Final Report

Towards transitioning to remote sensing based estimates of non-forest tree biomass for the Swiss GHGI: addressing potential forest edge effects

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1 Introduction

Switzerland produces an annual greenhouse gas inventory for the UN Framework Convention on Climate Change and the Kyoto Protocol and describes methods and data in the National Inventory Report (NIR). The inventory is maintained by the Federal Office for the Environment (FOEN) and is subject to the IPCC quality principle of continuous improvement. Within the framework of national climate policy, it is used to verify the reduction target under Article 3 of the CO2 Act (CO2 Ordinance Art. 131). At the Federal Office for the Environment, this work is embedded in the climate reporting process (Performance: 1,013 Containment and management of climate change).

The sector Land Use, Land Use Change and Forestry (LULUCF), in which the sources and sinks of the greenhouse gases carbon dioxide, methane and nitrous oxide are quantified as a result of land use, land use change and forestry, forms part of the greenhouse gas inventory. In non-forest areas, the data basis for estimating the central parameter "tree biomass" is inadequate, and in recent years there has been a push for the development of improved methods to estimate tree biomass on non-forest land.

Recent work (Price et al. 2017) has provided wall-to-wall estimates of living tree biomass for Switzerland based on vegetation height models derived from airborne laser scanning (ALS) data. This model is a raster dataset at 25m resolution and covers both forested and non-forest land use areas. These models offer a significant improvement on the relatively rough estimates of tree biomass for non-forest land used in the current NIR. However, there are a number of open questions on how to incorporate this model into future NIRs/how to transition from current NIR methods to reporting based on the new models. The Swiss National Forest Inventory (NFI) offers detailed information on tree biomass within forest areas, based on extensive fieldwork, and this information has until now informed the reporting for forested land.

The present project addresses the consequences of combining the NFI method on forested land with the wall-to-wall model method on non-forested land, and issues related to the remote sensing based determination of the tree biomass along the forest edge. It primarily serves the continuous improvement of climate reporting. In the future, the results may also contribute to improving the monitoring of emission reduction measures in the land use sector.

2 Current Tree biomass estimates for NIR reporting

The current methods for determining carbon stocks for NIR purposes are differentiated between forested land and non-forested land. The designation of the land use type is based on the Swiss Land Use Statistics dataset (SFSO 2013). The Swiss land-use/land cover statistics consist of point based interpretations of aerial photography for land use and land cover on a 100m grid across Switzerland. The Swiss land use statistics are classified 18 combined land use/land cover types (‘combination categories’ (CCs)), according to Table 6-6 of the Swiss National Inventory Report (FOEN 2020).

On forested land emission factors and carbon stocks are derived from plot level data from the Swiss national forest inventory (FOEN 2020). The values are reported as an average value per hectare in a number of different strata. It is assumed that a forest land use CC point (CCs 11,12 and 13) represent a hectare with 100% forest cover.

On non-forested land, per hectare estimates are derived from best available estimates based on research studies, field surveys and measurements, expert estimates and/or IPCC defaults values where no detailed biomass data is available (FOEN 2020).

3 Problem Description

While the Price et al. (2017) tree biomass model provides wall-to-wall estimates of tree biomass for Switzerland, both inside and outside of forest, it is calibrated with NFI plot data from within forests. It is a modelled representation of the NFI estimates. Using the NFI estimates themselves for NIR reporting on forested CCs is therefore still considered the most appropriate approach to tree biomass estimation within forests. However, for non-forested CCs the Price et al. (2017) tree biomass model can offer an improved estimate over the current NIR estimates.

The extent of forest according to the NFI forest definition is determined in a spatially explicitly manner from the basis of aerial photography independently from the Swiss land use statistics dataset (Waser et al. 2015). The definition of forest area for the Swiss land use statistics (which determines the designation to land use CCs) is slightly different to that of the Swiss NFI, and, given that the Swiss land use statistics are interpreted at points and the NFI forest mask is spatially explicit, therefore inconsistencies can be observed where non-forest CC points are within the NFI forest mask and vice versa. Near forest edges, the 1 hectare 'representative area' of each Swiss land use statistics point will often only be partially covered by forest according to the NFI definition (Figure 1A). In addition, the 1-ha representative areas of non-forest CCs, will often contain some partial coverage of forest (Figure 1B). It is also important to note that the Price et al. (2017) tree biomass model is at a 25m resolution (approximately equivalent to a NFI plot diameter), and as such estimates derived from this model, which are based on where the Swiss land use statistics points intersect with this raster, and have a much smaller representative area. For points outside the forest mask the 25m resolution means less potential overlap with forest edges than the 1 hectare representative area (Figure 1C), but for non-forest points within the forest mask this can mean an inflated estimate of tree biomass if the whole of the 25m pixel is covered by forest despite forest cover of a smaller proportion of the 1 hectare representative area (Figure 1D).

When combining the two methods there is the potential for double accounting of forest biomass at forest edges, if, for example, a non-forest CC point includes a 'corner' of forest (within the 25 x 25m pixel) which would have already been accounted for by the NFI methods.

In addition, there are non-forest CCs areas completely within the NFI forest mask and not at the forest edge, and likewise forest CCs outside of the NFI forest mask, both of which could be either assigned tree biomass values that do not match to what is expected for their land use type or do not match observed (by remote sensing) biomass levels depending on the estimated method used.

