Examensarbeten 2015:1

Fakulteten för skogsvetenskap
Institutionen för skogens ekologi och skötsel

Kan markfuktighetskartor användas för att hitta skogsmark med hög bonitet?

- Ett GIS-baserat försök med DTW-index och laserskannad övre höjd

Can wet areas mapping be used to find areas of high forest site productivity?

- A GIS-based attempt using DTW-index and laser scanned top-height

Anders Henriksson

Sveriges Lantbruksuniversitet
Examensarbete i markvetenskap, 30 hp, avancerad nivå A2E
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Summary

The depth-to-water-index (DTW-index) is derived from digital elevation models (DEM) to map soil wetness, in terms of distance from soil surface to the ground water table. The aim of this GIS based study was to investigate the existence of a relationship between DTW-index and forest site productivity (SP). The belief of such an assumed relationship was based on knowledge that the ground water level is related to site properties that can either promote or impede tree growth.

Data primarily comprised rasters of the Krycklan catchment in northern Sweden and depicted DTW-index and a laser scanned vegetation height. The 100th height percentile of each pixel in the vegetation raster was assumed to mirror the top-height, letting it act as a relative measure of SP within a delineated area of equal stand age. Areas of equal age were delineated by recognition of fresh clear-cuts in a digitized ortophoto from 1963. Influence from disturbing factors was reduced by selecting areas on till soil where Scots Pine (*Pinus Sylvestris* L.) dominated. The result suggests a weak and likely non-significant relationship between the variables. The lack of compelling evidence for such a relationship is attributed to the methods used and we suggest a repeated study with a more developed study design.

Keywords: DTW-index, site productivity, Krycklan, remote sensing, wet-areas mapping, forest hydrology, topography, site properties.

Sammanfattning

DTW-index härleds ur digitala höjdmodeller (DEM) vilket resulterar i kartläggning av markfuktighet, mätt som avståndet från markyta till grundvattennivå. Syftet med denna GIS-baserade studie var att undersöka förekomsten av ett samband mellan DTW-index och skoglig produktionsförmåga (bonitet). Ett sådant förmodat samband grundar sig på kunskap som pekar ut grundvattennivå som en faktor som kan gynna eller hämma träds tillväxt.

Data omfattade raster över Krycklans avrinningsområde för DTW-index respektive laserskannad vegetationshöjd. Den högsta percentilen i varje pixel av vegetationsrastret antogs motsvara övre höjd, vilket tillät användning av denna variabel som ett relativt mått på bonitet inom ett avfattat område av lika beståndsålder. Bestånd av lika ålder avfattades genom att identifiera färska kalhyggen i ett digitaliserat ortophoto från 1963. Påverkan från oönskade faktorer reducerades genom att välja områden på morän och med dominans av tall (*Pinus Sylvestris* L.). Resultatet visar på ett svagt och troligen ej signifikant samband mellan variablerna. Bristen på ett klart samband hänförs till metodval och vi föreslår en upprepad studie med en mer utvecklad metod.

Nyckelord: DTW-index, bonitet, Krycklan, fjärranalys, markfuktighet, kartläggning, markhydrologi, topografi, ståndortsegenskaper.

Contents

1. INTRODUCTION

A key component in sustainable forest management is knowledge of what the growing crop will yield. The yield partly depends on the productive potential of the forest site, explaining the relevancy of research related to the assessment of this potential. Some of this work has been focusing on how site properties contribute to tree growth (Hägglund & Lundmark, 1977)). It is intuitive to people with ecological insight that macro climate is related to tree growth and the general difference of the productivity between forests of northern and southern Sweden is linked to this factor. However, considering the local landscape, climatic variation is very low. Climate has a great temporal variation but varies little spatially compared to the spatial variation in tree growth, which can be great. This leads us to think that spatially varying factors must be responsible for spatial tree growth variation. One factor may be the shape of the land surface (i.e. topography) since it varies continuously in the landscape, just as tree growth does. The long-term effects of topography are of such importance that it is regarded as one of the soil forming factors. Topography also has short-term effects on the gravitational movement of water within soil, thus affecting the downward transport of both solid and dissolved species (Chesworth, 2008). Likewise, the pattern of water saturated areas is often controlled by topography (Grabs *et al*., 2009).

In forest hydrology, research often focuses on how forestry affects water resources adversely (Munthe & Hultberg, 2004; Akselsson & Westling, 2005). In contrast, water also affects forestry, as a controller of tree growth. Water is directly required in fundamental processes within the tree cell and for transport of vital elements between tree cells (Raven *et al*, 2005). Water has also indirect control on tree growth due to its vast influence on soil properties. In this study, we explore the influences of groundwater depth on site productivity.

1.1. Forest site productivity

1.1.1. The meaning of site productivity

In a broad sense, s*ite productivity* is a quantitative estimate of a site´s potential to produce plant biomass, regardless of biomass type and how much of the potential that is utilized for growth. Since the main objective in silviculture is the production of woody biomass, it is sound to narrow the concept to embrace only the part of the site potential that is expected to be realized by the trees for wood production (Skovsgaard and Vanclay, 2008). We can refer to that part as *forest site productivity*. However, from now site productivity (SP) refers specifically to *forest* site productivity (Figure 1.1).

The prevailing system for forest site assessment in Sweden defines SP as (freely translated):

"…the site´s inherent potential to produce merchantable wood in measures of m^3f^* per hectare and year, when the mean annual increment (MAI[**]) peaks in a stand that has been established and managed ideally in terms of wood production."(Hägglund & Lundmark, 1999)

[*] m^3f: Cubic meter stem wood over bark from stump to tip.
[**] MAI: (total volume produced per hectare)/(stand age).

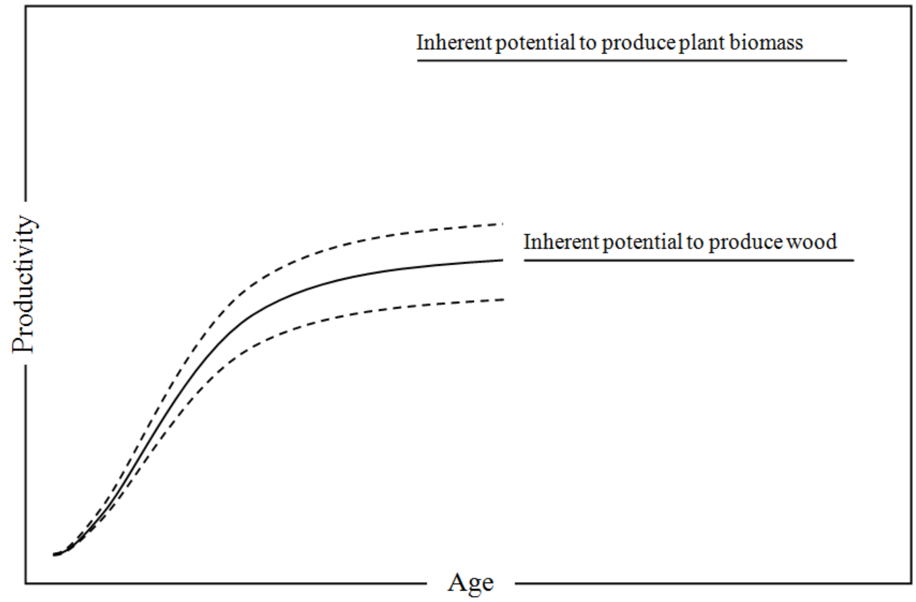

Figure 1.1. Site productivity in relation to forest site productivity for a given forest site. The upper bar represents site productivity in a broad sense whilst the lower bar represents the wood production share. The lined curve expresses how productivity in terms of mean annual increment develops under ideal conditions from stand establishment until culmination. The upper dashed curve represent the development if the potential is artificially improved (e.g. by fertilization). The lower dashed curve represents the development when forest management is non-ideal.

