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Perspective

Lean forestry – A paradigm shift from economies of scale to precise and sustainable use of ecosystem services in forests

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ABSTRACT

Modern forestry practices are based on the idea of ‘big is beautiful’. Especially in the regeneration phase, the operations are often excessive in relation to the profit that one can expect to gain in decades to come. Excessive operations also constrain the use of ecosystem services. Lean forestry is a novel philosophy of forestry practise that aims to direct the idea of “big is beautiful” in modern silviculture more into “do cost effectively only what is needed to fulfil the goals”. To succeed Lean forestry requires exact spatial information to be able to carry out forestry measures very precisely only where they are really needed to fulfil goals. This kind of a paradigm shift requires systems with new kinds of abilities to remotely sense the surrounding environment and to make better and faster decisions based on sensed data. Automated unmanned offroad vehicle that is able to sense the environment and to make lean decisions is presented as an example of initiatives that can make forestry more cost-effective and simultaneously improve utilisation of wide range of ecosystem services in forests.

1. Background

1.1. State of the art

Until the early 1900′s forest use in Fennoscandia can be characterised as inefficient but large-scale. In many parts slash-and-burn culture, charcoal production for the iron industry and tar production affected large forest areas. Silvicultural practice was mainly selection cutting, where only trunks of certain characteristics, such as diameter and height fulfilling needs of navy, mining, railroads or construction engineering, were cut but no regeneration efforts were carried out. Despite the inefficiency of this practise together with long lasting slash-and-burn culture (e.g. in Finland lasted 2000–3000 years), tar and charcoal production, burning for heat etc., led to the situation in the end of 1800′s – early 1900′s where national authorities were worried about the sufficiency of timber. This concern led to the establishment of Forestry laws (Leikola 1987, Enander, 2007) and World’s first National Forest Inventories (NFIs) in Norway, Sweden and Finland in 1920′s. The first NFIs confirmed the concern: in many places the timber use exceeded the sustainable use of forests, although the word “sustainability” came into use much later.

Gradually in the first decades of 1900′s it became evident that regeneration in forests managed by selection cutting (cutting only logs) was not enough to secure the establishment of the next tree generation. This led to favour different regeneration cuttings: e.g. seed tree cuttings in pine and shelterwood cuttings in spruce. However, especially northern spruce stands with thick moss layers were found to be hard to regenerate with any of the methods used at that time but were instead noticed to regenerated well after clear cut followed by prescribed burning and seeding. Gradually this method gained popularity also in more southern forests and paved the way for similar methods in all forests. When tractor replaced horse in agriculture also silviculture started to be more and more mechanised that helped to move to clear cuttings, soil preparation (instead of prescribed burning) and artificial regeneration by seeding or planting (Laitakari 1960, Leikola 1987). This eventually led to the so-called modern forestry that started in the Fennoscandian countries during 1950′s. It was a more industrial view on forestry than the previous one and with an overall goal to improve forest regeneration results and thus increase wood volume production. In addition to mechanization an important effort was the tree improvement programs, including optimal selection of provenances, that started in the end of 1940′s with the result that seedling survival increased during coming decades especially for pine. This period was also a start of research on suitable methods and guidelines for the different phases of clearcutting forestry, i.e., cutting, soil preparation, seeding/planting, pre-commercial thinnings, thinnings, etc. Mainly due to cost reasons the sizes of treated areas became bigger and the recommended treatments for each phase became similar. “Paradigm of simplicity” (i.e. Paradigm

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of mono-measures forestry) was created with the result that the same measures were done "always and everywhere".

Consequently, forestry practices during the past few decades are largely adopted from the idea of "big is beautiful". That is, generally similar operations are applied to an area as large as possible to minimise costs related to transportation of large harvesters, forwarders and soil scarifiers and limit repeat visits to the same and nearby stands. In addition, especially in the regeneration phase, the operations are often excessive in relation to the profit that one can expect to gain in decades to come. This was shown in a nationwide Swedish field experiment where the intensity of forest regeneration measures on stand development was studied (Hallsby et al. 2015). They concluded that "…from a strictly financial perspective, the investment in intense regeneration measures cannot be justified." This conclusion rises from the fact that in many places and at least partly harvested forest sites regenerate naturally without costly soil scarification or seeding or planting. In other words, the long-term natural regeneration capacity of forests is in many cases enough to produce viable seedlings that during a rotation period secures high wood production with good revenue making intensive, expensive regeneration measures often unnecessary. Afterwards, often too heavy precommercial thinning is applied too early resulting in heavy branching that in turn, impairs stem quality in especially pines from the point of view of high-quality saw timber production (Huuskonen and Hynynen 2006). Further, the costly pre-commercial thinning is also used according to the paradigm of simplicity with the result that one-layered stands are created, and the vertical diversity of stands is reduced. This is negative to biodiversity (Witzell et al. 2019) and reduces the possibility to cut down regeneration cost by making two storied stands that overarches rotational periods and reduces clear cut time. Common practise has also been to remove birch and other deciduous trees in coniferous stands even though, especially in spruce stands, birch has been shown to be beneficial for the stand quality and regeneration, as well as for biodiversity (Huuskonen et al. 2021, Felton et al. 2022).