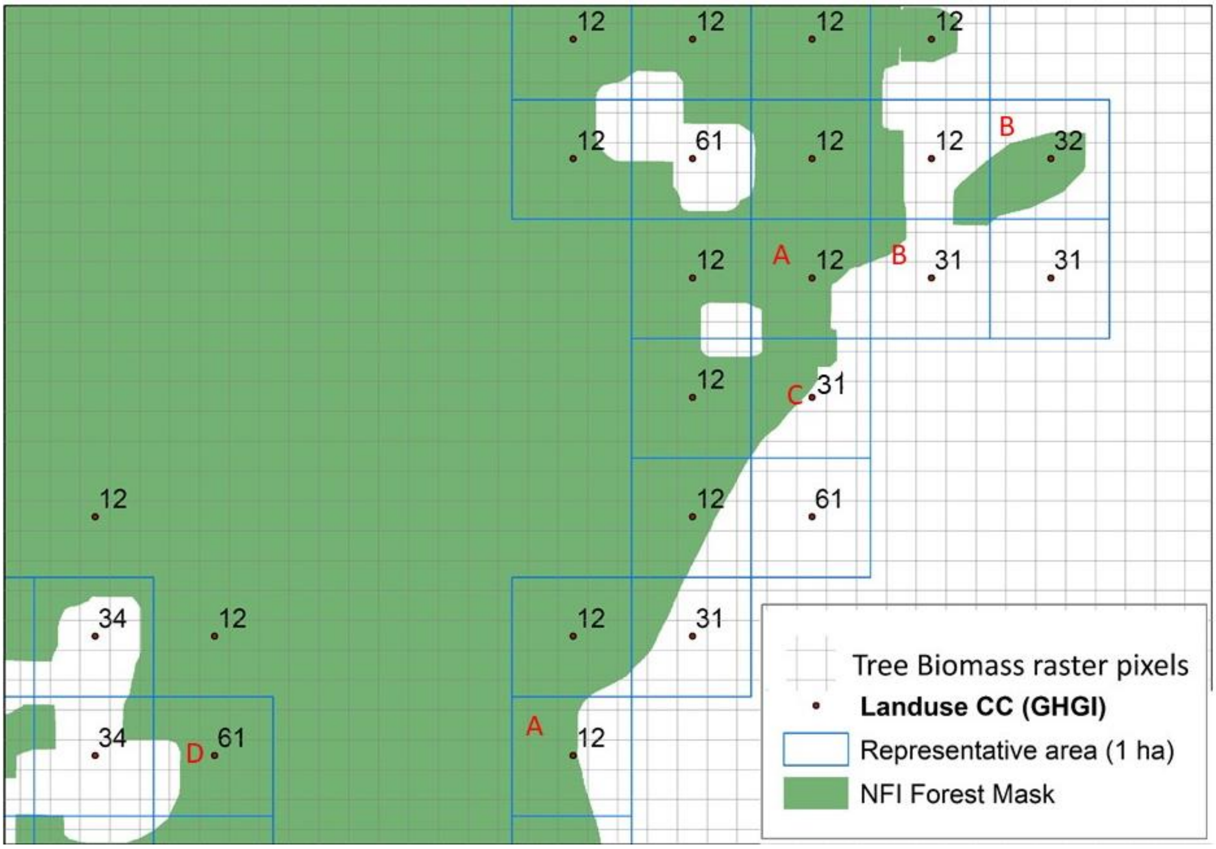

Figure 1: Schematic of forest edge area, showing Swiss land use statistics points within 71m of the forest border, their forest cover and landuse CC and the outline of the 25m pixel footprints for the living tree biomass raster model (Price et al. 2017) , where 12 = Productive Forest, 31 = Permanent Grassland, 32 = Shrub vegetation, 34 = Copse and 61 = Other Land. Red letter A indicates representative area of forest land use CC points at forest edges with partial forest cover, B indicates representative area of non-forest land use CC points near forest edges with partial forest cover, C non-forest land use CCs points with partial forest cover on the 25m pixel of the Price et al. (2017) tree biomass model, D non-forest land use CC points with 100% forest cover on the 25m pixel of the Price et al. (2017) tree biomass model.

4 Aims and Objectives

The aim of the work is to quantify 'edge effects' that may occur when combining the estimates based on the Price et al. (2017) wall-to-wall model (on non-forest land) with the NFI terrestrial based estimates for forested land. Does use of the two different methods result in 'double accounting'/'non-accounting' of tree biomass?

Following discussions amongst the expert group involved with the FOEN funded projects 'REFEWOODLAND' and 'REFETREE', the suggested method to combine the different approaches for forested land and non-forested land is to use the Price et al. (2017) tree biomass model to estimate biomass for non-forest trees (biomass for trees in forest areas would continue to be estimated using NFI methods). The NFI forest mask would be used to mask all forest areas from the Price et al. (2017) tree biomass model (effectively assigning the forest mask area a non-forest tree biomass value of 0), theoretically resulting in a model for only non-forest trees. From this model the average per hectare tree biomass and the total tree biomass per land use combination category (CC) could be calculated. These results can then be compared to results from using the model without masking to see to what extent tree biomass could be double counted.

Due to different definitions of forest and methods for assigning the landuse type and inaccuracies in the forest mask, there are areas of non-forest CC which fall within the NFI forest mask. Using the above masking approach, these areas will also be assigned 0 tree biomass. Thus, the tree biomass at these points will not be accounted for. The areas of forest CCs which fall outside of the forest mask could potentially compensate for this biomass. This project will therefore also determine the amounts of tree biomass on non-forest CCs within the forest mask and forest CCs outside the forest mask and discuss the best approach to avoid both double counting of tree biomass or unaccounted for tree biomass.

In addition, WSL also produces vegetation height models derived from stereo-aerial imagery, updated at regular intervals in alignment with the ongoing cyclical (6 yearly) capture of aerial imagery (Ginzler and Hobi 2015). Wall-to-wall models of living tree biomass are also available for several time steps on the basis of this data. Swisstopo is currently undertaking a Swiss-wide capture of new, high point density aerial laser scanning data, although with no stated intention of regular recapture/update of the dataset. This dataset could provide an up-to-date, more consistent and more detailed ALS dataset as a basis for a living tree biomass model than that used in Price et al. (2017). This new ALS dataset is already available for some areas of Switzerland (north-eastern and western Switzerland, Figure 2).

Given the availability of the two alternative sources of vegetation height information to the Price et al. (2017) base data, an additional aim of this proposed work is to compare the total land use CC living woody biomass estimates across the three data sources: Price et al. (2017); the latest stereo-aerial imagery VHM for the whole of Switzerland; and the new Swisstopo ALS capture for the available data areas of western and north-eastern Switzerland.

5 Project components

5.1 Quantification of land use CC inside and outside of forest

The Swiss forested area is defined by different methods for the NFI forest mask than for the land use CCs, (which are based on the Swiss land use statistics, a statistical data set derived from point interpretation of aerial imagery). As such, there is likely a number of land use CC points identified as forest outside the forest mask, and a number of non-forest land use CC points inside the forest mask.

Product: Quantification of forest land use CCs outside forest mask and vice versa

5.2 Living tree biomass model for non forest areas only

The Swiss-wide ALS data (2001-2014 data, as per Price et al. 2017), will be masked to the non-forest areas using the NFI forest mask. The Price et al. (2017) models for living tree biomass will then be applied to the resulting dataset

Product: Model of living tree biomass for non-forest area of Switzerland.

5.3 Quantification of average and total living tree biomass per non-forest land use CC

The land use CC dataset will be intersected with the modelled non-forest living wood biomass layer to determine a total and average per ha living tree biomass for each land use CC type. This will then be compared with the Price et al. (2017) results in order to achieve a quantification of edge effects, including a breakdown by land use CCs and coarser land use categories.

Product: Per land use CC quantification of living non-forest tree biomass, Quantitative comparison between masked methodology and Price et al. (2017) results

5.4 Comparison of results for different base datasets

A model of above ground tree biomass models based on the VHM derived from aerial stereo imagery (2011-2016) has previously been developed in the context of the Swiss NFI (Price et al. 2020), this model will be updated to reflect living tree biomass (including roots). Using the available new Swisstopo ALS data a new model will be created for North-eastern and western Switzerland (also masked to non-forest area with the NFI forest mask). The total non-forest living tree biomass estimates will be calculated and compared across the different base datasets, with breakdown by land use CCs.

<u>Product:</u> Living tree biomass models based on aerial imagery and based on new ALS data capture for north eastern Switzerland and Western Switzerland (see Figure 2).

<u>Product:</u> Quantitative comparison of average and total living tree biomass estimates per land use CC between, Swisswide ALS based model, Swisswide stereo-aerial imagery based model and new Swisstopo ALS based model (for the currently available areas)

6 Data

The **Swiss land-use/land cover statistics** consist of point based interpretations of aerial photography for land use and land cover on a 100m grid across Switzerland. The interpretation is generally for the point location only, and the Swiss land use statistics are not spatially explicit. However, for practical purposes, within the NIR each of the Swiss land use statistics points have been considered to be representative of a 1 hectare area, with the point at its centre. A complete Swiss wide land use statistics dataset has been developed for three time periods with a periodicity of 12 years: 1979-1985, 1992-1997 and 2004-2009 (SFSO, 2013a), the interpretation of the fourth time step (2013-2018) is partially complete and available (Figure 2). The Swiss land use statistics are classified 18 combined land use/land cover types (‘combination categories’ (CCs)), according to Table 6-6 of the Swiss National Inventory Report (FOEN 2020).

