ARBETSRAPPORT 1117-2022

# Digital mapping of retention zones around wetlands

A pilot study using geospatial data in forestry planning

Per Westerfelt & Gustav Friberg

Wetlands. Foto: Pixabay.

skogforsk

# Contents



Uppsala Science Park, 751 83 Uppsala
skogforsk@skogforsk.se
skogforsk.se

Kvalitetsgranskning (Intern peer review) har genomförts 15 februari 2022 av
Erik Willén, Processledare. Därefter har Magnus Thor, Forskningschef,
granskat och godkänt publikationen för publicering den 2 maj 2022.

Redaktör: Leslie Walke, leslie@communicaid.se
 ISSN 1404-305X

# Foreword

The aim of this study was to evaluate how geospatial data can be used to improve environmental consideration in forestry planning and also used in automation of the preplanning of forest operations prior to field visits. The study, which was performed as part of the EFFORTE project, received funding from the Bio-based Industries Joint Undertaking under the European Union Horizon 2020 research and innovation programme under grant agreement No 720712. Additional funding was provided by the Karl Erik Önnesjö Foundation. We would like to thank the funding organisations and others who contributed to the study. Map data and aerial photos in the report are all © Lantmäteriet.

# Sammanfattning

Det finns mycket geodata som kan underlätta planering av naturvård inom skogsbruket. I det praktiska skogsbruket används geodata data vid avverkningsplanering, men det görs via manuell tolkning av en stor mängd dataskikt. Detta är tidsineffektivt och kräver en uppdaterad GIS-kompetens bland praktikerna gällande både hantering av mjukvara samt tillhandahållande av kartmaterial. Att uppehålla en sådan kompetens är resurskrävande och kompetensen varierar mellan olika organisationer inom skogsbruket.

Denna studie undersöker möjligheten till en automatiserad process som kombinerar flera geodata för att i slutändan föreslå hänsynsområden kring våtmarker som bör lämnas orörda under en avverkning. En automatiserad process kan skapa kartlager över stora områden ”med ett klick”, givet att man har tillgång till de kartlager som är indata i processen. Utmaningarna är att få så hög noggrannhet på karteringarna som möjligt samt att få den generell, alltså att den kan appliceras överallt. Att skapa en generellt fungerande automatiserad karteringsprocess är ett stort jobb som kräver stor mängd data från olika geografiska regioner. Denna studie hade ambitionen att undersöka om det är möjligt att kartera hänsynsområden kring våtmarker med en automatiserad process med högre noggrannhet än befintliga våtmarkskarteringar i två olika geografiska regioner.

Just kantzoner kring våtmarker är överrepresenterade i statistiken över negativ miljöpåverkan av skogsbruk. I studien fältbesöktes 19 våtmarker och deras omkringliggande skog. Hänsynsområdet kring våtmarkerna märktes ut med GPS enligt målbilderna för god naturhänsyn. Målet var sedan att använda geodata och kartverktyg i en automatiserad process för att kartera hänsynsområdena kring våtmarkerna. Inledningsvis avgränsades öppna våtmarker med hjälp av laserdata och kartlager som baseras på visuell tolkning av flygbilder. För att sedan avgränsa den blöta skogen kring våtmarkerna skapades kostnadsraster av laserdata vilka användes för att hitta det slutgiltiga hänsynsområdet.

Avgränsningen av de öppna våtmarkerna hade en noggrannhet på 97 procent vilket var bättre än existerande kartskikt (75 %) och metoden avgränsade närliggande blöt skog med 80 procent noggrannhet jämfört med 40 procent noggrannhet i befintliga kartskikt. Noggrannheten förbättrades om man inkluderade en plasticitet i den automatiserade processen, d.v.s. att man lät kostnadsrastren variera beroende på våtmarkens karaktär. Detta innebär att om man vill öka karteringsnoggrannheten bör man först ”skanna av” våtmarken för att bestämma dess trädskikt, lutning och modellerade markfuktighet och vattenflöde, och sedan tillämpa en karteringsmetod som passar för just den våtmarken.

# Summary

Much current geospatial data have the potential to facilitate nature conservation in forestry. Operational personnel in the forestry sector often use geospatial data when a felling is planned, but this is done manually for one forest stand at a time and requires time-consuming and subjective assessments. This study examines the possibility of an automated process that combines several geospatial data to map conservation areas in forest landscapes that should be left untouched during a felling. There are many indicators that we are moving towards more automated forestry. If nature conservation is to keep up, we should be able to use existing geospatial data to delimit no-go areas. This study focused on open wetlands and their surrounding wet forest. Wetlands and wet forests are habitats for many red-listed species. According to the Swedish environmental objectives, wetlands and wet forests should be left untouched. Delimiting wet forests and leaving appropriate buffer zones around wetlands have proved difficult, and these kinds of biotopes are over-represented in statistics concerning negative impact from logging. Nineteen wetlands and their surrounding wet forest were surveyed in the field to digitally mark the area that should be retained in a final felling if the goals for good environmental consideration are to be achieved. The aim was to retrospectively find these target retention areas with the help of existing geospatial data and tools, a process we called modelling. The first step in the models was to find open wetlands by using a combination of visual interpretation of aerial photos and LiDAR data. The reasons for first locating open wetlands were simply because they have characteristics that make them relatively easy to delimit with remote sensing, and because they are depressions (or basins) in the terrain that lead to high water accumulation, which often means that parts of the surrounding forest are wet. The step to find the surrounding wet forests, and thereby the whole target retention area, was an outward extension from the open wetlands, applied using accumulated cost rasters based on LiDAR data. The models mapped 97% of the open wetlands accurately, compared to approx. 75 percent by existing map layers, and 80 percent of the adjacent wet forests were mapped accurately, compared to approx. 40 percent by existing map layers. The accuracy was improved if the outward extension varied according to the characteristics of the open wetland, characteristics that were all found by remote sensing. Consequently, to improve mapping accuracy, the first action should be to scan the terrain, and then choose the mapping procedure.

# Introduction

In environments exposed to large-scale human activities, it is important to identify and protect biotopes with high conservation values that depend on pristine conditions. Swedish forests are affected by human activities, since large areas are subjected to logging. Many small wetlands with adjacent wet forests with conservation values that lack formal protection are scattered in Swedish forests, and their conservation values depend on untouched conditions. They should therefore be left untouched according to the environmental goals set up by the Swedish Forest Agency together with a group of stakeholders.

Wetlands are vital habitats for many species. Nineteen percent of Sweden's red-listed species occur in different types of wetlands, of which eleven percent are directly linked to wetlands since it is their exclusive habitat type (The Swedish Species Information Centre 2015). Besides forming habitats for many threatened organisms, wetlands provide other essential ecosystem functions such as water supply and regulation, retention of nutrients and toxins, and fire barriers (Swedish Environmental Protection Agency 2017).

Prior to each forest operation in Sweden, it is the forest owner's responsibility to locate areas that need environmental consideration. It can sometimes be difficult to assess whether a forest area is to be classified as a retention area or production forest, and to identify more exactly where the boundary should be placed. Delimiting wet forests and leaving appropriate buffer zones around non-productive wetlands have proved difficult, since these kinds of biotopes are over-represented in statistics concerning negative impact from logging. Data from the national forest survey regarding environmental considerations in forestry for the harvesting period 2013-2016 show that environmental considerations can be improved, especially concerning wet forests, where a large negative impact from logging was observed in one-fifth of the cases. An explanation is that biotopes that require environmental consideration can often be difficult to identify and delimit. Additionally, different persons performing inventories assess conservation values differently, which makes delimitation more difficult (Swedish Forest Agency 2016). The trade-off between economic interests and conservation can be unbalanced when the decisions are the responsibility of one or a few persons (Keskitalo 2014). Despite this, few tools are currently available that can help to accurately identify areas that require environmental consideration. Environmental considerations taken in production forests, retention areas, are an important complement to other forms of protection, and fulfil an important function for biodiversity in the forest landscape.

Geospatial data regarding open wetlands and forest on wetlands are available on maps with comprehensive coverage of Sweden, the topographic map series (Lantmäteriet 2016) and the Swedish National Landcover Data (Metria 2017). Our aim was to investigate whether these map layers can be used to delimit appropriate retention areas around small (< 4 ha) open wetlands (Table 1, row 3 and 4), if the environmental goals are to be achieved. How accurately can these map layers guide a harvester when determining where to place the boundary of retention areas during logging operations? We also aimed to develop a remote sensing procedure, using models designed to specifically delimit open wetlands and their adjacent wet forests (Table 1, rows 1 and 2). We compared our models and the existing map layers with field inventories that had delimited the target retention area around 19 open wetlands based on their wetness and conservation values according to the goals for good environmental consideration (Swedish Forest Agency 2013)

Our aim was not to build an ultimate remote sensing model that could be applied anywhere. Such an intention would require more data. Instead, our aim was to take a first step towards an automated high-resolution mapping of forest areas that require environmental consideration, through remote sensing by using maps available for the whole of Sweden. The aim was to attain such a high level of accuracy that the mapping could be uploaded to a harvester's display and guide the operator in decisions on where to stop felling and leave retention areas. We aimed to test whether the accuracy could be increased if the models were plastic, i.e. by varying the mapping procedure according to the natural conditions (Table 1, row 1), compared to a static model, i.e. the same mapping procedure used for all 19 wetlands (Table 1, row 2). Our remote sensing procedure had similarities with the technique used by Murphy et al. (2007) and White et al. (2013) who created depth-to-water maps. A two-step procedure was used, where the first step involved finding apparently wet areas, and accumulated cost grids were then used to find the surrounding moist areas. The new ideas in this study are that we used LiDAR data and aerial photo interpretation in the first step, and that we tested altering the cost grids in the second step. The alteration included choosing different cost grids and varying the delimitation value on the cost grids according to the terrain conditions.

