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Land cover degradation in the reference and monitoring periods of the SDG Land Degradation Neutrality Indicator for Switzerland

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ABSTRACT

Land degradation impacts most terrestrial biomes across all world regions. To address global change challenges emanating from degrading natural resources, many countries voluntarily set themselves the goal of achieving Land Degradation Neutrality (LDN). Baseline conditions are to be established over a reference period (2000 – 2015). With seven more years to monitor this Sustainable Development Goal 15 indicator — SDG15.3.1 until the year 2030, the scientific basis for operationalizing LDN is still evolving. The non-availability of annual land use-land cover maps of sufficient resolution in various countries, among them Switzerland, is a major factor hampering the assessment at national and local levels. Land cover change is assessed for seven land categories (that is, Tree-covered area, Grassland, Cropland, Wetland, Artificial Surfaces, Otherland, and Waterbody). Land cover change is a major LDN sub-indicator required to assess the proportion of degraded land to total land area (SDG15.3.1). Annual land cover datasets from 2015 to 2020 were produced at 10 m from Sentinel-1 and Sentinel-2 images using a Remote Sensing and Geographic Information System-based workflow. An evaluation of degradation in land cover is presented in support of the operationalization of LDN in Switzerland. Drawing upon the understanding that changes made to land use-land cover may act as precursors to land degradation processes, transitions relating to the loss of natural cover were identified based on the land cover change criteria during the reference and the monitored periods. The criteria were developed for relating land cover transitions to degrading and non-degrading processes. Such transitions were grasslands to tree-covered areas and croplands to artificial surfaces due to settlement development. For example, the amount of cropland converted to artificial surface areas was greater in absolute terms during the monitored period than during the reference period. Also, the regeneration of natural cover involving transitions from otherland to grassland and from grasslands to tree-covered areas was found. Overall trends between 2000 and 2020 in Switzerland are the increasing settlement areas in the Central Plateau, the Alpine valleys of Valais and Ticino, largely at the expense of croplands and the bush encroachment of pastures such as in the Jura. This study's contributions include an enhanced workflow for annual land cover mapping for the entire Switzerland and the adaptation of the land cover change criteria to fit the Swiss context. The proposed mapping method has the potential to fill the gap between the production cycles of the Swiss Corine and *Arealstatistik* land use data.

1. Introduction

Land degradation as a global phenomenon affects most terrestrial biomes and agroecology (Nkonya et al., 2016; Schulze et al., 2021). Setting the Land Degradation Neutrality (LDN) baseline and monitoring its corresponding Sustainable Development Goal (SDG) indicator — SDG 15.3.1 proportion of degraded land to the total land area — were proposed as measures to address global change challenges emanating from the degradation of natural resources (Sims et al., 2021; Akinyemi et al., 2021). LDN seeks to stabilize and/or improve the extent and quality of land resources while avoiding, reducing and restoring degraded lands and soils, including lands affected by desertification, droughts and floods (United Nations Convention to Combat Desertification — UNCCD, 2019). The goal to achieve a land degradation-neutral world by 2030 is not so much on neutralizing degradation but on maintaining or enhancing the productive capacity of land and supporting the land's natural capital (UNCCD, 2015).

Three sub-indicators are used to assess, monitor and report on land

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degradation to the UNCCD. These are land cover change (LCC) (a proxy for change in land use), land productivity dynamics (LPD) and soil organic carbon (SOC) stocks as a proxy for carbon stocks (Cowie et al., 2018; Gonzalez-Roglich et al., 2019). The influence of LCC on LDN outcomes is pervasive as it drives changes in the other two sub-indicators, especially changes to vegetation and carbon. LCC is also implicated in ongoing sustainability crises such as land degradation, climate change and biodiversity decline (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2018; IPCC, 2019; IPCC, 2022). A reference period, defined as the period from 2000 to 2015, was chosen by the UNCCD as the baseline against which the status of land degradation is monitored until 2030 (Sims et al., 2021). The status and condition of land-based natural capital and the ecosystem services that flow from that land can be inferred using the initial numerical values of the three LDN indicators (UNCCD, 2019).

Although it is desirable to monitor on an annual basis, countries currently report on SDG 15.3.1 every 4 years. This is partly due to several challenges many countries face in operationalizing the LDN such as the lack of appropriate local and national level datasets as well as the level of available technical expertise (Ifejika Speranza et al., 2019; Akinyemi et al., 2021). More than 125 countries already set LDN targets but most reported estimates in 2018 with a low confidence level. This is mainly because these estimates were made from global datasets and field verification was lacking in many contexts (Akinyemi et al., 2021). The foregoing does not discountenance the usefulness of global datasets for monitoring land cover-related indicators. For example, globally consistent information is required to support the development of appropriate policy guidance appropriate to that scale. Existing global datasets were recommended for use by countries in the absence of local datasets (Sims et al., 2021), but the limitations of using global datasets at the local level are increasingly becoming obvious. The question remains about the appropriateness of relying on global datasets for taking policy action at the local and/or national levels (Akinyemi et al., 2021; Sims et al., 2021). Thus, solutions are needed to address these limitations.

Further, fundamental to assessing the LDN baseline and tracking changes afterwards is the creation of datasets with sufficient resolution for use at the national and/or local levels (Szantoi et al., 2020; Akinyemi and Ifejika Speranza, 2022). Ahead of many countries, the Swiss Federal Office for the Environment (BAFU), 2007 initiated the creation of the Swiss Data Cube (SDC) in 2016 aiming to provide Earth Observation (EO) Analysis Ready Data (Chatenoux et al., 2021). Exploring the SDC's potential for LDN assessment, Giuliani et al. (2020) had to use the European Space Agency's 300 m annual global land cover datasets (European Space Agency, 2017) instead of the 100 m national land use statistics, henceforth *Arealstatistik* (Federal Statistics Office — BFS, 2017) or the 100 m Swiss Corine (Coordination of information on the environment) land cover data (CLC). Both the *Arealstatistik* and CLC have a 6-year production cycle. This lack of annual land cover maps of adequate spatial and temporal resolution limits the use of available data for assessing LDN. Giuliani et al. (2020, 8) rightly noted that "neither the reduced spatial resolution nor the update frequency allows providing accurate and timely information to better understand the dynamics of LC changes (e.g., spatial and temporal heterogeneities of the landscape features and values) and their impacts across Switzerland".

In line with the aims of the SDC to facilitate EO data use, this study presents a Remote Sensing-based workflow for producing annual land cover (LC) data at 10 m resolution covering the whole of Switzerland. Aimed at developing annual LC datasets for use in LDN and other domains, this method is complementary to filling the data gaps between the production cycles of the Swiss Corine and *Arealstatistik*. The land cover change criteria proposed by the UNCCD good practice guidance for SDG15.3.1 was applied to the Swiss context for assessing and quantifying degradation in land cover (Sims et al., 2021). This effort contributes to further strengthening the Swiss national capacity to generate annual LC maps as newer EO datasets become available to assess and monitor degraded lands.

2. Material and methods

To foster LDN operationalization in Switzerland, we conducted LC change analyses for assessing land cover degradation during the reference period (2000 – 2015) and the monitored period from 2015 to 2020. Degradation processes were then inferred from changes to land cover (see details of such land cover transitions in Akinyemi et al., 2021; Sims et al., 2021; United Nations, 2022).

2.1. *Case study*

Compared to many countries, Switzerland as a case study offers a learning opportunity. It has regularly updated land cover datasets (i.e., 6-year cycle) but still lacks the land cover data for estimating LDN. An overview of the Swiss context is provided in terms of the topographical regions, elevation, temperature, and land cover in Fig. 1. Switzerland has an area of ~41285 km^2, with the Alps covering approximately half of its areal extent and forming a climate barrier (Begert and Frei, 2018) (Fig. 1). While the average rainfall in the Pre-Alps is 500–700 mm year^{-1}, precipitation increases southwards and northwards to about 2000 mm year^{-1} (Bundesamt für Meteorologie und Klimatologie (MeteoSwiss), 2023). With Alpine regions of ecological importance and wetlands recognized by the Ramsar Convention, amongst other features, Switzerland provides a good case to examine and interpret land cover transitions that have the potential to degrade ecosystems.

