0.2	Artificial lawns; sports, urban areas		<1% (2327 ha)	
4.1	**Pioneer vegetation on rocky surfaces**		**5% (66,667 ha)**	
4.2	**Thermophilic dry grasslands**		**4% (48,254 ha)**	
4.2.1	Subcontinental steppe grasslands	*Stipo-Poion carniolicae, Stipo-Poion xerophilae, Cirsio-Brachypodion*	<1% (4534 ha)	
4.2.2	Sub-Atlantic very dry calcareous grasslands	*Xerobromion*	<1% (38 ha)	
4.2.3	Insubrian *Mesobromion* grasslands	*Diplachnion serotinae*	<1% (1ha)	
4.2.4	Middle-European semi-dry calcareous grasslands	*Mesobromion*	3% (43,681 ha)	
4.3	**Unfertilised mountain grasslands and pastures**		**32% (429,334)**	
4.3.1	Blue moorgrass–evergreen sedge slopes	*Seslerion caeruleae*	4% (55,961 ha)	
4.3.2/4	Cushion sedge meadows	*Caricion firmae, Elynion myosuroides*	2% (24,286 ha)	
4.3.3	Northern rust sedge grasslands	*Caricion ferrugineae*	7% (90,336 ha)	
4.3.5	*Nardion* grassland	*Nardion strictae*	12% (161,354 ha)	
4.3.6	Subalpine thermophilic siliceous grasslands	*Festucion variae*	3% (38,270 ha)	
4.3.7	Crooked sedge swards	*Caricion curvulae*	4% (59,127 ha)	
4.4	**Snowbed communities**		**2% (28,133 ha)**	
4.5	**Fertilised grasslands**		**47% (630,712 ha)**	
4.5.1	Medio-European lowland hay meadows	*Arrhenatherion elatioris*	25% (336,271 ha)	
4.5.2	Mountain and subalpine hay meadows	*Polygono-Trisetion flavescentis*	3% (42,626 ha)	
4.5.3	Mesophile pastures	*Cynosurion cristate*	13% (175,973 ha)	
4.5.4	Rough hawkbit pastures	*Poion alpinae*	6% (75,842 ha)	
5	**Woodland edges, tall herbs communities, shrubs total**			**3%**
5.2	**Forest clearings**		**16% (18,511 ha)**	
5.3	**Shrubs, bushes, hedges**		**42% (49,814 ha)**	
5.3	Shrubs, bushes, hedges		9% (11,293 ha)	
5.3.0	Hedges and hedgerows		8% (9220 ha)	
5.3.9	Alpine green alder shrub heaths	*Alnenion viridis, Alnenion viridis*	25% (29,301 ha)	
5.4	**Dry dwarf shrub heaths**		**42% (50,554 ha)**	

