THE FOREST, AND MILITARY ASPECTS OF A TERRAIN: FOREST HEIGHT, CANOPY COVER AND VISIBILITY IN ESTONIA

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Abstract. Most military activities need good concealment from a top-down view, i.e. from surveillance carried out by flying assets[1]. On the one hand, well-hidden positions and sites are to be expected in forested areas. However, depending on the height of the trees and crown parameters as well as the tree species' composition, the concealing effect can be rather different. Even large-scale maps used by military terrain analysts do not give detailed information that would help do estimate concealment in a particular forested area, and certain map sheets can be outdated. Useful information about Estonian forest stands can be found in the forest management inventory database. However, the purpose of this database is to support forest management; therefore, it does not directly contribute to the planning of military operations. Still, a sufficiently high precision—temporal and spatial—makes it a very useful source for military terrain operation planning. On the whole, there is a need to define some general rules for analysts that can be used for interpreting forest inventory data. The aim of this paper is to discuss forest parameters that determine vertical concealment. In addition, the article includes some basic tables, relationships and a conclusion about the concealing effect of Estonian forest.

Keywords: vertical concealment, forest height, vertical canopy cover, angular gap fraction, stand relative density

1. Introduction

For military units and their activities, the most important feature of a wooded area is its overall capability to provide good concealment. That is the primary effect of forests in comparison to open areas. Concealment is important

[1] This article is composed in the framework of the scientific project No 42O (T-005) "Determination of the mechanical properties of soils in relation to military vehicle trafficability, and development of the mapping tool to visualize the tactical properties of forest" (29.04.2019–01.08.2023).

for any unit type: infantry[2], artillery[3,4], mortar units[5], etc. According to FM 34-130, the aspect of concealment is especially important for identifying a defensible terrain as well as for the determining assembly areas, deployment areas and dispersal areas[6]. Since on a standard topographic map, forest land areas are often depicted without any additional information, one of the primary questions for a unit commander considering a specific wooded area is whether there actually grow trees that can be used to hide their unit under and between. Thus, the question is about the height of trees, i.e. is there sufficient vegetation cover reaching over the heads of soldiers and military vehicles or is it just a clear-cut area or recently forested area with knee-length small plants. On a standard 1:50 000 Estonian military map, areas with tall trees and young forest stands (with trees up to 4 m) are indicated as separate thematic classes. However, the specific map sheet can be up to ten years old and, thus, information about the condition of the forest can be significantly outdated. One possible source for determining forest height, as well as other important information about forest, is the forest management inventory database. It is a database provided for public access by the Estonian Environment Agency. Information on actively managed wooded areas is regularly updated through forest inventory carried out for forest data collection by forest specialists.

Besides the height of growing trees, actual visibility from a vertical direction affects the degree of concealment. Tree crowns, including branches, needles, and leaves, obstruct the view for air surveillance carried out by manned and unmanned aircraft assets. Recent conflicts have shown that unmanned aerial vehicles (UAV) have been increasingly used on battlefields[7],

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2 **ATP-3.2.1 = NATO Standard No. 3.2.1**: Allied Land Tactics. Edition B, Version 1, August. 2018. NATO Standardization Office (NSO), p. 8–2.

3 **AArtyP-02 = NATO Standard No. AArtyP-02**: NATO Counterbattery fires doctrine. Edition A, Version 1 December 2020. NATO Standardization Office (NSO), p. 3–8.

4 **FM 6-40 = U.S. Marine Corps Manual No. 6-10:** Tactics, Techniques, and Procedures for the Field Artillery Manual Cannon Gunnery, 1 October 1999. https://www.marines.mil/Portals/1/Publications/mcwp3_16_4.pdf (02.12.2022), p. 12–1.

5 **FM 7-90 = U.S. Marine Corps Manual No. 7-90:** Tactical Employment of Mortars. 9 October 1992. https://www.trngcmd.marines.mil/Portals/207/Docs/TBS/MCWP%203-15.2%20Tactical%20Employment%20of%20Motars.pdf (02.12.2022).

6 **FM 34-130 = U.S. Army Field Manual No. 34-130**. Intelligence preparation of battlefield. Headquarters Department of the Army, Washington DC, 8 July 1994. https://www.marines.mil/Portals/1/Publications/FM%2034-130.pdf (02.12.2022), p. 2–11.

7 **Yousif, E**. 2022. Drone Warfare in Ukraine: Understanding the Landscape. – Conventional Arms. Stimson. June 30. https://www.stimson.org/2022/drone-warfare-in-ukraine-understanding-the-landscape/ (02.12.2022).

and thus the issue of vertical concealment has gained substantial importance. Here, again, some general conclusions can be made from the forest inventory data and forest canopy studies to differentiate forest areas with good and less suitable concealment conditions.

In the following paper, the important parameters of trees and canopy are discussed, such as height, crown dimensions, deciduousness or seasonality, canopy cover, fraction of gaps and their effect on concealment as well their estimation possibilities according to the Estonian forest inventory database. The aim is to elaborate what tactically useful information a military terrain analyst can gather from an inventory database.

2. Trees and forest

2.1. Tree height and its estimation based on stem diameter

The height of the top of a vertically standing tree over a ground surface is a variable that is easy to understand. However, in a forest inventory, the reference point is not ground surface but the position of the tree root collar. In most cases, the error of using ground surface as the reference point instead of the root collar results in a small 0–30 cm positive bias. In drained peatlands, peat decay causes topsoil to sink, and tree root collars in older forests may be exposed easily 0.5–1 m above the current ground surface. Thus, actual tree height can be overestimated by 1 m. The opposite can be found in natural transitional bogs and raised *Sphagnum* moss bogs where the ground level rises each year about 1 mm as moss grows and the root collars of old trees are slowly buried[8,9]. In the forest inventory database, the height (h) of a tree is defined as a strictly vertical distance between the top of the tree and the level of the tree root collar. If a tree is not standing vertically but is tilted at an angle, then the length of the tree stem is greater than the height of the tree.