1.2. *Vision of Lean forestry*

Identifying the cases where regeneration measures should be kept to a minimum and thus minimizing the disturbance to the natural regeneration process while maximising the forestry values and optimising timing and intensities (or even the need) of thinnings are the key elements of the 'Lean forestry' concept. Lean forestry is a novel philosophy of forestry practise that aims to direct the idea of "big is beautiful" in modern silviculture more into "do cost effectively only what is needed to fulfil the goals".

Coined originally by Krafcik (1988) the concept of Lean was developed as a management philosophy within the automotive industry where focus is on resource efficiency while maintaining productivity (Womack et al. 1990). The basic idea in Lean is to minimize time consumption and waste (i.e. costs) while maximising productivity. A lean philosophy in forestry can therefore be interpreted as silvicultural measures that are as precise and resource efficient as possible, not only to minimise expenses and maximise high biomass and wood production, but also to maintain the potential for other forest ecosystem services, in other words sustainable forestry.

Ecosystem services (ESs) are defined by the Millennium Ecosystem Assessment (2003) as benefits that people obtain from ecosystems. In forest ecosystems these services include not only raw materials (e.g. biomass, timber, pulpwood, bioenergy) and food (berries, mushrooms, game), but also global climate regulation (carbon sequestration, light retention, albedo) and cultural values (e.g. landscapes for recreation and tourism) (Hansen and Malmaeus 2016). Globally even 'food production' is over double the value of 'raw materials' obtained from temperate/boreal forests (Costanza et al. 1997; Ninan and Inoue 2013). In the Nordic-Baltic region the value of ecosystem services differs clearly from the global values listed above. As an example, in Finland the proportion of timber of the total ES value is assessed to be around 40 % (Matero and Saastamoinen 2007) and in Sweden the share of wood (timber, pulpwood and bioenergy) of the total value of the known forest ESs about 43 % (Hansen and Malmaeus 2016). But even these figures show that more than 50 % of the ESs in northern forests could be something else than timber, highlighting the importance of holistic sustainability of forest use. As an example, pertained to forest regeneration, a recent Swedish study (Sandström et al. 2016) showed that over the last 60 years ground lichen-abundant forest, that are the main winter grazing grounds for reindeer, have declined by over 70 %. This creates pressure to leave the remaining ground lichen-abundant forest outside of cutting plans, which in turn raises objection among forest owners and wood industry. In recent years, the conflicts between various interests related to ESs of forests in northern Europe have escalated (Sandström et al. 2016). In northern parts of Fennoscandia (northern Finland, Sweden and Norway), these conflicts have mainly concerned forestry, reindeer herding, tourism and recreation by local users.

If forestry measures could be economically viable at smaller scales, replacing large clearcuts with, for example, small gap openings (Hallikainen et al. 2019), seed tree cuttings (Hyppönen 2002), shelterwood cuttings (Hånell et al. 2000) or other economically reasonable measures, this could bring benefits in several ways. First, smaller scale measures would avoid most of the current conflicts with other ESs, thus allowing silviculture to continue even in the vicinity of settlements, tourist resorts or in reindeer herding areas. Secondly, other silvicultural practises than the conventional clear cut could be used to prolong rotation periods or to bridge between periods in a more sustainable way. Thirdly, following the lean management principles by concentrating heavy, expensive measures precisely to the areas where they are really needed – like applying soil scarification to places that are covered by thick raw humus layer, leaving the places that are already naturally regenerated untouched – the resource efficiency could be maximised.

However, all above is easier said than done. In forestry, many harvesting processes are mechanized with manually operated machines while in forest regeneration, manual labour is still common (Ersson and Petersson 2013). To succeed Lean forestry requires exact spatial information to be able to carry out forestry measures very precisely only where they are really needed to fulfil goals. This information needs to be both global, i.e. based on landscape and stand level information (e.g. from aerial photographs, radar or optical sensors mounted on satellites or (un)manned aircrafts), and local in stands to identify e.g. small scale obstacles like deadwood, stumps and stones or vegetation types such as lichen carpet, (e.g. from sensors like Time of Flight, Lidar, IR and RGB) to be avoided. Landscape or stand level information – like forest types, stand structure, tree species composition – can be obtained by using remote sensing data from satellites or airborne sensors on aircrafts and drones. Local spatial information on the position and size of tree trunks etc. could be obtained from 3D imagery of stands created from data acquired by drones and by sensors attached to machines operating in situ (see examples below).