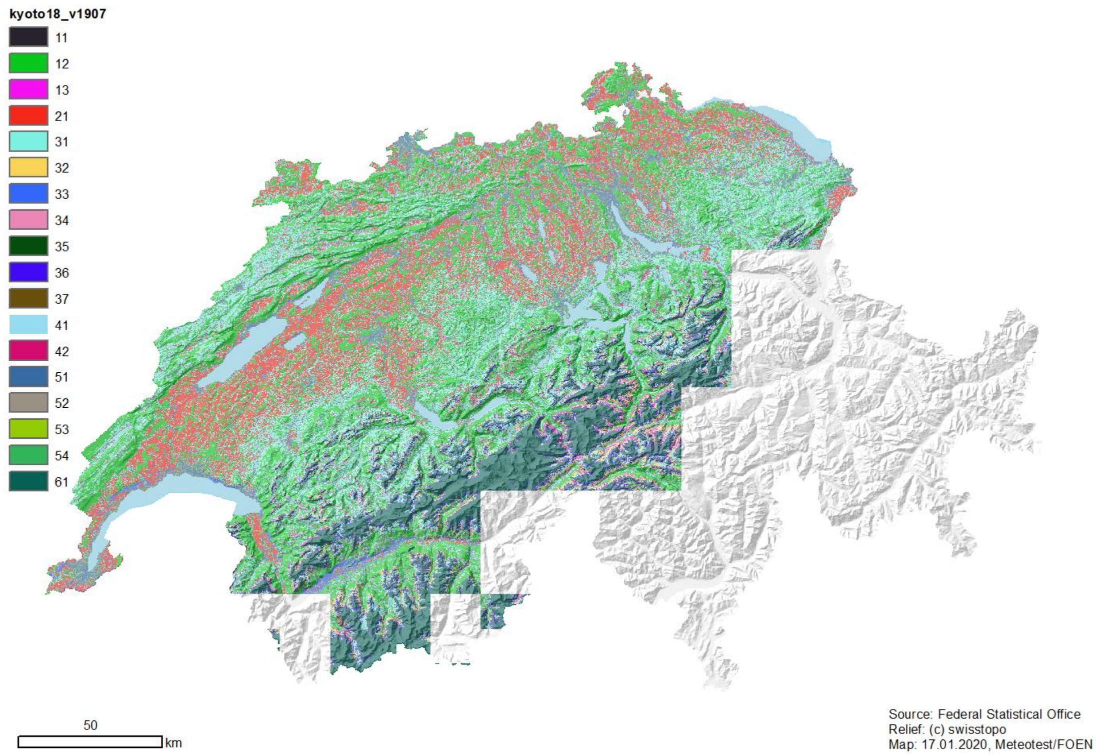

Figure 2: Current area of available data for Swiss Land Use Statistics 4

The **Price et al. (2017) model of living tree biomass** is derived from ALS data captured through a variety of projects with differing specifications across the time period 2001-2014, excluding high elevation areas above approximately 2000 m.a.m.s.l. The model is a spatially explicit generalised linear model with explanatory variables being metrics derived from the ALS vegetation height (average height and standard deviation of height) and elevation at 25m resolution. The response variable of this dataset is living tree biomass (including roots) measured in tonnes per hectare. The spatial resolution of the raster dataset is 25m, which most closely represents the 25m plot diameter of the NFI plot data that forms the training data for the model. Although the spatial resolution is 25m, the response variable is T tree biomass per hectare and as such the value for any given pixel is not the total biomass in the pixels' footprint on the ground but a representation of what the tree biomass per hectare value would be for a sample point falling within that pixel.

Vegetation height models (VHMs) have been derived from stereo aerial imagery in–house at WSL for various time periods. Within the framework on the Swiss NFI, models of above ground tree biomass have been created for 4 time steps associated with the four instances of the Swiss NFI. The most recent model was adjusted slightly to the response variable of living tree biomass (including tree roots) and using imagery from 2010-2015 for this project (Ginzler and Hobi (2015)). The modelling methodology is very similar to that used for the ALS model and the same as described in Price et al. (2020). The model is a spatially explicit generalised linear model with explanatory variables being metrics derived from the stereo-imagery vegetation height (average height and canopy cover) and elevation at 25m resolution.

The **current Swisstopo ALS acquisition** campaign will have the following specifications: No foliage or snow during acquisition to facilitate ground information and production of a digital terrain model, minimum point density of 5 pts/m2, and mean density around 15-20 pts/m2, Classification: unclassified, ground, vegetation, buildings, water, bridges, Planimetric accuracy: 20 cm (1 sigma), Altimetric accuracy: 10 cm (1 sigma). (Swisstopo: https://www.swisstopo.admin.ch/en/knowledge-facts/geoinformation/lidar-data.html). The timing of acquisition is shown in Figure 3.

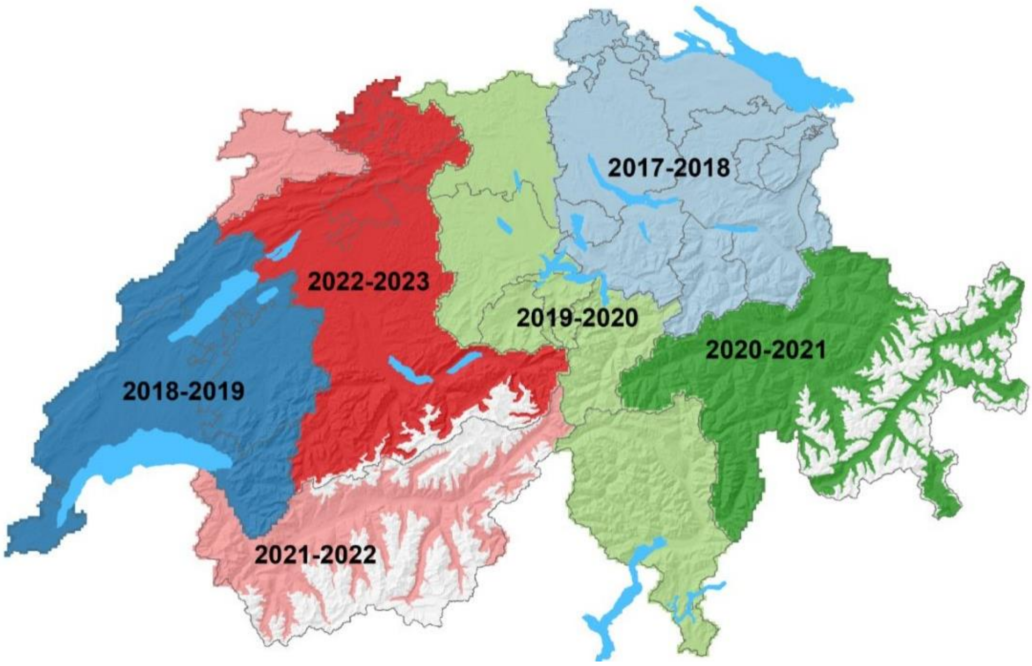

Figure 3: ALS data acquisition campaign timetable, spread over a six-year period. Currently available data areas are those in pale blue and dark blue. Source: Swisstopo https://www.swisstopo.admin.ch/en/knowledge-facts/geoinformation/lidar-data.html

The **tree biomass model** derived from this **new Swisstopo ALS** data is also derived using a generalised linear modelling approach, with vegetation height metrics derived for 25m pixels. This ALS data has a higher point density than that used in the Price et al. (2017) model, and additional vegetation metrics which could be valuable for predicted tree biomass could be calculated, such as green volume (calculated as mean vegetation height per 25m pixel multiplied by canopy cover per 25m pixel) and number of vegetation voxels. However, to allow comparison with the other models we have used the same predictor variables of Elevation, average tree (where a tree is vegetation over 3m tall) height, standard deviation in tree height, and canopy cover per 25m pixel.

The **Swiss NFI forest mask** is derived from the stereo-imagery based VHM, and defines forest according to the Swiss NFI definition as an area of cover of trees over 3 m in height at least 50 m wide and with greater than 20% projected crown cover. This forest mask will be used to define forest and non-forest area in the proposed work. The forest mask is available in vector format and in raster format at 10m resolution raster version of the forest mask was used. The vector version of the forest mask as used to determine whether a landuse CC point is either within or outside of the NFI forest mask. The 10m resolution raster forest mask was resampled to 25m resolution in order to mask the forest area from the 25m resolution tree biomass model.