A quick estimate of tree height can be calculated by retreating from the tree to distance (l) where the treetop (or the highest point of the crown over ground) is visible and the angle of sight is 45 degrees in respect to ground. In

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[8] **Burns, M. R.; Honkala, H. B**. 1990. Silvics of North America: Volume 1. Conifers. Agriculture Handbook 654. Washington, DC: U.S. Department of Agriculture, Forest Service, p. 147.

[9] **Ohlson, M.; Økland, R. H.; Nordbakken, J.-F.; Dahlberg, B**. 2001. Fatal interactions between Scots pine and Sphagnum mosses in bog ecosystems. – Oikos, Vol. 94, pp. 425–432, here p. 430.

this case, the height of the tree is approximately equal to $l+h_{eye}$ where h_{eye} is about 1.5 m, i.e. the eye-level. On slopes, the measurement position for this simple method has to be neither up nor down from the tree but across the slope direction to avoid bias.

Tree height has a strong correlation to stem diameter (*d*) at breast height. This relationship is used in predicting tree height from *d* using regression models. Some examples of the stem diameter and height relationship for different tree species like Norway spruce, Scots pine and silver birch are presented in Figure 1.

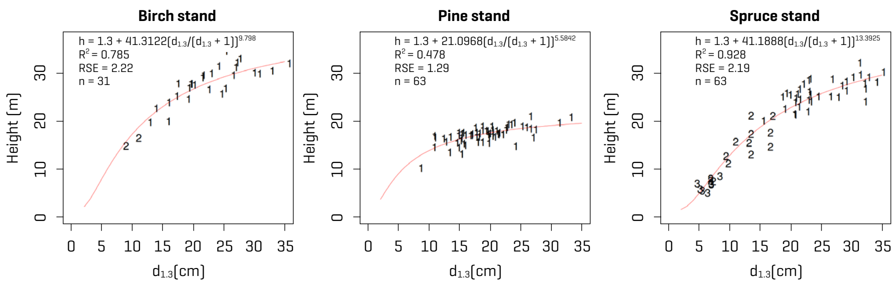

Figure 1. Examples of the relationship between tree height (*h*) and stem diameter at breast height ($d_{1.3}$) from three forest stands growing in Järvselja, South-East Estonia[10]. A regression model fit on *n* empirical observations is described by the model residual error RSE and determination coefficient R^2. Labels: 1 – upper layer, 2 – second layer, 3 – understorey.

Based on the empirical observations and models presented in Figure 1, we can see that the ratio of tree diameter to height can largely vary. For example, a tree with a diameter of 20 cm has a predicted height of 26.6 m in the birch stand, 17.4 m in the old pine stand that grows on a transitional *Sphagnum* bog, and 22.7 m in the spruce stand. We also see that the relationship tends to be nonlinear and specific to a particular forest stand because of the influence of stand density during a tree's life span and soil fertility. To use tree diameter at breast height as a reliable predictor for tree height, one must measure both *d* and *h* and fit the prediction model to the empirical data.

[10] **Lang, M.; Kuusk, A.; Kaha, M.; Pisek, J.; George, J.-P.; Kiviste, A.; Laarmann, D.; Türk, K.; Arumäe, T**. 2021. Changes during twelve years in three mature hemi-boreal stands growing in a radiation model inter-comparison test site, Järvselja, Estonia. – Forestry Studies | Metsanduslikud Uurimused, Vol. 74, pp. 112–122, here p. 113. [**Lang et al**. 2021]

2.2. Forest height and its impact on tactical activities

We define "forest" as a set of trees growing on a patch of land. Forest height $H=(1/N)\cdot\Sigma(h_i)$ is the mean height of N trees. Forest inventories use the weighted mean of a tree basal area instead of the arithmetic mean of tree heights to give more weight to larger trees because tree height is used to calculate wood volume. Another definition used in modelling is dominant height that is based on a selection of the biggest trees of a stand[11]. Forest height is a variable that is easy to understand for plantations or single layer and even age stands. For young stands, after establishing a new forest on a clear-cut area, it is rather simple to determine the height of the trees. With age, stand structure becomes more versatile and makes it more difficult to estimate forest height. In multilayer stands, the mean height of trees is not too informative and, therefore, in the forest inventory database H is given for each stand element distinguished according to its social layer (e.g. dominant or upper, mid or second, regrowth, and understorey), tree species and age class.

Forest height indicates whether there will be enough concealment for personnel and equipment like vehicles, tents, or other signs of military activities. Considering the specifics of military activities, it can be argued that in the first order, a military commander is interested in the heights of the highest trees, i.e. the dominant layer. However, the existence of middle layers of trees as well as understorey layers and bushes will contribute to concealment at a specific site. In Estonia, the middle layer is usually inhabited by the shade tolerant Norway spruce. Since at mid layer and lower layers, the shade tolerant spruce branches are not well self-pruned and the trees tend to have wide crowns, these trees provide considerable cover from air observation (Figure 2). Frequently encountered bush types in Estonian forests like common hazel, bird cherry, willow, alder buckthorn, and honeysuckle also substantially contribute to vertical concealment. However, a larger number of trees and bushes has a contradictory effect on the activities of military units because there is less empty space between the stems. In short, the forest stands that provide excellent concealment are not usually penetrable with larger units and assets. Even if the mid and second layer trees and bushes do have sufficiently small dimensions to be pushed over by vehicles and self-propelled military weapons, horizontal visibility is heavily impeded and drivers cannot select a suitable path

[11] **Tarmu, T.; Laarmann, D.; Kiviste, A**. 2020. Mean height or dominant height – what to prefer for modelling the site index of Estonian forests? – Forestry Studies | Metsanduslikud Uurimused, Vol. 72, pp. 121–138, here p. 122.

in the forest. In addition, the placement of tents or other assembly area facilities is complicated and needs some site preparation. In another paper in this journal, Vennik et al. introduce the typical forest classes of Estonia based on the height and average free space between stems[12]. The first impression of free space values between stems in different forest types (Table 2, Vennik et al.[13]) allows to conclude that penetration into a forest is a complicated task in general. In the following, this will be elaborated in more detail.