In Lean forestry silvicultural measures should also be able to perform on small scale. An example would be a stand that has been regenerated by selective cutting (i.e. removing individual mature trees) or small gap openings. Operating in this kind of environment could be made more sustainable if as much spatial-related global and local information is preprogrammed in the system operating in the stand. This information, complemented with real-time in situ information, will enable more precise and resource efficient forest operations through automated activities (Fig. 1).

Part of the process leading to lean forest operations in stands can be done beforehand in the planning phase. These offboard operations using data collected from stands, taking into considerations of possible constraints and ESs valuations lead to lean goal formulations that help stand and landscape level decision making (Fig. 2). In the operated stand these decisions are put in practise with aid from real time environment sensing and analysis. Environment sensing combined with data collected from the stand and proper technological prerequisites — e.g. machine vision

Fig. 1. Vision for "LEAN FORESTRY" exemplified where both global and local information is used to select suitable and avoid unsuitable places for soil scarification and planting or seeding using an unmanned vehicle in a forest stand where the regeneration cutting is done creating small gap openings.

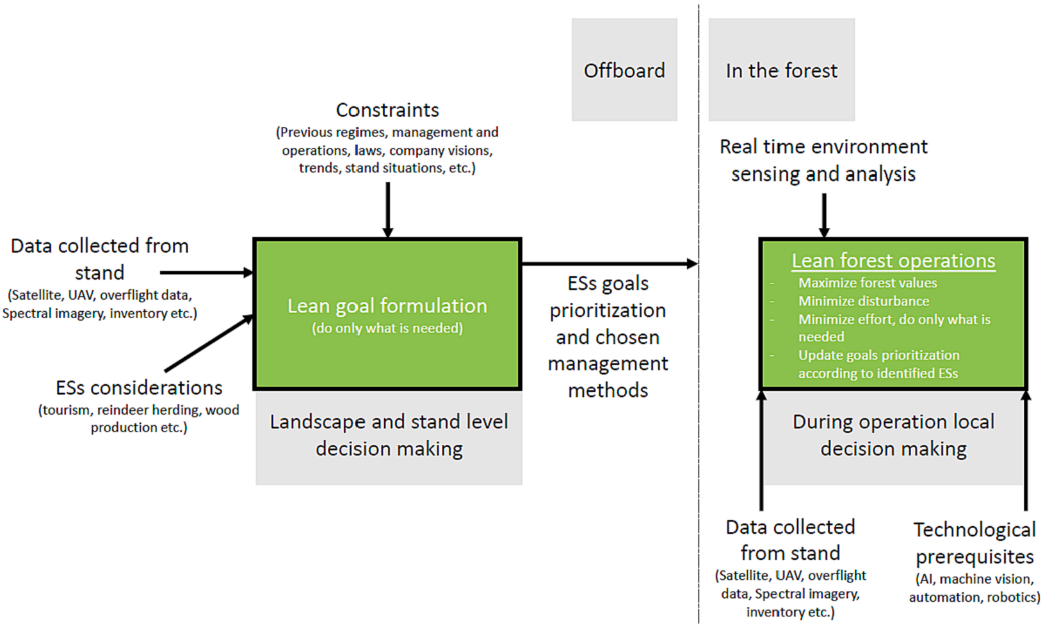

Fig. 2. Lean forestry requires information on global and local level to enable decision making on large and small scales.

and artificial intelligence (AI) — are needed to make decisions at the local stand level, enabling lean forest operations (Fig. 2). We would like to emphasise, that many of the needed decisions to be made at the stand level are not humanly possible but require co-operation of machine vision, AI and automation to succeed. As an example, in order to save biodiversity rich dead wood, avoid lichen rich forest floors, while cutting trees of certain species and sizes, and the same time removing sick trees infected by invasive disease requires an interplay of automated object identification, AI and robotics (cf. Fig. 1).

1.3. *Technological advances for Lean forestry prerequisites*

It has been predicted that autonomous operations will soon be a reality during both silvicultural (Nilsson et al. 2010) and harvesting operations (Hellström et al. 2009), but these need to be targeted more intensively within the research and development sector in order to improve the forest regeneration practices (Ersson 2014).