The definition implies that SP depends on the two components *inherent potential* and *silviculture*. The latter can influence SP by the selection of regeneration methods, tree species etc, or by practical aspects of forest operations, such as soil compaction (Conlin & van den Driessche, 2000). Comparisons of SP between stands is enabled by assuming that management is ideal, meaning that one imagine that the forest stand have been established and treated in a way that maximises the production of stem wood per forest area. The first component of SP embraces the inherent potential of a given site, and is primarily determined by soil and climatic characteristics (Skovsgaard & Vanclay, 2008). Site characteristics relevant for tree growth can be referred to as site properties. A textbook in plant biology may account for the fundamental requirements of plant cell growth from a biochemical perspective (Raven *et al*., 2005). One can argue that site properties represent the very same plant requirements, but expressed in the wider *site* perspective.

1.1.2. Assessing forest site productivity

Knowledge of SP may serve a range of purposes in forest planning, which explain the importance to rank stands according to their productive potential. Since the standard unit for SP (m^3f per hectare and year at MAI), is hard to measure straightforwardly, managers use quantifiable indicators, known empirically to relate to SP. For instance, moist forests are often more productive than dry forests, making soil moisture one indicator for SP. Even if it gives no absolute value of wood production one can argue that it might be enough to point out the more fertile site. Several indicators are often required to obtain absolute numbers of SP. Multiple regression analysis of the relationship between indicators and realised yield, have resulted in *systems* for SP assessment, such as the Swedish SIS system (Corns & Pluth, 1984; Hägglund & Lundmark, 1977).

Productivity indicators can be either *phytocentric* or *geocentric*. Phytocentric indicators are based on characteristics of a site's vegetation. From the phytocentric indicators one can extract the subgroup *dendrometric indicators* which are specifically based on metrics of trees, e.g. height and age. Geocentric productivity indicators are features of the site´s physical nature and can include properties of climate, soil, and topography etc (Skovsgaard & Vanclay, 2008). Which indicators one may use depends on the condition of the stand to be assessed and availability of a system for SP assessment applicable for the area. Geocentric indicators might be the only option when lacking dendrometric indicators.

1.1.3. The site index hypothesis

SP for a given tree species, in even aged stands can be estimated by using stand height as a dendrometric indicator. This basically means that SP can be assessed by using tree height as a biological gauge. The validity is based on the argument that wood volume produced in an even-aged monoculture stand is highly correlated to the top-height* trees. This idea, generally referred to as the *site index hypothesis*, propose that the productivity of forest sites can be classified by stand height at a given age. However, thinning must not be from above because it would remove the indicator trees that correlate to SP. It also relies on the assumption that the top-height trees are somewhat independent of stem number and thinning grade in even-aged stand. The great advantage is that top-height is an indicator inexpensive to measure and generally not much affected by silviculture. Classification of sites using stand top-height is therefore one of the most suitable indicators of SP for management purposes in even-aged forest stands (Skovsgaard & Vanclay, 2008).

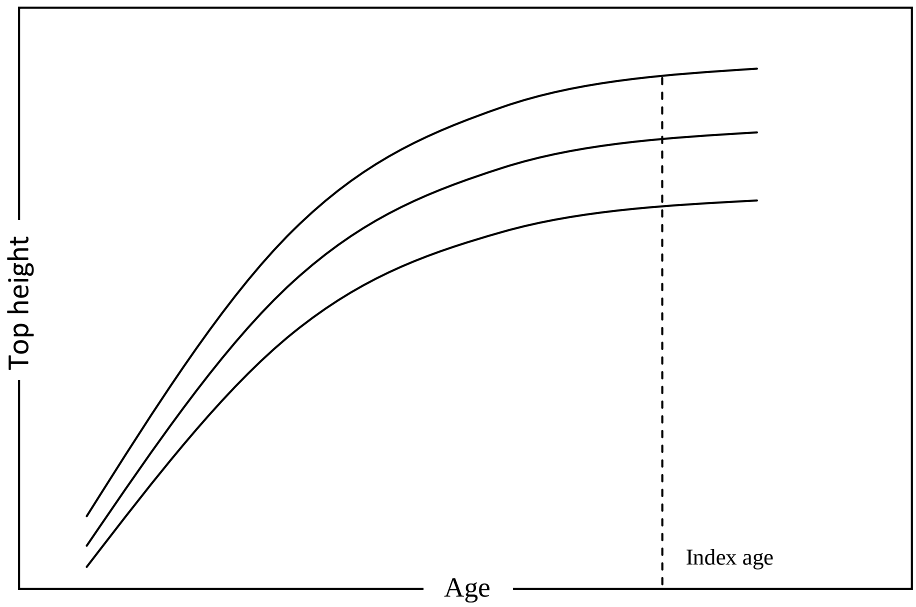

Figure 1.2. Top-height trees generally follow deterministic height-age trajectories where higher SP allow higher top-height. The *site index hypothesis* state that stand height can be used to classify site productivity. The argument is that height growth is correlated with stand volume growth.

* Top-height: The definition varies but is in Sweden defined as the mean height of the 100 highest trees per hectare. In practice, this is measured as the mean height of the two thickest trees in a 10 meter radius plot (Hägglund & Lundmark, 1999).

1.2. Site productivity in the context of topography

As stated previously, SP is greatly determined by soil and climatic characteristics (Skovsgaard & Vanclay, 2008). Thus, one area of similar climate can vary considerably in SP due to different parent material and textural composition, but variation in SP may be vast even within climatically similar areas where parent material and textural composition is the same (Giesler *et al*., 1998). Topography, along with parent material, climate, biota, and time, is one of the principal factors of soil formation (Chesworth, 2008). Topography, soil hydrology and SP are features that are interrelated in a very complex way. The following paragraphs give a brief idea of how they are related.

1.2.1. Topography is a controller of soil hydrology

The idea that topography can explain soil variation within geologically and climatically similar areas is recognized as the *catena* concept (Hook & Burke, 2000). The concept assumes that topography-related processes generate consistent patterns of soil development along hill-slopes (Siebert *et al*., 2007). The long-term processes account for the evolution of landforms and parent material (Hook & Burke, 2000). In Scandinavia, this would be associated to processes related to the glaciations, which have distributed materials in an often predictable way (Chesworth, 2008; Eriksson *et al*., 2005). Long-term effects of soil formation may indeed affect SP greatly. However, topography affects SP also by processes related to short-term soil hydrology. Topographical features influence the hydrological conditions of a site and generate different soil moisture conditions and flow patterns (Siebert *et al*., 2007). Topography is a major controller on the spatial pattern of saturated areas and spatial modeling of ground water level using topography is suggested to be possible on till soils (Grabs *et al*., 2009).

1.2.2. Groundwater influence SP directly

That living trees requires water to grow is a well known fact. This relationship between water and SP can be described as simple and direct. However, it is also known that the typical limiting element for tree growth in Swedish forests is nitrogen (N) (Tamm *et al*., 1999). Even if water deficit does not typically limit tree growth, it likely occurs occasionally. Water deficit has shown to limit growth for Norway spruce (*Picea abies* (L.) *Karst.*) in southern Sweden (Bergh *et al*., 1999) and for Scots pine (*Pinus sylvestris* L.) in central Sweden during dry summers (Cienciala *et al*. 1998). Water deficit results in stomatal closure of leaves and needles and consequently inhibition of photosynthesis (Raven *et al*., 2005). The amount of water available for root uptake is reflected by the soil moisture which is closely related to the ground water level (Hägglund & Lundmark, 1977). Tree roots generally reside in the unsaturated vadose[*] zone above the ground water table. If water table rises, so does also the soil water content in the vadose zone and vice versa. A wet[**] site with a shallow groundwater table is likely more resilient to dry spells than dry ones, leading to a higher long-term SP. On the other hand, an excess off water can be detrimental to tree roots due to the anaerobic conditions and reduced root respiration that is the result of saturated soils (Brady and Weil, 2008).