Figure 2. Evergreen Norway spruces in second layer growing under the dominant deciduous tree layer still provide substantial concealment for units and assets. However, such spruces complicate pathfinding for vehicles.

Based on visual inspection, it can be claimed that trees with a height of approx. 4 m offer enough concealment for a standing man to find a hidden position from vertical observation. Trees of this height can be found in forest stands called young forest (Table 2, Vennik et al.[14]). The average free space between trees in this type of a stand is approx. 1 m (Table 2, Vennik et al.[15]). The width of a soldier carrying a backpack and a machine gun is approx. 80 cm. Thus, it is extremely difficult to carry out dismounted movement or prepare

[12] **Vennik, K.; Piip, K.; Lang, M**. 2023. Typical forest classes in Estonia reflecting military aspects of terrain based on size of tree stems and forest density. – Sõjateadlane (Estonian Journal of Military Studies), Vol. 21, pp. 103–119. [**Vennik et al**. 2023]

[13] **Vennik et al.** 2023, p. 114.

[14] Ibid., p. 114.

[15] Ibid.

battle positions in this thicket. Military vehicles like tanks (height typically 2.2–3 m), infantry fighting vehicles and armoured personnel carriers (height 1.8–3.1 m) or military trucks (height 2.9–3.5 m) are able to push over trees in young forest stands[16]. However, again, experiments conducted in the forest indicate that the line of fallen trees will expose the location of the vehicle and, thus, even a height of 10 m would not be enough to effectively obstruct the view of vertical assets like UAVs or other aircraft. For a pole forest stand, the average tree height is 10–15 m[17], so the tree height is more or less enough to conceal vehicles. Also, free space is wider compared to a young forest stand, i.e. 1–3 m. Still, dead branches will obstruct troops and some vehicles. Free space of up to 3 m would not be enough to set up a squad tent (diameter approx. 4 m and height 2.5 m), but it can technically be done if some trees were cut down.

Mature forest stands usually develop different tree layers and, below the dominant layer of mid or secondary layers, their appearance depends on soil fertility and the density of the upper layer of the habitat. According to the forest inventory database, we can distinguish two basic groups of forest stands: the first is a sparse forest where only a dominant layer of pines exists—also, in the winter season, this group includes old deciduous forests; the second includes other mature forest stands where in addition to the dominant layers, there exist other layers contributing to vertical concealment—also, in the summer season, this group includes the deciduous forest. Table 1 summarizes these findings regarding concealment. For practical uses, the forest management inventory database contains rather detailed tree species and dimension data enabling suitable areas to be selected for specific military activities, taking into account concealment versus free space in a forest.

[16] **Vennik, K.; Lang, M.; Piip, K.; Põldma, A**. 2021. Eesti metsade taktikalised omadused: 2020. aasta uuringute kokkuvõte. – EMA Occasional Papers, Vol. 12, pp. 43–58, here p. 45.

[17] **Vennik et al**. 2023, p. 114.

Table 1. Combined effect of vertical concealment and average space between trees in typical forest classes of Estonia. Given classes may be further subdivided to account for soil trafficability conditions. (*D*) average diameter of trees at breast height; (*H*) average height of trees; and (*L*) average distance between trees [Table 2, Vennik et al.[18]].

Forest designation and condition for designation	Soldiers	Vehicles	Placement of tents, assembly area facilities
Clearing $H \leq 1.5$ m	No vertical concealment	No vertical concealment	No vertical concealment
Young forest stand 1.5 m $< H \leq$ 10 m $D \leq$ 10 cm 1 m $< L \leq$ 2 m	Sufficient concealment for a single soldier	No vertical concealment	No vertical concealment
Pole forest stand 10 m $< H \leq$ 15 m 10 cm $< D \leq$ 20 cm 1 m $< L \leq$ 3 m	Sufficient concealment for a group of soldiers	Good concealment but limited open space	Good concealment but limited open space
Mature forest stand: sparsely located pine trees and deciduous trees during the winter 15 m $< H \leq$ 45 m 20 cm $< D \leq$ 40 cm 3 m $< L \leq$ 7 m	Insufficient concealment	Insufficient concealment	Insufficient concealment
Mature forest stand: with mid and secondary regrowth layer bushes and trees 15 m $< H \leq$ 45 m 20 cm $< D \leq$ 40 cm 3 m $< L \leq$ 7 m	Good concealment for all units	Good concealment for all vehicles	Good concealment for all facilities

2.3. Forest height distribution in Estonia

The height of the dominant species in Estonian forest stands can reach up to 35–42 m on fertile soil, as illustrated in Figure 3 which is based on a query from the Estonian forest management inventory data (1.14 million stands, covers about 75% of wooded land). In the majority of the inventoried stands, however, tree height remains between 12 and 30 m. Thus, irrespective of the location on Estonian territory, there is a high probability of finding a more

[18] Ibid.

or less concealed site in a forest. One important aspect on landscape level is the stand high fragmentation and spatial pattern of forested areas that has an influence on path planning. Due to the variability of the habitat and forest management activities in Estonia, a forest stand with a uniform structure usually covers an area with a maximum diameter of up to 250 m. This is mainly caused by forest management rules that set limits on the maximum size (5–7 ha) of regeneration felling (usually clear-cut).