7 Methods and Results

7.1 Quantification of land use CC classes inside and outside of forest

A point dataset on a 100m grid covering the whole of Switzerland was created by combining the available data from the 4th edition of the Swiss land use statistics (Figure 2), and filling any gaps with the data from the 3rd edition of the Swiss land use statistics. The classification to the NIR land use combination categories was provided by Beat Rihm of Meteotest and is according to Table 6-6 of the Swiss National Inventory report (FOEN 2020). The point data set was intersected with the vector version of the NFI Forest mask using the software ArcGIS version 10.8 and the number of points inside and outside the forest mask and per land use CC were tallied. In addition, two buffers were created around the NFI forest mask, 100m and a negative 100m (internal buffer) in order to provide an initial picture of how many points are close to the forest edge (Table 1a and b).

The points were also overlaid on the ALS based Tree biomass model (Price et al. 2017) to gain a value of tree biomass for each point. To obtain the mean and total tree biomass per land use combination category, a sum and mean value of these point values was calculated per land use CC using ArcGIS's summary statistics function (Table 2a and b).

The available ALS data as used to produce the Price et al. (2017) tree biomass model does not offer complete wall-to-wall coverage of Switzerland, elevations above approximately 2000 m.a.m.s.l were not flown and result in 'NoData' areas, also water bodies are no data areas. For some land use classes, i.e., water bodies, calculating a mean biomass value only over the area of present data results in an inflated average tree biomass per hectare values, as such, for the Price et al. (2017) model, an assumption was made which assumed that areas of NoData had no tree biomass for the non-forest land use CCs. For Forest CCs (11, 12, and 13) it was assumed that no data areas can be excluded from the calculation of average biomass per hectare.

Table 1a: Swiss land use statistics points inside and outside the NFI-forest mask, and within 100 m of the forest edge by NIR land use combination category (CC). The Swiss land use statistics data is a combination of the available data from the 4th time step, in-filled with data from the 3rd time step where newer data are not yet available

Land use CC code	**Land use CC name**	**no. points outside forest**	**no. points inside forest**	**Total points (ha)**	**% in NFI Forest**	**within 100m of forest edge**	**% within forest + 100m**	**% within forest - 100m**
11	Afforestations	277	349	626	55.75	244	94.73	
12	Productive forest	45689	1093514	1139203	95.99	44395	99.89	
13	Unproductive forest	63065	43812	106877	40.99	44331	82.47	
21	Cropland	389428	1098	390526	0.28	598		0.13
31	Permanent Grassland	897245	30438	927683	3.28	14908		1.67
32	Shrub vegetation	138191	14952	153143	9.76	6250		5.68
33	Vineyards, low stem Orchards Tree Nurseries	24778	500	25278	1.98	368		0.52
34	Copse	54355	17754	72109	24.62	9902		10.89
35	Orchards	1052	266	1318	20.18	234		2.43
36	Stony Grassland	148673	4245	152918	2.78	1390		1.87
37	Unproductive grassland	59982	2204	62186	3.54	862		2.16
41	Surface waters	158798	2574	161372	1.60	870		1.06
42	Unproductive wetland	24094	1509	25603	5.89	825		2.67
51	Buildings and Constructions	203713	8810	212523	4.15	3985		2.27
52	Herbaceous biomass in settlements	78249	2004	80253	2.50	1146		1.07
53	Shrubs in settlements	3350	624	3974	15.70	350		6.89
54	Trees in settlements	26185	2241	28426	7.88	1679		1.98
61	Other land	572329	11104	583433	1.90	3193		1.36
		2889453	1237998	4127451	29.99			

Table 1b: Swiss land use statistics points inside and outside the NFI-forest mask, and within 100 m of the forest edge by aggregated NIR land use combination category (CC). The Swiss land use statistics data is a combination of the available data from the 4th time steps, in-filled with data from the 3rd time step where newer data are not yet available

Landuse CC code	**Land use CC name**	**no. points outside forest**	**no. points inside forest**	**Total**	**% in NFI Forest**	**within 100m of forest edge**	**% within forest + 100m**	**% within forest - 100m**
1X	Forest	109031	1137675	1246706	91.25	88970	98.39	
2X	Cropland	389428	1098	390526	0.28	598		0.13
3X	Grassland and Agriculture	1324276	70359	1394635	5.04	33914		2.61
4X	Water and wetlands	182892	4083	186975	2.18	1695		1.28
5X	Settlements	311497	13679	325176	4.21	7160		2.00
6X	Other land	572329	11104	583433	1.90	3193		1.36
		2889453	1237998	4127451	29.99			

Table 2a: Total and mean tree biomass inside and outside of the NFI forest mask by NIR land use combination category (CC), according to Price et al. 2017 Tree biomass model

landuse CC code	Land use CC name	Tree biomass outside forest (T)	Tree biomass inside forest (T)	Tree biomass outside forest Avg T/ha (T C / ha)	Tree biomass inside forest Avg T/ha (T c/ha)
11	Afforestations	17 196	26 443	62.3 (31.2)	79.4 (39.7)
12	Productive forest	7 317 460	255 046 047	162.0 (81.0)	233.9 (117.)
13	Unproductive forest	2 978 699	4 009 097	48.8 (24.4)	92.1 (46.4)
21	Cropland	6 810 241	134 129	17.5 (8.08)	122.2 (61.1)
31	Permanent Grassland	24 108 196	3 790 556	26.9 (13.5)	124.5 (62.3)
32	Shrub vegetation	1 325 074	1 115 075	9.59 (4.80)	74.5 (37.3)
33	Vineyards, low stem Orchards, Tree Nurseries	678 190	44 953	27.4 (13.7)	89.9 (45.0)
34	Copse	4 294 736	2 026 416	79.0 (39.5)	114.1 (57.1)
35	Orchards	55 497	18 745	52.8 (26.4)	70.5 (35.3)
36	Stony Grassland	597 728	356 948	4.0 (2.00)	84.1 (42.1)
37	Unproductive grassland	534 344	225 790	8.9 (4.45)	102.4 (51.2)
41	Surface waters	1 734 201	378 265	10.9 (5.45)	147.0 (73.5)
42	Unproductive wetland	810 724	188 872	33.6 (16.8)	125.2 (62.6)
51	Buildings and Constructions	11 708 558	1 487 069	57.5 (28.8)	168.8 (84.4)
52	Herbaceous biomass in settlements	4 502 233	281 857	57.5 (26.8)	140.7 (70.4)
53	Shrubs in settlements	207 834	72 107	62.0 (31.0)	115.6 (57.8)
54	Trees in settlements	2 362 471	326 037	90.2 (45.1)	145.5 (77.8)
61	Other land	2 126 772	1 211 978	3.7 (1.86)	109.2 (54.6)

Table 2b: Total and mean tree biomass inside and outside of the NFI forest mask by aggregated NIR land use combination category (CC), according to Price et al. 2017 Tree biomass model

Landuse CC code	Land use CC name	Tree biomass outside forest (T)	Tree biomass inside forest (T)	Tree biomass outside forest Avg T/ha (T C / ha)	Tree biomass inside forest Avg T/ha (T c/ha)
1X	Forest	10 313 355	259 081 588	95.6 (47.3)	227.7 (113.9)
2X	Cropland	6 810 241	134 130	17.5 (8.80)	122.2 (61.1)
3X	Grassland and Agriculture	31 593 765	7 578 484	23.9 (11.9)	107.7 (53.9)
4X	Water and Wetlands	2 544 926	567 137	13.9 (7.00)	138.9 (69.5)
5X	Settlements	18 781 096	2 167 072	60.3 (30.2)	158.4 (79.2)
6X	Other land	2 126 772	1 211 978	3.7 (1.86)	109.2 (54.6)

7.2 Living tree biomass model for non forest areas only

The NFI forest mask was resampled to a 25m resolution raster, snapped to the 25m resolution tree biomass raster with the centre of the raster cell being at the land use CC point location. A raster calculation was then performed which assigned all pixels within the forest mask area the value of 0 tree biomass and all other pixels the same value of tree biomass as the Price et al. (2017) model.