2.2. *Data*

2.2.1. *Existing Swiss land cover data*

The 100 m CLC at the most detailed level of the LC classification scheme (i.e., level 3) comprises 44 categories. CLC datasets are generated mainly from satellite images (Sentinel-2 and Landsat) and have thematic reliability of at least 85% (European Environment Agency, 2017). In Switzerland, data is available for 1990, 2000, 2006, 2012 and 2018, following a 6-year cycle (Steinmeier, 2013). Since the CLC was verified for accuracy (Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft (WSL), 2021), the year 2000 dataset (CLC2000) was used for the initial year of the reference period, whereas the LC map of 2015 (LC2015) was created for the final year of the reference period. CLC classes that are present in Switzerland were grouped to match the land cover (LC) classes in LDN (see supporting information in Table SI1).

The *Arealstatistik* is the official source of information on land use and changes in Switzerland since 1985. With a resolution of 100 m, the data were mostly obtained by visual interpretation of digital aerial photographs. Datasets were published for the 1979–1985, 1992–1997, 2004–2009 and 2013–2018 survey periods (BFS, 2019). This study uses data from surveys overlapping the study periods. Data comprising major categories of settlement, agriculture, wooded and unproductive areas were matched to the LDN classes (see supporting information in Table SI2). Trends in LC change computed during the reference and monitored periods were compared with trends in the *Arealstatistik*.

2.2.2. *Image datasets used for land cover mapping*

To produce the annual LC maps (i.e., 2015, 2016, 2017, 2018, 2019 and 2020), Sentinel-2 (S2) 10–20 m Multispectral Instrument (MSI) surface reflectance (SR) datasets were used (European Space Agency, 2015). SR images improve land cover classification because variability is reduced between multiple images of different dates as images are atmospherically corrected and orthorectified, i.e., corrected for topographic effects (Akinyemi, 2017; Young et al., 2017). For further details about the processing of S2 SR images as well as the algorithms used, see European Environmental Agency (2023). However, SR images might be obscured by clouds hence it is necessary to complement with Sentinel-1 (S1) Synthetic Aperture Radar (SAR) data (10 m VV — Vertical transmit-Vertical receive) and VH — Vertical transmit-Horizontal receive) (European Space Agency, 2016). SAR overcomes the limitations of optical

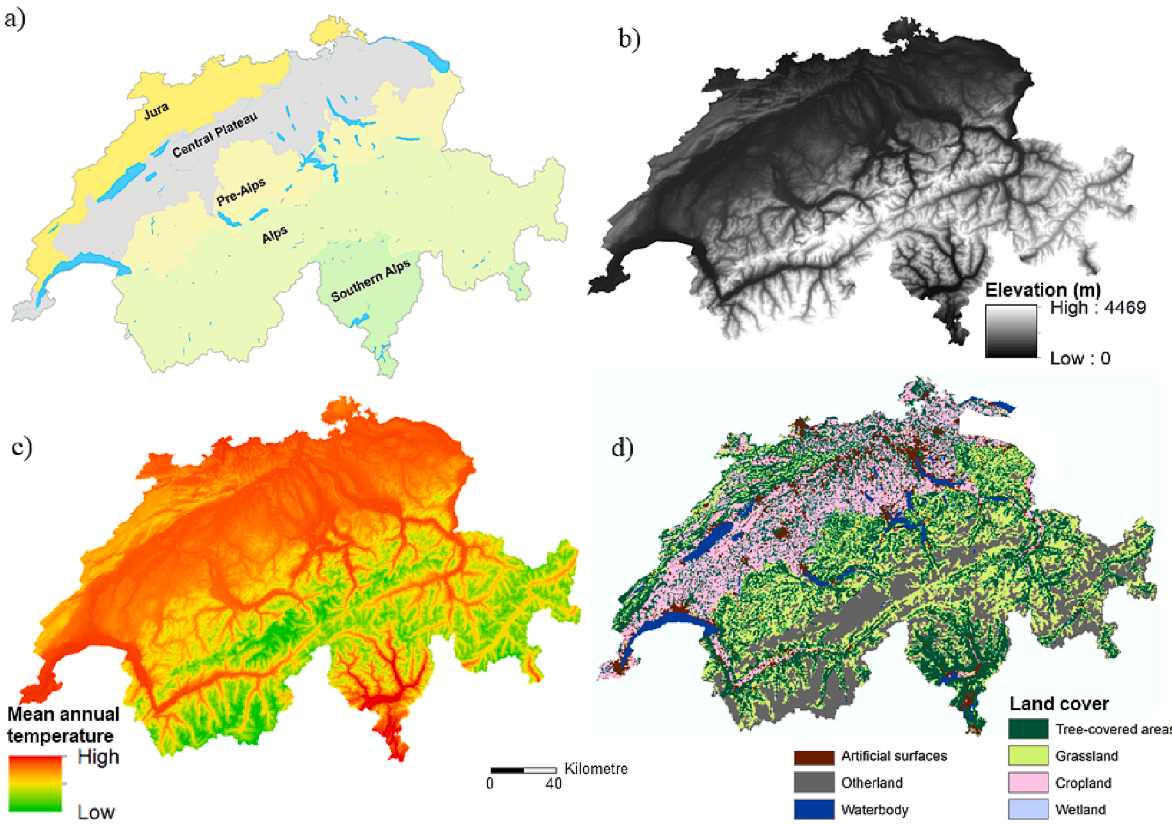

Fig. 1. Study location a) Swiss geographical regions (BAFU), b) Elevation (USGS GTOPO30), c) average temperature over Switzerland (Swiss opendata), d) Land cover types in 2000 (aggregated from CORINE land cover data of 2000).

images by penetrating cloud cover for example (Joshi et al., 2016). The VV and VH polarization Ground Range Detected data have been processed in Google Earth Engine (GEE) with the Sentinel Application Platform for noise removal, thermal noise removal, radiometric calibration, orthorectified with the SRTM 30 and converted to decibels (dB) using log scaling (GEE, 2023).

Elevation data from the USGS Digital Elevation Model (DEM) GTOPO30 were used to further support image classification in identifying shadows, especially in mountainous areas. With 30 arc seconds horizontal grid spacing, the GTOPO30 was produced from both raster and vector data sources (Earth Resources Observation and Science Center — EROS, 2018). An additional Normalized Difference Vegetation Index (NDVI) band was created from S2 data and added to the image composite for clarity of vegetated areas during classification.

2.2.3. Auxiliary data

Ground-based data were produced from high resolution satellite images on Google Earth Pro (GEP) for image classification and verification. The Swiss international boundary from Swisstopo was used to clip all datasets and constrain analysis within Switzerland. All datasets were resampled to 100 m for compatibility with the CLC.

2.3. Methods

2.3.1. Image compositing and preprocessing

Annual LC datasets were created for the years 2015, 2016, 2017, 2018, 2019 and 2020 using all S1 and S2 archived images for those years in GEE (see Fig. 2, step 1). These years were chosen to test the suitability of the proposed Remote Sensing and Geographic Information System (GIS)-based method to generate annual LC maps for Switzerland with speed and enhanced accuracy.

To minimize snow and cloud cover in the S2 composite, images from May/June to September were used with a maximum cloud probability of 30%. An additional task in image preprocessing, as applied to the S2 composite, is the computation of the median of the S2 bands. For image composites with gaps due to excessive snow and cloud cover such as in the Swiss Alps, images of the nearest years for the same months were used. For example, images from 2014, 2016, and 2017 had to be used in places missing images for 2015, whereas for gaps in the 2020 image composite, images from 2018 and 2019 were used. Images from 2010 were used in extreme cases with perpetual snow cover for 2018 and 2019. S1 data used were for the same months for all years with a speckle filter applied.

The final composite used for classification contained all S1 and S2 bands with the DEM and NDVI. NDVI and DEM images were included in the composites to better detect vegetation and minimize misclassification in shaded mountainous areas which are typical of Swiss landscapes.