We also checked whether our study wetlands were mapped by 'Våtmarksinventeringen' (Wetlands Inventory) and 'Sumpskogsinventeringen' (Wet Forest Inventory) (Swedish Forest Agency 1999), two large-scale inventories in Sweden.

Table 1. Summary of the four mappings compared in this study, used to examine their accuracy in mapping open wetlands and their adjacent wet forest.

| Mapping | Mapping method | Aim of the map | Origin |
|---|---|---|---|
| **Plastic model** | Image interpretation and LiDAR – *altered mapping procedure depending on the terrain* | To specifically map wet forest retention areas | Created in this study |
| **Static model** | Image interpretation and LiDAR – *same mapping procedure for all wetlands* | To specifically map wet forest retention areas | |
| **Topographic map** – Marshland | Image interpretation - *same mapping procedure for the whole of Sweden* | A comprehensive land cover map of Sweden in vector data, including two marshland categories. | Existing map |
| **SNLCD,** Swedish National Land Cover Data – Forest on wetlands and Open wetlands | Image interpretation and LiDAR - *same mapping procedure for the whole of Sweden* | A comprehensive land cover map of Sweden in raster data (pixel size: 10x10m), including categories with forests on wetlands and open wetlands. | |

# Material and Methods

## Identification of study sites and study area

Digital maps were used to find suitable low-productive wetlands for inclusion in the study. The topographic map polygon layers 'Marshland, normal' and 'Marshland, liable to flooding' (Lantmäteriet 2016) (see below for more detailed information) were used to find wetlands in the size interval 0.5-4 hectares. Orthophotos (Lantmäteriet 2020a) and the Swedish Forest Agency map layer 'Logging Reports' were used to exclude wetlands that were partly surrounded by felled forests, which would make the assessment of suitable retention area around the wetland more difficult. Tree height estimates from LiDAR data were used to ensure that the wetlands were low-productive, i.e. without trees or sparsely vegetated with low trees or shrubs.

The digital search was conducted in two areas in Sweden: Uppsala and Mora (Fig 1). The region around Uppsala is a flat landscape at low altitude, while the region around Mora comprises hilly terrain at higher altitude. Field visits were made to 20 wetlands, equally divided between Uppsala and Mora during May-September 2018. One wetland outside Mora was excluded because of difficulties in estimating its appropriate buffer zone in the field, so data for 19 wetlands are presented in this study. Some wetlands comprised several neighbouring 'Marshland polygons', and a total of 29 'Marshland polygons' were included in the study. To ensure a randomised selection, we included the ten closest wetlands from Uppsala and Mora respectively in the chosen size interval that were surrounded by intact forest.

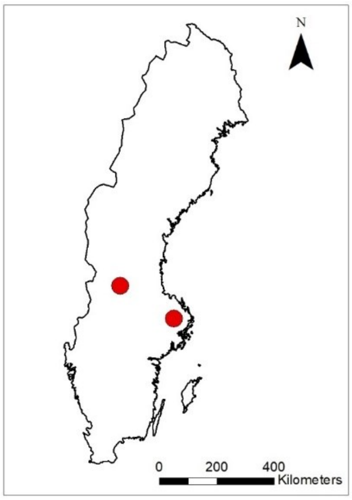


Fig 1. Map of Sweden with the study regions marked as filled circles. The eastern circle shows the region situated around the city of Uppsala in the county of Uppland and the western circle shows the region situated around the city of Mora in the county of Dalarna.

## Map data

**Topographic Map**, vector format (Lantmäteriet 2016). The layers used from this map were the 'MS-layers', '**Marshland, normal** – category code 32' and '**Marshland, liable to flooding** – category code 31'. The topographic map, including the MS layers, originates from field work during 1930-1977, and was digitalised in 1992-1997 using the existing field work information in combination with interpretation of aerial images. The MS layers have an estimated positioning accuracy of 20 metres. Despite this being an old map layer, we found it surprisingly reliable in mapping open wetlands, especially when combined with LiDAR data, as described in this paper. The map is distributed by Lantmäteriet, the public agency responsible for supplying information on land in Sweden.

**LiDAR** - Light Detection and Ranging. This is a remote sensing method that uses light in the form of a pulsed laser to measure the distances between the aircraft or drone carrying the LiDAR device and the ground. Differences in laser return times can then be used to make point clouds. Sweden was scanned with LiDAR in 2009-2019 (Lantmäteriet 2020b) and a second scanning has been initiated, which will continue for many years until complete coverage is attained. The Swedish LiDAR data, or more precisely the point cloud, have been processed into a **tree height raster** (Swedish Forest Agency 2020a *in Swedish*) and a **digital terrain model, DTM**, (Lantmäteriet 2020c *in Swedish*). These maps are rasters (2x2m) where each pixel has a tree height value and an altitude value respectively. The LiDAR data, with the DTM as base, has been used by Canadian researchers to develop a **depth-to-water, DTW** map (White 2012, Murphy 2007). A DTW map is distributed in Sweden by the Swedish Forest Agency (Swedish Forest Agency 2020b *in Swedish*). This map is a raster (2x2m), and each pixel has a modelled value representing the distance between the ground surface and the groundwater, where lower values indicate moister ground. In our study, **flow accumulation** maps were also used. This map is not distributed anywhere but it is created from the DTM and a component when creating DTW maps. It is raster data (2x2m), and each pixel has a modelled value representing its catchment area, thereby indicating the wetness of the ground in the pixel.

**Swedish National Land Cover Data – SNLCD**, CadasterENV Sweden (Metria 2015 *English*) (Metria 2017 *Swedish*). The map has been produced by satellite images in combination with LiDAR data, and is coordinated by the Swedish Environmental Protection Agency. SNLCD is raster data (10x10m) where each pixel is assigned a land cover category. There are 24 categories in total, 16 of which are 'forest categories'. The forest categories are differentiated into wet and dry forest, whether it is mature or newly cut forest, and according to the mixture of tree genres (coniferous, soft- and hardwood deciduous trees). The category used to distinguish low-productive open wetlands in this study was **'Open wetlands' (category number 2)**. The categories used to discriminate adjacent wet forests with conservation values was '**wet forest'** irrespective of tree genre **(category numbers 121-127)**.

Digital geospatial data on wetlands are also available from the Wet Forest Inventory and the Wetland Inventory conducted by the Swedish Forest Agency and the Swedish Environmental Protection Agency, respectively. They were used in the validation.

## Field data collection

The wetland areas were visited in the field to digitally map the target retention area, including the non-productive open wetland and their adjacent wet forests with conservation values. The delimitation was determined using the characteristics listed in Table 2, which are considered to characterise wet forests requiring protection according to the environmental goals set up by the Swedish forest sector and the Swedish Forest Agency (Swedish Forest Agency 2013). The surveyor walked along the edges of the low-productive open wetlands and digitally mapped them using the ArcGIS Collector app. The digitally drawn line was, as standard, 5 metres from the border of the low-productive open wetland, since this is the minimum width of the edge zone to low-productive wetlands according to the environmental goals set up by the forest sector and the Swedish Forest Agency. If the adjacent forest would require environmental consideration in a hypothetical felling, the edge zone was widened, so the line was drawn at the boundary between the wet forest with high conservation values and the production forest (see Figure 2). We use the term 'wet forest' since these areas varied greatly in size and shape, and the term 'buffer zone' could therefore give the wrong impression. However, the adjacent wet forest also functions as a buffer zone around the open wetlands. The wet forest with high conservation values requiring environmental consideration had, in addition to moist ground, also at least two of the characteristics listed in Table 2.

Table 2. Features that characterised the wet forests with conservation values adjacent to low-productive wetlands. This kind of wet forest requires environmental consideration according to goals for good environmental consideration.

| Characteristics of wet forest adjacent to low-productive wetlands with conservation values and requiring environmental consideration |
| --- |
| High proportion of deciduous trees |
| Deviating ground flora |
| High abundance of dead wood |
| Trees growing on pedestals (elevated ground) |
| Elevated ground formations |
| High abundance of crooked and growth-depressed trees |