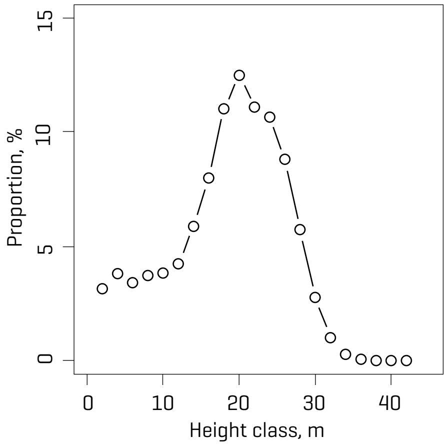

Figure 3. Distribution of forest stand heights in Estonia according to the forest inventory data register. Two metre bins are used for classes.

The distribution of the area of forest stands with a height between 1 to 12 meters is uniform, and in each 2 m height class, we have about 4% of stands. Thus, altogether 16% of woods have less height than needed for adequate vertical concealment or are too dense to penetrate inside. However, trees grow taller each year. The yearly height increment of a forest depends on site fertility, forest density and tree age. Trees in denser stands invest more in height growth compared to open-site trees which have less competition. Trees growing on fertile soil see greater height increment. The height increment decreases with tree age and ranges from 0.35–70 cm in young[19] and middle-aged stands (approx. 20–40 years old) to less than 25 cm in old stands (approx. 40 years and older)[20]. One exception here are sprouts from the tree

[19] **Kängsepp, V.; Kangur, A.; Kiviste, A**. 2015. Tree height distribution dynamics in young naturally regenerated study plots. – Forestry Studies | Metsanduslikud Uurimused, Vol. 63, pp. 100–110, here p. 103.

[20] **Tappo, E**. 1982. Eesti NSV puistute keskmised takseertunnused puistu enamuspuuliigi, boniteedi ja vanuse järgi. Tallinn; Eesti NSV Põllumajandusministeeriumi Informatsiooni ja Juurutamise Valitsus, p. 25. [**Tappo** 1982]

root system of the European aspen or grey alder which can grow up to 1 m per year during the first years after a clear cut. Knowledge about the forest height increment is important to consider when using the forest inventory database records which may even have an update delay of more than 10 years. Therefore, the military terrain analysts using the Estonian forest database have to consider the age of the inventory records and estimate the current age and tree height of a specific forested area. For a clear cut area, tree plant height is not registered by forest specialists before the height of a young forest reaches over 1.3 m. Thus, for a new, just afforested or naturally regenerating forest area, information about the actual tree height can be inaccurate by over 10 years. During that time, the height of a young forest can reach up to 6 meters[21].

2.4. Tree crowns, canopy cover, and fraction of gaps

The vertical concealment of spread activities and service points distributed spatially on larger areas needs, besides the proper height of trees, a good dense coverage to obstruct a downward view from above. For example, an assembly area is a position where all the preparation and regrouping for further battles are carried out, including for maintenance and resupply[22]. So these areas must accommodate more than just one vehicle, tent or soldier and are, thus, more susceptible to detection. In the first place, the concealment effect of an object depends on its location in the vertical direction from a canopy and the dimension of branches that make up the tree crown. Forest trees in Estonia usually have crowns that can be modelled as ellipsoids (most deciduous broadleaved trees, Scots pine) and cones (Norway spruce) (Figure 4). The lower part of the crown of older Norway spruces may resemble the shape of a cylinder. The volume of a tree crown contains a structure of branches, needles and leaves. In nature, however, trees are not arranged according to any strictly regular pattern[23] and the shapes of tree crows vary as trees grow their branches towards a more open space to better capture solar light.

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[21] **Tappo** 1982, p. 46.

[22] **FM 71-3 = U.S. Army Field Manual No. 71-3.** 1996. The armored and mechanized infantry brigade. Headquarters Department of the Army, Washington DC, 8 January, p. D-2. https://www.globalsecurity.org/military/library/policy/army/fm/71-3/index.html (02.12.2022).

[23] **Vennik et al**. 2023, p. 109.

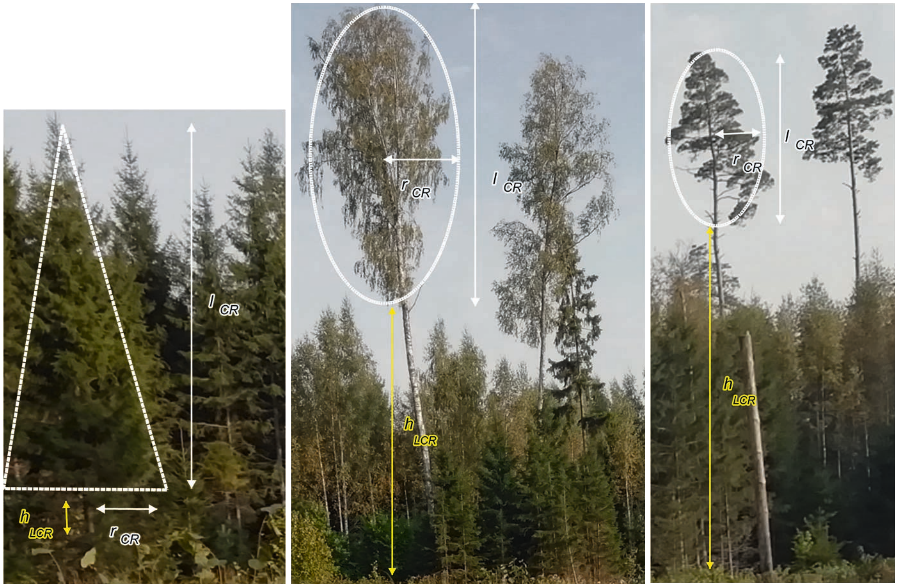


Figure 4. Tree crown types: a) cone for spruce, b) ellipsoid for birch, and c) ellipsoid for pine. Parameters: l_{CR} tree crown length, r_{CR} – tree crown radius, h_{LCB} – live crown base height.