2.3.2. Annual land cover classification and mapping

For training and validation of the classified images and land cover maps, high resolution satellite images on GEP were used to create 700 stratified sampling points per seven LC classes utilized for assessing LDN (Fig. 2, steps 2 and 3). The classes are tree-covered areas, grassland, cropland, wetland, artificial surfaces, otherland and waterbody. The 31 LC classes in the Swiss Corine and 17 classes in the *Arealstatistik* were grouped into these seven classes (see details about these groupings in supporting information Tables SI1 and SI2 respectively). In Switzerland, tree-covered areas comprise forests, brush forests and woods including shrublands. Artificial surfaces comprise settlement and urban areas, including infrastructures such as roads and tracks. Agricultural areas are distinguished into grasslands such as pastures and croplands. It is important to distinctly identify wetlands in consonance with efforts in recent years to protect them. However, mapping Swiss wetlands is not straightforward because it comprises inland marshes and moors. The

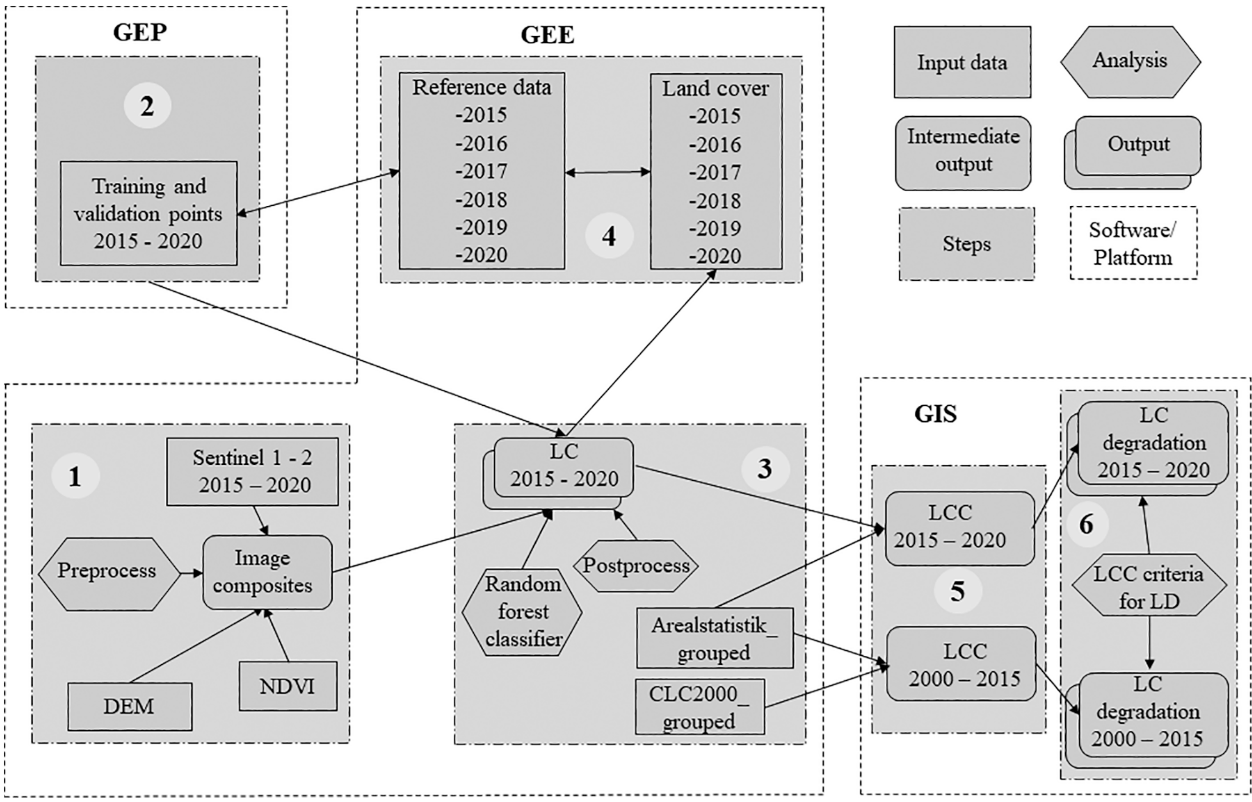

Fig. 2. Study workflow used for data processing and analysis. CLC = Corine land cover, DEM = Digital Elevation Model, GEE = Google Earth Engine, GEP = Google Earth Pro, GIS = Geographic Information System, LC = land cover, LCC = land cover change, LD = Land degradation, NDVI = Normalized Difference Vegetation Index. Numbers 1 to 6 in each box represent steps in the workflow.

CLC classified moors as forests and semi-natural areas, whereas the *Arealstatistik* classified wetlands as unproductive areas (this term does not mean worthless). The Otherland class in the CLC comprising barelands, areas of low vegetation cover, mountain massifs, and glaciers is slightly different from the *Arealstatistik* unproductive area class as it excludes lakes and other waterbodies.

From each annual LC map (i.e., 2015 - 2020), approximately 1400 reference points were created. These points created from the previous year's LC map were visually compared to satellite images of October and November for the current year and updated accordingly (Fig. 2, step 4). Images in these months were selected to avoid overlap with images from May to September which were used for the classification. This step ensured that the reference datasets were correctly attributed to the appropriate LC type in case conversion occurred over the last year. These reference datasets, used for training and validation, are independent to avoid overfitting the model (Akinyemi, 2017).

2.3.3. Postprocessing and land cover change analysis

Before the analysis and quantification of LCC, post-processing involved resampling all annual maps to 100 m for compatibility with CLC2000 (Fig. 2, step 3). Since the CLC classified moors and heathlands as forest and semi-natural areas, it was necessary to classify internationally recognised Ramsar moors such as Kaltbrunner riet and Laubersmad-Salwidili in Switzerland as wetlands. A wetland mask was created for all Ramsar sites in Switzerland from the Ramsar Sites Information Service. On the assumption that wetlands are protected in Switzerland since 1987 (Federal Office for the Environment (BAFU), 2007), the wetland mask was used to postprocess LC2015 and LC2020 by relabelling misclassified wetland pixels. Explicitly identifying moors and heathlands as wetlands in the LC maps will enhance the use of these maps in supporting wetland conservation efforts. An artificial surface mask was created from CLC2018 and used in LC2020.

Change detection entailed identifying areas where LC persisted during both periods and those converted to other uses. Land cover change (that is, the transition from one LC class to another class) was conducted for the reference period using the LC2000 and CLC2015 maps, whereas LC2015 and LC2020 were used for the monitored period (Fig. 2, step 5). When a transition has the potential to deteriorate ecosystems, this is interpreted as degrading, otherwise, a transition to another LC class is interpreted as an improvement such as when a degraded site is restored (Fig. 2, step 6). For details about the LC transition criteria, see Sims et al. (2021). Finally, we compared values of the different LC transitions to the *Arealstatistik*, which is the official land use data in Switzerland.

3. Results

Against the backdrop of improvement and advancement in land cover assessment, is the need to map annual land cover for use in several domains. Additional to the creation of annual LC maps, an assessment of LCC from which to infer the level of land cover degradation is needed to monitor LDN. Land cover degradation is interpreted as concerning LCC processes that degrade ecosystems, including ecosystems in human-managed landscapes.

3.1. Annual land cover mapping and accuracy assessment

In comparison with the baseline situation established between 2000 and 2015, annual LC data is required for the regular monitoring of LDN from 2016 onwards till 2030. We tested the proposed method for generating annual LC maps using the case of Switzerland. Fig. 3(a – f) depicts the six annual LC maps from 2015 to 2020.