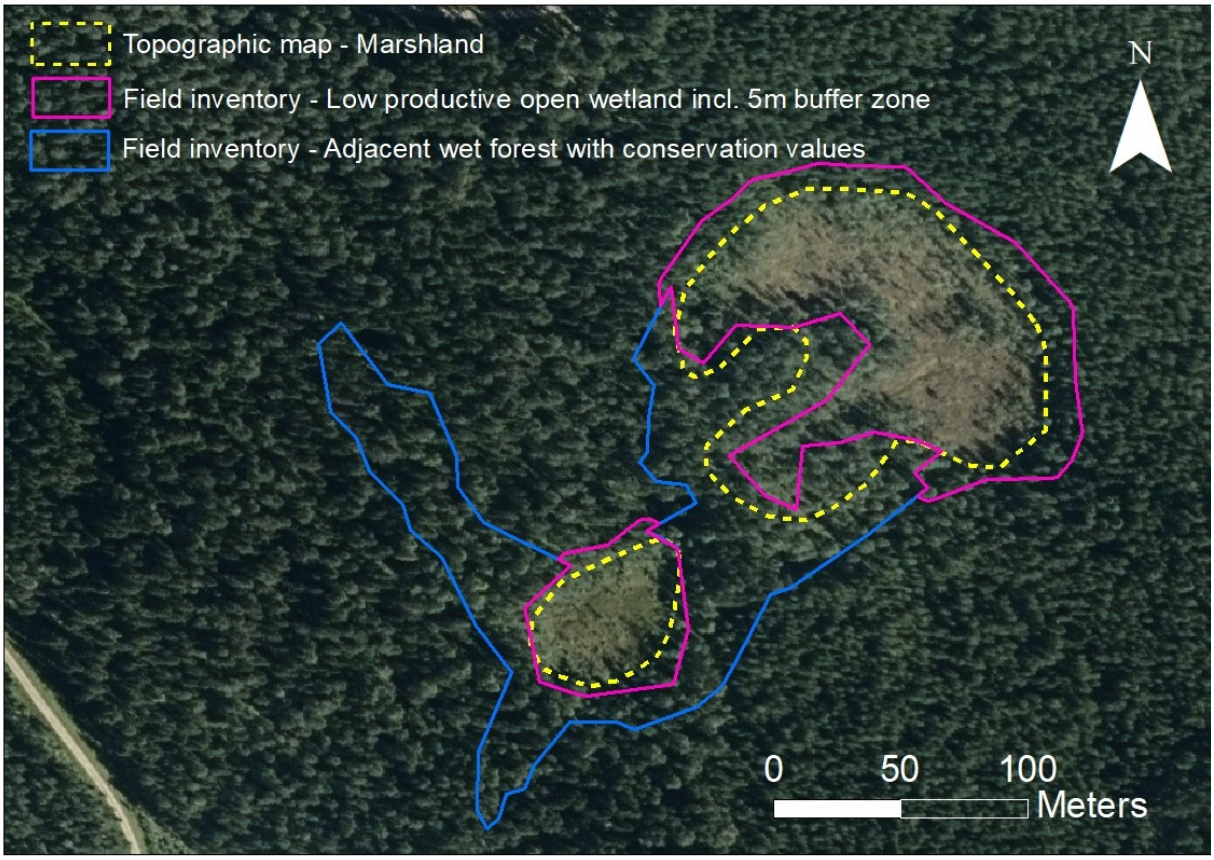


Figure 1. One of the wetlands in the study with orthophoto as background map. The dashed yellow line shows the wetland according to the topographic map. The solid lines show the field inventory's delimitation for the low-productive open wetland (pink) and adjacent wet forest with conservation values that require environmental consideration (blue) when this area will be subjected to logging. The forest delimited by the field inventory had at least two of the features listed in Table 2.

## Remote sensing models

The aim of the remote sensing models was to find the target retention area that had been digitally marked in the field survey. We used map layers available for whole Sweden (Lantmäteriet 2016, Lantmäteriet 2020b). The basic idea of the model procedure can be divided into two steps. Step 1 - finding truly wet areas that were usually open wetlands, i.e. wetlands with little or no vegetation. An exception was when an area had a canopy but was still mapped as a wetland by the image interpretation (topographic map) and had shallow groundwater depth according to the DTW map. Step 2 - extend the surface outwards to add areas of open wetland that may have been missed in the first step and locate the surrounding wet forest that needs consideration during logging operations. The two steps are not dependent on each other – any raster or feature data can replace the one we used in Step 1 and any raster data can be used in Step 2. This procedure is inspired by Canadian researchers who created depth-to-water maps (Murphy 2007, White 2012)

### Step 1 – Locating truly wet areas using image interpretation and LiDAR data

Within the marshland polygons (based on image interpretation), pixels were selected that had tree height below 12 metres. We used the tree height 12 metres as a threshold value to find areas where tree growth was suppressed (due to the wet conditions), but any values between 7 and 12 metres could have worked equally well (see Table 3). An exception was when there was no distinct open wetland, i.e. when the topographic map marshland polygon had median tree height above 12 metres. In such cases, the pixels within the polygon that had modelled depth-to-water (DTW) less than or equal to 1.25 were selected.

### Step 2 - Locating the retention areas around the truly wet areas

The pixels selected in Step 1 were the starting point for the creation of accumulated cost grids. A cost grid identifies the cost of traveling through each pixel, and an accumulated cost grid summarises the total cost from a defined starting point. Accumulated cost grids expand outwards continuously from the starting point, enabling control over the size of the surface by selecting a delimiting value (Fig 3).

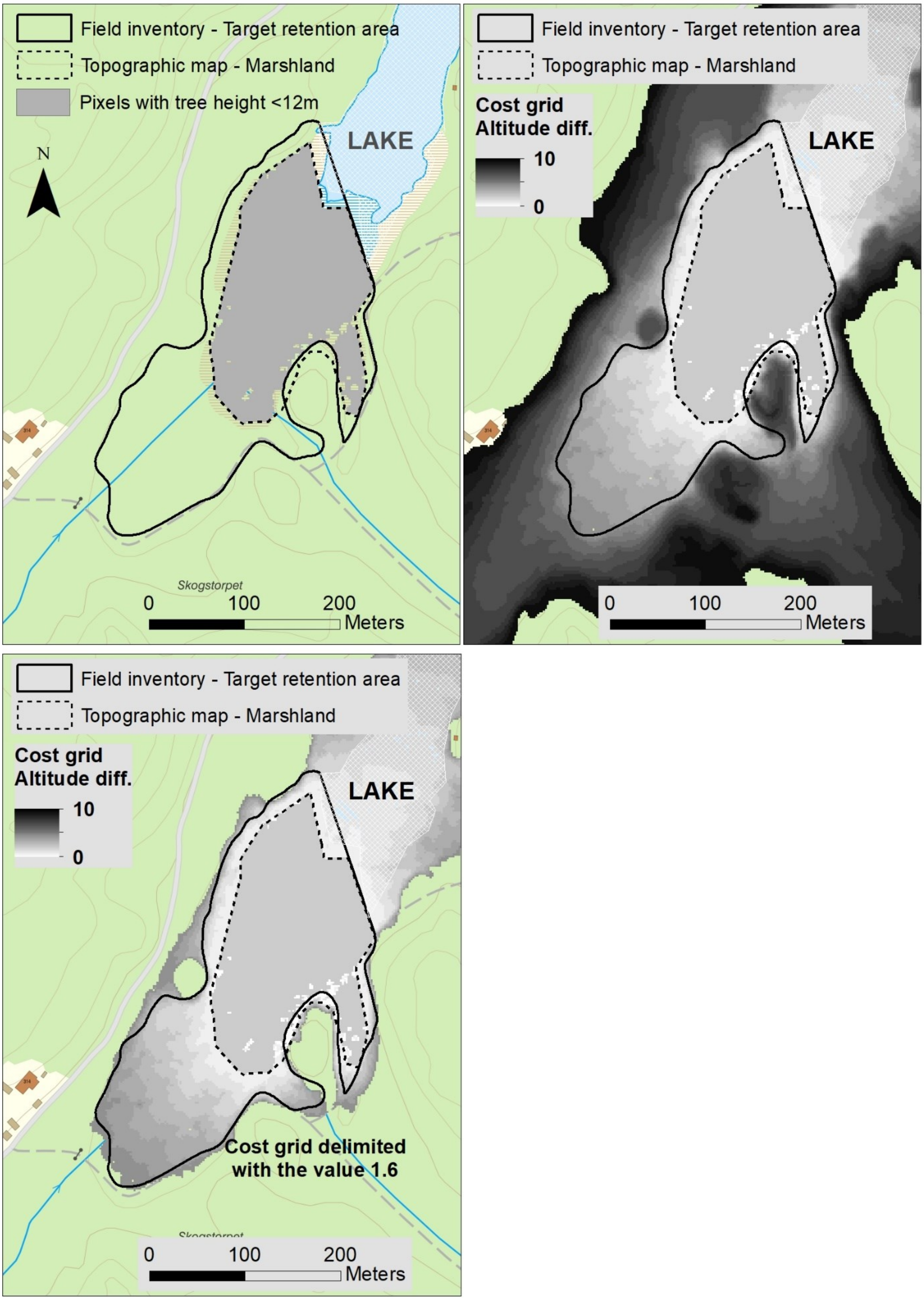


Fig 3. The first step in the model was to select pixels with tree height < 12 m within the marshland polygon (upper left). The second step was to create an accumulated cost grid that originated from the pixels in step one (upper right) and to delimit the cost grid to map the target retention area (lower left). Note that the cost grid values >10 are made invisible in the upper right map.

The use of different cost grids will result in different ways to delimit a retention area around a wetland, so choosing an appropriate cost grid could be essential for accurate mapping of the target retention area (Fig 4). In the plastic model, the cost grids were based on the DTW map, DTM (altitude difference), or a combination of DTW, DTM and the flow accumulation depending on the characteristics of the open wetland. The first action in step 2 in the plastic model was therefore to characterise the open wetland according to the flowchart in Figure 5. This resulted in five different alternatives, which we call Models 1-5.

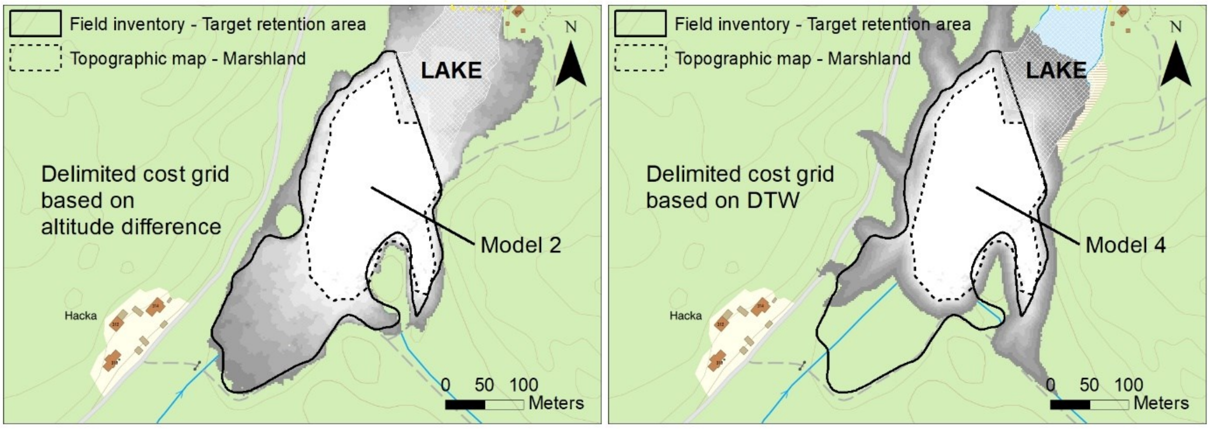


Fig 4. An illustration of the importance of choosing the appropriate mapping procedure, including choosing the appropriate cost raster, to accurately find the target retention area. The maps illustrate a wetland situated in a flat landscape with scattered modelled flow accumulation and a relatively dry modelled ground wetness according to the DTW, which were characteristics that made altitude difference (left) a better alternative as cost grid when finding the retention area compared to the DTW map (right).