Tree crowns can be described by their length l_{CR} and radius r_{CR} (Figure 4). Tree crown length is measured from the live crown base height (h_{LCB}) to the top of the tree, and equals h-h_{LCB}. The location of the live crown base height may be difficult to determine exactly in the field as there are single remaining branches on the lower part of a tree. In such a situation, the outlier branch can be ignored. The length of a growing tree crown depends on the availability of light and the shade tolerance of a tree. When trees grow, the upper part of their crown intercepts most of the solar radiation, leaving lower branches to die since there is insufficient light for photosynthesis. Therefore, the live crown base height increases with the age of the tree and height growth. In managed forests, trees are thinned to regulate their stand density and enable them to maintain a l_{CR} of at least about 25–60% of their height[24].

The practical effect of tree crown length, tree crown radius and live crown base height on vertical concealment is visualised in Figure 5. The picture from ground level in the upward direction was taken in a Scots pine stand in winter (Figure 5A). The larger radius, longer tree crowns and evergreen needles will

[24] **Muiste, L**. 1989. Metsa raiesüsteemid. Metsamajanduse alused. Taimre, H. (toim.). Tallinn: Valgus, p. 116.

significantly increase the concealment effect. Concealment is even better if the forest stand includes spruces in different layers of the stand (Figure 5C).

A B C

Figure 5. Upward looking pictures of (A) mature pine stand, (B) mature birch stand, (C) mature spruce stand in wintertime.

Crown radius has a strong linear relationship with tree stem diameter at breast height[25, 26]. This knowledge is used to construct models for predicting the tree crown radius when the measurements of *d* are available[27, 28]. However, this relationship is influenced by stand density because neighbouring trees intercept solar light and this limits the survivability of lower branches. Similarly to measurements of tree crown length, measurements of tree crown radius involve a substantial amount of uncertainty as, in nature, tree branches do not grow simply radially and symmetrically away from the stem but prefer an open space with more available solar light[29]. From the tree crown radius

[25] **Spurr, S. H**. 1948. Aerial photography in forestry. New York: The Ronald Press Company, p. 283.

[26] **Hasenauer, H**. 1997. Dimensional relationships of open-grown trees in Austria. – Forest Ecology and Management, Vol. 96, pp. 197–206, here p. 203.

[27] **Jakobsons, A**. 1970. The correlation between the diameter of tree crown and other tree factors – mainly the breast-height diameter. – Research notes, Vol. 14. (pp. 75+). 10405 Stockholm 50, Sweden Department of Forest Survey, Royal College of Forestry (in Swedish with English summary), p. 11.

[28] **Lang, M.; Nilson, T.; Kuusk, A.; Kiviste, A.; Hordo, M**. 2007. The performance of foliage mass and crown radius models in forming the input of a forest reflectance model: A test on forest growth sample plots and Landsat 7 ETM+ images. – Remote Sensing of Environment, Vol. 110, pp. 445–457, here p. 447. [**Lang et al**. 2007]

[29] **Lang, M.; Kurvits, V**. 2007. Restoration of tree crown shape for canopy cover estimation. – Forestry Studies | Metsanduslikud Uurimused, Vol. 46, pp. 23–34, here p. 30.

we can calculate an estimate of the area occupied by a tree as $s_{CR}=0.25 \cdot \pi \cdot d_{CR}^2$ where $d_{CR}=2 \cdot r_{CR}$.

In a forest stand, its canopy is a composite of single tree crowns. If we assume tree crowns as opaque shapes, each characterized by their length l_{CR} and projection area s_{CR} on the ground in a nadir direction, then the canopy can be characterized by the mean canopy depth and total projection area of crowns S_{CR}. By dividing S_{CR} by the area of the stand A, we obtain the vertical crown cover $C_{CR}=S_{CR}/A$. It is common for tree crown projections to overlap in a forest to some extent. If these overlapping areas are considered a single cover, then we get the vertical canopy cover C_{CA}[30]. From their definitions it follows that $C_{CA} \leq C_{CR}$ and $0 \leq C_{CA} \leq 1$. If the tree crown projections are not overlapping, then $C_{CA}=C_{CR}$, otherwise the $C_{CA}= 1-\exp(-c_B \cdot C_{CR})$ with $c_B=(-\ln \zeta) / (1-\zeta)$, where ζ is the Fisher grouping index of the tree distribution pattern on a horizontal plane calculated as relative variance of the number of trees per area corresponding to a size of the average tree crown vertical projection (s_{CR}) in the stand[31]. As an example, C_{CA} for different forest types is presented in Figure 6 for 50×50 m^2 areas. The first row is made of orthophotos taken by the Estonian Land Board once every four years.