This kind of a paradigm shift requires systems with new kinds of abilities to remotely sense the surrounding environment and to make better and faster decisions based on sensed data. And although researchers have stressed the need for automation in forest regeneration (Kemppainen and Visala 2013), few solutions for forestry remote sensing exist that are used in practice during silvicultural operations. Rantala et al. (2009) stated that innovations in communication and sensor technology could offer solutions to streamline mechanized planting. With such solutions, the degree of automation could possibly be increased to an extent that makes forest operations competitive in terms of productivity and quality (compared to today's methods), which is expected to happen in the medium- to long-term (Ersson 2014) granted sufficient stimuli. At the same time – sometimes in clash with economic targets – sustainable processes are necessary (Brundtland 1987) that could be addressed by reducing soil disturbance (Örlander et al. 1998) or GHG emissions from forest operations (Berg and Karjalainen 2003), by leaving retention trees and deadwood on stands to secure biodiversity (Koivula and Vanha-Majamaa 2020) or by avoiding large clear-cuts to retain reindeer pastures (Turunen et al. 2020) and scenery for nature-based tourism (Tyrväinen et al. 2015).

Development of remote and proximal sensing technology will provide continuous data from which useful information can be extracted and used for decision support, monitoring and evaluation (Talbot et al. 2017). Recent advances have shown potential for using such data also in silviculture in combination with AI technology. Li and Lideskog (2021) developed a terrain surface object identifier that could be utilized for machine and equipment control for both targeting or avoidance purposes. For example, a successful implementation of the system on a continuously advancing spot mounders could decrease failed mounding attempts significantly, since surface terrain objects constitute a major reason for creating subpar mounds (Larsson 2011). On the same theme, Kemppainen and Visala (2013) developed a system that utilized stereo camera data to automatically detect good planting spots on spot mounded clearcuts. In combination, these efforts could form a basis on which site preparation and planting is automated.

Unmanned Aerial Vehicles (UAVs) has gained much attention in forestry in recent years as the technology has been improved while purchasing costs has decreased (Cruzan et al. 2016). Using such technology, different important ecosystem services (ESs) and changes in ESs can be mapped from above the canopies, for example for caribou management (Fraser et al. 2021), forest health monitoring (Dash et al. 2017), tree species discrimination (Tsuya et al. 2021) or detection of root rot on tree stumps (Puliti et al. 2018). UAVs can also be used to move payloads over inaccessible terrain, e.g. carrying seeds for germination (Mohan et al. 2021). The increased ESs mapping possibilities around forestry vehicles with elevated precision enable machines to consider such information when operational tasks are planned both on– and offboard; i.e. a basis for Lean forest operations.

2. Practical examples of Lean forestry

2.1. Soil preparation and artificial regeneration

It is widely acknowledged that on most forest types soil preparation enhances the regeneration success and increases the growth of seedlings (Sikström et al. 2020, and references therein). At the same time, however, soil preparation is one of the main factors in forestry practices that creates conflicts with other ecosystem services, especially with berry and mushroom picking, recreation, tourism and reindeer herding. The damage to existing ground vegetation is proportional to the area affected by soil preparation, normally between 30 and 50 percent in e.g. disc trenching. To reconcile these land use conflicts Lean forestry with exactly directed small scale operations could provide a tool needed for this purpose.

Forest regeneration in Fennoscandia is generally carried out by applying mechanical site preparation, followed by direct seeding (Wennström et al. 1999) or planting tree seedlings (Eriksson 2013, Juntunen and Herrala-Ylinen 2014, Granhus et al. 2015). Compared to disc trenching, intermittently created planting spots using mounding site preparation has been shown efficient in terms of subsequent seedling survival and growth (Örlander et al. 1990, Sutton 1993, Saksa et al. 2005), and even better seedling survival has been found when using an inverting procedure preceding planting (Hallsby and Örlander 2004). Intermittently created planting spots also have the advantage of lower soil disruption than disc trenching, which is important for advance regeneration and other environmental, recreational, and archaeological values (Örlander et al. 1998). However, when compared to disc trenching, mounding is not only more expensive but also highly sensitive to obstacles found on clearcuts. Larsson (2011) have shown that on average every other mounding attempt fails. Consequently, on obstacle rich clearcuts disc trenching is often chosen at the expense of mounding (Lundmark 2006). With help of machine vision, sensors, and automated object identification soil scarifiers can be developed in near future to do more finer scale operations (Fig. 3a) that can help to preserve also other ESs and to alleviate land use conflicts.