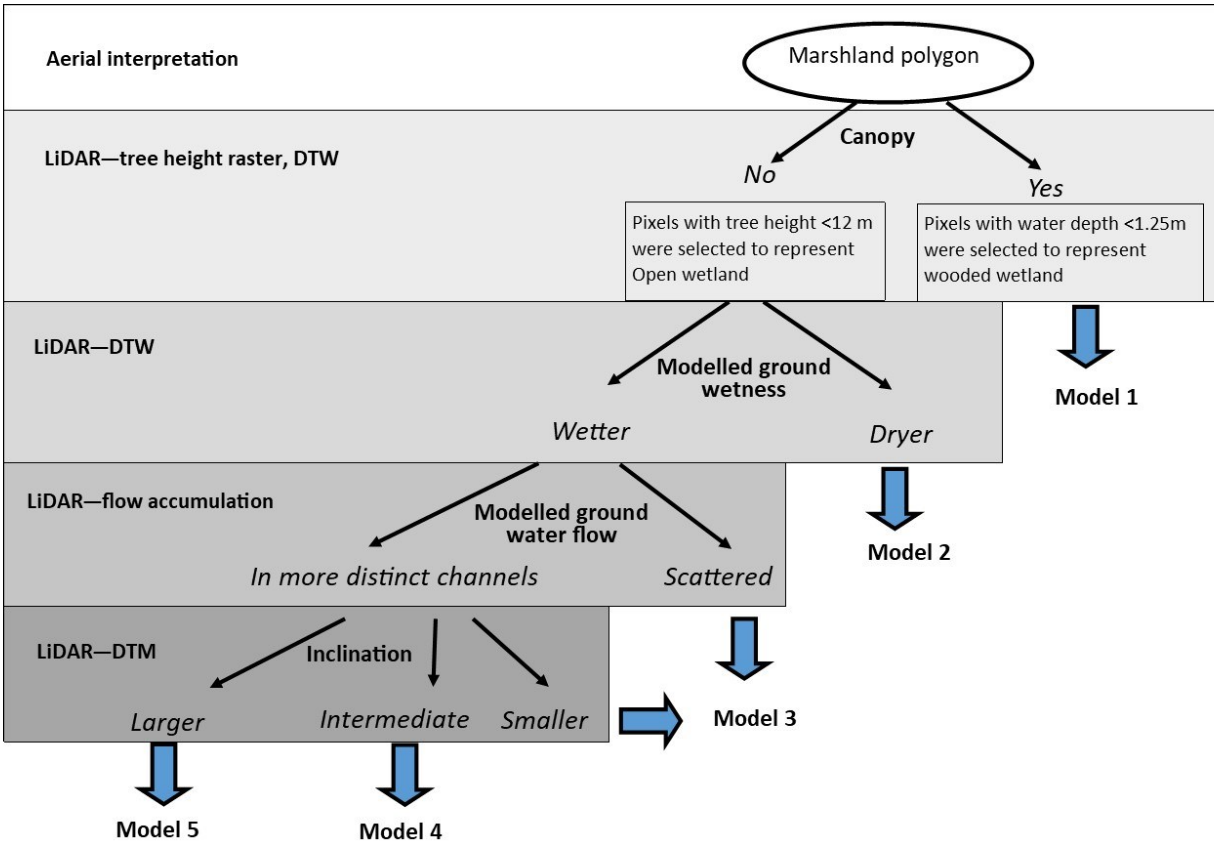


Fig 5. Flowchart describing the model selection in the plastic model. The characteristics were measured inside the topographic map marshland polygons. Note that the inclination is relative to wetlands, and a large inclination for a wetland is perceived as flat terrain in general. For technical info and values in the models, see Appendix 1.

## Measurement of wetland characteristics

The tree height (canopy) was estimated with the tree height raster. The modelled ground wetness was estimated with the depth-to-water (DTW) map. The modelled groundwater flow was estimated by applying the ArcMap tools 'Fill', 'Flow direction' and 'Flow Accumulation' on the DTM. The inclination was calculated as an index, which was the difference between the median altitude of the wetland and the minimum altitude (according to the DTM map), divided by the area of the marshland polygon (according to the topographic map). The inclination index can therefore be estimated as half of the wetland's altitude difference per hectare. The maximum altitude value was not used because a small location error of the marshland polygon can give a strongly misleading maximum value in hilly terrain.

## The models

The static model was Model 3, since this was the model that was applied on most wetlands in this study. The plastic model mapped the wetlands differently depending on their characteristics (see Fig 5).

The same procedure was used in all models, using the two-step method described above. Pixels in the marshland polygons were selected and became the starting point for an accumulated cost grid. In Models 1 and 4 the modelled water depth (DTW) was the cost grid. In Models 2 and 3 the altitude difference (DTM) was the cost grid. In Model 5 a combination of the modelled water depth (DTW) and the altitude difference (DTM) was the cost grid, where water depths between 0-100 were given the value 1 and all other water depths were given the value 8; this raster was multiplied by the altitude difference. The values for delimiting the accumulated cost grids, which determines the size of the retention target area, were constant in Models 1, 4 and 5 – 20, 20 and 0.6, respectively. The delimitation value varied in Models 2 and 3 depending on the modelled groundwater flow (flow accumulation). In Model 2, if the modelled groundwater flow was scattered (median flow accumulation > 1), the delimitation value was set to 1.6, and if the modelled groundwater flow was in more distinct channels (median flow accumulation = 1), the delimitation value was set to 0.4. In Model 3, if the modelled groundwater flow was extremely scattered (median flow accumulation > 30), the delimitation value was set to 4, otherwise it was set to 2.

An additional cost grid was mapped if three conditions were fulfilled: 1) >70 percent of the marshland polygon had a modelled water depth < 1 m; 2) the modelled groundwater flow was in more distinct channels (flow accumulation < 3); and 3) inclination was higher than 6 m per hectare or the cost grid was based on altitude values (DTM). These conditions were the case in Model 5 and in some cases of Model 3. The already mapped surface worked as a starting point for a new cost grid. The new cost grid was based on the flow accumulation. Pixels that had flow accumulation value < 500 were transformed to NoData, meaning that all pixels with a catchment area larger than 1/5 of hectare (= 500 pixels) were the base for the cost grid. This created linear structures with the width of only one pixel extending out from the wetland, representing modelled in- and outlet water flow channels (see Fig 6D). Since a higher flow accumulation value should give lower cost, the values needed to be the denominator in a division to create a representative cost grid. The flow accumulation values had an interval of 500-100,000, so the cost grid was created by 1,000,000 divided by the flow accumulation values and then log-transformed. In Model 5, value 150 was used to delimit the flow accumulation and in Model 3 the value 100 was used. These linear structures were the starting point for a new cost grid, where a modified DTW map served as cost grid. Pixels with modelled water depth ≤ 100 were given the value 1 while the remaining pixels were given value 8. Value 7 was used to delimit the area.