Table 4. *Cont.*

TypoCH	Name	Latin Name	Area	
6	**Forests total**			**32%**
6	**Forests**		**1% (10,400 ha)**	
6.0	**Plantations and trees outside forest**		**4% (55,786 ha)**	
6.1	**Swamp forests total**		**<1% (5320 ha)**	
6.1	Swamp forests		<1% (1031 ha)	
6.1.1	Alder swamp forests	*Alnion glutinosae*	<1% (3409 ha)	
6.1.2	White willow gallery forests	*Salicion albae*	<1% (601 ha)	
6.1.3	Grey alder gallery forests	*Alnion incanae*	<1% (166 ha)	
6.1.4	Medio-European stream ash–alder woods	*Fraxinion excelsioris*	<1% (113 ha)	
6.2	**Beech forests total**		**51% (669,671 ha)**	
6.2	Beech forests		9% (115,447 ha)	
6.2.1	Beech forests with orchids	*Cephalanthero-Fagenion*	4% (51,940 ha)	
6.2.2	Woodrush beech forests	*Luzulo-Fagenion*	1% (14,055 ha)	
6.2.3	Neutrophilic beech forests	*Galio odorati-Fagenion*	14% (187,977 ha)	
6.2.4	Bittercress beech forests	*Lonicero alpigenae-Fagenion*	9% (116,126 ha)	
6.2.5	*Asperulo-Fagetum* beech forests	*Abieti-Fagonion*	14% (184,126 ha)	
6.3	**Other deciduous forests total**		**8% (103,968 ha)**	
6.3	Other deciduous forests		<1% (4940 ha)	
6.3.1	Ravine sycamore–maple forests	*Lunario-Acerion*	<1% (2744 ha)	
6.3.2	Thermophilic alpine and peri-alpine mixed lime forests	*Tilion platyphylli*	1% (8179 ha)	
6.3.3	Oak–hornbeam forests	*Carpinion betuli*	1% (11,448 ha)	
6.3.4	Downy oak forest	*Quercion pubescenti-petraeae*	1% (8504 ha)	
6.3.5	*Quercus pubescens* woods	*Orno-Ostryon*	<1% (1818 ha)	
6.3.6	Acidophilous oak forests	*Quericion robori-petraeae*	<1% (2424 ha)	
6.3.7	Insubrian acidophilous oak and chestnut forests	*Castaneo-Quercetum*	5% (59,991 ha)	
6.3.8	Deciduous forest with evergreen undergrowth		<1% (124 ha)	
6.3.9	Black locust plantations	*Balloto nigrae-Robinion*	<1% (3805 ha)	
6.4	**Thermophilic pine forests total**		**3% (24,545 ha)**	
6.4	Thermophilic pine forests		1% (6718 ha)	
6.4	Thermophilic pine forests		1% (6718 ha)	
6.4.1	Purple moor grass–Scots pine forests	*Molinio-Pinion*	<1% (156 ha)	
6.4.2	Spring heath–Scots pine forests	*Erico-Pinion sylvestris*	1% (14,642 ha)	
6.4.3	Inner-alpine restharrow steppe forests	*Ononido-Pinion*	<1% (3029 ha)	
6.5	**Bog forests total**		**<1% (3512 ha)**	
6.5	Bog forests		<1% (2278 ha)	
6.5.1	*Sphagnum* birch forests	*Betulion pubescentis*	<1% (196 ha)	
6.5.2	Mountain pine bog forests	*Ledo-Pinion*	<1% (1 ha)	
6.5.3	Peatmoss subalpine and *sphagnum* spruce forests	*Sphagno girgensohnii-Piceetum*	<1% (1037 ha)	
6.6	**High-altitude coniferous forests total**		**34% (441,186 ha)**	
6.6	High-altitude coniferous forests		6% (75,015 ha)	
6.6.1	Fir forests	*Abieti-Piceion*	3% (39,422 ha)	
6.6.2	Spruce forests	*Vaccinio-Piceion*	9% (122,679 ha)	
6.6.3	Larch–*cembran* pine forests	*Larici-Pinetum cembrae*	7% (91,571 ha)	
6.6.4	Limestone larch forests	*Junipero-Laricetum*	3% (34,852 ha)	
6.6.5	Mountain pine forests	*Erico-Pinion mugo*	6% (77,647 ha)	

Table 4. *Cont.*

TypoCH	Name	Latin Name	Area	
7	**Pioneer vegetation of disturbed areas (ruderal vegetation) total**			**1%**
7.1	**Trampled and ruderal areas**		**100% (38,920 ha)**	
8	**Plantations and cropland total**			**9%**
8.1	**Tree nurseries, orchards, vineyards total**		**6% (23,093 ha)**	
8.1	Tree nurseries, orchards, etc.		2% (8432 ha)	
8.1.6	Vineyards		4% (14,661 ha)	
8.2	**Cropland total**		**93% (345,849 ha)**	
8.2	Cropland		93% (344,601 ha)	
8.2.3	Gardens		<1% (1248 ha)	
9	**Built habitats total**			**3%**
9.2	**Buildings**		**40% (51,994 ha)**	
9.3	**Transport routes total**		**58% (74,824ha)**	
9.3	Transport routes		<1% (139 ha)	
9.3.2	Sealed roads		40% (51,994 ha)	
9.3.3	Unsurfaced roads, tracks, lanes		15% (19,149 ha)	
9.3.4	Railway		3% (3542 ha)	
9.4	**Sealed sports grounds, car parks, etc.**		**2% (2830 ha)**	