Forest regeneration today faces the need for productivity much higher than in previous decades (Rantala et al. 2009). Consequently, future forest regeneration processes need to utilize a larger share of mechanization in order to reduce costs and enhance productivity (Nilsson et al. 2010). According to Rantala et al. (2009) competitive mechanized processes in forestry require high production at low cost and high technological availability. One way to improve productivity in forest regeneration processes is to automate machines (Ringdahl 2011). In practical forestry, processes are still mechanized with manually operated machines during harvesting or forwarding (Nordfjell et al. 2010), while in silviculture manual labour is still common (Ersson and Petersson 2013) and the field of automation is poorly explored (Hallongren et al. 2014).

In many other industries, such as automotive and construction, machines and vehicles are already transitioning to semi-automation or full automation. In the US for example, level 4 autonomous road vehicles are forecasted to penetrate 25 % of the market by 2045 (Bansal and Kockelman 2017), only being held back by the cost of technology. In fact, autonomous vehicles have successfully driven on American and European roads in many decades (Urmson and Whittaker 2008). Exteroceptive sensors collecting data on moving vehicles have attracted interest in research and development in recent years as the automotive industry continues this strive towards self-driving vehicles, determined to outcompete humans' own sensing.

In silviculture, semi-automated, continuously advancing planting machines were developed in research scale already in the 1960 s and operational attempts were made in the 1970 s – the Swedish Silva Nova and the Finnish Serlachius planting machines are examples – but were considered too expensive to keep in use at the time (Ersson 2014), although these devices showed decent planting quality (Kaila 1984, Hallonborg 1995). In actual fact, today's planting devices are less automated than the machines introduced in previous decades (Rantala et al. 2009), the reason being to reduce investment costs and to increase technical availability. Certainly, as other industries put great efforts to reach higher levels of automation, so can opportunity rise to transfer such technologies at a lower development cost to be utilized in forestry and silviculture to accelerate the automation transformation (Vestlund and Hellström 2006).

2.2. Timber harvesting and forwarding

In addition to soil preparation and artificial regeneration, exact spatial information, machine vision, sensors, robotics and AI can naturally be used in harvesters and forwarders. In timber harvesting one example of a challenging task is to do thinnings or selection cuttings the optimal way. In both operations not only trees that exceed the required diameter, but also those that do not have growing potential or are situated in wrong places should be removed. An additional challenge is that sick trees that could transmit an infection, e.g. Scots pine blister rust

Fig. 3. The Arctic Off-Road Vehicle Platform (AORO). Autonomous tests of inverse scarification to the left (a) and forwarding demonstration to the right (b). AORO is developed in collaboration initiative between Luleå University of Technology, Swedish University of Agricultural Sciences and The Cluster of Forest Technology.

(Cronartium flaccidum) that is spreading in many places in northern Sweden and Finland, should be removed as well to stop the infection. Doing all this also during the wintertime, when it is dark and trees are partly covered with snow, is a humanly impossible task. With the help of machine vision and automated object identification a harvester can have a 360° vision all the time that, with the help of AI and robotics, can operate the harvester to harvest trees with predefined specifications. Having this sensing capability, preceding undergrowth clearing, commonly done to help thinning operators to work efficiently, could be avoided. For example, research shows that between 10 and 70 % of penetration can be achieved with Lidar data (Chevalier et al. 2007). Consequently, when undergrowth is kept after thinning, other forestry methods such as continuous cover forestry are not disabled.

An automated harvester can be programmed beforehand to avoid e.g. biodiversity hot spots in a stand or lichen rich patches in reindeer pastures. As harvesters also forwarders can, by using machine vision, automated object identification, AI and robotics, be programmed to select or avoid objects. As an example, simply avoiding decaying lying dead wood and selecting only trunks of certain diameter cut by the harvester (Fig. 3b) a forwarder can be programmed to avoid major parts of the negative effects the operation could have on biodiversity.

2.3. *Offroad vehicle platform for on-site Lean forestry research*

An offroad vehicle platform, especially developed for research on methods, tools and technologies for automated activities has been developed within the initiative “Arctic Off-Road Robotics Laboratory” (see Fig. 3). This is an example of the current initiatives to develop and test methods, tools and technologies to reach the above Lean forestry visions. The platform carries capabilities to acquire and process large amount of data in real time from various sensors. Based on this data the vehicle can take precise “lean decisions” on the fly. Although small (~10 tonnes), the platform is still in a scale where tests can be performed under realistic conditions and in correct environments. Fig. 3 shows examples of use of this platform for autonomous forwarding and tests of a new type of inverse scarification equipment used for autonomous site preparation.

This type of initiatives enables innovative Lean forestry measures that make forestry more cost-effective and simultaneously improve utilisation of ESs other than wood production in the same areas, in other words promotes sustainable forestry.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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