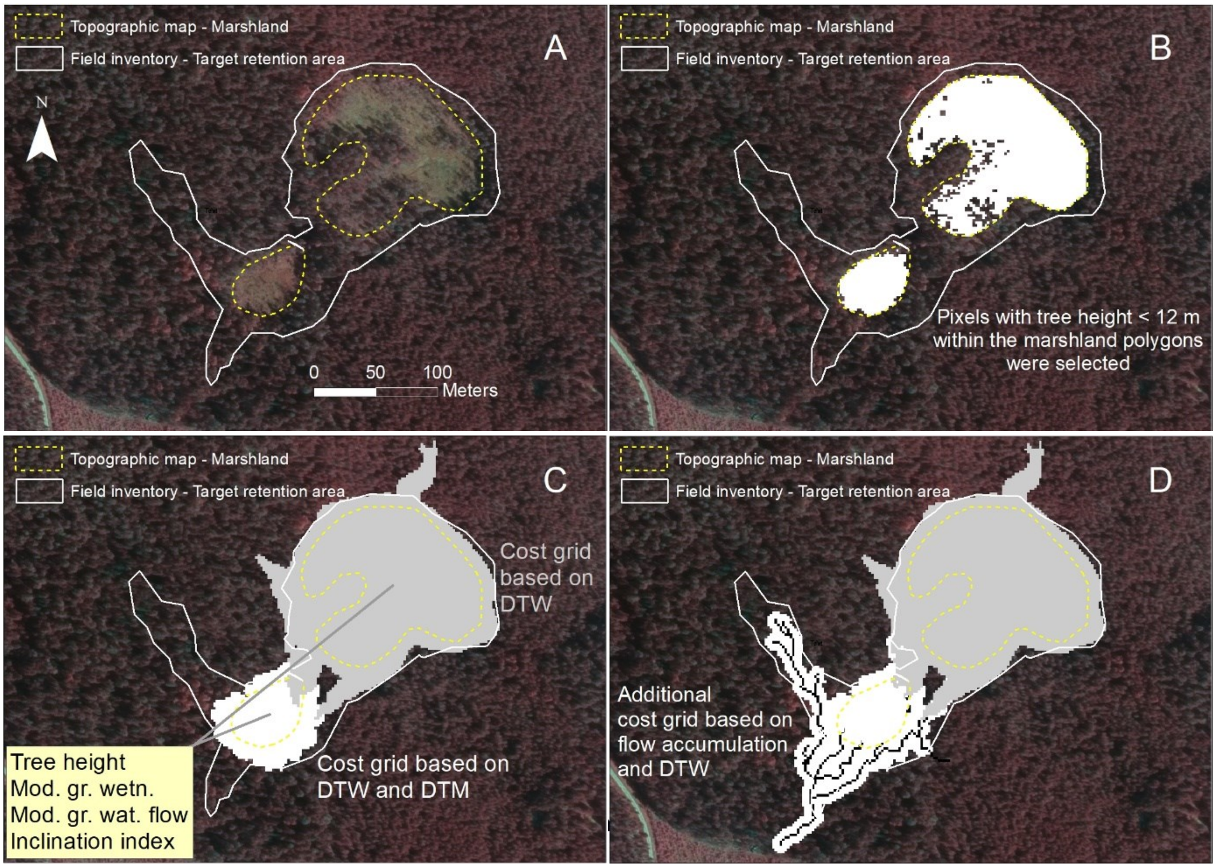


Fig 6. The mapping of the target retention area by the plastic model is illustrated in Figures 6B-6D for one of the studied wetlands. A – The target retention area (white solid polygon) comprised two open wetlands and their adjacent wet forest. The topographic map, which is based on image interpretation (pale dashed polygon), captured most of the open wetland but missed most of the wet forest. B – The first step in the model was the selection of pixels with tree height < 12 m within the marshland polygon, which became the starting point of accumulated cost grids. C – The northern marshland polygon had characteristics regarding its tree height, modelled ground wetness, modelled groundwater flow, and inclination index that made a cost grid based on DTW map most accurate in finding

the retention border (Model 4). The southern marshland polygon had characteristics that made a cost grid based on DTW map and DTM most appropriate, with the addition of a cost grid based on flow accumulation, visualised as black lines, and DTW (Model 5) which is shown in D.

## Geographical tools used

To select pixels within the marshland polygons, the tool 'Extract by mask' was used. To select pixels with tree height ≤ 12m or pixels with water depth ≤ 1.25 the tool 'Set Null' was used. To transform pixels in the tree height raster that was classified as NoData, the tool 'Raster calculator' was used with the expression "Con(IsNull("%TreeHeightRaster%"),0,"%TreeHeightRaster%")".

To create cost grids, the tool 'Path distance' was used. To log-transform, the tool 'Log10' was used. Before the raster values were log-transformed, the number 2 was added to each value with the tool 'Plus' to enable log-transformation and avoid zeros.

To transform the DTW so that values ≤ 100 were given the value 1 and all other values were given the value 8, the tool 'Raster calculator' was used, with the expression "Con("%DTW%" < = 100,1,8)".

To calculate the correct, missed, and exaggerated areas, the tools 'Clip' and 'Erase' were used concerning the topographic map and the models when each polygon was compared to the field inventory polygons. The SNLCD is a raster and the tool 'Extract by mask' was used to find the pixels within the field inventory polygons.

## Statistics and software

To analyse the difference in missed surface area between the four mapping methods, concerning both non-productive open wetlands and adjacent wet forest with conservation values, a general linear mixed model was used with in-transformation (plus one to avoid zeros). The missed surface area was treated as a fixed variable and the wetland area was treated as a random variable to control for the random effect of site. To analyse the difference in exaggerated area between the four methods, concerning both non-productive open wetlands and adjacent wet forest with conservation values, a generalised model assuming negative binomial distribution was used. This was because the exaggerated areas did not meet the criteria of normal distribution and the data was over-dispersed.

All analyses and figures (excluding maps) were performed in R, version 3.5.1 (R-core team 2018). All geographical tools and map figures were made in ArcMap, version 10.7.

# Results

The total field surveyed area of all 19 wetlands had an area of 46.3 ha, of which 31.9 ha was non-productive open wetlands and 14.4 ha was adjacent wet forests that should be left untouched as retention areas during logging because of their conservation values. All 19 wetland areas had some area of non-productive open wetland, and 17 wetland areas had also adjacent wet forest with conservation values. The 19 wetlands comprised 29 marshland polygons (according to the topographic map) of which 13 were located in Dalarna and 16 in Uppland. It was evident that non-productive open wetlands were easier to map compared to their adjacent wet forests with conservation values, and the results are therefore differentiated into these categories.

## Mapping of non-productive open wetlands

The four mapping methods in this study differed in how well they mapped non-productive wetlands ($p < 0.001$)). The large-scale mappings 'Våtmarksinventeringen' and 'Sumpskogsinventeringen' missed 14 of the 19 wetlands and are not shown in the figures. The plastic model had an accuracy of 97 percent (31 of 31.9 ha), and the model exaggerated the area by a total of 3.5 ha (Fig. 7, upper left corner). The static model had an accuracy of 94 percent (29.1 of 31.9 ha), and the model exaggerated the area by a total of 2.7 ha (Fig. 7, upper right corner). The Swedish National Land Cover Data (SNLCD) had an accuracy of 76 percent (24.3 of 31.9 ha), and this exaggerated the area by a total of 0.6 ha (Fig. 7, lower left corner). The topographic map had an accuracy of 73 percent (23.4 of 31.9 ha) and exaggerated the area by a total of 0.8 ha (Fig. 7, lower right corner).

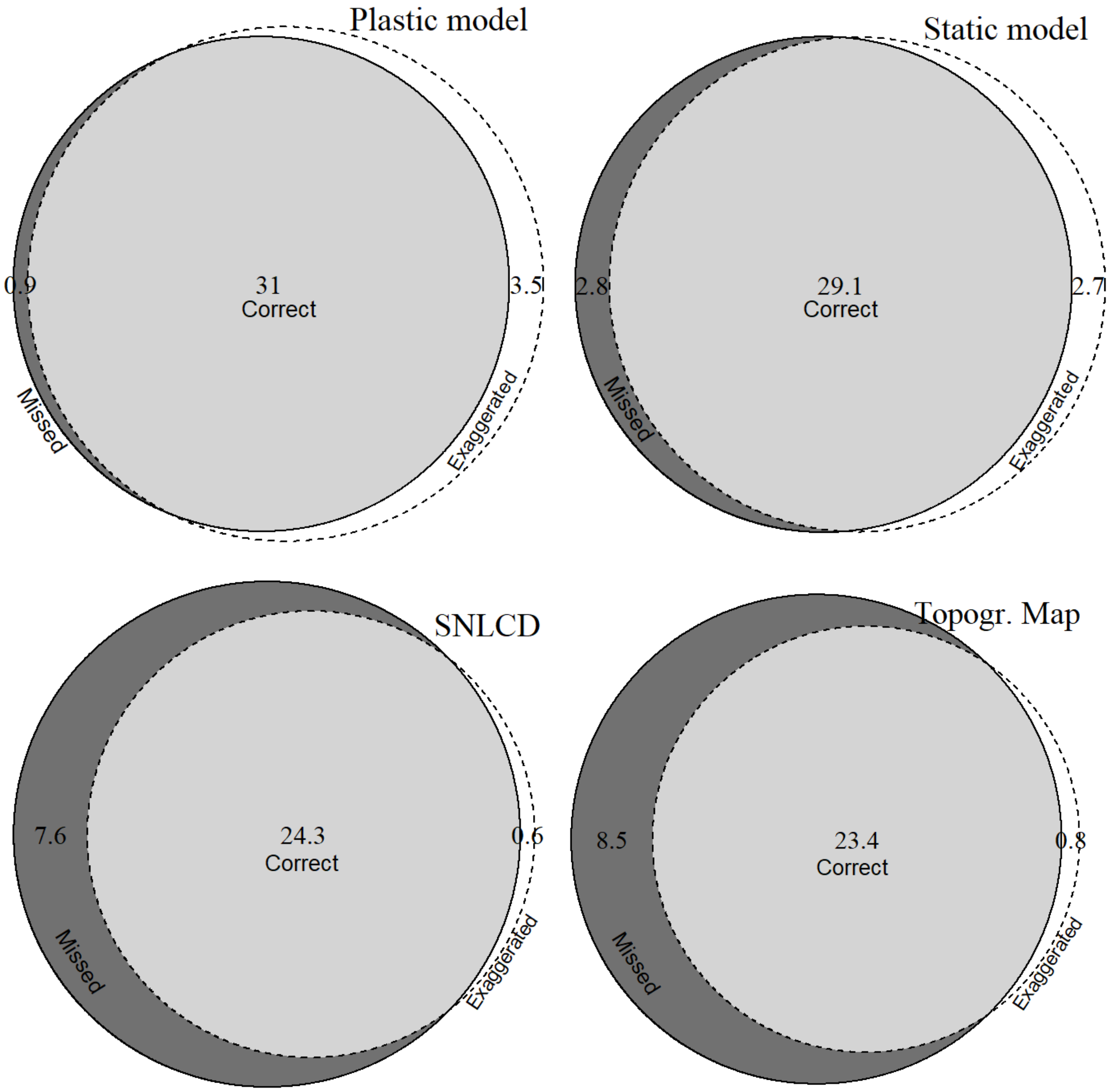


Fig 7. Venn diagrams illustrating how well the four mapping methods (dashed circles) mapped the field surveyed non-productive open wetlands (solid circles); Plastic model – upper left corner, Static model – upper right corner, the Swedish national land cover data (SNLCD) – lower left corner, topographic map – lower right corner. The field surveyed surface area of non-productive open wetlands (solid circle) was 31.9 ha. The numbers display the surface area in hectares of each category (missed, correct and exaggerated). The dark grey sections illustrate the area missed by each mapping method, the light grey sections illustrate the correctly mapped area, and the transparent section the exaggerated area. The exaggerated area was forest growing on solid ground without distinctive conservation values.