Validation

Comparison with the Delarze maps showed that if we consider the habitat map generated here to be 'predicted' and the Delarze maps to be 'observed' values, mapping accuracy was greater than or equal to 0.8 for 56% of the compared habitat types, greater than 0.75 for 78% of the compared habitat types and greater than 0.70 for 93% of the compared habitat types. Four forest habitat types had mapping accuracy values below 0.70, i.e., 0.68, 0.63, 0.61 and 0.49 for 6.3.1, Ravine sycamore–maple forests; 6.1.4, Middle-European stream ash–alder woods; 6.3.3, Oak–hornbeam forests; and 6.6.5, Mountain pine forests, respectively.

Figure 3 shows the sensitivity and specificity resulting from the comparison with the Delarze maps. Habitat types in the upper left corner have good results for both sensitivity and specificity and can thus be considered well predicted. In particular, 2.2.3, Calcareous fens and 6.6.5, Mountain pine forests appear to be overpredicted. Many forest types and two grasslands—4.2.2, Sub-Atlantic very dry calcareous grasslands, and 4.2.3, Insubrian *mesobromion* grasslands—are mapped as absent in several areas where the Delarze maps consider them present. Most of these low-specificity and high-sensitivity results are for habitats with very few presence observations (zero inflated).

Comparison to the Swiss land use statistics, Table 5 shows a very good match for the majority of these habitat types. Exceptions are 1.2, Running water; 3.4, Cliffs and exposed rocks; 5, Woodland edges, tall herb communities, shrubs; 6.0, Plantations and trees outside forest; and 9.3.3, Unsurfaced roads, tracks and lanes.