The LC maps of 2015 to 2020 were validated with reference data generated from high resolution images. An overview of the user

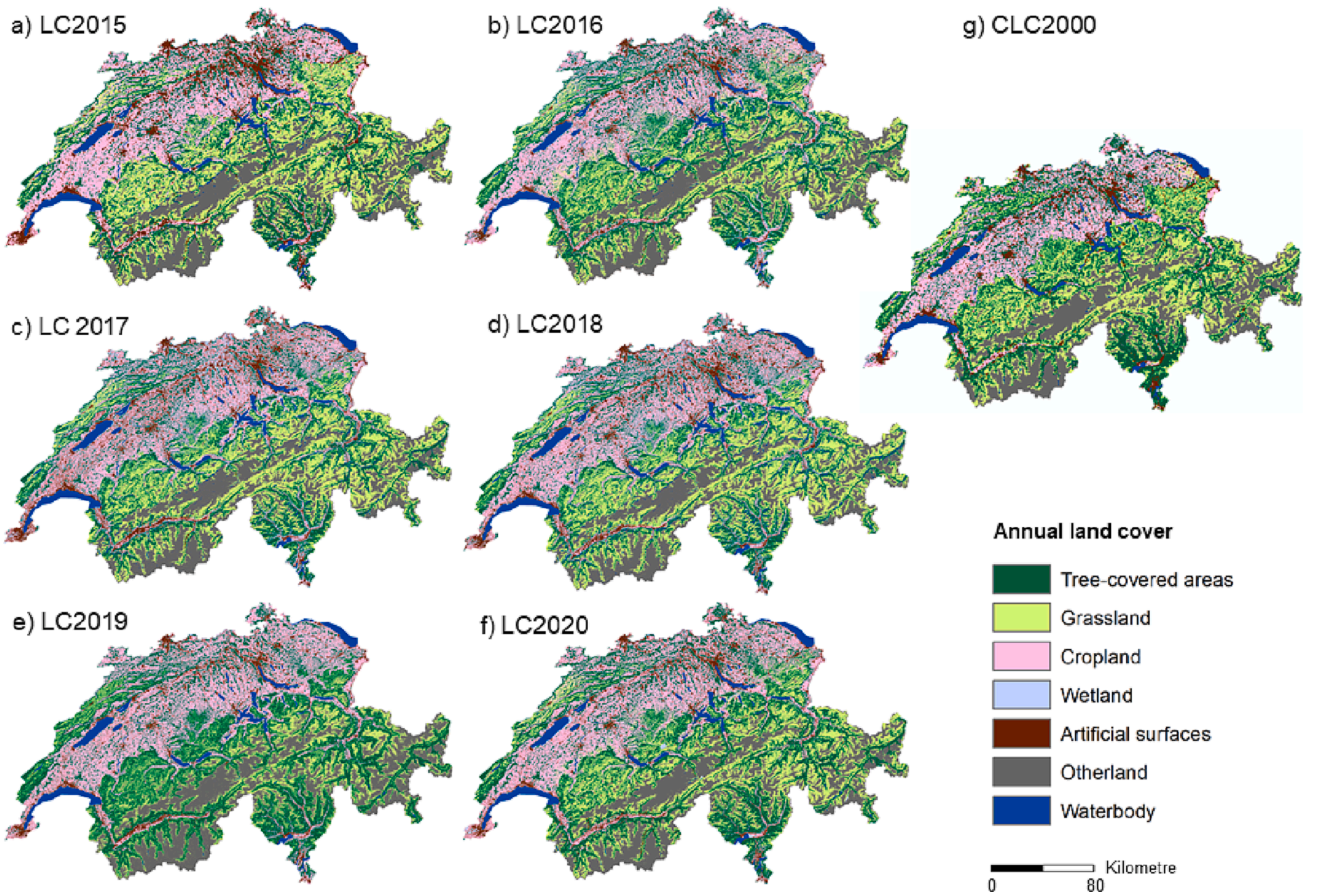

Fig. 3. Land cover maps of Switzerland. a – f) Annual land cover maps for the years 2015 to 2020 (maps of 2015 and 2020 were postprocessed mainly for wetland areas before the detection of change), g) Regrouped Corine land cover map of 2000.

Table 1
User, producer and overall accuracy in each land cover class in the annual maps.

Land cover class	Metric	2015	2016	2017	2018	2019	2020
	OA	92.4	79.7	80.1	83.9	77.3	92.2
Tree-covered areas	UA	95.8	73.3	88.0	83.0	76.7	94.9
	PA	91.9	87.0	71.5	79.0	80.9	95.9
Grassland	UA	91.5	77.3	86.0	95.0	52.1	91.1
	PA	86.9	85.0	79.6	82.6	52.8	84.5
Cropland	UA	84.5	62.3	73.0	90.0	76.2	87.2
	PA	82.8	81.0	73.0	71.4	84.6	77.3
Wetland	UA	86.6	70.3	53.0	57.0	62.5	84.6
	PA	91.3	45.0	73.6	83.8	27.8	96.7
Artificial Surfaces	UA	92.2	89.2	78.0	69.0	88.9	90.2
	PA	96.0	74.0	73.5	83.1	75.6	94.9
Otherland	UA	99.0	91.9	95.0	97.0	84.8	98.9
	PA	98.0	91.0	95.0	95.1	84.8	96.9
Waterbody	UA	97.1	99.0	96.7	96.0	88.5	99.0
	PA	100	95.0	88.0	95.0	100.0	100

Note: User accuracy (UA), Producer accuracy (PA), Overall accuracy (OA).

accuracy (UA) and producer accuracy (PA) in each LC class for the annual maps is presented in Table 1 (details of the confusion matrixes are provided as supporting information in Table SI3).

The overall accuracy (OA) achieved in producing the annual LC maps was 84% on average. Although the accuracies varied between LC classes and between the years, the tree-covered area class and waterbody were most well classified. The lowest OA occurring in 2016 and 2019 can be largely attributed to the wetland and grassland classes. Checking the classified maps against the backdrop of high resolution images revealed wetlands as the main source of confusion between LC classes as these were often misclassified as tree-covered areas. To a lesser degree, artificial surfaces were confused with croplands, whereas grasslands were confused with tree-covered areas (Fig. 4). The challenge with classifying Swiss wetlands is due mainly to wetlands being largely omitted from the classification because of their small sizes which required some measures of postprocessing.

The Corine maps could not be used to capture Ramsar wetlands in LC2015 and LC2020 because CLC classifies moors as forest and semi-natural areas instead of wetlands (Fig. 4c, left). Not all artificial surface areas were detected in LC2015 and LC2020 probably because of the differences in spectral reflectances of settlement, infrastructure (e.g., transportation, industrial, recreation), and cemeteries with trees which were all combined into an artificial surface class. This class was relabelled using the artificial surface area mask. Postprocessing was done only for LC2015 and LC2020 as the intermediate and end period of the study respectively.

3.2. Land cover change and land cover degradation in Switzerland (2000 – 2020)

3.2.1. Baseline setting for the reference period

Analysis of change in the LC sub-indicator of the LDN for setting the baseline was conducted for the reference period, i.e., between 2000 and 2015. Of the total land area, 84% of the land remained unchanged (Table 2).

There was about 3795 km^2 of land potentially degraded between 2000 and 2015, which amounts to ~9% of Switzerland‘s land area. The main LC transitions were tree-covered areas to grasslands and croplands, cropland transitioning to grassland and artificial surfaces, especially