7.3 Quantification of average and total living tree biomass per non-forest land use CC

To determine to what extent the total area of forest differs between the Swiss land use statistics 'representative area' approach and the NFI forest mask, all points with 71m of a forest edge were identified (71m is the maximum distance that a point can lie from the forest edge and it's representative area intersect with the forest edge line). To determine forest cover according to the NFI forest mask, for each point the total area of forest cover according to the vector version of the NFI forest mask within the 1 hectare representative area is calculated (Table 3a and b). In the 'representative area' approach it is assumed that all points with a forest land use CC (CCs 11,12 and 13) have 100% forest cover (= 1 hectare per point), and all other land use CCs have 0 forest cover.

The land use CC points were overlaid on the non-forest Tree biomass model (i.e. forest area assigned 0 tree biomass) to gain a value of non-forest tree biomass for each point. To obtain the mean and total non-forest tree biomass per land use combination category, a sum and mean value of these point values was calculated per land use CC using ArcGIS's summary statistics function (Table 4a and b).

Table 3a: Forested area for landuse CC points near forest edges and their 1 hectare ‚representative areas'

Land use CC code	Land use CC name	Assumed forest cover for forest edge point Swiss NIR 2020	NFI forest mask forest cover
11	Afforestations	520	274
12	Productive forest	**462327**	**346949**
13	Unproductive forest	70571	30925
21	Cropland	*0*	8052
31	Permanent Grassland	*0*	72564
32	Shrub vegetation	*0*	15358
33	Vineyards, low steam Orchards, Tree Nurseries	*0*	1038
34	Copse	*0*	14660
35	Orchards	*0*	199
36	Stony Grassland	*0*	4396
37	Unproductive grassland	*0*	2648
41	Surface waters	*0*	3914
42	Unproductive wetland	*0*	2740
51	Buildings and Constructions	*0*	11061
52	Herbaceous biomass in settlements	*0*	3668
53	Shrubs in settlements	*0*	662
54	Trees in settlements	*0*	2209
61	Other land	*0*	10321
	Total	**533418**	**531637**
	Difference	**1781**	

Table 3b: Forested area for landuse CC points near forest edges and their 1 hectare ‚representative areas‘

Land use CC code	Land use CC name	Assumed forest cover for forest edge point Swiss NIR 2020	NFI forest mask forest cover
1X	Forest	533418	378148
2X	Cropland	0	8052
3X	Grassland and Agriculture	0	110862
4X	Water and Wetlands	0	6654
5X	Settlements	0	17599
6X	Other land	0	10321

Table 4a: Total tree biomass for non-forest NIR Landuse Combination categories, after first masking all areas of forest trees with the NFI forest mask (Forest areas are masked to 0 tree biomass, and assumed accounted for separately in the NFI based calculations for average forest land biomass), compared to the unmasked results from Table 2.

landuse CC code	Land use CC name	Non-forest Tree biomass (T) with mask	Non-forest Tree biomass (T) without mask
21	Cropland	6 760 083	6 944 370
31	Permanent Grassland	22 105 378	27 898 752
32	Shrub vegetation	1 227 422	2 440 149
33	Vineyards, low stem Orchards, Tree Nurseries	672 232	723 143
34	Copse	4 019 991	6 321 152
35	Orchards	52 537	74 242
36	Stony Grassland	564 593	954 676
37	Unproductive grassland	504 266	760 134
41	Surface waters	1 604 793	2 112 466
42	Unproductive wetland	743 962	999 596
51	Buildings and Constructions	11 455 827	13 195 627
52	Herbaceous biomass in settlements	4 439 539	4 784 090
53	Shrubs in settlements	200 154	279 941
54	Trees in settlements	2 306 811	2 688 508
61	Other land	2 012 671	3 338 750
Total		58 670 259	73 515 596

Table 4b: Total and average tree biomass for non-forest aggregated NIR land use Combination categories, after first masking all areas of forest trees with the NFI forest mask (Forest areas are masked to 0 tree biomass, and assumed accounted for separately in the NFI based calculations for forest land)

Landuse CC code	Land use CC name	Non-forest Tree biomass (T) with mask	Non-forest Tree biomass (T) without mask
2X	Cropland	6 760 083	6 944 370
3X	Grassland and Agriculture	29 146 419	39 172 248
4X	Water and Wetlands	2 348 755	3 112 062
5X	Settlements	18 402 331	20 948 166
6X	Other land	2 012 671	3 338 750
Sum		58 670 259	73 515 596

7.3.1 Double counting or non-accounting of biomass with combined dataset approach

Table 1 shows us that the area of NIR forest (points with landuse CCs 11, 12 and 13) that falls outside the NFI forest mask (109,031 hectares) is relatively similar to the area of NIR non-forest (all other and use CCs) that fall within the NFI forest mask (100,323 hectares). Therefore, on the basis of area, we could make a broad assumption that these 'misclassifications' cancel each other out. However, if we are considering a remote sensing based, spatially explicit model to estimate tree biomass for non-forest land use CCs, the spatial variation in the biomass is important. The value of tree biomass per hectare within the NFI forest mask could be assumed to be higher than the value for a hectare outside of the forest mask. Table 2 shows that according to the Price et al. (2017) model, Forest tree biomass outside the forest mask sums to 10,313,355 T Biomass, while non-forest tree biomass inside the forest mask sums to 11,658,797 T Biomass, a difference of 1,345,442 T biomass in the favour of forest areas.

Looking in detail at the issue of forest edges, non-forest points outside forest but near forest edges will sometimes include small areas of forest biomass ('corners') that fall into the area of the 25m pixels of the tree biomass model (Figure 1C). These areas inflate the estimates of non-forest tree biomass for these land use points by including this forest tree biomass. From Table 3, we can see that the assumed area of forest cover along forest edges according to the NIR landuse CCs (from the Swiss land use statistics) is almost the same as the area of forest cover according to NFI forest mask. Table 5 shows us the sum and mean per hectare value of tree biomass for this area of non-forest points close to forest edges, i.e. with partial forest cover (total for edge points both inside and outside the forest mask).

Table 5: Tree biomass on the forested portions of the 25m pixels of non-forest landuse CC points near forest edges

landuse CC code	Land use CC name	Non-forest Tree biomass at forest edges (T) unmasked Avg T/ha (T C / ha)	Non-forest Tree biomass at forest edges (T) unmasked	Non-forest Tree biomass at forest edges (T) masked Avg T/ha (T C / ha)	Non-forest Tree biomass at forest edges (T) masked
21	Cropland	74.91	5 214 630	33.58	2 337 378
31	Permanent Grassland	46.21	3 167 151	43.59	2 987 388
32	Shrub vegetation	61.02	21 481 063	48.48	17 067 851
33	Vineyards, low stem Orchards, Tree Nurseries	40.01	1 900 861	22.19	1 054 353
34	Copse	52.03	314 967	38.54	233 310
35	Orchards	99.24	4 267 890	55.97	2 407 063
36	Stony Grassland	65.19	45 371	38.05	26 483
37	Unproductive grassland	41.51	616 028	24.48	363 264
41	Surface waters	50.69	485 416	32.93	315 340
42	Unproductive wetland	83.55	1 185 226	62.64	888 674
51	Buildings and Constructions	63.14	748 971	46.65	553 437
52	Herbaceous biomass in settlements	84.16	4 113 924	60.68	2 966 179
53	Shrubs in settlements	78.43	1 467 801	63.46	1 187 543
54	Trees in settlements	85.61	170 365	54.24	107 937
61	Other land	111.78	967 769	75.29	651 868
	Total		42 515 328		31 670 537

Let's assume that a) non-forest areas within the forest mask and b) forested corners of non-forest pixels are already compensated for by a) forest areas outside of the forest mask and b) forest points that are close to forest edges and have missing 'corners' of (forest) tree biomass. Then, when combining the NFI and spatially explicit model based estimates, there is a potential for double counting of this forest biomass, since it would be counted in both estimates. This double counting potential can be estimated as the total value of tree biomass for non-forest land use CCs from the non-masked model minus the total value estimated with the masked model (Table 4), which comes to a total of **14,845,337 T tree biomass** for all land use classes across Switzerland (11,658,797 T inside the forest mask and 3,186,460 T outside the forest mask). Non-forest points within the mask will not be accounted for with the NFI methods, since those methods are not spatially explicit and calculated as an average value of biomass per forest type and strata, but are only assigned spatially using the land use CCs derived from the Swiss land use statistics.