The plastic model missed less surface area of the non-productive open wetlands compared to SNLCD ($p < 0.0001$) and the topographic map ($p < 0.0001$) (Fig 8, left). There was no obvious difference in the amount of much surface area missed by the plastic and the static models. However, the plastic model had a weak significance of missing less than the static model ($p = 0.063$) (Fig 8, left). The plastic model exaggerated more surface area of the non-productive open wetlands compared to SNLCD and the topographic map (p < 0.0001) (Fig 8, right). There was no difference in the amount of surface area exaggerated by the plastic and the static models (p = 0.4) (Fig 8, right).

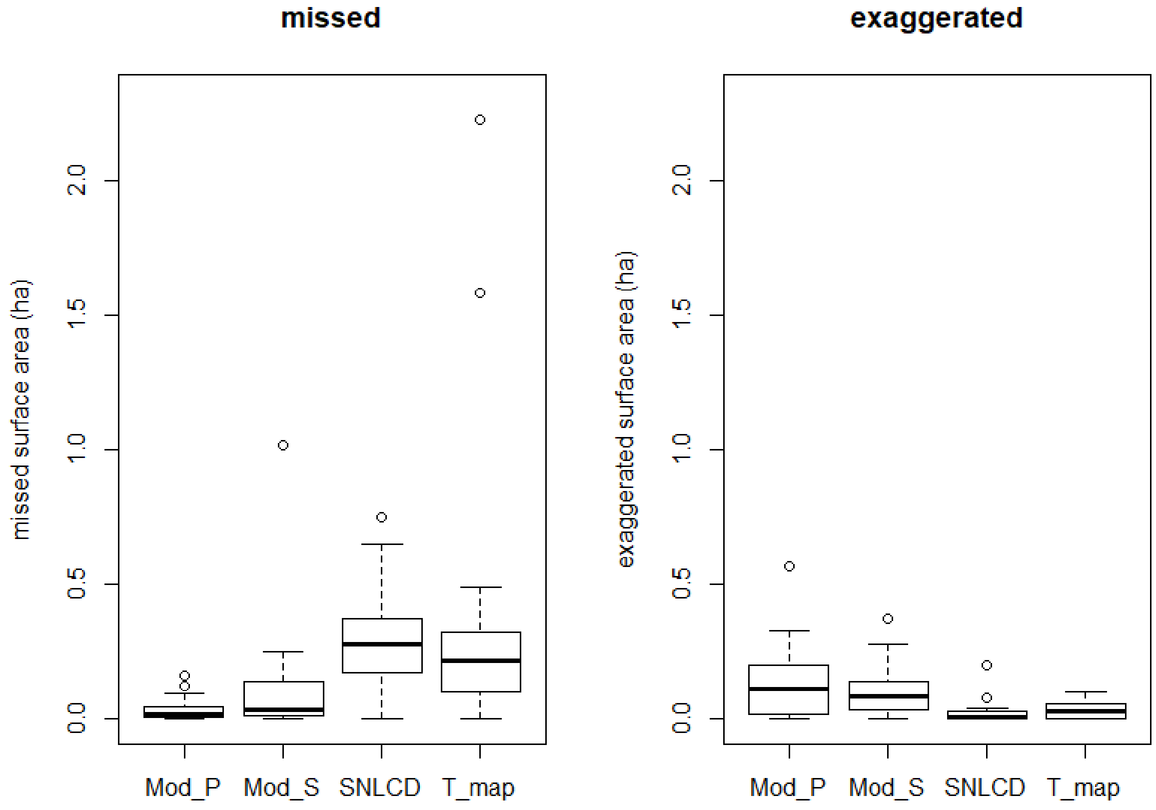


Fig 8. Boxplot showing the missed (left) and exaggerated (right) surface areas of low-productive open wetlands by the four mapping methods (Mod_P – Plastic model, Mod_S – Static model, SNLCD – Swedish National Land Cover Data and T_map – topographic map). Each mapping method was applied on 25 wetland polygons, so each box represents 25 values.

## Mapping of wet adjacent forests with conservation values

The four mapping methods in this study differed in how well they mapped wet adjacent forests with conservation values (p < 0.0001). The large-scale mappings 'Våtmarksinventeringen' and 'Sumpskogsinventeringen' missed 13 of the 18 adjacent wet forests and are not shown in the figures. The plastic model had an accuracy of 80% (11.5 of 14.4 ha) and exaggerated the area by a total of3.6 ha (Fig. 9, upper left corner). The static model had an accuracy of 57% (8.1 of 14.4 ha) and exaggerated the area by a total of 2.7 ha (Fig. 9, upper right corner). The Swedish National Land Cover Data (SNLCD) had an accuracy of 41% (5.8 of 14.4 ha) and exaggerated the area by a total of 0.4 ha (Fig. 9, lower left corner). The topographic map had an accuracy of 35% (5.0 of 14.4 ha) and exaggerated the area by a total of 0.4 ha (Fig. 9, lower right corner).

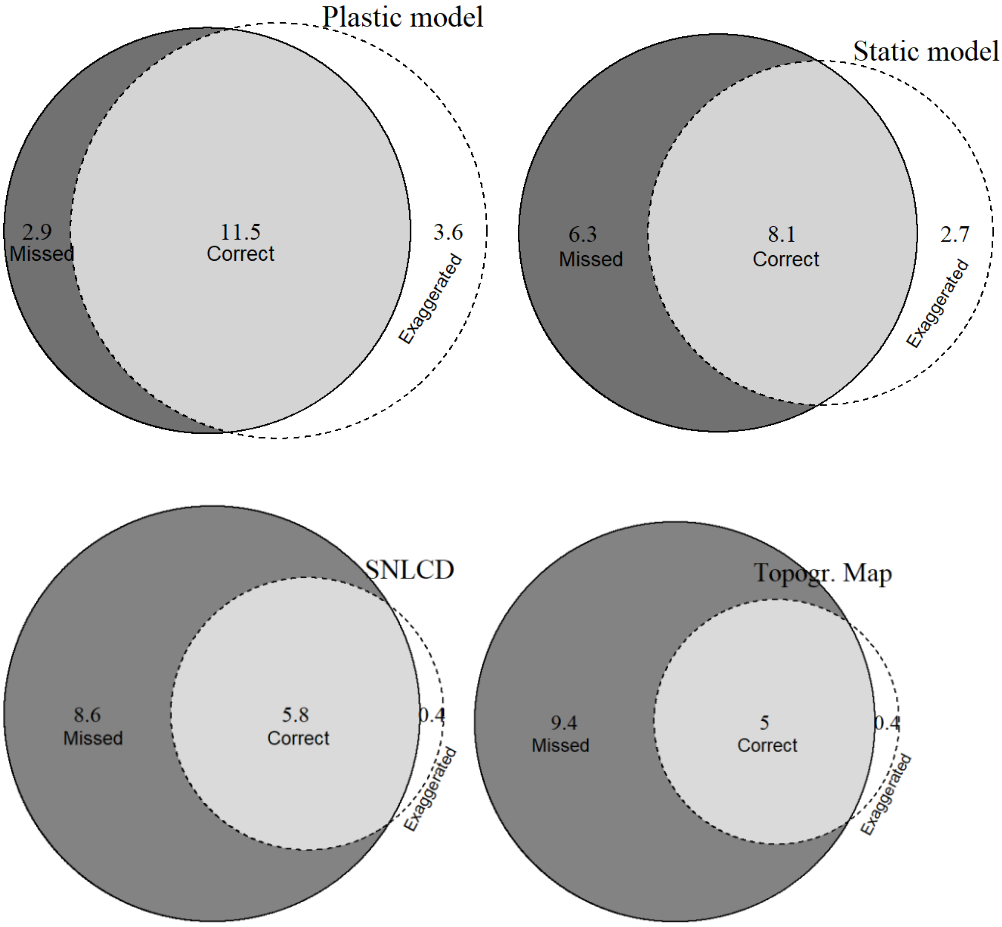


Fig 9. Venn diagrams illustrating how well the four mapping methods (dashed circles) in this study mapped the field surveyed adjacent wet forests with conservation values (solid circles); Plastic model – upper left corner, Static model – upper right corner, the Swedish National Land Cover Data (SNLCD) – lower left corner, topographic map – lower right corner. The field surveyed surface area of these adjacent wet forests (solid circle) totalled 14.4 ha. The numbers display the surface area in hectares of respective category (missed, correct and exaggerated). The dark grey sections illustrate the area that was missed by each mapping method, the light grey sections illustrate the correctly mapped area, and the transparent section the exaggerated area. The exaggerated area was forest growing on solid ground without distinctive conservation values.

The plastic model missed less surface area of the adjacent wet forests with conservation values than the SNLCD ($p < 0.0001$), the topographic map ($p < 0.0001$), and the static model ($p = 0.006$) (Fig 10, left). The plastic model exaggerated more surface area of the adjacent wet forests with conservation values than the SNLCD and the topographic map ($p < 0.0001$) (Fig 10, right). There was no difference in the amount of surface area exaggerated by the plastic and the static model ($p = 0.3$) (Fig 10, right).