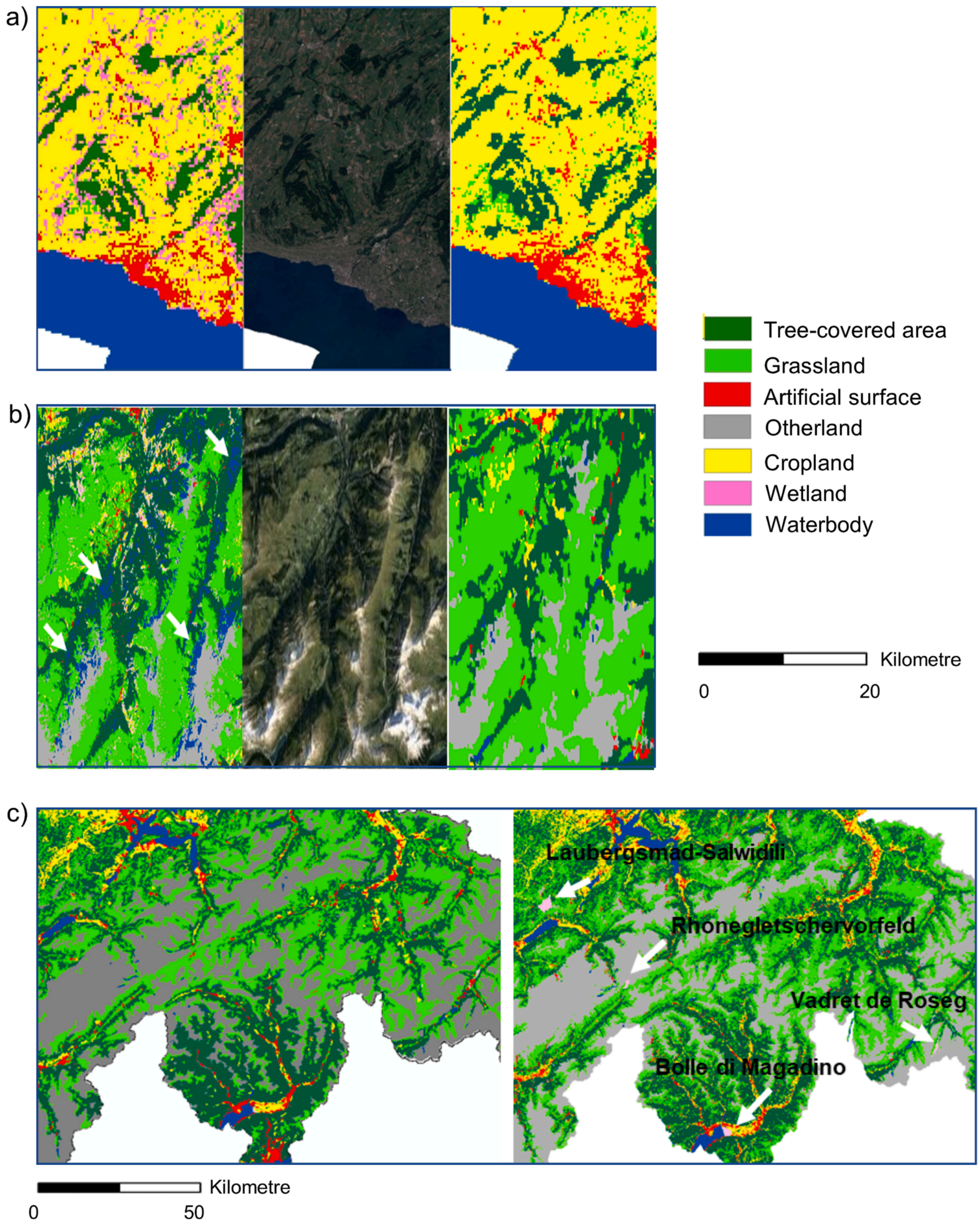

Fig. 4. Comparing the classification of some land cover classes with Sentinel-2 (S2) images. a) Misclassified wetland class in LC2020 (left), corresponding S2 scene (middle), and improved final classification with NDVI and DEM included in image composite (right), b) White arrows show mountain shadow/shaded areas which were misclassified as waterbody in the initial classification (left), the corresponding S2 scene (middle), and final classification after applying NDVI and DEM (right), c) In Corine land cover (e.g., CLC2018), moors and heathlands, which include some Ramsar wetlands, were not classified as wetlands but forest and semi-natural areas (left), postprocessed LC2020 with wetland data (some Ramsar wetland sites are depicted in pink with white arrows pointing to their location, right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

settlements. In contrast, 2896 km^2 (7%) of land was improved, implying the regeneration of mostly natural cover between 2000 and 2015. Transitions from otherland to grassland, from grassland to tree-covered area and from cropland to tree-covered area accounted for the largest share of land with improved conditions. The land areas lost by each LC type during the reference period were mapped (Fig. 5a) and these were related to degradation using the LC change criteria (Fig. 5b).

Fig. 5a depicts the distribution of LC class losses during the reference period and Fig. 5b depicts areas where the transition from one land use to another could degrade the ecosystems. Examples of such degrading land transitions are bush encroachment into pastures in the Jura, expanding settlement areas at the expense of croplands in the Central Plateau and the Alpine valleys of Valais and Ticino.

3.2.2. Monitored period

This study extends the analysis of change in land cover to the monitored period. Additional to setting the LC baseline during the reference period, we monitored change in terms of the conversion

Table 2
Land cover change matrix in km^2 and criteria for 2000–2015. Land cover change matrix in km 2015–2020 and criteria for 2015–2020.

	Tree-covered areas	Grassland	Cropland	Wetland	Artificial Surfaces	Otherland	Waterbody
Tree-covered areas	10724 Stable	773 Vegetation loss	735 Vegetation loss	23 Inundation	265 Deforestation	79 Vegetation loss	1
Grassland	546 Afforestation or Bush encroachment	8247 Stable	339 Agricultural expansion	12 Inundation	84 Urban Expansion	92 Vegetation loss	1
Cropland	576 Afforestation	504 Stoppage of Agriculture	6111 Stable	18 Inundation	810 Urban Expansion	1 Vegetation loss	3
Wetland	3 Bush encroachment	1 Wetland drainage	4 Wetland drainage	25 Stable	1 Wetland drainage	0 Wetland drainage	1
Artificial Surfaces	41 Afforestation	25 Vegetation establishment	168 Agricultural expansion	3 Wetland establishment	1844 Stable	1 Withdrawal of Settlements	1
Otherland	190 Afforestation	976 Vegetation Establishment	25 Agricultural expansion	6 Wetland establishment	125 Urban expansion	5886 Stable	1
Waterbody	29	4	8	17	30	17	1375

Note: To visualize the LC change criteria developed for relating LC transitions to degrading and non-degrading processes, dark brown is used for land cover transitions with potential to degrade ecosystems during 2000-2015, green is used for improvement and light brown is used to depict stable areas that remained unchanged (refer to Fig. 2, step 5). All values are rounded.

