

**Dissertationes Forestales 291**

**The availability and supply of marketed mushrooms in  
Eastern Finland**

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Academic dissertation

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## ABSTRACT

The use of marketed mushrooms is predicted to increase worldwide. Currently, the marketed mushroom yields in Finland remain largely unutilized, and forest management mainly aims at timber production. In this thesis, the availability and limitations of the raw material procurement and market supply of marketed mushrooms in Eastern Finland were studied. Empirical yield models were formulated for the most marketed species in spruce stands: cep (*Boletus edulis*), milk cap (*Lactarius* spp.) and all marketed mushrooms. Optimal stand management was defined for the joint production of timber and mushrooms. The socially acceptable limits for mushroom picking on private land were investigated through a forest owner survey, and the supply of marketed mushrooms was modeled to study which factors affect the marketed quantities of mushrooms in Eastern Finland.

The results suggest that the Eastern Finnish spruce stands produced their highest mushroom yields right before the first commercial thinning, and precipitation during the yield season promoted the yields. The production of timber and marketed mushrooms was largely in synergy, and if mushrooms are picked for sale, the total soil expectation value (SEV) in good mushroom stands can be remarkable. The forest owners in Eastern Finland expressed some restriction needs for organized commercial picking, but they were otherwise content with the everyman's rights regarding mushroom picking. The supply of marketed mushrooms was affected by biological and economic factors; precipitation had a positive influence on cep and milk cap supplies and market price negatively impacted the supplies of ceps and chanterelles.

The results contribute to a more stable and sustainable raw material supply to the mushroom supply chains by providing novel information on the supply of marketed mushrooms and limits of socially acceptable mushroom picking and by developing concrete tools to integrate mushroom production into forest management planning and to plan for mushroom picking.

Keywords: Multiple use forestry, Non-Wood Forest Products, *Boletus edulis*, *Lactarius* spp., wild edible mushrooms

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Joensuu, February 2020

Veera Tahvanainen

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## LIST OF ORIGINAL ARTICLES

This dissertation is a collection of four articles and a summary. All articles are reprints of published articles. The articles are reprinted here with the kind permission of the publishers and are referred to in the text by the Roman numerals (I–IV).

- I** Tahvanainen, V., Miina, J., Kurttila, M., Salo, K. (2016). Modelling the yields of marketed mushrooms in *Picea abies* stands in eastern Finland. *Forest Ecology and Management* 362: 79–88.  
<https://doi.org/10.1016/j.foreco.2015.11.040>
- II** Tahvanainen, V., Miina, J., Pukkala, T., Kurttila, M. (2018). Optimizing the joint production of timber and marketed mushrooms in *Picea abies* stands in eastern Finland. *Journal of Forest Economics* 32: 34–41.  
<https://doi.org/10.1016/j.jfe.2018.04.002>
- III** Tahvanainen V., Kurttila M., Miina J., Hujala T., Väkeväinen T., Salo K. (2016). Pohjoiskarjalaisten ja kainuulaisten metsänomistajien mielipide marjastuksesta ja sienestyksestä yksityismetsissä. *Metsätieteen aikakauskirja* 2/2016: 95–110.  
<https://doi.org/10.14214/ma.5958>
- IV** Tahvanainen, V., Miina, J., Kurttila, M. (2019). Climatic and economic factors affecting the annual supply of wild edible mushrooms and berries in Finland. *Forests* 10(5): 385.  
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### Author's contributions in co-authored articles:

The contribution of Veera Tahvanainen to the articles of this thesis was as follows:

**Articles I & II:** analyzed the data and wrote the manuscript together with co-authors.

**Article III:** planned the study, collected data, analyzed the data and wrote the manuscript together with co-authors.

**Article IV:** planned the study, analyzed the data and wrote the manuscript together with co-authors.

## ABBREVIATIONS

CPR	Common pool resource
DSS	Decision support system
FTE	Full-time equivalent
G	Stand basal area
MARSI	Statistics on annual quantities of berries and mushrooms bought by trade and industry
N	Number of observations
NLMM	Non-linear mixed-effect modelling
NWFP	Non-wood Forest Product
$R^2$	Proportion of explained variance
RMSE	Root mean square error
RMSE%	Relative root mean square error
SEV	Soil expectation value
var( $\cdot$ )	Variance component in mixed-effect model