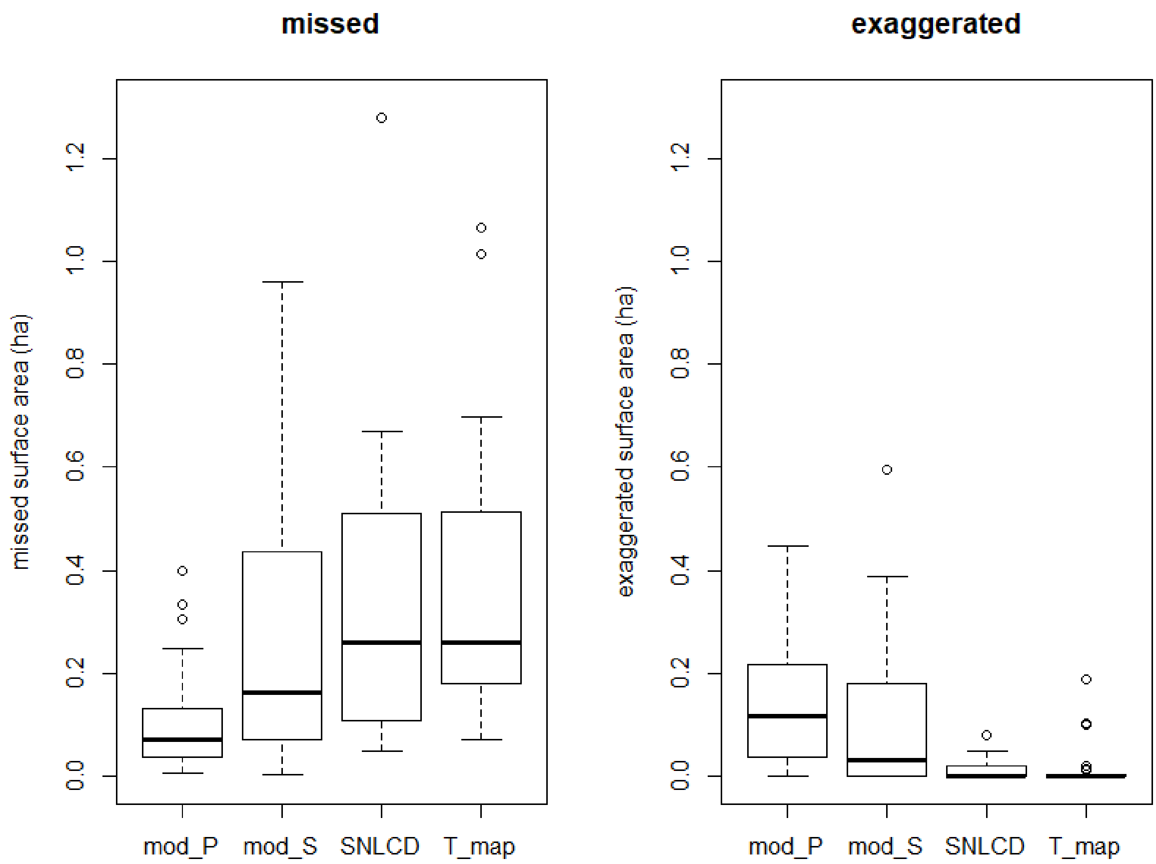


Fig 10. Boxplot showing the missed (left) and exaggerated (right) surface areas of adjacent wet forests with conservation values by the four mapping methods (Mod_P – Plastic model, Mod_S – Static model, SNLCD – Swedish National Land Cover Data and T_map – topographic map). Each mapping method was applied on 29 wetland polygons, so each box represents 29 values.

## Criteria for parameters in the plastic model

The characteristics within the topographic map wetland polygons used to determine the parameters in the plastic model were tree height, proportion modelled wet ground, slope (or inclination) and modelled water flow patterns (Table 3) (see Appendix for more detailed information). The tree height was found using the tree height grid. The proportion of wet ground was found using the DTW map. The slope was measured by subtracting the median altitude value with the minimum altitude value divided by the area of the wetland polygon. The water flow patterns (scattered or in distinct channels) were found by using the ArcMap tool ‘Flow accumulation’ where a higher median value means a more scattered water flow.

Table 3. Wetland characteristics for each model and which cost grid was used, and whether additional in- and outflow areas was mapped. The measurements were taken from LiDAR data and were measured inside the marshland polygons (aerial interpretation).

| Model ($n_{Marshland\ polygons}$) | Tree height medians (m) | Proportion of pixels with water depth < 1m (%) | Flow accumulation medians | Inclination index | Cost grid | Addition of in- and outflow areas |
|---|---|---|---|---|---|---|
| Model 1 (4) | 12-18 | 75-100 | 1 | 0.25-0.8 | DTW | No |
| Model 2 (2) | 4-7 | 9-40 | 1-29 | 0.09-0.8 | DTM | No |
| Model 3 (12) | 0.2-7 | 79-100 | 3-60 or 1 | 0.16-0.7 or 0.05-0.12 | DTM | Yes |
| Model 4 (7) | 0.3-7 | 85-100 | 1 | 0.5-2.2 | DTW | No |
| Model 5 (4) | 0.3-4 | 60-100 | 1 | 3.3-6.6 | DTW, DTM and Flow acc. | Yes |

# Discussion

## Mapping accuracy

It was evident that non-productive open wetlands were easier to map than their adjacent wet forests with conservation values. The study showed that remote sensing improved the mapping of small (< 4 ha) low-productive wetlands, since 97 percent of the open wetland area was found compared to approximately 75 percent in existing map layers. The improvement in the mapping of adjacent wet forests was even higher, since 80 percent of the area was found with the remote sensing models while only approximately 40 percent was mapped in existing map layers. Low-productive wetlands are relatively easy to recognise in the field, even in the dark and in snow covered terrain, while their adjacent wet forests with conservation values can be more difficult to identify and delimit. This means that the greatest strength of the models is the improvement of mapping of the adjacent biologically valuable forest, which also serves as edge zones around the low productive wetlands. The downside of the remote sensing models was that they exaggerated the retention area more than the existing map layers. However, the exaggerated area was relatively small compared to the one found, which makes the model a useful tool for finding retention areas around wetlands.

The plastic model, which allowed the remote sensing procedure to be determined by the wetland characteristics, had better accuracy than the static model, which had the same procedure for all wetlands. It improved the accuracy of open wetlands from 94 percent to 97 percent, and from 57 percent to 80 percent for the adjacent wet forest, and the exaggerated area was similar. This means that, to improve mapping accuracy, the first action should be to scan the terrain, and then choose the mapping procedure. Mappings with higher accuracy in identifying appropriate retention areas should reduce negative impact from logging, which is a known problem. It also provides opportunities for better calculations of the amount of forest land that should be set aside to achieve the environmental goals.

## Method

### A two-step procedure

Using a two-step procedure to locate open wetlands and their adjacent wet forest with remote sensing seemed like an appropriate strategy for several reasons. Firstly, open wetlands possess deviating characteristics that are relatively easy to find with remote sensing. Secondly, open wetlands occur in depressions in the terrain which is a good place to start when trying to locate wet forest areas. Thirdly, open wetlands are often surrounded by wet forests with high conservation values, which are relatively hard to find and delimit using remote sensing compared to open wetlands. This is because the tree height is relatively similar to the surrounding forest, they are not necessarily located in depressions in the terrain, and the canopy can have similar appearance to neighbouring forest that does not require protection. In this two-step procedure, we used the fact that wet forest for protection is often located next to open wetlands, i.e. areas around the topographic depressions that have shallow groundwater because of the in- and outflow.

#### *First step – finding truly wet areas*

We found it helpful to use aerial image interpretation in the first step when finding truly wet areas. Image interpretation has the advantage of not being dependent on modelling, but is instead a visual assessment of different biotopes or land use categories. When looking at a digital photo of a forest landscape, open wetlands have a distinctive appearance, which makes their delimitation relatively easy (see Fig. 2 for an example).

The wet conditions suppress tree and bush growth and result in lower and hydrophilic vegetation, e.g. *Sphagnum*, which makes them distinguishable in a forest landscape. Laying the marshland polygons over the DTM enabled location of the truly wet areas in the terrain. The image interpretation was adjusted with LiDAR data by removing areas with tree height over 12 m. This slightly improved the mapping accuracy of open wetlands by excluding the relative few areas that were exaggerated by the image interpretation, by detecting their normal tree growth.

In four cases, the image interpretation mapped a marshland that did not contain open wetland, i.e. it had a canopy according to the tree height grid (Model 1). Removing areas with tree height over 12 m would totally exclude them as wetlands for protection. Even though these areas were not truly wet, we still found them to be wet forests that required protection. The image interpretation was approximately 25 years old, and it is likely that these areas were wetter at the time of interpretation. Nevertheless, our study suggests that if such areas have a modelled depth-to-water of less than 1.25 metres, they probably possess characteristics that qualify them as retention areas if the Swedish environmental goals are to be achieved.

*Second step – finding retention areas around the truly wet areas*

The aerial image interpretation mapped 73 percent of the open wetland and 35percent of the wet adjacent forest, i.e. it underestimated the area that should be retained during logging. This study showed that it was possible to find most of the appropriate retention area around the truly wet areas by using accumulated cost grids, based on LiDAR data, which extends the area outwards. This study also showed that the accuracy was improved if the outward extension was controlled by the wetland's slope (DTM), modelled soil moisture (DTW), and modelled groundwater flow (flow accumulation), which were all assessed with LiDAR data

On flat wetlands where the altitude difference was less than 0.3 m per hectare, or when the modelled groundwater flow was scattered, the DTW map was less reliable in finding wet ground, and thereby an unreliable map layer for finding the borders of the retention area. Therefore, the DTW map was excluded in the mapping procedure in Models 2 and 3, and the altitude difference was used as a cost grid to find the wetland and the adjacent wet forest that was not covered by the image interpretation. A higher median value of the modelled groundwater flow meant that it was necessary to increase the limit value of the cost grid. In other words, a step higher in the terrain was needed to capture the retention area around the open wetland. This indicates that a scattered groundwater flow in flat terrain gives a larger area of wet forest around an open wetland compared to where the groundwater flows in more distinct channels.

In more inclined terrain (altitude difference between 1-4 metres per hectare) and where the modelled groundwater flow was in distinct channels, the DTW map was more accurate in finding the retention borders. Consequently, the cost grid was solely based on the DTW map in Models 1 and 4. We found no reason to vary the limit value of the cost raster in these models, so kept it constant at 20.