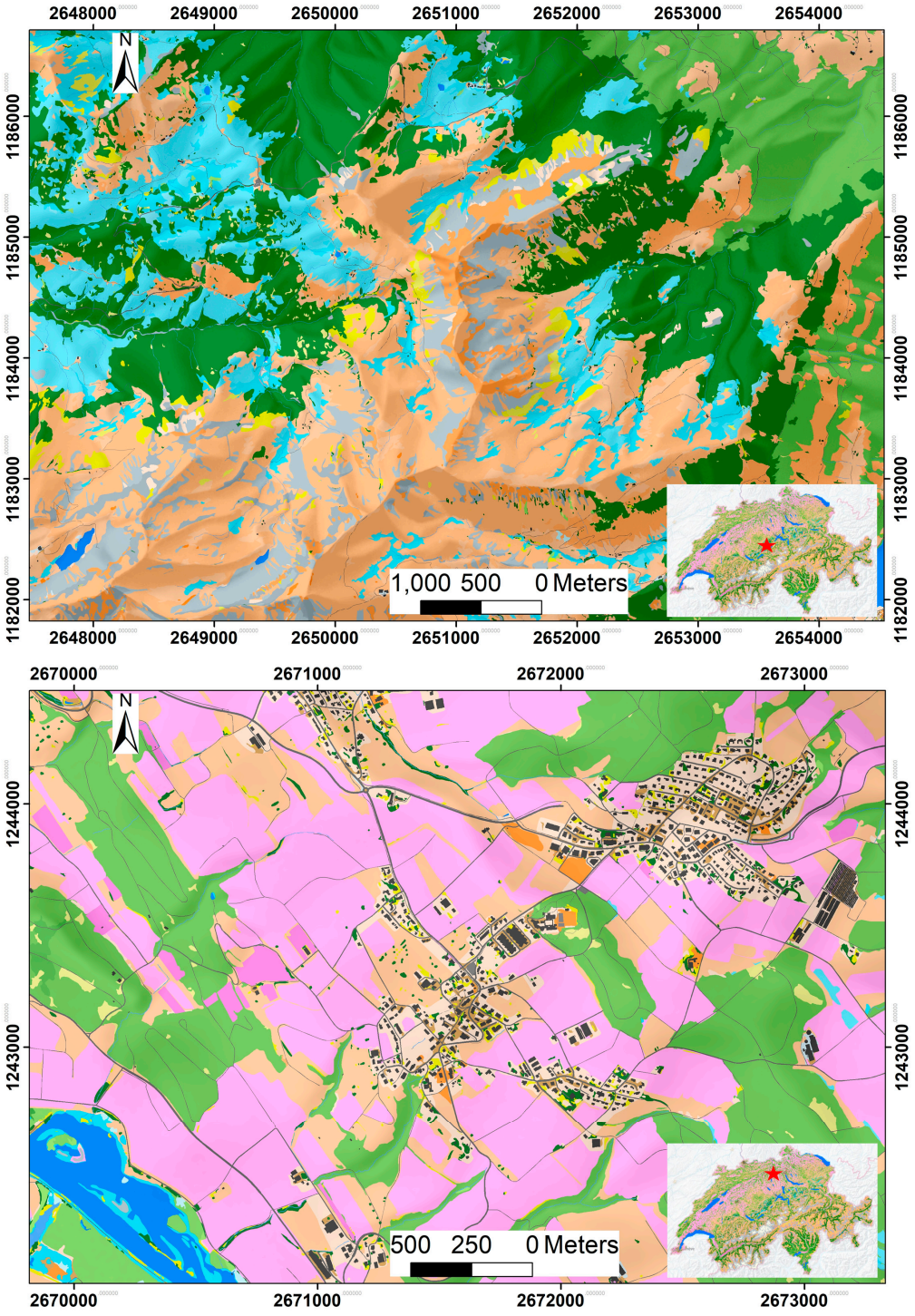


Figure 2. *Cont.*

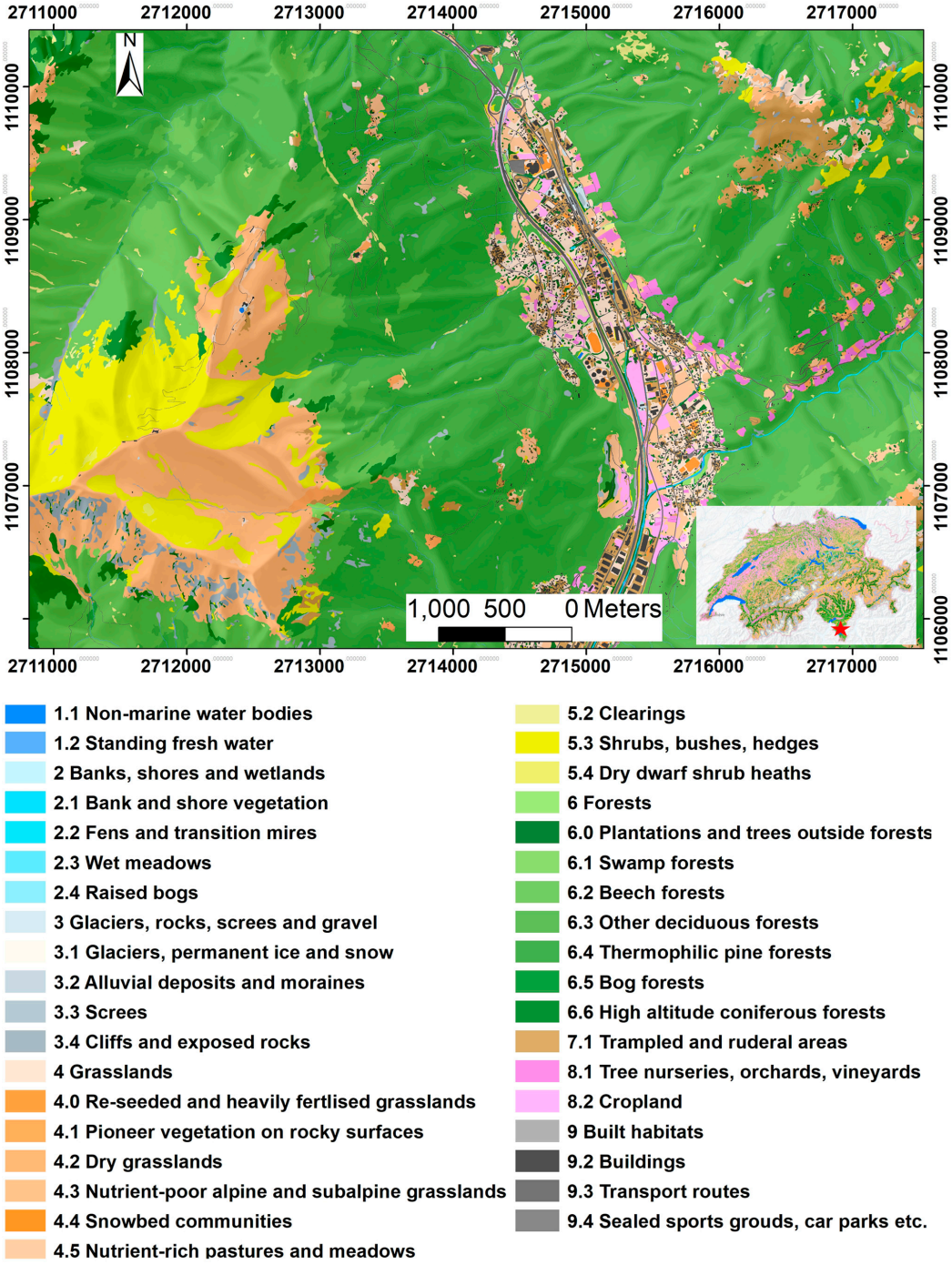


Figure 2. The Habitat Map of Switzerland in three regions of Switzerland, overlaid on the open access swissalti3D topographical relief map [37].

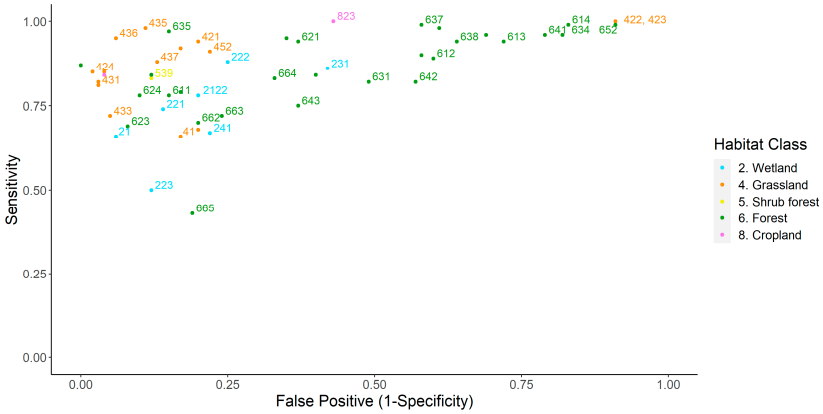


Figure 3. Specificity versus sensitivity resulting from the comparison between the habitat mapping ('predicted') and the Delarze maps ('observed'). The presences and absences according to the two mapping products were compared in 625 mapping areas for 54 wetland (blue), grassland (orange), shrub forest (yellow), forest (green) and cropland habitat types (purple).

Table 5. Comparison between the Habitat Map of Switzerland and the Swiss Land Use statistics for habitat types mapped according to land cover attributes. For each habitat type or group, the % of the total number of points (from the 100 m Swiss land use statistics grid) of that type/group where the mapped habitat type matches the Swiss land use statistics classification is given. The final column lists the Swiss land use statistics classes that are considered a match in definition to the habitat group or type.