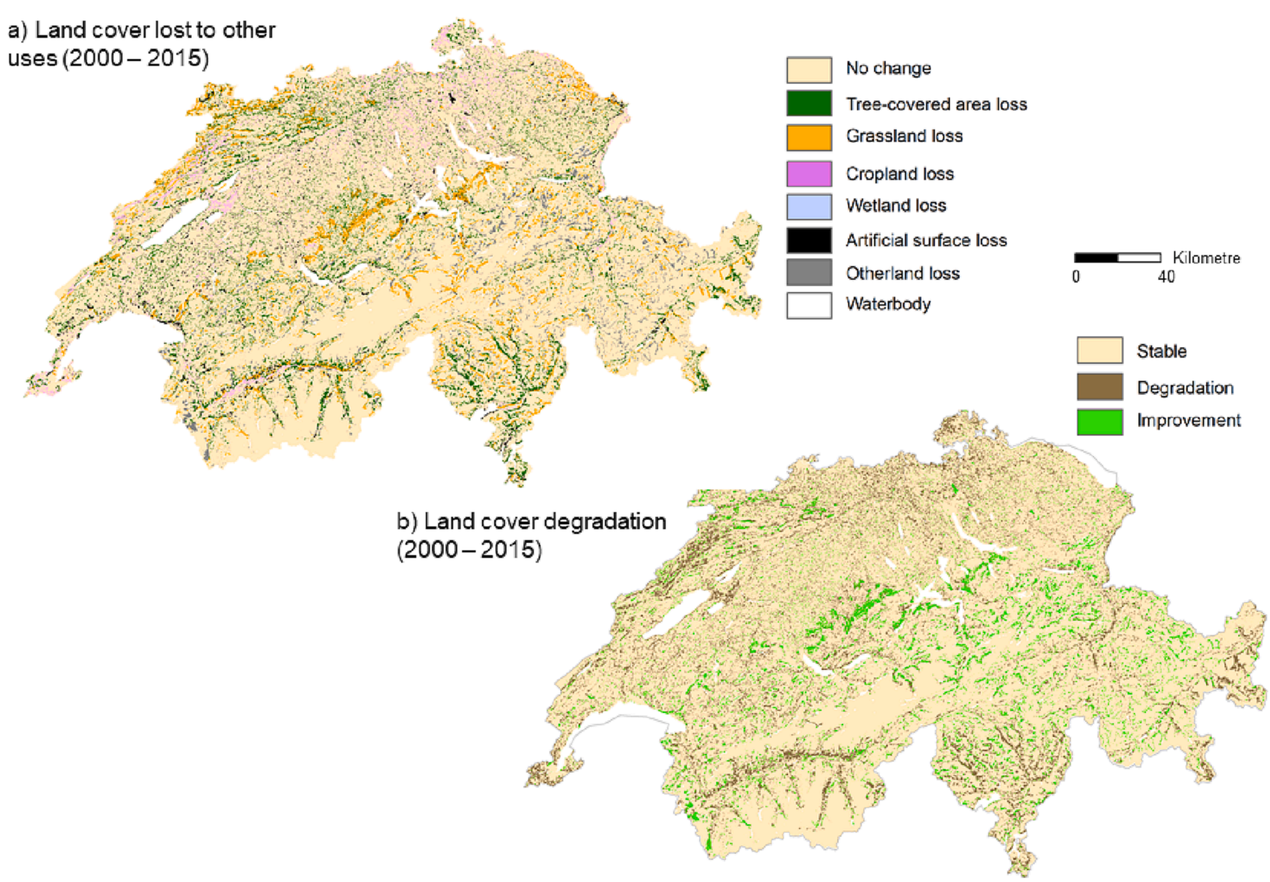

Fig. 5. Changing land cover conditions as related to degradation during 2000 – 2015. a) Areas lost by individual land cover classes to other uses, b) Status of land cover degradation.

Table 3
Land cover change matrix in km^2 and criteria for 2015–2020.

	Tree-covered areas	Grassland	Cropland	Wetland	Artificial Surfaces	Otherland	Waterbody
Tree-covered areas	11260 Stable	301 Vegetation loss	434 Vegetation loss	1 Inundation	56 Deforestation	42 Vegetation loss	18
Grassland	292 Afforestation or Bush encroachment	9670 Stable	369 Agricultural expansion	1 Inundation	50 Urban expansion	140 Vegetation loss	0
Cropland	346 Afforestation	209 Stoppage of Agriculture	6406 Stable	3 Inundation	429 Urban expansion	7 Vegetation loss	2
Wetland	1 Woody	0	2	106 Stable	0	0	1
	encroachment	Wetland drainage	Wetland drainage		Wetland drainage	Wetland drainage	
Artificial Surfaces	117 Afforestation	35 Vegetation establishment	529 Agricultural expansion	0 Wetland establishment	3025 Stable	43 Artificial surface loss	15
Otherland	83 Afforestation	210 Vegetation establishment	4 Agricultural expansion	0 Wetland establishment	16 Urban expansion	5757 Stable	10
Waterbody	1	0	2	1	0	2	1664 Stable

Note: Based on the transitions between the LC types and their persistence in Table 3, dark brown is used for land cover transitions with potential to degrade ecosystems during 2015–2020, green signifies improvement and light brown is stable, signifying that these areas remained unchanged (values are rounded).

between LC classes. Monitoring these changes from 2015 to 2020 indicated that, 87% of the total land area remained unchanged, approximately 5% (1910 km^2) was degraded and 8% was improved amounting to 3216 km^2 (Table 3).

The type and direction of some LC transitions during the monitored period were similar to those identified in the reference period. Examples are transitions from cropland to grassland and cropland to artificial surfaces, with the amount for the latter transition greater during the monitored period than the baseline period (Fig. 6).

Estimates of regeneration of natural covers in croplands and otherlands totalled 1080 km^2 and 1197 km^2 respectively during the reference period (67.5 km^2 and 74.8 km^2 annual change), and 555 km^2 and 297 km^2 (111 km^2 and 59.4 km^2 annual change) for the monitored period.

Similar to the reference period, natural covers regenerating on some agricultural lands approximated 1070 km^2, which was higher than estimated for the reference period (592 km^2). The estimated amount of natural covers regenerating in otherland areas, approximated 853 km^2 during the reference, which was higher than during the monitored period (583 km^2).

3.2.3. *Land cover change during the reference and monitored period with Arealstatistik*

Comparing estimates of LCC for each cover type during both periods and with the *Arealstatistik* is not meant to gauge the absolute values of the change. As the methods and periods are different, the comparison is to better understand the direction of LCC as determined with Remote Sensing compared to that from statistics (Table 4). Table 4 shows the net changes in each class in the reference period and the monitored period in comparison with the *Arealstatistik*.

The land area in Switzerland for which land cover remained stable (i.e., unchanged) in the datasets are shown in Table 4. Tree cover during both observation periods declined, whereas *Arealstatistik* shows an increase in forests. If a distinction is made between forest types in *Arealstatistik*, the increase was only in the forest (+5%) and brush forest (+10%) types, whereas woods that were mostly adjacent to agricultural lands declined (-5%). The decrease in cropland and otherland as well as the increase in artificial surfaces during the baseline period agree with the *Arealstatistik*. Although there is no distinct wetland class in the *Arealstatistik*, BFS (2021) confirmed an increase in wetlands due mainly to rewilding measures. Wetland increase probably also is related to the reclassification of some moors and Ramsar sites alongside marshes into a distinct wetland class for LU2015 and LU2020.

4. Discussion

In this study, the focus was on developing a methodology for the LC sub-indicator of the LDN due to the pervasive influence of land use on the other two sub-indicators, i.e., land productivity dynamics and soil organic carbon.

4.1. *Generating land cover data on an annual basis for Switzerland*

This study produced land cover data for Switzerland with improved spatial (10 m) and temporal (yearly) resolution. Using a workflow that is entirely based on Remote Sensing and GIS, the production of annual LC maps from 2015 to 2020 was demonstrated. It complements the 6-year production cycle of the Swiss Corine and the *Arealstatistik* survey periods (2004 – 2009 and 2013 – 2019) (Fig. 7). The proposed method has the advantage that the production of the annual LC datasets are very efficient in cost and time.

Although it is proposed to shorten the production cycle of the *Arealstatistik* to six years (BFS, 2021), a four-year update cycle of land use data will better serve LDN and other purposes (Sims et al., 2021). Our proposed methodology can support the shortening of the update frequency of the *Arealstatistik* and CLC for enhanced and timely information to better understand changes to land cover in Switzerland.

With the developed method, we demonstrate it is possible to create LC data on an annual basis for Switzerland. This effort is relevant to not only Switzerland but to other countries and/or regions in need of annual land use and land cover data.

4.1.1. *Image classification accuracy*

The image classification accuracy (that is, UA, PA and the OA) varied between LC types and on an annual basis. Some LC types such as wetland