[*] Vadose zone: the profile above the water table where soil is unsaturated in terms of soil water content
[**] Note that the terms wet/moist and wetness/moisture are used interchangeably.

1.2.3. Indirect effects of groundwater on SP

In addition to the direct effects, water influence SP indirectly by enabling chemical reactions central in the supply and cycling of nutrient in soils. Soil moisture is one factor that strongly controls nitrogen mineralization (Powers, 1990). An excess of soil water can decreases aeration and the decomposition of organic material, which can be seen on the thickness of the O –horizon in the soil profile (Seibert *et al*., 2007). Soil moisture may also be linked to the fixation of atmospheric N. Mosses form a symbiotic relationship with N-fixing cyanobacteria (Lindo & Gonzalez, 2010). Prolonged drought was shown to reduce N-fixation of the feather moss associated cyanobacteria, compared to a persistent moisture level (Gundale *et al*., 2009). Thus, forest sites with persistent moist forest floor might promote SP by having a higher net fixation of N.

1.2.4. Groundwater redistribute nutrients and water

Water is a great solvent that can store, accumulate and reallocate mineral nutrients within forest soils (Eriksson *et al*., 2005). Groundwater is believed to transport nutrients from higher elevated dry areas to wet areas downslope (Figure 1.3). Giesler *et al*. (1998) describes a gradient of SP along a hill-slope in northern Sweden that stretches from a water recharge area of poor SP in the higher end, to a water discharge area of high SP in the lower end. The increase in SP was ascribed the higher abundance of available N and they argued for five possible explanations, including a higher net fixation and turnover of N due to the supply of groundwater from upslope water recharge areas. They also argued for the possibility for N-enrichment as groundwater travels downslope. This mechanism was also suggested by Kuglerova *et al.* (2014) who found groundwater discharge sites to host higher species richness due to a higher soil N supply.

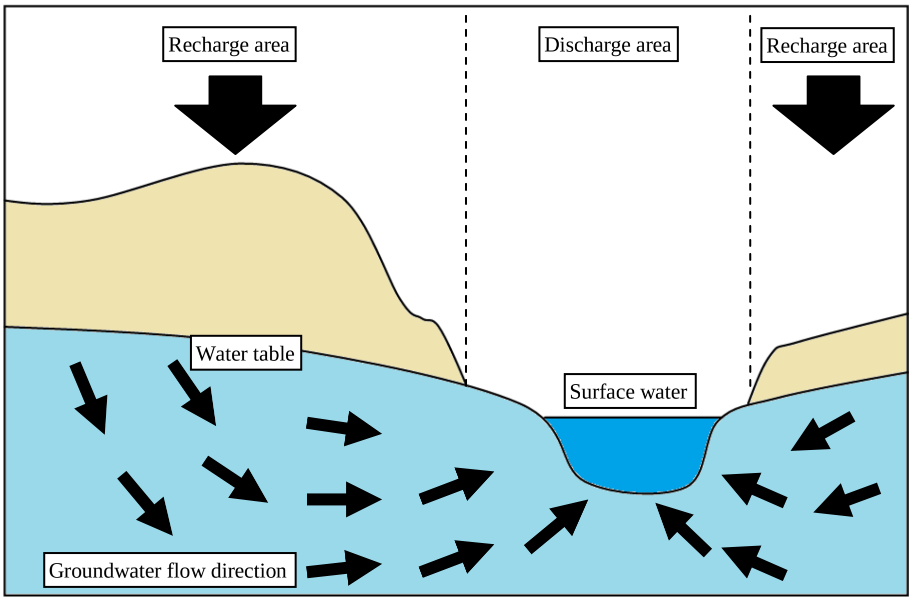

Figure 1.3. Simplified idea of soil water movement in a landscape perspective. The surface can be divided into recharge and discharge areas. In recharge areas soil water flow has a downward direction. In discharge areas soil water flow has an upward direction, towards soil surface.

1.2.5. Mapping the soil moisture

Ground water depth can be used as a geocentric indicator for assessing SP. The SIS system, uses the indicator soil moisture, which is closely related to ground water depth (Hägglund & Lundmark, 1977). Surveying of soil moisture is often done on basis of the local topography, plant community and presence of surface water. One major disadvantage with field based methods is the substantial time and labor requirements which restricts detailed large scale mapping. One single moisture class is assigned to whole stands since surveyors generally do not map the soil moisture continuously in the stand. Detailed maps of soil wetness have until recently been very rare. Since soil hydrological properties rely on topography, remote sensing can be used to derive soil hydrological models. Airborne laser scan (ALS) enables detailed mapping of vegetation and topography to a relatively low cost (Nordkvist & Olsson, 2012). With topography presented as a digital elevation model (DEM) it is possible to derive the depth-to-water-index (DTW-index) to map soil wetness in the forest landscape (Murphy *et al*., 2009).

1.3. Aim of the study

This study addresses the question if the depth-to-water-index (DTW-index) can explain spatial variation in SP. If a relationship can be detected, it may contribute to develop methods to detect areas of high SP, using remotely sensed data. Such methods can assist in the planning and management of sustainable forests. The objective is to investigate how DTW-index varies with SP, using ALS-derived tree height, in areas of equal age as a relative indicator for forest SP.

Topography can be a major controller of soil moisture and consequently SP. As we described, groundwater depth is a variable that relates to e.g. tree supply of water, N-mineralisation, N-fixation and downslope enrichment of groundwater N. We therefore assume that the groundwater level does not only represent a certain supply of water for tree growth, but also mirror other SP-related properties in the forest soil.

2. MATERIAL & METHODS

In brief, this study investigated the relationship between tree height at a certain age and soil moisture expressed as DTW-index. Tree height data was in the shape of a raster derived from ALS. With ESRI ArcGIS 10.1, areas of equal age was delineated by identifying cut-blocks in aerial images from 1963, thus letting tree height act as a dendrometric indicator for SP. The relationship between DTW-index and stand height was investigated using stand averages (Figure 2.1), sample of data points as a whole (Figure 2.2) and data points for a single selected stand (Figure 2.3), respectively.

2.1. Description of the Krycklan catchment

The area of study is the 6790 ha Krycklan catchment, approximately 50 km northwest of Umeå, Sweden (64°, 14´N, 19°46´E). The catchment has been target to some intense hydrological research the last three decades and does also enclose the experimental forest of Svartberget. Plenty of silvicultural research is running here, albeit the main reason for selecting this area was because of the availability of data.

Bedrock in the Krycklan area is dominated by Svecofennian metasediments/metagraywacke with pockets of acid to basic metavolcanic rocks. Quaternary deposits are dominated by till and sorted sediments. Catchment elevation ranges from 114 to 405 m a.s.l. The region was glaciated and is undergoing isostatic rebound, so the highest postglacial coastline traverses the catchment at approximately 257 m a.s.l. At higher altitudes the quaternary deposits are dominated by till and peat whilst postglacial sedimentary deposits dominate in lower altitudes. In the till soils, well-developed iron podzols dominate the forest floor soils, but near the stream channels, the organic content increases, forming a riparian peat zone along the streams. Forest covers 87% of the catchment, mires 9%, and thin soils and rock outcrops 7% and 1%, respectively. The land use is dominated by forestry of witch most is second growth forest. From satellite imagery, 76 clear cuts were detected in the catchment between the years 1999–2010, covering a total of 7% of the catchment. (Laudon *et al*., 2013).

The forests are dominated by Scots pine (63%) and Norway spruce (26%) with an understory dominated by ericaceous shrubs on moss mats. The climate is characterized as a cold temperate humid type with persistent snow cover during the winter season. The 30 year mean annual temperature (1981–2010) is +1.8° C, January –9.5° C, and July +14.7° C, mean annual precipitation is 614 mm, annual mean runoff is 311 mm (Laudon *et al*., 2013).