Using the NFI forest mask to mask out areas of forest trees, with the assumption that then only non-forest trees will be included in the biomass estimates for non-forest, we avoid any potential double counting of this forest biomass. However, to compensate for the biomass occurring on non-forest CCs within the forest we then also assume that the biomass estimates for forest CCs that occur outside the forest mask will be equivalent to this 14.8 million T biomass. As discussed above and shown in Table 1 and 3, the area of these points is compensated by the area of forest CCs outside of the forest mask. The question arises of whether the biomass estimates are also equivalent. This depends on how tree biomass is estimated on these points. Since they are forest CCs according to the Swiss land use statistics they could be assigned the NFI estimates by forest type and strata (Table 6-4 and 6-18 from Switzerland's National Inventory report, FOEN 2020). This method would result in **16,141,496 T** biomass on forest CCs outside the forest mask (a difference of 1,296,159 T biomass compared to the non-forest biomass within the forest mask). However, if we continue with the assumption that the forest boundary is defined by the NFI forest mask, given that these points fall outside the forest mask, it may be logical to assign these points the biomass values from the spatially explicit model. This approach would result in **10,313,355 T** biomass (Table 2, a difference of -4,531,982 T biomass compared to the non-forest biomass within the forest mask).

7.4 Comparison of results for different base datasets

The modelling of tree biomass based on the aerial imagery and on the new ALS data, was conducted using the same methodology and explanatory variables (average height above 3m, standard deviation of height, canopy cover and elevation for 25m pixels) as with the older ALS based models described in Price et al. (2017). The model performance for the aerial imagery model and the new ALS model is shown in Table 6., as well as that for the best performing linear model using the new ALS data incorporating vegetation voxels.

Table 6: Model performance for living tree biomass models based on aerial imagery and the new Swisstopo ALS data. Stratification by elevation strata did not improve the performance of the aerial imagery model and was not used for the final model which instead included elevation as an explanatory variable.

Model	**0-600 m**		**600-1200 m**		**>1200**	
	R-sq	**RSME**	**R-sq**	**RSME**	**R-sq**	**RSME**
Aerial imagery VHM 2015	0.52			101.3		
New ALS data (variables as Price et al. 2017)	0.50	127.3	0.55	111.6	0.44	114.6
New ALS data with vegetation voxels	0.57	116.74	0.55	111.1	0.51	106.2

As with the methodology described above for the Price et al. (2017) ALS based tree biomass model (Price et al. 2017), the land use CC points were also overlaid on the aerial imagery based model to gain a value of tree biomass for each point. To obtain the mean and total tree biomass per land use combination category, a sum and mean value of these point values was calculated per land use CC using ArcGIS's summary statistics function (Table 7a and 7b).

Within the area of available new Swisstopo ALS data (blue shaded areas in Figure 3), we compared to outputs of the three models (Price et al. 2017, Stereo aerial imagery VHM and new ALS), with the same point overlay and summary statistics method as described above (Figure 4, Table 8a and 8b).

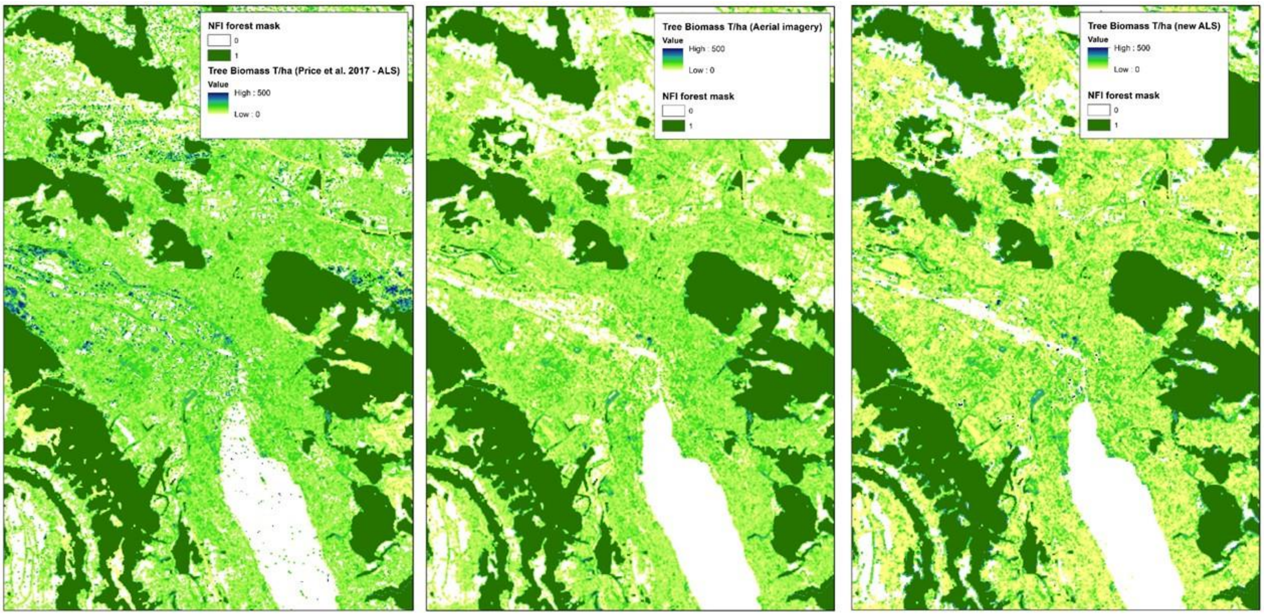

Figure 4. Living tree biomass within the Zurich area as modelled based on: left: the original Swiss ALS data set according to Price et al. (2017), centre: The stereo aerial imagery VHM, right: The new Swisstopo ALS capture. Dark green areas are the Swiss NFI forest mask.

Table 7a: Total and average tree biomass according to the aerial-imagery derived model (VHM 2015) for non-forest NIR Landuse Combination categories (Combination of Swiss land use statistics 3 and 4), after first masking all areas of forest trees with the NFI forest mask (Forest areas are masked to 0 tree biomass, and assumed accounted for separately in the NFI based calculations for average forest land biomass), compared to ALS derived Price et al. 2017 estimates

landuse CC code	Land use CC name	Aerial imagery Tree biomass outside forest (T)	Aerial imagery Tree biomass outside forest Avg T/ha (T C / ha)	Price et al. 2017 Tree biomass outside forest (T) with mask	Price et al. 2017 Tree biomass outside forest Avg T/ha (T C / ha) with mask
21	Cropland	2 220 343	5.7 (2.9)	6 760 083	17.4 (8.70)
31	Permanent Grassland	19 482 066	21.7 (10.9)	22 105 378	24.6 (12.3)
32	Shrub vegetation	3 842 455	27.8 (13.9)	1 227 422	8.8 (4.44)
33	Vineyards, low stem Orchards, Tree Nurseries	276 918	11.2 (5.60)	672 232	27.1 (13.6)
34	Copse	6 091 281	112.1 (56.1)	4 019 991	74.0 (37.0)
35	Orchards	50 334	47.9 (24.0)	52 537	49.9 (25.0)
36	Stony Grassland	3 215 891	21.3 (10.7)	564 593	3.8 (1.90)
37	Unproductive grassland	1 590 997	26.5 (13.3)	504 266	8.4 (4.2)
41	Surface waters	1 008 498	6.35 (3.18)	1 604 793	10.1 (5.1)
42	Unproductive wetland	662 725	27.5 (13.8)	743 962	30.9 (15.5)
51	Buildings and Constructions	6 587 495	32.3 (16.2)	11 455 827	56.2 (28.1)
52	Herbaceous biomass in settlements	3 101 469	39.6 (19.8)	4 439 539	56.7 (23.4)
53	Shrubs in settlements	147 722	44.1 (22.1)	200 154	59.7 (29.8)
54	Trees in settlements	2 420 313	92.4 (46.2)	2 306 811	88.1 (44.1)
61	Other land	6 210 473	10.9 (4.45)	2 012 671	3.5 (1.75)