In hilly terrain where the altitude difference was greater than 6 m per hectare and the modelled groundwater flow was in distinct channels, the DTW map was less useful for solely delimiting the target retention area. This was because such conditions led to narrow and elongated areas with high conservation values along the in- and outflow areas to and from the truly wet areas. The cost grid was based on the DTW map and the altitude difference in Model 5, and the modelled flow accumulation was used as an additional cost grid to find the narrow and elongated in- and outflow areas (see Fig 6). Another situation when it was useful to also map in- and outflow areas using the flow accumulation was on wetlands in flat terrain (slope < 0.3 m / ha) where the height difference was used as a cost grid, but a high proportion (> 70percent) of the wetland was modelled as wet according to

DTW and the modelled flow accumulation was in more distinct channels ($Median_{FlowAcc}$ = 1). This is because a cost grid based on the height difference does not increase the area more at the inflow and outflow, which a cost grid based on DTW does to some extent. The fact that a high proportion of the wetland was modelled as wet according to DTW and that the modelled flow accumulation was in more distinct channels indicates that the modelled flow accumulation corresponds to reality (despite the flat terrain) and can therefore be used to find in- and outflows.

Other national remote sensing inventories of wetlands (Våtmarksinventeringen - Naturvårdsverket) and wet forests (Sumpskogsinventeringen – Skogsstyrelsen) covered only five of the 19 wetland areas in the study. These kinds of inventories are made on a large scale with coarser resolution, and should therefore not be used to find the accurate border of retention areas in everyday forestry management. The minimum size of mapped wetlands in the national wetland inventory (Naturvårdsverket) was 20 ha in southern Sweden and 50 ha in northern Sweden. The minimum size of mapped wet forests was 2 ha (Skogsstyrelsen). The mapped areas in these two remote inventories greatly exaggerated the wetland areas compared with our field inventory of the target retention area.

## Conclusions

An automated process could be used to obtain more accurate mapping of open wetlands and their surrounding wet forest with high conservation values. It was worth making the mapping process more complicated by allowing it to vary with the natural conditions, as this increased accuracy. Having access to a map layer where wetlands have been drawn with visual interpretation from images was valuable for finding the borders to the truly wet areas, since the LiDAR data alone was inadequate for finding such boundaries. By laying the marshland polygons (that were based on visual interpretation) over the digital terrain model (DTM), it was possible to locate how much of the topographic depressions was truly wet. From there, LiDAR data could be used to step up in the terrain to delimit the adjacent wet forest. It was not surprising that tree height, modelled ground moisture, inclination, and modelled groundwater flow (scattered or in more distinct channels) were helpful in determining how the outward increase (i.e. stepping up in the terrain) should be applied and thereby determine the size and shape of the target retention area. All these characteristics should reflect the forest conditions, such as wetness, and thereby have the potential to reveal whether the forest should be protected and which mapping method that should be most appropriate.

# References


Lantmäteriet. 2016. GSD-Topographic Map, vector format, Document version: 3.9.

Lantmäteriet 2020a. Ortophoto, Product description. Document version: 2.5.

Lantmäteriet 2020b. LiDAR data – laser data NH, Product description. Document version: 2.6.

Lantmäteriet 2020c. GSD-Höjddata, grid 2+, Product description. Document version: 2.8.

Metria 2015. CadasterENV Sweden – a multi-scale and multi-purpose land cover monitoring system. Version 3.0.

Metria 2017. Nationell marktäckedata – ett nationellt system för information om landskapet och dess förändringar. Version 1.1

Murphy P.N.C., Ogilvie, J., Connor K. & Arp P.A. 2007. Mapping wetlands: a comparison of two different approaches for New Brunswick, Canada. Wetlands, 27:4, p. 846-854.

Keskitalo E. C. H. & Liljenfeldt J. 2014. Implementation of forest certification in Sweden: an issue of organisation and communication, Scandinavian Journal of Forest Research, 29:5, 473-484, DOI: 10.1080/02827581.2014.919355

R Core Team 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Swedish Environmental Protection Agency. 2017. http://www.naturvardsverket.se/Sa-mar-miljon/Vatten/Vatmark/ (*last update: 24 November 2020*).

Swedish Environmental Protection Agency. 2017. Kunskapsunderlag om våtmarkers ekologiska och vattenhushållande funktion. Ärendenr: NV-05712-17.

Swedish Forest Agency 1999. Sveriges sumpskogar - Resultat av sumpskogsinventeringen 1990-1998. Meddelande 3 – 1999.

Swedish Forest Agency. 2013. Goals for good environmental consideration, *in Swedish*. Report 5, 1883.

Swedish Forest Agency. 2016. Current situation assessment of woodland key habitats, *in Swedish*. Report 7, 1856.

Swedish Forest Agency. 2020a. Trädhöjdsraster laser – produktbeskrivning

Swedish Forest Agency. 2020b. Markfuktighet – produktbeskrivning

The Swedish Species Information Centre. 2015. Red-listed species in Sweden 2015.

White B., Ogilvie J., Campbell D.M.H., Hiltz D., Gauthier B., Chisholm K.H., Wen H.K., Murphy P.N.C & Arp P.A. (2012) Using the Cartographic Depth-to-Water Index to Locate Small Streams and Associated Wet Areas across Landscapes, Canadian Water Resources Journal / Revue canadienne des ressources hydriques, 37:4, 333-347, DOI: 10.4296/cwrj2011-909.

# Appendix

### Models in the plastic model, technical information

Model 1 - Pixels from the wet map with value < 125 were selected within the terrain map's wetland polygon. This raster (selected pixels) was the starting point of the tool 'Path Distance'. Pixels from the wet map with value > 125 were transformed to NoData and the remaining pixels were log-transformed. This became the cost grid in 'Path Distance'. To delimit the surface, the value 20 was selected (Set Null > 20). This model was applied on four of 26 surfaces.

Model 2 - Pixels from the tree height grid with value ≤ 120 were selected within the terrain map's wetland polygon. This raster (selected pixels) was the starting point of the tool 'Path Distance'. The change in altitude was used as cost raster. The altitude change was calculated with the tools 'Slope' and 'Raster Calculator'. This model was applied to only two of 26 surfaces and therefore it was difficult to find a universal value for delimiting the surface. On one of the wetlands that was very flat (slope index = 0.09) and had a scattered water flow (Flow Accumulation median = 29), the limit value was chosen to be 1.6 (Set Null > 1.6) while in the other basin that had a larger slope (slope index = 2.7) and had a water flow in more distinct channels (Flow Accumulation median = 1), the limit value was set to 0.4 (Set Null > 0.4).

Model 3 - Pixels from the tree height grid with value ≤ 120 were selected within the terrain map's wetland polygon. This raster (selected pixels) was the starting point of the tool 'Path Distance'. The change in altitude was used as cost raster. The altitude change was calculated by subtracting the altitude pixels with the median altitude of the terrain map's wetland polygon. To avoid negative values, the absolute values were used. If the Flow Accumulation median was ≤ 30, the value 2.0 was chosen to delimit the surface, if the Flow Accumulation median was > 30, the value was chosen to be 4.0. This model was applied to 12 of 26 surfaces. If the Flow Accumulation median was ≤ 3 (but the slope index < 0.2), an additional surface was mapped. The already mapped raster was the starting point in 'Path Distance' and pixels having a catchment area > 0.2 ha (value 500 in the Flow Accumulation grid) were cost raster. This created linear structures with the width of only one pixel extending out of the wetland representing in- and outlet water flow channels. Since a higher flow accumulation value should give lower cost, and the values had an interval of 500-100,000, the cost grid was created by 1,000,000 divided by the flow accumulation value and then log-transformed. Value 100 was used to delimit the water flow channels. These linear structures were used as a starting point in 'Path Distance' and a modified wet map served as cost raster, where all pixels with value ≤ 100 were given a value of 1 while the remaining pixels were given the value 8. Value 7 was used to delimit the area. Two of the twelve wetlands to which this model was applied on had Flow Accumulation median ≤ 3 and slope index < 0.2.

Model 4 - Pixels from the tree height grid with value ≤ 120 were selected within the terrain map's wetland polygon. This raster (selected pixels) was the starting point of 'Path Distance'. Pixels from the wet map with value > 150 were deleted and the remaining pixels were log-transformed. This became the cost raster in 'Path Distance'. To delimit the surface, the value 20 was selected (Set Null > 20). This model was applied to six of 26 surfaces.

Model 5 - Pixels from the tree height grid with value ≤ 120 were selected within the terrain map's wetland polygon. This raster (selected pixels) was the starting point of 'Path Distance'. A combination of the wet map and altitude change was used as cost raster. The altitude change was calculated with the tools 'Slope' and 'Raster Calculator'. The wet map was modified with 'Raster Calculator' so that all pixels with value ≤ 100 were given value 1 while the remaining pixels were given value 8. The altitude change raster and the modified wet map were multiplied with each other and then constituted the cost raster in 'Path Distance'. To delimit the area, the value 0.6 was chosen (Set Null > 0.6) In this model, an additional surface was always mapped. The already mapped raster was the starting point in 'Path Distance' and pixels having a catchment area > 0.2 ha (value 500 in the Flow Accumulation grid) were cost rasters. This created linear structures with the width of only one pixel extending out of the wetland representing in- and outlet water flow channels. Since a higher flow accumulation value should give lower cost, and the values had an interval of 500-100,000, the cost grid was created by dividing 1,000,000 by the flow accumulation value and then log-transformed. The value 150 was used to delimit the water flow channels. These linear structures were used as a starting point in 'Path Distance' and the modified wet map where all pixels with value ≤ 100 were given the value 1 while the remaining pixels were given value 8, served as cost raster. Value 7 was used to delimit the area. This model was applied to four of 26 surfaces.