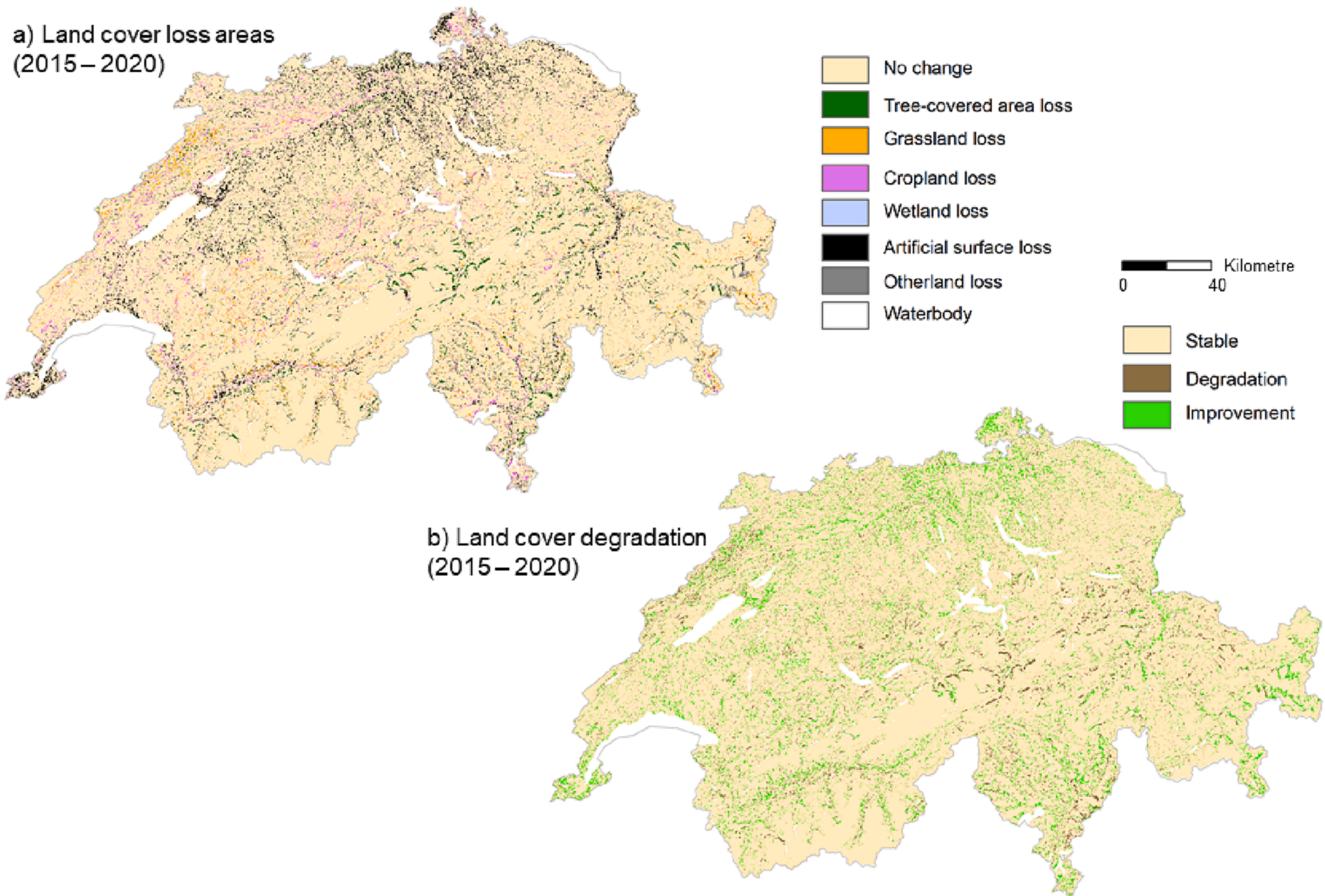

Fig. 6. Changing land cover conditions as related to degradation during 2015 and 2020. a) Areas lost by individual land cover classes to other uses, b) Status of land cover degradation.

Table 4
Comparison of the net change in land cover types.

Land cover type	Baseline Period (2000 – 2015)	*Arealstatistik* (1985–2009)	Monitored Period (2015 – 2020)	*Arealstatistik* (*2013 – 2018)
Stable areas (unchanged)	80%	85%	91%	98%
Tree-covered areas	−0.04 km^2	+385 km^2	−12 km^2	+203 km2
Grassland	+1211 km^2	−383 km^2	−97 km^2	−44 km2
Cropland	−633 km^2	−522 km^2	+343 km^2	−216 km2
Wetland	+70 km^2	Not available	+3 km^2	** +18 km^2
Artificial surfaces	+1075 km^2	+584 km^2	−189 km^2	+192 km2
Otherland	−1133 km^2	−77 km^2	−88 km^2	−141 km2
Waterbody	−99 km^2	* +15 km^2	+40 km^2	+12 km2

Note: * data from 2009 to 2018 is used when data is not available for the 2013 – 2018 period, **1985 – 2018 (BFS, 2021, 32).

and grassland had the lowest accuracy as they were mostly confused with other LC types. The confusion arising with classifying the wetland class can be attributed to several reasons among which are the differences in assigned classes between land use data sources and the small size of many wetlands in Switzerland. For example, moors were classified in the CLC as forests and semi-natural sites and small wetland polygons are either deleted or combined. Such limitations of the CLC for classes with small area sizes were confirmed by Aune-Lundberg and Strand (2020) for Norway. As an example of what a harmonized, distinct wetland class looks like and to better capture Ramsar wetlands, since these are of international importance, all pixels over Ramsar sites were reassigned to a wetland class in the LC2015 and LC2020 before change detection. This partly explains the increasing trend in wetlands between 2015 and 2020. If the CLC dataset is to serve as a reference for annual LC mapping in Switzerland as was done in this study, more complete future mapping of wetland areas is important.

Confusion between grasslands and croplands and between grasslands and otherlands was partly attributed to alternating cover between grasslands and croplands, and between grasslands and otherlands. For example, some farmers by design rotate the use of agricultural lands, whereby land is used interchangeably for cultivation and non-permanent pastures. This trend is confirmed by the *Arealstatistik* as most newly cultivated lands in Switzerland between 1985 and 2018 were mostly natural meadows and farm pastures (BFS, 2021). Distinguishing grassland from other LC types was exceptionally poor in 2019 as this period was drought-stricken with impacts on grass cover (Boergens et al., 2020). Similarly, CLC2000 and CLC2018 had large differences in the classification of otherlands. Possible causes for the differences between these years are variations in grassland and snow cover between the years.

The use of field data for training and validation can further improve the accuracy of the annual LC maps produced from high resolution

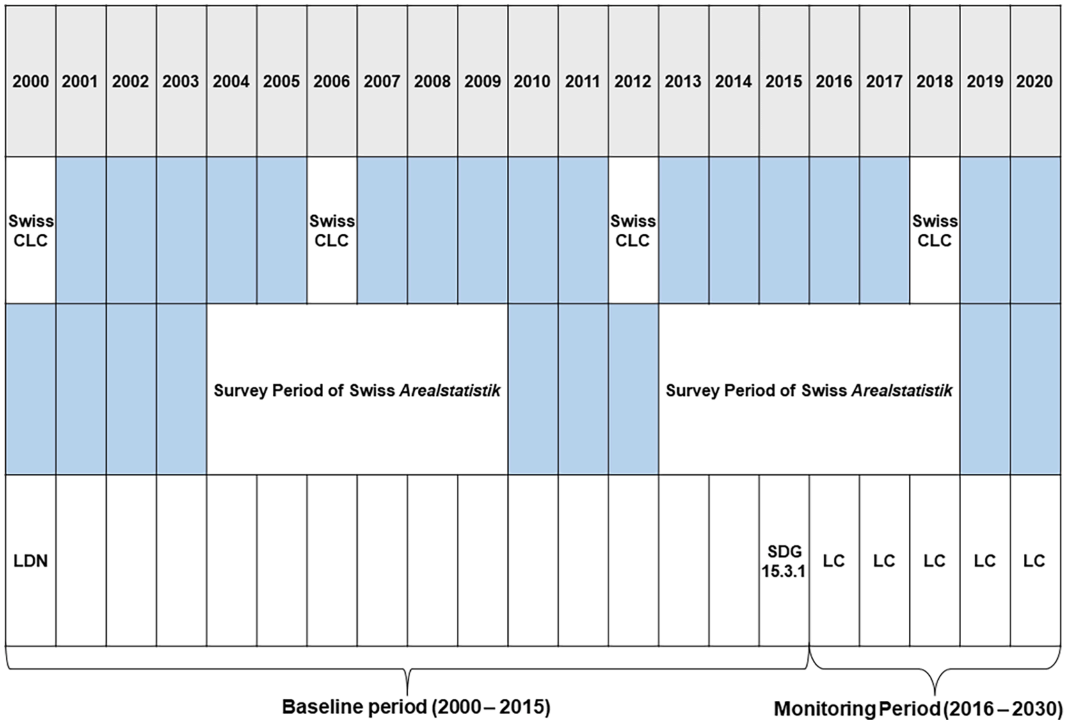

Fig. 7. Comparison of production cycles of the Swiss Corine (CLC) and *Arealstatistik* data with the generated annual land cover data. Years without coverage by either CLC or *Arealstatistik* are signified by the coloured blue boxes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

images. For example, the confusion arising from the alternating covers between grassland and cropland, which are difficult to distinguish and lead to misclassification, can be improved upon with better field data. For the subsequent use of these annual LC products to meet the data needs for operationalizing LDN, ground reference data collected on the field are required to further improve the accuracy of the image classification.