Table 7b: Total and average tree biomass according to the aerial-imagery derived model for non-forest aggregated NIR land use combination categories (Combination of Swiss land use statistics 3 and 4), after first masking all areas of forest trees with the NFI forest mask (Forest areas are masked to 0 tree biomass, and assumed accounted for separately in the NFI based calculations for average forest land biomass), compared to ALS derived Price et al 2017 estimates

Landuse CC code	Land use CC name	Aerial imagery Tree biomass outside forest (T)	Aerial imagery Tree biomass outside forest Avg T/ha (T C / ha)	Price et al. 2017 Tree biomass outside forest (T)	Price et al. 2017 Tree biomass outside forest Avg T/ha (T C / ha)
2X	Cropland	2 220 343	5.7 (2.9)	6 760 083	17.4 (8.70)
3X	Grassland and Agriculture	34 549 945	26.1 (13.1)	29 146 419	22.0(11.0)
4X	Water and Wetlands	1 671 223	9.14 (4.6)	2 348 755	12.8(6.42)
5X	Settlements	12 257 001	39.3 (19.7)	18 402 331	59.1 (29.5)
6X	Other land	6 210 473	10.9 (4.45)	2 012 671	3.5 (1.75)

Table 8a: Comparison of total and average tree biomass according to the Price et al. 2017 ALS model, the aerial-imagery derived model and the new Swisstopo ALS model within the area of available new ALS data (Figure 3) for non-forest NIR Land use Combination categories

Land use CC code	Land use CC name	Price et al. 2017 Tree biomass outside forest (T)	Price et al. 2017 Tree biomass outside forest Avg T/ha (T C / ha)	Aerial imagery Tree biomass outside forest (T) with mask	Aerial imagery Tree biomass outside forest Avg T/ha (T C / ha) with mask	New ALS Tree biomass outside forest (T)	New ALS Tree biomass outside forest Avg T/ha (T C / ha)
21	Cropland	3 805 207	22.23	936 769	5.47	1 787 231	10.44
31	Permanent Grassland	9 428 186	32.69	7 018 018	24.3	10 917 779	37.86
32	Shrub vegetation	244 373	18.29	535 523	40.1	822 169	61.54
33	Vineyards, low stem Orchards, Tree Nurseries	332 753	31.04	94 590	8.83	101 467	9.47
34	Copse	1480 247	87.20	1 825 689	107.5	1 878 236	110.64
35	Orchards	42 866	52.60	38 180	46.8	40 983	50.29
36	Stony Grassland	96 122	6.97	463 644	33.6	423 874	30.75
37	Unproductive grassland	171 521	19.56	373 000	42.5	376 129	42.88
41	Surface waters	561 842	17.31	315 964	9.73	384 455	11.84
42	Unproductive wetland	413 722	39.43	312 100	29.8	482 206	45.96
51	Buildings and Constructions	5 012 933	60.18	2 633 848	31.6	3 320 329	39.86
52	Herbaceous biomass in settlements	2 035 935	61.04	1 306 998	39.2	1 365 575	40.94
53	Shrubs in settlements	76 931	61.06	49 006	38.9	42 037	33.36
54	Trees in settlements	1 012 666	90.42	1 020 774	91.1	948 253	84.67
61	Other land	224 904	5.69	970 854	24.6	885 435	22.40

Table 8b: Comparison of total and average tree biomass according to the Price et al 2017 ALS model, the aerial-imagery derived model and the new Swisstopo ALS model within the area of available new ALS data (Figure 3) for aggregated non-forest NIR Landuse Combination categories (Combination of Swiss land use statistics 3 and 4)

Land use CC code	Land use CC name	Price et al. 2017 Tree biomass outside forest (T)	Price et al. 2017 Tree biomass outside forest Avg T/ha (T C / ha)	Aerial imagery Tree biomass outside forest (T) with mask	Aerial imagery Tree biomass outside forest Avg T/ha (T C / ha) with mask	New ALS Tree biomass outside forest (T)	New ALS Tree biomass outside forest Avg T/ha (T C / ha)
2X	Cropland	3 805 207	22.23	936 769	5.47	1 787 231	10.44
3X	Grassland and Agriculture	11 796 069	33.43	10 348 647	29.33	14 560 637	41.27
4X	Water and Wetlands	975 564	22.71	628 065	14.62	866 661	20.18
5X	Settlements	8 138 465	63.03	5 010 626	38.81	5 676 194	43.96
6X	Other land	224 904	5.69	970 854	24.56	885 435	22.40

8 Discussion

8.1 Edge effects

Spatially explicit wall-to-wall models of tree biomass based on remote sensing data offer significant potential to improve on the current estimates of tree biomass outside of forest used within the Swiss NIR. However, the most appropriate approach to combining NFI based methods to estimate tree biomass within forest and the remote sensing based models in non-forest areas, remains unclear.

The work presented here shows that if we use NFI methods for forest CCs and assign tree biomass values from the ALS based Price et al. (2017) model to non-forest CCs there is a potential for double accounting of tree biomass at forest edges and through the difference in forest/non-forest classifications between the methods of the NFI forest mask from Waser et al. (2015) and those of the Swiss land use statistics. However, determining the level of this potential double classification is not straight forward. 100,323 hectares of non-forest landuse CC points occur within the NFI forest mask, the biomass on which amounts to **11,658,801 T**, assuming the tree biomass values of Price et al. (2017), summed for all land use CC types across the whole of Switzerland. This area is theoretically compensated for by 109,031 hectares of forest land use CCs which occur outside of the NFI forest mask. The biomass on these forest points outside forest can be estimated to be **16,141,496 T tree biomass** using the NIR methods (FOEN 2020), or **10,313,355 T tree biomass** by the Price et al. (2017) model (assuming forest area is defined by the NFI forest mask).

The Price et al. (2017) model is a prediction based on forest allometries, and, due to a lack of non-forest tree data, its ability to predict values outside of forest remains untested. The model has been shown to explain between 48 and 62% of the variability in tree biomass for forest trees (Price et al. 2017). Therefore, we should expect an unknown level of inaccuracy in the total amounts of non-forest tree biomass estimated. Through other ongoing projects for FOEN collecting data on trees outside forest (e.g., REFEWOODLAND) we will soon be better able to estimate biomass for non-forest trees and understand the uncertainties in the models.

Whether the approach of removing forest areas from non-forest land use CCs makes sense depends largely on the goals of the final data set. There may be some advantages in this approach if the goal is to limit double accounting of total tree biomass for the whole of Switzerland and the spatial variation in tree biomass across the landscape is not important. The advantage of the spatially explicit model based on remote sensing data is that we can model the spatial variability in tree biomass across the landscape as observed with the vegetation height model. If we assume that spatially distant forest areas outside of the forest mask will compensate for non-forest areas within the forest mask we lose this spatial explicitness. We would have a model which no longer represents what can be observed in the vegetation height model or by viewing the remote sensing imagery (Figure 5).