TypoCH	Name	Percent Match	Swiss Land Use Statistics Classes
1	Non-marine water bodies		
1.1	Standing fresh water	0.99	Standing water (61)
1.2	Running water	0.72	Running water (62)
2	Banks, shores and wetlands		
2.1	Bank and shore vegetation	0.86	Standing water (61), Running water (62), Wetlands (67)
2.x	Wetlands	0.82	Meadows (42), Alpine meadows (45), Favourable alpine pastures (46), Wetlands (67)
3	Glaciers, rocks, screes and gravel		
3.1	Glaciers, permanent ice and snow	0.97	Glaciers and permanent snow (72)
3.2.1	River gravel banks	0.87	Running water (62), Gravel, sand (70)
3.2.2	Moraines	0.99	Rock surfaces (69), Scree, gravel, sand (70), Glaciers and permanent snow (72)
3.3	Screes	0.80	Rock surfaces (69), Scree, gravel, sand (70)
3.4	Cliffs and exposed rocks	0.79	Rock surfaces (69), Scree, gravel, sand (70)
4	Grasslands		
4.1	Pioneer vegetation on rocky surfaces	0.92	Unproductive grass and shrubs (65), Rocks (69)
4.x	All other grasslands	0.90	Building surrounds (2,4,6,8,10,12,14), Green road/airport environs (16, 18, 19, 23), Construction sites (29), Unexploited urban areas (30), Recreation areas (31–36), Arable land, pastures, meadows (41–49), Unproductive grass and shrubs (65)
5	Woodland edges, tall herb communities, shrubs		
5.2	Forest clearings	0.71	Felling areas (53), Damaged forest areas (54), Open forest (55, 56)
5.3, 5.4	Shrubs, bushes, hedges; Dry dwarf shrub heaths	0.77	Brush alpine pastures (47), Brush forest (57), Scrub vegetation (64), Unproductive grass and shrubs (65)

Table 5. *Cont.*

TypoCH	Name	Percent Match	Swiss Land Use Statistics classes
6	Forests		
6.0	Plantations and trees outside forest	0.66	Building surrounds (2,4,6,8,10,12,14), Green road environs (18), Recreation areas (31, 33, 34, 36), Field fruit trees (38), Woods (58–60)
6.x	All other forests	0.93	Wooded areas (50–60)
8	Plantations and cropland		
8.1	Tree nurseries, orchards, vineyards	0.92	Orchards (37), Fruit trees (38), Vineyards (39), Tree nurseries (40)
8.1.6	Vineyards	0.97	Vineyards (39)
8.2	Cropland	0.88	Cropland (41)
8.2.3	Gardens	0.95	Garden allotments (35)
9	Built habitats		
9.2	Buildings	0.85	Buildings (1,3,5,7,9,11,13)
9.3	Transport routes	0.97	Car parks (19), Railway areas (20)
9.3.2	Sealed roads	0.94	Building surrounds (2,4,6,8,10,12,14), Motorways (15), Roads and paths (17), Carparks (19), Airports (22)
9.3.3	Unsurfaced roads, tracks, lanes	0.63	Building surrounds (2,4,6,8,10,12,14), Roads and paths (17,18), Car parks (19, 31), Building sites (28,29),
9.3.4	Railway	0.93	Railway areas (20,21)
9.4	Sealed sports grounds, car parks, etc.	0.96	Building surrounds (2,4,8,10,12,14), Car parks (19, 31), Building sites (29,30), Sports grounds (32)

Comparison to the aerial image interpretation resulted in g-mean values of 0.6 or higher for the majority of the compared habitats, with the exception of 3.2, Alluvial deposits and moraines and 5.2, Forest clearings (Table 6). The g-mean values for the validation of forest habitat mapping with the SwissFungi data also showed good results, with g-mean values also above 0.6 for all forest groups, except for 6.1, Swamp forests, with a g-mean value of 0.54.

Table 6. Results of the validation comparison between the Habitat Map of Switzerland and the aerial image interpretation and the SwissFungi observations.