2.2. Mapping forest site productivity

A tree height raster (10 m)* covering the Krycklan catchment, derived from ALS in 2010, was obtained from the department of Forest Resource Management, SLU. The raster depicted the 100th height percentile in the height range of all the returns in each pixel, meaning that each pixel value corresponded to the most elevated point in the 10 x 10 m area projected over the tree canopy. Following raster is from now on denoted the top-height raster.

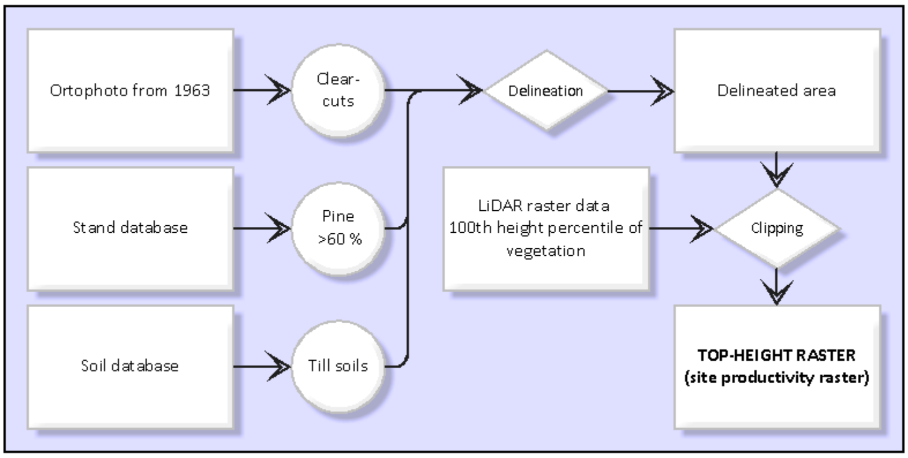

Figure 2.1. Flow chart describing the general process of data transformation. Data from an old ortophoto was combined with data from a stand database plus soil database. This resulted in the delineated area which was used as a cookie cutter for the LiDAR-raster data to obtain the site productivity raster (referred to as top-height raster). Rectangles represent data entities, circles represent criteria and diamonds represent operations.

2.2.1. Delineation of even-aged stands of equal age

In order to use pixel values in the top-height raster as dendrometric indicators for SP, only areas of equal stand age were included. For this we obtained a digitalized ortophoto from 1963 from the department of Forest Resource Management, SLU, in which we delineated areas of newly final felled forests (Figure 2.1). It was assumed that these stands had been adequately reforested the same year. The fact that these stands once were clear-cuts suggested that stands also were inherently even-aged. Clear-cuts covered by seed trees and parts of clear cuts that looked shrubby in the photo from 1963 were excluded.

2.2.2. Delineation due to stand and soil characteristics

Trying to exclude the impact of factors other than ground water depth a number of criteria were set in an effort to achieve an all-else-equal-assumption. A stand database covering the Krycklan catchment was obtained, also from the department of Forest Resource Management. This database included stand borders represented as vector data and other stand parameters based on interpretation of recent aerial photos. By using this stand database, the even-aged area delineated on basis of 1963 year´s ortophoto, was further delineated by

* The number within the brackets denotes the length of the raster pixels, so when mentioning a raster with 10 m × 10 m pixels, it is followed by “(10 m)” etc.

excluding stands where the share of Scots pine was suggested to be ≤ 60 percent. Additionally one stand with an even higher share of Scots pine (90 percent) was identified for close up inspection (Figure 3.3).

A soil map established by the Swedish Geological Survey (SGU) was utilized to select only areas dominated by till. Sedimentary soils was avoided since surface topography is a less related to soil wetness due to hydro-geological characteristics (Grabs *et al.*, 2009).

2.2.3. Stand buffering

Stand borders were negatively buffered with 7,07 m. The reason for this was that the delineated area was in the shape of a vector polygon. However, when using polygons as templates for clipping raster data, ArcMap consider raster pixels to be inside a polygon if pixel mid-points are within the polygon. This may cause pixels with values partly based on bordering stands to be included in the analysis. The issue was resolved by buffering the polygon by $-\sqrt{5m^2+5m^2}$ (half the diagonal of a pixel), ensuring that pixels only completely enclosed by the delineation were included (Figure 3.2). After this, stands and remnants of stands < 0,5 hectares were excluded due to practical reasons. The remaining area was the sample area in which the DTW-index and SP relationship was to be investigated.

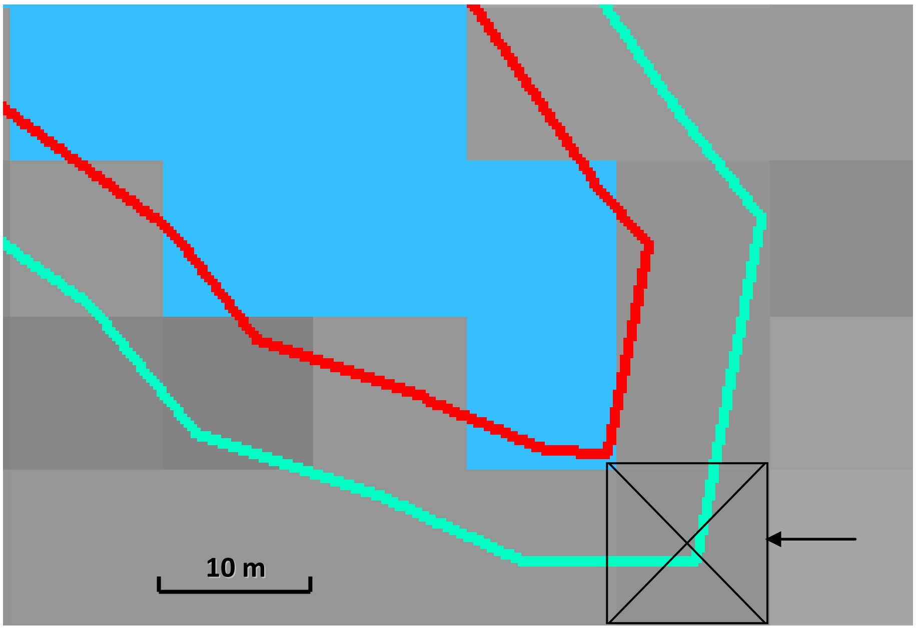

Figure 2.2 One example of a stand border buffered by $-\sqrt{5m^2+5m^2}$ (half the diagonal of a pixel) to prevent pixels influenced by bordering stands to be included in the analysis. The pixel in the black box would risk representing a height of the bordering stand. Height grid (grey) and highlighted stand pixels (blue). Original stand borders before (cyan) and after (red) buffering.

2.3. Preparation of the ground water table raster

The DTW-index raster (2 m) was conveniently obtained from the department of Forest Ecology and Management, SLU. The only thing required was to aggregate the raster by a factor of 5 using the AGGREGATE function of ArcMap in order to harmonize the resolution of the DTW-index raster to the resolution of the tree height raster (10 m). The pixels were assigned the arithmetic mean value of the 25 input pixels and were snapped to the tree top-height raster to perfectly align.

2.3.1. DTW-index – a brief background

The following DTW-index raster was obtained in a ready to use format. Nevertheless, a brief description of the functionality of DTW-index is in place.

A depth-to-water-index (DTW-index) raster is partly a derivative of a digital elevation model (DEM); generated in a process also referred to as wet areas mapping (WAM). The following raster was based on the New Digital Elevation Model, which has a resolution high enough (2 m) to predict soil wetness with satisfying accuracy (Ågren *et al*., 2014). First step is to derive a flow direction raster from the DEM. One way of doing so is by using the D8 –method, which rout flow from each pixel in a DEM to the adjacent pixel with the steepest downward slope (Jenson and Domingue, 1988).