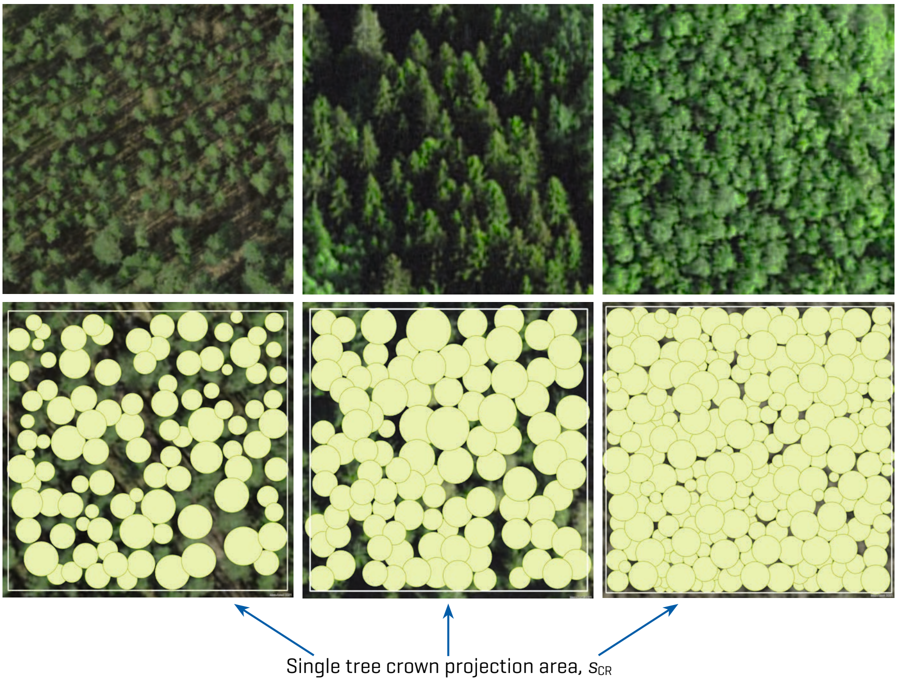
Canopy cover can be used to calculate the probability of seeing a clear sky from below the tree canopy in a vertical direction (zenith, view zenith angle $\theta_Z=0$ degrees) between the tree crowns as $p_{sky}(0)=1-C_{CA}$. Both the crown and canopy cover can be estimated from point sampling: if the point is located inside the tree crown projection area, an observer records a value of 1, otherwise a 0 is recorded. For example, if 70 readings out of 100 occur on the crown projection area then $C_{CA}=0.7$. On orthophotos, canopy cover is estimated using canopy density scales[32] which give a visual reference for an analyst based on the point sampling principle. From examples given in Figure 6, it can be concluded that concealment is best in a deciduous forest, however, the effect of the seasons needs to be taken into account. A lack of green leaves will substantially reduce the effect of crown cover.

[30] **Jennings, S. B.; Brown, N. D.; Sheil, D**. 1999. Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures. – Forestry, Vol. 72, pp. 59–73, here p. 62. [**Jennings et al**. 1999]

[31] **Nilson, T**. 1999. Inversion of gap frequency data in forest stands. – Agricultural and Forest Meteorology, Vol. 98–99, pp. 437–448, here p. 440. [**Nilson** 1999]

[32] **FM 5-33 = U.S. Army Field Manual No. 5-33**. Terrain Analysis. 11 July 1990. Washington, D.C.: Department of the Army. http://www.bits.de/NRANEU/others/amd-us-archive/fm5-33(90).pdf, p. 3–10. [**FM 5-33** 1990]

During military terrain analysis, canopy cover C_{CA} (always check the definition in the particular source because the frequently used variable "canopy closure" has a different meaning) is presented as a percentage in four groups: 0–25, 25–50, 50–75 and 75–100[33]. Based on this classification, a commander can determine how well concealed an area is needed.



Dry pine forest	Dry spruce forest	Birch forest
C_{CA}=1397/2500=0.6	C_{CA}=2008/2500=0.8	C_{CA}=2368/2500=0.9
p_{sky}= 0.4	p_{sky} = 0.2	p_{sky} =0.1

Figure 6. Canopy cover C_{CA} (canopy projection area divided by stand area) and probability of seeing open sky (p_{sky}) of old forest types: for a dry pine forest, a dry spruce forest and a moist birch forest.

Considering the probability of detection of aircraft, its position against ground elements and flight speed are important. Flying assets conducting a reconnaissance flight over forested areas are only located over the area of interest for a short time. If the flight speed of a UAV is assumed to be from 18 to 100 km/h, the overflight over a 5 m distance lasts from 1 to 0.2 seconds. For example, the length of an infantry fighting vehicle CV90 used by the Estonian

[33] **FM 5-33** 1990, p. 3–8.

army is 6.6 m. Thus, the UAV can be located exactly vertically over the CV90 for just 1 to 0.2 seconds. In addition, the camera's framerate will influence the detection of a hidden CV90 under the tree crowns. The path length of a sounding beam or a camera view through the canopy is the shortest and equal to the forest height at the zenith when looking upward; on average, this is the region where we have the greatest chances for seeing open sky. This, however, also corresponds to the shortest observation time for sensors with a fixed view nadir angle and a narrow field of view. Path length increases with an oblique view because the view nadir angle θ_N increases with UAV. The path length through the forest canopy is related to forest height as $l_{sight}=H/\sin\theta_G$ if the view angle is measured in respect to the horizontal plane (ground surface) (Figure 7). Together with the path length, the probability increases that a leaf, shoot, branch or stem will block the view in that particular direction and there is less chance of seeing open sky or, *vice versa*, sensors seeing the ground through plant elements that are not transparent.