TypoCH	Name	Sensitivity	Specificity	G-Mean
Aerial Image Interpretation				
4	Grassland	0.95	0.91	0.9
6	Forests	0.96	0.94	0.9
3.1	Glaciers, permanent ice and snow	0.85	0.99	0.9
3.2	Alluvial deposits and moraines	0.31	0.99	0.5
3.3	Screes	0.69	0.96	0.8
3.4	Cliffs and exposed rocks	0.69	0.96	0.8
4.1	Pioneer vegetation on rocky surfaces	0.54	0.95	0.7
5.2	Forest clearings	0.03	0.99	0.2
5.3	Shrubs, bushes, hedges	0.64	0.99	0.8
5.4	Dry dwarf shrub heaths	0.38	0.99	0.6
SwissFungi forest data				
6.1	Swamp forests	0.29	0.99	0.54
6.2	Beech forests	0.94	0.51	0.69
6.3	Other deciduous forests	0.76	0.93	0.84
6.4	Thermophilic pine forests	0.42	0.99	0.64
6.5	Bog forests	0.52	0.99	0.72
6.6	High-altitude coniferous forests	0.45	0.98	0.67

4. Discussion and Conclusions

Relying on a variety of remote sensing mapping and modelling products, we developed the first wall-to-wall very high spatial and thematic resolution map of the current distribution of Swiss habitats. The Habitat Map of Switzerland is a vector dataset product that is available for open download [43] from the Swiss Federal Research Institute for Forest Snow and Landscape research's data sharing platform, EnviDat [44] and interactive viewing on map.geo.admin.ch. The methodology is semi-automated, with all input

models or data either regularly updated by federal authorities or with a well-documented methodology based on openly available remote sensing data.

The habitat map offers a wide range of applications. It can serve as a base dataset in conservation planning and management or be used in species distribution models, connectivity analyses, ecosystem services mapping or future landscape scenario modelling. The data also form the basis of the analyses and planning of ecological networks and serve as a reference system for field campaigns for Swiss monitoring programs such as SwissFungi [45] or the Federal Inventory of Amphibian Spawning Sites of National Importance [46].

The composite approach combining the best available remote sensing based datasets for each habitat type allowed us to achieve a high spatial and thematic resolution habitat mapping product in a timely manner. While the consistent machine learning approaches used in habitat mapping products such as the Living England habitat map [14] and the habitat map of Norway [19] offer a uniform methodology across all habitat types, fine-scale features are not identified through these methods and high levels of uncertainty occur within areas with a fine-scale mosaic of different habitat types—for example, in urban areas [14]. The integration of existing mapping and modelling data has numerous advantages, not least with regard to time efficiency. This approach also allows for the inclusion of habitats that may not be well differentiated through spectral signals or other ancillary environmental datasets used in distribution modelling [47] and ensures that the best current knowledge and models are incorporated. A hierarchical approach of classifying habitats firstly into broad habitat classes and then further into habitat groups and types benefits not only the initial implementation, but also updates of the map. When the number of target habitat types is large and thematically variable, a single modelling approach is often not feasible and hierarchical approaches can improve model accuracy [4]. Improvements and updates to the map can be applied separately to different habitat classes, while retaining the information on other habitat classes. This is particularly advantageous since the habitat modelling used for our map [29–32], as well as in many other studies (e.g., [48–51]), is very often conducted with a focus on specific biomes or habitat types.

The comparison of the Swiss Habitat Map with existing land use data from the Swiss land use statistics and the broad-scale Delarze maps of habitat types showed that our map is plausible for most habitat types. While the comparison between the mapped habitat types and the Delarze maps provides a good estimation of the plausibility of the spatial distribution of each habitat type across Switzerland, it does not estimate how well the total area of a given habitat type is modelled. Such an analysis would require additional data that are not currently available for most habitat types; however, a proportional area comparison [52] was conducted for the grassland habitat models by [29].

According to the comparison with the Delarze maps, habitat types with low reliability are mostly forest habitat types. Nevertheless, validation with the SwissFungi data shows that the forest mapping performs well at the habitat group level. Many forest habitat types of the TypoCH typology are differentiated from one another through understorey species, particularly within the habitat group [21]. However, the forest habitat type mapping is dependent on available species distribution models of woody species [31]. This explains the better performance of the mapping at the group level and some of the limitations in our forest type mapping, particularly for mountain pine forest (6.6.5), the least reliably predicted of the mapped habitat types.