4.2. Land cover change in Switzerland during the reference and monitored periods

In line with trends from the *Arealstatistik* and CLC, natural cover regenerated on croplands and otherlands. The transitions of cropland and otherland to grassland and/or tree-covered areas imply vegetation succession, the former due mainly to agricultural land abandonment (Walther, 1986; Gellrich and Zimmermann, 2007; Price et al., 2015). These trends were confirmed for abandoned alpine pastures and meadows found at higher altitudes, which transitioned first to otherland areas and subsequently to forest (BFS, 2021). There were distinct differences between the reference and the monitored periods. Cropland and otherland conversion to natural cover was lower during the reference (2000–2015) than the monitored period (2015–2020).

By comparing with the *Arealstatistik*, the results obtained provide not only statements about LC and LCC in Switzerland between 2000 and 2020, but also insights into the direction of change for the seven LC categories. Although the LC data generated were validated by comparison with the Swiss Corine and the *Arealstatistik*, the need for field data to better distinguish wetlands, grasslands and croplands is apparent. Steinmeier (2013) documented difficulties in distinguishing grassland from cropland, which necessitated manually correcting the classification for the Swiss Corine dataset. Apparent discrepancies in the *Arealstatistik* with the reference or monitored periods can be partly due to the differences in the periods covered by the survey (1979-1985, 1992-1997, 2004-2009 and 2013 – 2018) and the studied periods (2000 – 2015 and 2015 – 2020).

4.3. Degradation in land cover during the reference and monitored periods

Major trends in LC over Switzerland during the reference period were the expansion of settlement into the cultural landscapes at the expense of mostly cropland and to a lesser degree tree-covered areas. Expanding artificial surfaces into natural and cultural landscapes has the potential to drive land degradation in Switzerland due to its sealing effects on soils. This finding is consistent with the increase in soil sealing across Europe such as in Germany (Wunder and Bodle, 2019), Bosnia and Herzegovina (Solomun et al., 2020), Ukraine and Latvia (Parsova et al., 2019).

We considered the difficulties of distinguishing grasslands from otherlands as grasslands transitioning to otherlands foster degradation in these natural and human-managed ecosystems. This problem in the alpine areas in Europe is partly attributed to erosional processes, especially in unwooded grasslands and pastures (Konz et al., 2010). Other transitions mainly occurring in the Alpine agricultural areas are related to increasing tree-coverered areas at the expense of grasslands. Noting that tree-covered areas are not necessarily forests as this class includes woodlands and shrublands, the increase in wooded vegetation is largely resultant from the less intensive use of alpine meadows and pastures. Studies have found that as livestock pressure reduces, bush encroachment ensues due to overgrowth and eventually the lands are abandoned (Chételat et al., 2013; Snell et al., 2022; Rumpf et al., 2022). Both trends are confirmed by the *Arealstatistik*. An explanation is the decline of alpine pastures as these become bush encroached initially and later shrubs are replaced by larger woods and trees (BFS, 2021). Herzog and Seidl (2018) found negative impacts on summer farming for livestock as Alpine pastures are lost due to shrub overgrowth. However, these bush-encroached areas appear greener and tend to have an increasing trend in Remote Sensing vegetation indices as there is more vegetation cover (Akinyemi et al., 2021; Rumpf et al., 2022). Further studies are needed to examine whether bush and/or woody encroachments such as in the Alpine pastures are desirable or not in the Swiss context. The need to further adapt the LC change criteria to better fit the Swiss context is apparent.

In the LC change criteria of the UNCCD good practice guidance for SDG15.3.1, the assumption is that the waterbody class is stable (Sims et al., 2021). This assumption does not hold in all contexts such as Switzerland where river dynamics were confirmed, especially exchanges with tree-covered areas (BFS, 2021). Reasons include the reappearance of permanent vegetation in places where little or no water reaches, widening of stream channels for ecological reasons and flood control, reopening of artificial stream closures or dam removal (BFS, 2021). Other transitions include grassland conversion into tree-covered areas which is interpreted as regeneration, whereas grassland conversion into otherlands is interpreted as degrading (Sims et al., 2021). If grassland transitions into tree-covered area occurs in cattle-based systems, this can be a degrading process due to increasing non-palatable plant species. It can also be argued that converting grasslands to woodlands is not an improvement because of the negative impacts such transitions can have on biodiversity that is acclimatized to grassland ecosystems. Field-based studies confirm that bush/wood encroachment is degrading with varying effects on biodiversity (Anthelme et al., 2007; Zehnder et al., 2020; BAFU, 2015; Boch et al., 2019). Zehnder et al. (2020) examined the response of plant species diversity to shrub encroachment and found that *A. viridis*, the most frequently occurring shrub species in the prealpine region, severely impaired plant species richness as a low shrub cover.

Focusing on the land cover change dimension of the LDN, this study provides information about degradation in land cover and illustrates the application for both the reference and monitored periods. The operationalization of LDN in Switzerland holds promise to sustainably use the land as LDN seeks to maintain and/or improve the land's productive capacity. Meeting the increasing and often conflicting demand for land requires tailoring current land uses and their subsequent changes to likely future conditions based largely on current and historical trends. To elucidate options for future land uses with the overarching goal of neutrality, it is imperative to focus on not converting more natural surfaces to human settlements and infrastructure, and maintaining the productive capacity of lands, especially in areas where land is already converted to other uses such as agriculture. To sustainably use land-based resources, effecting changes to land uses as policy options ought to support the maintenance of the functioning of ecosystems and land's natural capital.

5. Conclusions

The assessment and monitoring of the SDG15.3.1 indicator, i.e., the proportion of degraded land to total land area, require inputs from three LDN sub-indicators. These are changes to land cover, soil organic carbon stock and land productivity. Focusing on land cover change, the main trend in Switzerland is cultivated land loss to artificial surfaces, e.g., settlements and infrastructure such as roads. The amount of this transition in absolute value was greater during the second observation period (i.e., monitored period from 2015 to 2020) than during the reference period between 2000 and 2015. A benefit of the study is the application of the land cover change criteria for assessing and quantifying land cover degradation in Switzerland. Issues arising include the need to further adapt these criteria to better fit the Swiss context. For example, whether the increase of shrub and tree cover in the Swiss Alpine pastures is beneficial to nature and people or should be interpreted as degrading is still uncertain. It is imperative to better interpret LC transitions as enhancing or degrading ecosystems from a contextual lens.

A major contribution of this study is the development of a Remote Sensing-based method to generate annual data for monitoring land cover using freely available satellite image datasets from the Sentinel missions. This method is complementary to fill the data gaps between the 6-year production cycle of the Swiss Corine and *Arealstatistik* land cover data. The complete reliance on remotely sensed sources for generating ground data for training and validation is a limitation of this study. Remote Sensing data sources to be used when the Swiss Corine and *Arealstatistik* data are not available ought to be field verified. Verification of remotely sensed products with field data collected for the Swiss Corine and *Arealstatistik* will minimize the occurrence of temporal inconsistencies in the land cover time series. For example, a given pixel can be mapped as an artificial surface in the entire 2015–2020 time series, except in one year when it is mapped as cropland. It is imperative to minimize inconsistencies such as artificial surface transitioning to cropland and afterwards to an artificial surface in the time series, especially when information about land cover change is required.

This study offers three commencement points for further studies. First, it contributes to the scientific basis for operationalizing LDN in Switzerland. By adapting the initial land cover change criteria to the Swiss context, future studies can benefit from a coherent and consistent interpretation of land degradation processes. Second, is the need to refine the proposed method for use in mapping annual land cover to cater for the needs of LDN and other application domains. Third, is the urgent need to develop methods for the field verification of LDN estimates as these are still grossly lacking in many countries reporting on LDN and the corresponding SDG 15.3.1 indicator, i.e., the proportion of degraded land to total land area.

CRediT authorship contribution statement

Valentin Bär: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft. **Felicia O. Akinyemi:** Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Chinwe Ifejika Speranza:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Sources of all datasets used are specified in the manuscript and others provided as supplementary information. Datasets are available upon request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110252.

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