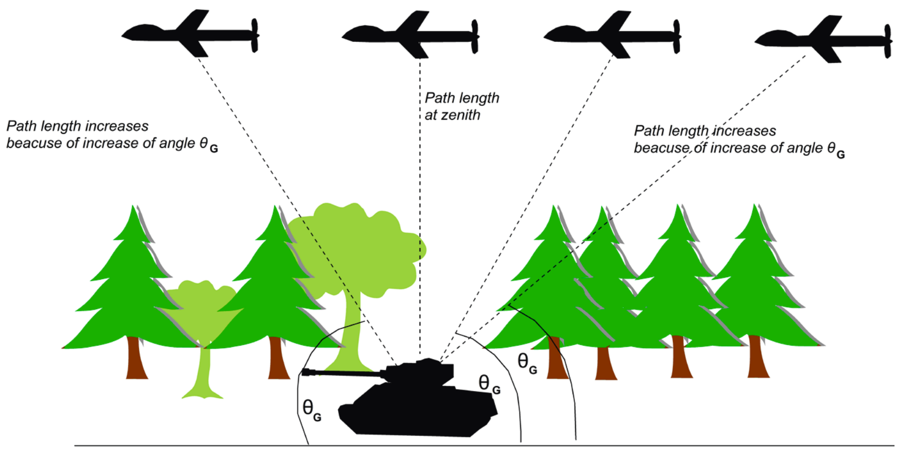


Figure 7. The effect of nadir angle change to path length from flying assets to the spotted object.

If we average a forest canopy cover over all view directions, we will obtain the angular canopy closure C_{CC}, which is the ratio of the open sky and plant element projection areas considering the whole hemisphere (Figure 8) or a solid angle. Canopy openness—i.e. the visible proportion of the sky over the hemisphere or within a solid angle—is calculated as 1-C_{CC}[34]. Angular canopy

[34] **Jennings et al.** 1999, p. 62.

closure is influenced by forest height in contrast to crown cover or canopy cover[35]. When comparing two stands that have equal vertical canopy cover, C_{CC} is greater in higher forests. Until now, we have assumed that tree crowns are opaque; however, in nature, the probability of seeing open sky through a tree crown is greater than zero. Remember that the gaps within tree crowns are much smaller than those between them. Canopy closure accounts for the gaps within. If the crown gaps within are considered for vertical canopy cover, then the variable describes the effective canopy cover C_{CAe}, i.e. the projection area of plant elements and not the crown radius-based crown area projection. The vegetation season has a substantial impact on effective canopy cover and canopy closure in deciduous forests (Figure 8).

summer **winter**

Figure 8. Upward looking hemispherical photos taken in a multi-layer fertile silver birch dominated stand located in southeast Estonia, Järvselja, where the forest height of the upper layer reaches 30 m[36].

The variable that describes the amount of gaps between tree crowns, as well within tree crowns, as a function of the view zenith angle is the angular gap fraction $p(\theta_Z)$. Vegetation seasons have a substantial influence on the angular gap fraction as $p(\theta_Z)$ increases after leaf fall (more gaps) and decreases again in spring with the development of new foliage (Figure 9). The gap fraction in a zenith direction can be greater than 0.8 in a deciduous stand during the leafless period, and only 0.1–0.15 during summer in full foliage conditions.

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35 Ibid., p. 63.

36 **Lang et al.** 2021, p. 115.

With an increase of the view, the zenith angle $p(\theta_Z)$ decreases, i.e. there is less chance of seeing open sky through the forest canopy when looking obliquely. For example, during the wintertime in leafless conditions $p(\theta_Z)$, the mature birch stand can decrease from 0.8 at zenith to 0.5, if θ_Z=45 degrees (Figure 9).

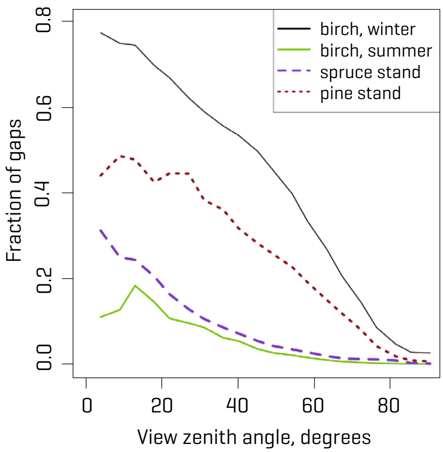

Figure 9. Fraction gaps canopy in three mature forests in Järvselja as a function of view from a zenith angle. Description of the stands is given in Lang et al.[37]

All the canopy variables—crown cover, canopy cover, effective canopy cover, angular canopy closure, canopy openness and angular gap fraction—were defined using the assumption that the canopy elements are opaque and large enough to block the signal between the sensor and the observed object. This is true for sensors operating in the visible or in general in the optical spectral range (400–2500 nm) of the electromagnetic spectrum, as well as for the thermal infrared spectral region. However, with microwave sensors (usually radars), signal penetration depth depends on the band (signal wavelength). For example, in the C-band, the wavelength is about 5.5 cm and tree shoots and leaves interact with the signal, but in the P-band (30–100 cm), scatterers the size of tree trunks have the greatest influence on radar pulses[38]. Comprehensive knowledge about the gap amount effect on the detection probability of military objects like tanks, infantry fighting vehicles, tents and units, etc. is still missing and has to be clarified in relation to the concealment effect of different forest types.

[37] **Lang et al**. 2021.

[38] **Chen, Y., Feng, Z., Li, F., Zhou, H., Hakala, T., Karjalainen, M., Hyyppä, J.** 2020. Lidar-aided analysis of boreal forest backscatter at Ku band. – International Journal of Applied Earth Observation and Geoinformation, Vol. 91, 102133, pp. 1–9, here p. 2.