With knowledge of how water flows from one point in the DEM to another, one can derive stream networks and discharge areas etc. In addition to a DEM, DTW-index utilize conventional photo-interpreted hydrographical data (Murphy *et al*., 2009). The DTW-raster expresses the distance to the ground water from soil surface according to the formula:

$$DTW[m] = \left[\sum \frac{dz_i}{dx_i} a\right] x_c$$

Here, *dz/dx* is the slope of a pixel, *i* represents a pixel along the flow path, *a* is 1 when the path crosses the pixel parallel to the pixel boundaries and $2^{0,5}$ when it crosses diagonally and x_c is the grid pixel size [m]. The formula is a least-cost function meaning that it by iterational solving finds the route from one pixel in the raster to surface water of least cumulative value (Murphy *et al*., 2009). It should be made clear that even though the DTW-index is expressed as the distance to groundwater in the unit meter, it should be interpreted as a relative measure of soil wetness. To the author's knowledge, DTW-index has mostly been used for the mapping wet areas near surface waters, where the groundwater table is near soil surface. Relating DTW-index to actual depths for the groundwater table in upland areas should therefore be made with caution.

When producing a DTW-raster, it is of central importance to determine the extent of the surface water. Stream network extent can be adjusted with the parameter denoted flow initiation threshold. This is the size of the upslope drainage area at which surface runoff starts. The raster used in this study was based on a grid of 2 ha for flow initiation since it corresponded best to field surveyed soil moisture in the Krycklan catchment (Ågren *et al*, 2014).

2.4. Extraction of data

The delineated stand polygons (Chapter 2.2) were rasterised (10 m) and snapped to the tree height raster using the POLYGON TO RASTER tool. The pixels were assigned numbers corresponding to their initial stand number. This would ease the calculation of stand average values.

Vector points were created for each pixel in the stand raster using the tool RASTER TO POINTS. To this layer of points we joined underlying values for stand number, DTW-index and tree height, by using the tool MULTI VALUES TO POINTS. The process resulted in a table of data points which were exported to MS Excel for data analysis and presentation.

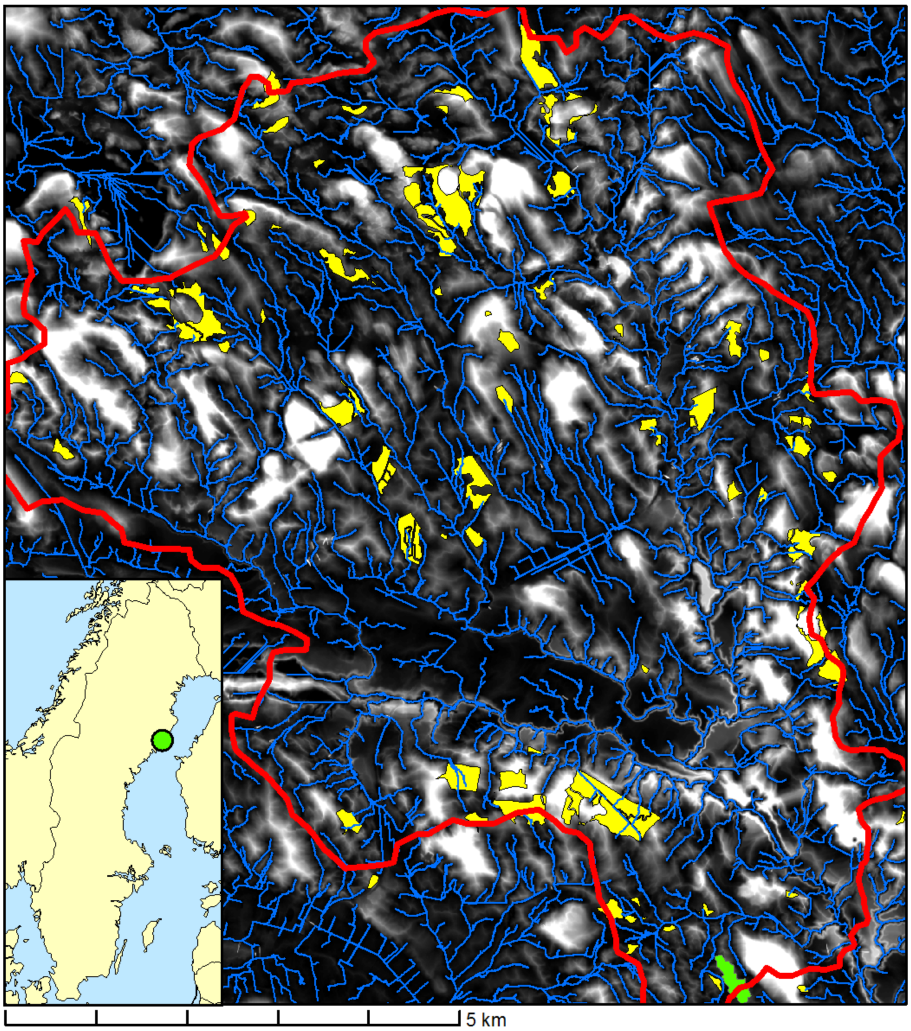

Figure 3.3. Area of study. Boundary of the Krycklan catchment (red). DTW-raster (darker = wetter, lighter = dryer). Stream network used for DTW-raster generation (blue). Sampled stands after amendments and buffering (yellow). The selected stand for close up study (green).

3. RESULTS

A total of 26821 pixels were sampled from the data for tree height and DTW-index respectively. With a pixel size of 10 x 10 meters, this represents an area of approximately 270 hectares. In order to find a relationship between SP and any of the DEM-derived variables, data was analysed in three focal levels.

3.1. Stand mean values

The clear-cuts we delineated in the ortophoto from 1963 were delineated further so the final result was 74 even-aged stands on till soil with at least 60 percent of Scots pine. In these 74 stands, arithmetic mean values stretched: 0,8 m to 22,0 m for DTW-index; 12,7 m to 20,0 m for top-height (Figure 3.1). Just for clarity, mean top-height refers to the mean value of the stand pixels in the top-height layer, where each pixel represents the highest return obtained from ALS. The size of the sampled stands stretched: 0,5 to 19,7 hectares. Coefficient of variation (CV) stretched: 3 to 19 percent for stand height; 8 to 93 percent for stand DTW-index.

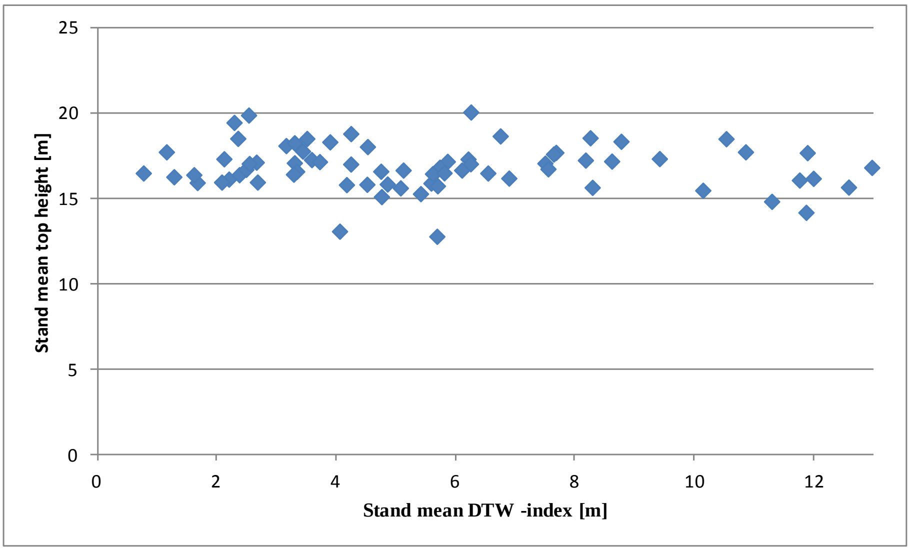

Figure 3.1. Stand top-height as function of stand average DTW-index. n =74.