The comparison with the coarse Delarze maps also resulted in low specificity and high sensitivity values for several habitat types, generally characterised by restricted geographic distributions, i.e., presence in few mapping units. In these cases, the comparison suggests that the limited presences were not well mapped. These results certainly reflect well-known difficulties in modelling the distributions of rare species or habitat types [53]. However, the threshold set for determining presence in the Delarze maps also influences the results and may be too low for some habitat types. In addition, for certain forest habitat types, our approach of identifying habitats as locations where all character and other indicator species intersect may be too restrictive. This is likely the case for 6.1 Swamp forests, for

which the comparison to the SwissFungi data resulted in high specificity but low sensitivity values, indicating that the habitat map underestimates the distribution of this habitat group. Improvements to forest habitat type modelling might be achieved by considering understorey character and indicator species, or by the direct modelling of habitat types instead of species [20]; however, this would require additional training data.

Wetland type 2.2.3 Calcareous fens was also overestimated in comparison to the Delarze maps. In discussing the wetland and grassland models, the authors of [29] noted that differentiating between oligotrophic fens and nutrient-rich meadows was challenging. However, in their comparison with Swiss monitoring programs, no clear overestimation of type 2.2.3 was found.

Comparison with the Swiss land use statistics showed low reliability for the typically small-scale features of 6.0, Plantations and trees outside forest and narrow linear habitats; 1.2, Running water; and 9.3.3, Unsealed tracks and lanes. The location of these fine-scale features may not correspond geographically exactly to their location on the aerial imagery from which the current (2013–2018) point-based Swiss land use statistics are interpreted. In the case of the habitat group 3.4, Cliffs and exposed rocks (79% match to Swiss land use Statistics), a large proportion (14%) of the area mapped is classified as 'Unproductive grass and herb vegetation' (65) in the Swiss land use statistics [5], which includes vegetated rocky substrate that should be mapped as TypoCH habitat group 4.1, Pioneer vegetation on rocky surfaces. Likely, the NDVI thresholds used to define this habitat (Table 3) do not capture its full distribution area. However, in the comparison to the aerial image interpretation, the g-mean results for both groups 3.4 and 4.1 were good, at 0.8 and 0.7, respectively, albeit with high specificity and lower sensitivity. The validation with the aerial image interpretation also suggested poor performance for 3.2 Alluvial deposits and moraines (g-mean 0.5) and 5.2 Forest clearings (g-mean 0.2). These findings point to the limitations of the relatively simple rule-based classification described in Table 3, which will require further investigation and refinement in any updates of the habitat map. The results for 5.2, Forest clearings are dominated by false positives, and it is worth noting that this habitat group is perhaps defined somewhat differently in our mapping than in the image interpretation, which focused on the transition between forest and grassland. Such definition disparities are also a factor in the comparatively low performance of habitats in class 5, Woodland edges, tall herb communities, shrubs, when compared to the Swiss land use statistics.

While a large number of habitat types and groups were plausibly mapped, a number of habitat types could not be included in the current Habitat Map of Switzerland. This is mainly due to limited data availability, the inability to detect these habitats adequately with remote sensing data or the dynamic nature of the respective habitat type. Furthermore, due to very-fine scale habitat mosaics in urban areas, simple classification rules were applied to classify habitats dominated by herbaceous or grassy species within settlements. The current Swiss national LiDAR campaign (to be completed in 2023) and improved resolution aerial imagery offer opportunities to improve urban area mapping [27,54], as shown by [55], for example.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs15030643/s1, Table S1: MoGLI Species distribution models used to determine the distribution of each forest habitat type.

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Data Availability Statement: The Habitat Map of Switzerland dataset, the distribution maps of grassland habitats and the cropland/grassland map are available for interactive viewing, and for download from

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