The Estonian forest management inventory database does not contain data fields about canopy cover, canopy closure or the fraction of gaps in the stand's canopy. One option to get an estimate for crown cover C_{CR} would be via the tree crown radius models and stand density for each stand element in the database. Then, by using the equations given by Nilson[39], it is possible to calculate canopy cover C_{CA} by setting the tree location distribution pattern variable $\zeta=1$ for a random case, $\zeta<1$ for a more regular pattern, and $\zeta>1$ for a clumped pattern. However, this approach is somewhat complicated while the tree crown radius models are specific to tree species and geographic region. In addition, the tree distribution pattern can be reliably assumed as being approximately "regular" only for cultivated stands, while the value of ζ remains largely uncertain for other cases. Therefore, we evaluated the forest inventory variables in the database to find a simple proxy for a military analyst for a quick assessment of vertical concealment. The most promising variable found is the stand relative density *T*, which is the ratio of the stand basal area *G* to G_{norm} (m^2 ha^{-1}) as given in a standard table[40] for a stand with the same height. G_{norm} is assumed to represent a stand where trees use the growth space efficiently—i.e. the canopy is almost closed—but where competition does not cause any substantial increase in tree mortality. In forest management practice, stand relative density is approximated with canopy cover[41].

For a quantitative assessment of stand relative density as a proxy for canopy cover and, hence, vertical concealment (from sensors working in the optical range of the electromagnetic spectrum), we first calculated crown cover using model (14) from Lang et al[42]. Then we calculated canopy cover C_{CA} by using equations given by Nilson[43], assuming a regular pattern of tree locations ($\zeta=0.5$). For an additional indicator we used a simple model[44] $C_{CA}=0.898T+0.044$ constructed from a small empirical dataset of canopy cover measurements in Järvselja, Estonia.

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39 **Nilson** 1999, p. 440.

40 **ForInvRules** 2022. Standard table. Metsa korraldamise juhend. – RT I, 07.10.2022, 3. Appendix 13. https://www.riigiteataja.ee/akt/107102022003?leiaKehtiv (20.12.2022).

41 **Vaus, M**. 2005. Forest mensuration. (Metsatakseerimine). Tartu: OÜ Halo Kirjastus, p. 109.

42 **Lang et al**. 2007, p. 447.

43 **Nilson** 1999, p. 440.

44 **Nilson, T.; Lang, M.; Kuusk, A.; Anniste, J.; Lükk, T**. 2000. Forest reflectance model as an interface between satellite images and forestry databases. – Remote sensing and forest monitoring. IUFRO conference. Luxembourg: Office for Official Publications of the European Communities, pp. 462–476, here p. 466. [**Nilson et al**. 2000]

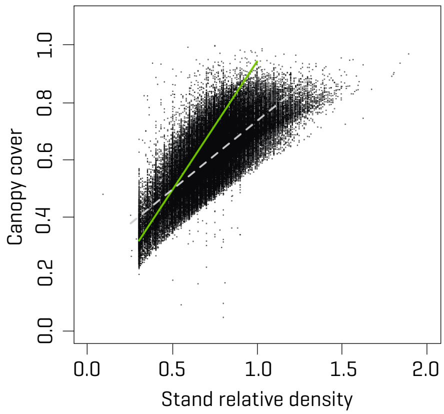

Figure 10. The forest management inventory database contains a stand relative density variable that is a good proxy for canopy cover (calculated using tree crown radius models and stand density) and, hence, vertical concealment. Each dot represents a forest stand. The dashed line corresponds to a linear model fitted to the empirical data. The continuous line corresponds to a canopy cover model taken from Nilson et al.[45]

The comparison between canopy cover predictions and stand relative density indicated a strong correlation between the two variables (Figure 10). The correlation strength is probably somewhat overestimated since both variables C_{CA} and T in this experiment are related to the stand basal area. However, the results are in good concordance with the empirical linear model[46] based on field measurements and, therefore, we conclude that stand relative density is an informative variable for a quick assessment of vertical concealment. If such predictions are made using a similar approach as here, then the analyst is responsible for accounting for the seasonal dependence of the cover related to the proportion of deciduous and evergreen trees in particular stands. The proportions of tree species are directly available in the forest management inventory database. In practical exercises it is important to keep in mind that vertical concealment also depends on forest height and any final judgement for a particular stand must be made considering canopy cover and forest height. The final decision about the suitability of a particular location in a wooded area for a particular military operation also requires consideration of the free space between the trees and soil trafficability.

4. Summary

In summary, the following conclusions and instructions can be given for using the Estonian forest management inventory database.

[45] **Nilson et al**. 2000, p. 466.

[46] Ibid.

- To get adequate concealment for most military activities, the height of the dominant tree layer needs to be over 10 m, but too small a space between stems will, with high probability, hinder penetration of the wooded area if forest height is less than 15 m.
- Approx. 16% of Estonian forests have less height than needed for concealment. However, the yearly increase in the height of young forests (up to 40 years) is in the range 0.35 to 1 m. Due to the update policy of the forestry inventory database, the difference in the real height of a forest in situ after clear-cut activity can be up to 6 m compared to database record information.
- Vertical cover from a down-looking observation depends on tree crown parameters—crown length, crown radius, live crown base height—and the flying and observing assets' parameters—position against ground elements and flight speed. To describe vertical cover, the following parameters are differentiated: crown cover, vertical canopy cover, angular canopy closure, effective canopy cover, angular cap fraction.
- Throughout the year, the best vertical concealment is offered by Norway spruce trees, but in the summer season, birch and other deciduous tree stand canopies may have a fraction of gaps as small as in spruce stands. However, vertical concealment decreases by about four times in deciduous stands during the winter season after shedding their leaves.
- The stand relative density given in the forest inventory database provides a good approximation of vertical concealment and allows one to delineate with sufficient accuracy the four vertical canopy groups needed by military planners.

There is a definite need for further research about the probability of detection of military objects inside forests depending on the angular gap fraction and in relation to various sensors.

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