3.2. DTW-index classes

In the whole sample of pixels, individual pixel values stretched: 0,03 m to 47,85 m for DTW-index; 3,75 m to 25,55 m for top-height. Top-height of DTW-index class shows a low degree of variation in the range from 0 until 20 meters for DTW-index. The higher DTW-index classes show an increase in top-height and thereafter a huge scatter for the driest areas (Figure 3.2a).

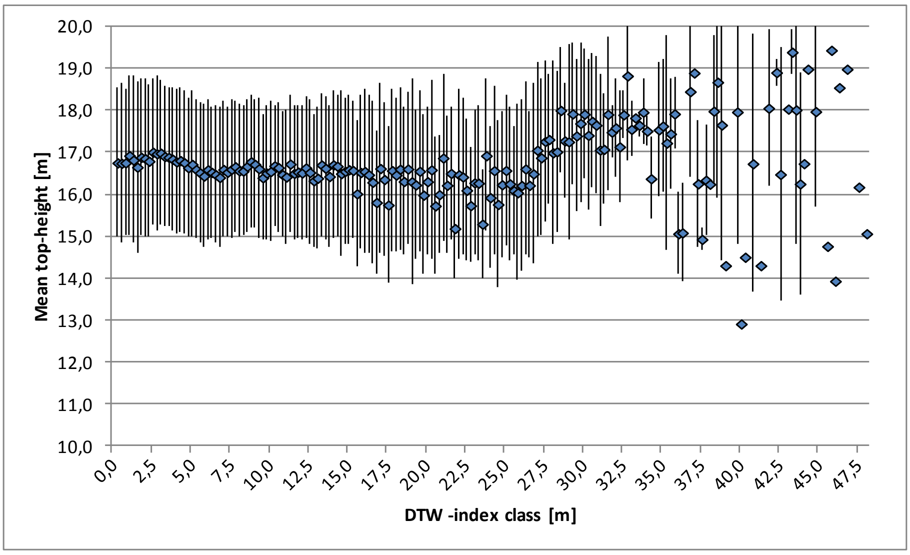

Figure 3.2a. Mean top-height (blue) of DTW-index class (25 cm) in full range. Black whiskers means ±1 SD. Note that vertical axis is broken. Letters on horizontal axis denote the upper boundary of each class.

We here choose to focus on top-height in the 0 m to 5 m range of DTW-index since this range makes up more than 46 percent of the data. We also think that the index is most accurate for the lower values considering the study by Ågren *et al.* (2014). Beyond 20 m for DTW-index, every class comprises very few values which make us believe that the scatter should be interpreted as noise. Nevertheless, in the 0 m to 5 m range, when plotting mean top-height as a function of DTW-index class the relationship is slightly mound-like with an R^2 -value of 0,48 (Figure 3.2b). Dispersion of the data is with all data points within one standard deviation in the vertical axis.

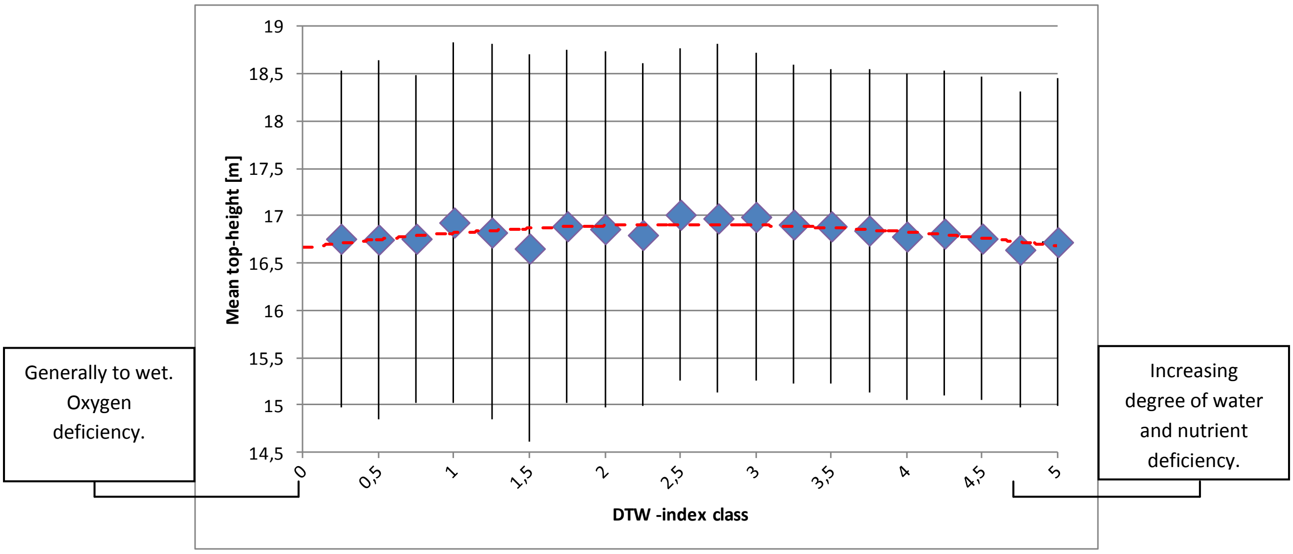

Figure 3.2b. Mean top-height (blue) of DTW-index class (25 cm) in range 0 to 5 m. Whiskers stretch ±1 SD. R^2 = 0,48 for a bipolynomial function. Note that vertical axis is broken. Letters on horizontal axis denote the upper boundary of each class.

3.3. The selected stand

The close-up stand was selected from the stand database for its high share of Scots pine (90 %). Like the rest of the data points we collected, the stand is situated on till soil and was assumed to have undergone reforestation in 1963. The stand comprise 861 pixels, which equals to 8,61 ha. Values stretched: 0,86 m to 8,82 m for DTW-index; 10,3 m to 20,0 m for top-height. The relationship is weakly hump shaped with a very poor correlation ($R^2 = 0,05$). Visual comparison of the top-height raster and the DTW-raster reveals no patterns or relationships between the variables (Figure 3.4).

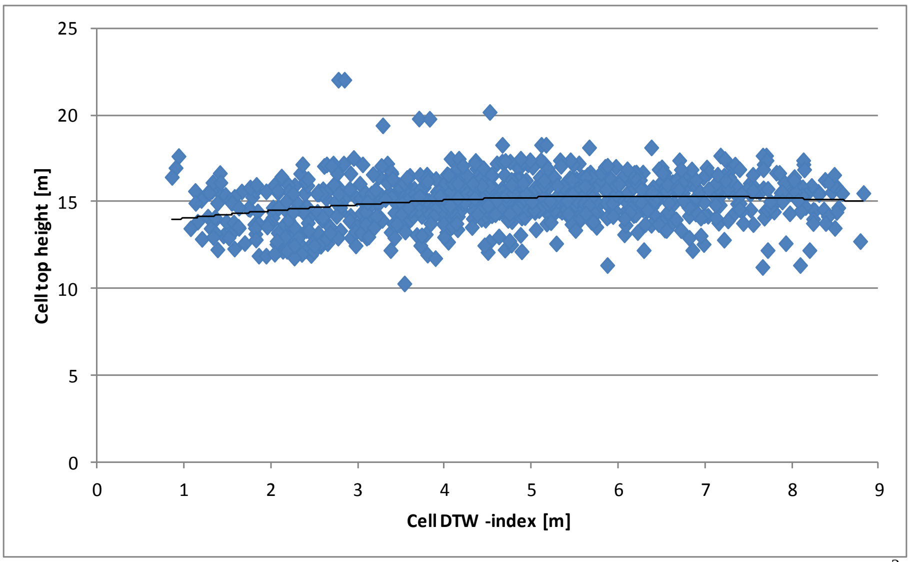

Figure 3.3. Top-height as function of DTW-index in the selected stand. (n = 861, R^2 = 0,05)