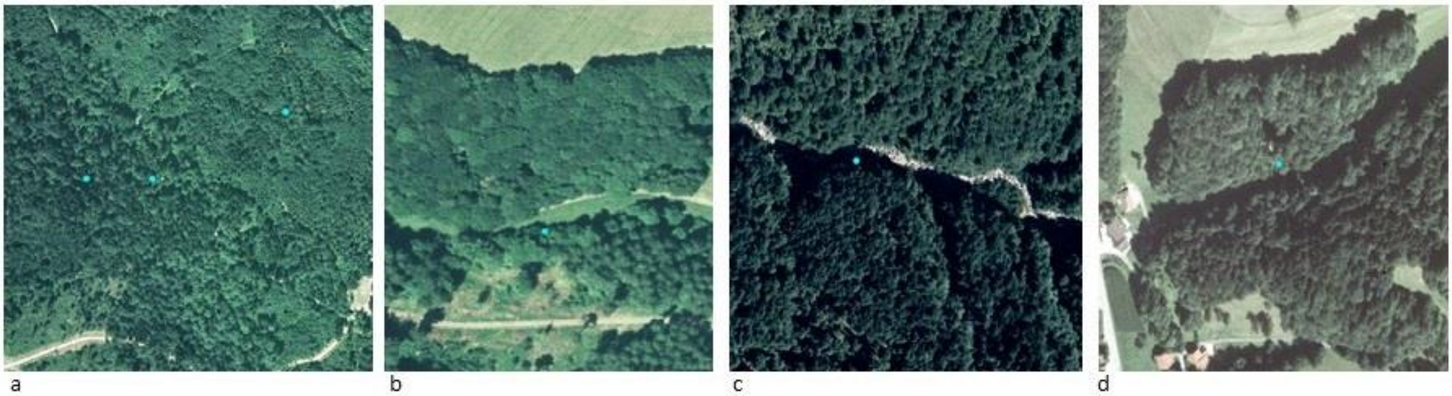

Figure 5: Examples of non-forest points (bright blue) inside the NFI forest mask, a) NIR landuse CC 51 (buildings and constructions), Swiss land use statistics classification: ‘paths and roads’, b) NIR landuse CC 31 (permanent grassland), Swiss land use statistics classification: ‘Meadows’, c) NIR Landuse CC 61 (Other land), Swiss land use statistics classification: ‘Rivers’, d) NIR landuse CC 31 (permanent grassland), Swiss land use statistics classification: ‘farm pastures’.

The difference in the definitions of forest and in the methodologies of determining forest cover between the two datasets (Swiss land use statistics and the NFI forest mask) result in the land use discrepancies. The forest cover removed from the tree biomass model, in order to identify non-forest trees may therefore not be compatible with the Swiss land use statistics definition used to determine the land use CCs.

We see from Table 3 that 153,489 hectares of forest edges occur on non-forest CCs near forest edges (within 71m of a forest edge). Even taking into account the smaller footprint area of the 25m resolution Price at al. 2017 model, the difference between the model masked for NFI forest and non-masked model for these forest edges is **10,844,791 T tree biomass** (Table 5), the majority of which is for points within the forest mask (where the 25m pixel will often have a majority forest cover). This 10.8 M T of biomass is approximately 3% of the total tree biomass in the landscape according to the Price at al. (2017) model (Table 2).

The Swiss land use statistics dataset is a well-established and widely used dataset, with a consistent method to describe land use and land cover over an extended time period, dating back to 1979. The dataset continues to be updated and can be expected to be available at the same quality into the future. A clear and established methodology is available for translating the land use statistics categories to the land use types required for the NIR. While the NFI forest mask is also a well-documented and reliable dataset, the forest boundary is delineated under a different definition of forest to that of the Swiss land use statistics and international definitions of forest. The NFI forest mask boundary is defined at the tree trunk, tree crowns therefore extend over the forest boundary. These crown areas will be included in an ALS based model of tree biomass such as the Price et al. (2017) model.

8.2 Model comparison

The models based on the three different base data sets, have differing results for total tree biomass and mean tree biomass per hectare by land use class, as would be expected. However, for many land use classes the results can be considered to be relatively similar to one another. Price et al. (2017) report a root mean square error in the range on 37-40% for the Price et al. tree biomass model on forested land, for many land use classes the estimates from the other models are within this error range. Key differences are for Cropland and Other Land, where the Price et al. (2017) model has a much larger estimate of tree biomass on Cropland than the two other models and a much smaller estimate on Other Land. It is likely that areas of tall crops are more prone to being misclassified as trees on the older ALS datasets with lower point densities and variations in the data specifications and processing across the range of projects required to achieve the Swiss wide dataset. In addition, it has been shown that the Price et al. (2017) model tends to over-estimate areas of low tree biomass. The under estimation of tree biomass on grassland and shrubland CCs has already been noted in the Price et al. (2017) publication. In addition, the no data areas above 2000 m.a.m.s.l. add a bias for land use classes which largely occurs at high elevations, such as Other Land. The comparison to the models based on datasets that do not have this limitation suggests that the Price et al. (2017) approach of assigning 0 tree biomass to no data areas above 2000m may result in a significant amount of tree biomass being ignored.

9 Recommendation

9.1 Edge effects

The Swiss land use statistics dataset remains the most detailed land use land cover dataset for Switzerland despite it not being spatially explicit. It is also the only landuse dataset for Switzerland that is derived from a consistent basis over time and allows for motoring land use use/land cover change. It is also a ‘known entity’ in the context of the NIR, and the methodology for determining the landuse CCs from it basis is well defined. As such, it should remain as the source for designation of landuse class. It should therefore be assumed that landuse, including forest/non-forest classification, according to the Swiss land use statistics is the ‘true’ land use in the context of the NIR. Artificially applying a dataset with a different forest definition, such as the NFI forest mask, may not necessarily accurately remove forest trees.

In additional, assigning 0 tree biomass to the forest mask and then assuming that the biomass on non-forest land use points that occur within the forest mask will be compensated by forest points outside of the forest mask, results in the model no longer being spatially explicit. This approach artificially removes observed (by remote sensing) tree biomass from a point with one land use class and assigns it to another, spatially distant point with a different land use class. Given the above and that the estimated total tree biomass on non-forest land within the forest mask is 11,658,797 T (approximate 3.4% of total oberseved tree biomass across Switzerland (Table 2)) and the estimated total forest biomass on non-forest CCs at the forest edge is 10,844,791 T tree biomass (approximately 3.1% of total oberseved tree biomass acorss Switzerland (Table 2)), it does not seem to make sense to use the somewhat complicated method of masking forest trees with the NFI forest mask.

Rather it should be assumed that the Swiss land use statistics offer a ‘true’ depiction of land use/land cover and that forest land use classes are assigned the NFI based estimates and the non-forest CCs the value at the point according to the remote sensing based model of tree biomass.

9.2 Model comparison

With the ongoing related projects such as REFEWOODLAND, new field data for trees outside forest will soon be available for calibrating and validating Tree biomass models for non-forest areas. Although the models based on the new Swisstopo data did not necessarily perform significantly better than the models based on old ALS data or aerial imagery (with the same explanatory variables), with the use of variables that take advantage of the high point density of the new ALS capture and ability to penetrate the canopy (such as vegetation voxels or green volume) should result in more accurate models of Tree biomass. In addition, vegetation height models derived from aerial imagery are available dating back to the 1980s and have been shown to consistently predict tree biomass in forest over time (Price et al. 2020). Here, we have seen that this dataset can also provide a comparable estimate of non-forest tree biomass to the ALS based models. The available of historical data will enable estimation of change in in tree biomass over time from a consistent data source. The capture of aerial imagery across Switzerland is intended to be ongoing, which means a consistently dataset available also into the future. Therefore an approach to future modelling of tree biomass for non-forest areas could include an approach fusing the aerial imagery and the ALS data to obtain the best model and allow motoring of change over time.

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