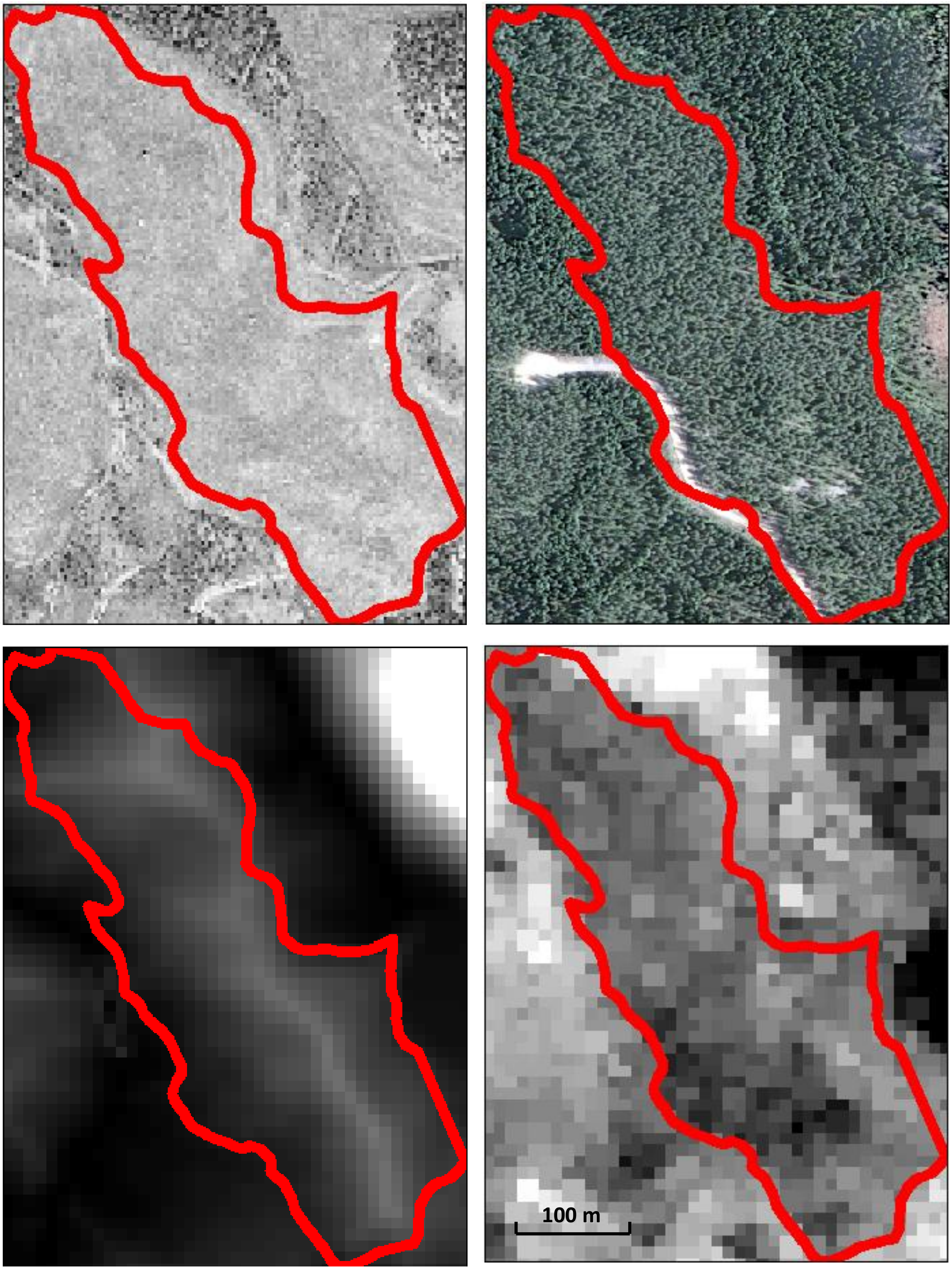

Figure 3.4. The close up stand depicted as: aerial image of stand in 1963 (upper left); aerial image in 2011 (upper right); DTW-raster with 2 hectares for flow initiation (lower left); top-height raster derived from ALS (lower right).

4. DISCUSSION

4.1. Results

With the approaches used, only poor relationships between DTW-index and top-height were seen. The result is likely not significant and does not support the idea that DTW-index can be used to locate areas of high SP. The lack of a strong relationship was obvious already in an early phase of this study, explaining why the statistical analysis is set to a basic level.

4.1.1. Stand mean values

With the first approach, arithmetic mean values were used with the argument to catch the wide concept when reducing the impact of outlier data points. The approach suggests top-height does not vary with DTW-index (Figure 3.1). The stands of this study were delineated from ortophotos, with no concern taken to soil moisture. Each stand therefore represents a wide span of DTW-values integrated into a single mean values. This is why coefficient of variation (CV) for the DTW-index stretched from 8 up to 93 percent for the stands. Distribution of top-height values in each stand is less, simply as it is one of the main characteristics used for stand delineation. The CV for DTW-index is generally too high to be representative. Using mean values is thereby an improper way to reveal a DTW-index to top-height relationship, and that is why an approach with higher level of detail was warranted.

4.1.2. DTW-index classes

In the second approach the first intention was to present all individual data points as a scatter plot. Due to the extreme scatter of the data only the central tendencies was considered, but not as stand mean values but as mean top-height as function of 25 cm DTW-index classes. The DTW-index often show unreasonable high values, which probably is attributed to the DTW-methods' inconsideration of the more or less impermeable bedrock. Even with a deep bedrock, a compacted basal till may act impervious to water and make a ground water table tens of meters deep unlikely. In highly elevated areas, the ground water level is often close to soil surface in areas cover by till soils (Magnusson, 2009). The resulting mound-like curve in the 0 m to 5 m range can be interpreted as a positive result but the meaning should not be exaggerated (Figure 3.2b). Within the DTW-index range, top-height vary less than 0,5 m. The magnitude of one standard deviation is about 1,5 m for all classes, so the result is likely far from significant.

4.1.3. The selected stand

Even with all stands reforested the same year, top-height may have been affected by management. Remembering that SP is a product of inherent properties and silviculture and since the study area is represented by different land owner categories with different incentive levels, it is unlikely that management have been ideal in terms of wood production. In the selected stand we tried to reduce the impact of silviculture by observing data from a single homogenous stand.

The stand was delineated by aerial image interpretation but it is likely that it has also been treated as one stand by the land owner. Since the share of Scots pine was about 90 percent, quality of comparison was high, knowing that trees species have different height to age increment trajectories (Albrektsson *et al*., 2012). In the other stands the share of pine was usually lower which entails a risk that top-height can be represented by other tree species in some pixels. The result show very little that can support the idea of a relationship between the variables (Figure 3.3). Keep in mind that DTW-index only stretched down to 0,86 m and it is below this value that a big drop in top-height is expected, due to insufficient aeration of the wet soil. This deficiency of data at the lower spectrum of DTW can be an explanation to why this approach does not reveal a trend in the lower range of DTW-index. Yet, it is strange that there is no drop in the higher range of DTW-index where we actually have data.

4.2. Methods

As with every study, methodology can be improved. For instance, the close-up stand could have been selected more carefully so that it covered the full DTW-range, even if that would have reduced data quality in other aspects. Nevertheless, it can be concluded that finding sites with high SP seems trickier than first thought. This is surprising as the relationship between SP and soil wetness seems so intuitively correct when descending a forested hill in Sweden. In the final stage of this study, we heard that others have come to the same conclusion at the University of Alberta. They have used a series of aspen trials, representing a range in DTW-values together with careful measurements of tree heights, but was unable to find any relationship whatsoever between the variables (B White 2014, pers comm., 8 December).

We admit that other factors than just soil wetness contribute to tree growth but studies show how DEM derived wetness indices can be used to find relationships between soil wetness and SP related variables like floral composition, depth of O –horizon and C:N –ratio (Kuglerova, 2014; Siebert *et al* 2007). Moreover, if it is true that discharge areas receive nutrients from upslope areas, that wet areas promote fixation of nitrogen, or that the mineralization of nitrogen is faster (Giesler *et al*., 1998; Gundale *et al*., 2009), why is this effect not seen in growth of trees? In the following paragraphs we present methodological reasons why we could not find the relationship.

4.2.1. Uncertainties related to stand age

That top-height can mirrors SP is a cornerstone in the study design, but interpreting stand age is tricky from a single ortophoto. Even if we delineated clear-cuts, it is hard to see if they were actually logged in 1963 or earlier. An aerial image from 1962, would have given answers to that but even if stands where actually harvested the same year, season of regeneration could differ since seedlings were impossible to detect. A precise, yet time consuming option would have been to extracting increment cores from trees.

4.2.2. Non-regarded site properties

The efforts to limit the study area to sites with similar site properties where far from complete since many properties could not be detected in the data we used. We argue that the most critical property is the depth of soil, which may vary a lot in the area. Depth of soil is a parameter that has a strong influence on SP (Hägglund & Lundmark, 1977). Many visible rock outcrops where excluded in the delineation process but areas of thin soil layers and reduced top-height probably remain. When comparing the ortophotos with the top-height raster, we observed lower top-heights in the vicinity of suspected outcrops (Figure 3.4).

To include only sites on till soil was one way to reduce variation, though it may still be a considerable textural variation between and within stands. Moreover, both moraines above and below the highest shoreline was included, but the properties of the moraine above and below this line may be vast. The terrain aspect of the site was not considered, though it can affect SP by the amount of incoming solar radiation. The low trajectory of the sun in this latitude makes north-facing slopes colder and moister (Bonan *et al*. 1989). Terrain aspect can thereby affect the amount of radiation for photosynthesis, but also the soil temperature, which may increase mineralization rate and concentration of nutrients (Siebert *et al*. 2007).

4.2.3. Uncertainties related to the site index hypothesis

That top-height trees mirrors site quality according the site index hypothesis is a good rule of thumb, but there are issues. No consideration was taken to stem density even though it is clear that high as well as low stem densities may influence stand height in comparison to similar stands at more normal stem densities (Skovsgaard & Vanclay, 2008). Studies have shown that wind may interfere mechanically with exposed trees and reduces their height growth, even though the different studies are not conclusive (Lundqvist & Valinger, 1995).

We never tried to obtain any numerical values for SP but just to make a relative comparison of SP using top-height as a gauge. The site index hypothesis is inappropriate to assume in stands that have been thinned from above. Thinning from above is a rare practice (Agestam, 2009), but we cannot exclude that top-height trees have been removed during stand life-span and been replaced by smaller trees. Nor can we exclude that some stands have been fertilized. Fertilization would improve SP artificially, masking possible effects linked to DTW-index.

The 100th height percentile of all the returns from ALS was thought to be the closest to true top-height on could obtain as a continuous raster that covers the study area. We do not fully know how well this represents true top-height but we know that LiDAR system presents difficulties in detecting the uppermost portion of the plant canopy and the height of the canopy may be underestimated (Lefsky, 2002). The top-height shoots represents a very small target and we are not sure how much true top-height deviates from the 100th height percentile.

4.2.4. Uncertainties attributed to the DTW-index

As stated earlier, the DTW-index is a method primarily for the mapping of wet areas and may fulfill this job with the appropriate flow initiation threshold (Ågren *et al*., 2014). The unreasonably high values for DTW-index for some cells indicate the shortcomings of the DTW-index in areas far from surface waters. The high values is a result of the mathematical formula which only incorporate distance to surface water and accumulated slope along the flow path. These two factors are in reality influential close to lakes and streams. In upland areas other factors, that vary widely, increase in influence so relating the DTW-index to actual water table depth would need to be verified by region (Murphy *et al*., 2007).

The hydrology of the soil is far from being a static system. Rather it is a dynamic system driven by climate. Main factors are the annual precipitation and how it is distributed and melt during the year. The tree height that was used as a productivity proxy is the result of nearly

50 years of growth. The hydrological conditions of a site during this period might have changed due to climate and forest operations, including the establishment of ditches and roads. Incorporation of such dynamics seems like a big challenge because of its complex nature.

The DTW-raster used in this study was based on a flow direction grid calculated with the D8-algorithm. The D8-algorithm generates a simplified model of soil water movement; mainly because it assumes that subsurface flow follow the same pathways as surface runoff. Both layering of soils with different hydraulic properties and the shape of the bedrock may make the modeled flow paths to deviate from the real ones. A DEM gives no information about such subsurface features.

4.2.5. Other methodological issues

The tree-species distribution data from the stand database is done by subjective interpretation, which may entail errors. Similar the soil data, species composition was not available on a pixel level, but only as homogenous entities on a stand level. After the selection of stand to be included in the study, they were edited to reduce the impact of edge effects along of stand borders. No renewed photo interpretation was done after this edit, so the editing might have change the proportion of the tree species, as initially set by the interpreter.

Only stands where selected with a share of ≥ 60 % Scots pine according to the stand database. There are other tree species present but the spatial distribution of these where unknown and impossible to exclude. Thus, there is a considerable possibility that the height represent other tree-species than Scots pine, with a different height to age increment trajectory. The implication of this is that it reduces the reliability of height as a proxy for SP.

4.3. Recommendations for future studies

This is a pioneering study design and might by some be regarded as a long shot. On the other hand, to learn from unexpected results is one of the cornerstones of science and we cannot reject the idea of a relationship between DTW-index and SP. Even less can we reject the idea that DEMs can guide us to high productive sites. To anyone who is trying to repeat this study, the author suggests to rewind the tape and ensure data reliability. Special focus should be laid on measuring the top-height. We also recommend others to analyse the relationship between DTW-index and other tree species. No such analysis was made in this study due to data deficiency but we hypothesise that other tree species (e.g. Norway spruce) varies more clearly with soil moisture than Scots pine.

This study was located to the Krycklan catchment primarily as it was easy to get the hands on the necessary data and not due to any extraordinary forest or soil conditions. A better localization would be an area with a simple and well recorded management history. There are likely many areas in Sweden and elsewhere of enormous size that have been reforested after wild fires or massive logging campaigns and managed relatively uniformly by a single company or public owner. Such areas should be older since top-height between trees growing on sites with different SP diverges increasingly with age (Figure 1.2). In fact, another project at University of Alberta is looking at pine productivity in 70-year-old stands that regenerated following fire. Unfortunately, no results have been presented as when this is written (B White 2014, pers comm., 8 December).

The purpose of this study was to contribute to the task to develop methods to detect high productive sites, using data remotely sensed data. Using DTW-index might not be the best way in doing so. Other methods including satellite sensing of foliar reflectance from ground vegetation is emerging and show results that possibly can be utilized in forestry (Jin & Eklundh, 2014).

4.4. Concluding remarks

- Literature supports the idea that topography is one controller of soil moisture and SP.
- In the range 0 to 5 m for DTW-index, a poorly hump-shaped relationship is seen when mean top-height is plotted as function of 25 cm DTW-index classes. Except from that, no clear variation in top-height is with DTW-index is seen.
- The methods used in this study suffer from many weaknesses resulting in the disability to prove the hypothesised existence of a relationship between DTW-index and SP.

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