# 1 INTRODUCTION

## 1.1 Marketed mushrooms and their commercial use

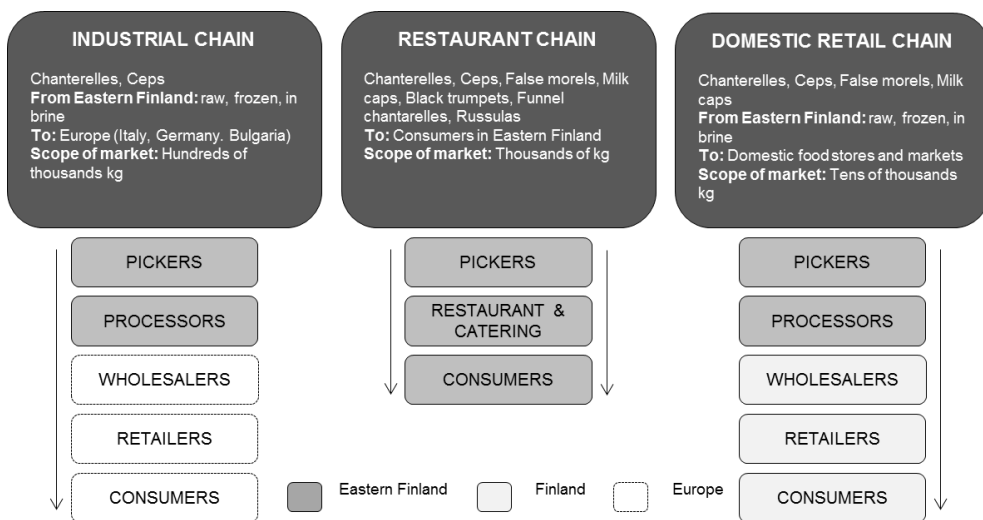
The use of wild edible mushrooms among other non-wood forest products (NWFPs) is gaining popularity in Europe (Schulp et al. 2014). Consumer preferences toward healthy and locally produced foods (Kearney 2010; Mithril et al. 2012; Lehtikoinen and Salonen 2019) support the consumption of wild edible mushrooms and other NWFPs in Nordic countries (Mithril et al. 2012) as well as globally. Therefore, the commercial use of mushrooms in Europe can also increase in areas that have not traditionally favored mushrooms in their diets (Peintner et al. 2013). Wild edible mushrooms are considered NWFPs, which are defined by the Food and Agriculture Organization of the United Nations (FAO) as “goods of biological origin other than wood derived from forests, other wooded land and trees outside forests” (FAO 1999). Despite some attempts, the definition of NWFPs remains vague (Mantau et al. 2007; Vidale et al. 2016), and the use and value of NWFPs is therefore impossible to calculate extensively. NWFPs, however, are used all over the world, and their importance for food can be locally remarkable (Arnold et al. 2011; Cai et al. 2011; Stryamets et al. 2011; State of Europe’s Forests 2015; Rowland et al. 2017).

Marketed mushrooms are edible species with established domestic or international markets, and here, therefore, they are referred to as marketed mushrooms. The official list of 31 species of marketed mushrooms that can be sold for food was maintained by the Finnish Food Safety Authority at the time of the sample plot network’s establishment (Suositeltavat ruokasienet 2019). However, since 2012, the list is only regarded as recommended wild edible species. The genus *Boletus* (e.g., *B. edulis*), *Cantharellus* (e.g., *C. cibarius*) and *Lactarius* (e.g., *L. deliciosus*) are important worldwide and have well-established markets (Wang and Hall 2004). Particularly *B. edulis* is highly appreciated in international markets (Sitta and Floriani 2008; Sitta and Davoli 2012). The commercial use of marketed mushrooms has not been extensively documented, and international statistics on their use are likewise incomplete (Vantomme 2003). Yet there are some studies on supply chains of wild edible mushrooms and factors affecting their supply (Voces et al. 2012; Diaz-Balteiro et al. 2013; Alfranca et al. 2015). According to the study on *Lactarius* spp. markets, the market price had a positive effect on the supply of marketed mushrooms in Spain (Diaz-Balteiro et al. 2013; Alfranca et al. 2015) following the general principles of supply: the higher the price the higher the marketed quantities (Marshall 1890). On the contrary, Kangas (1999) noticed an inverse price-quantity relationship in the markets of cowberries in Finland in the study of the wild edible berry supply.

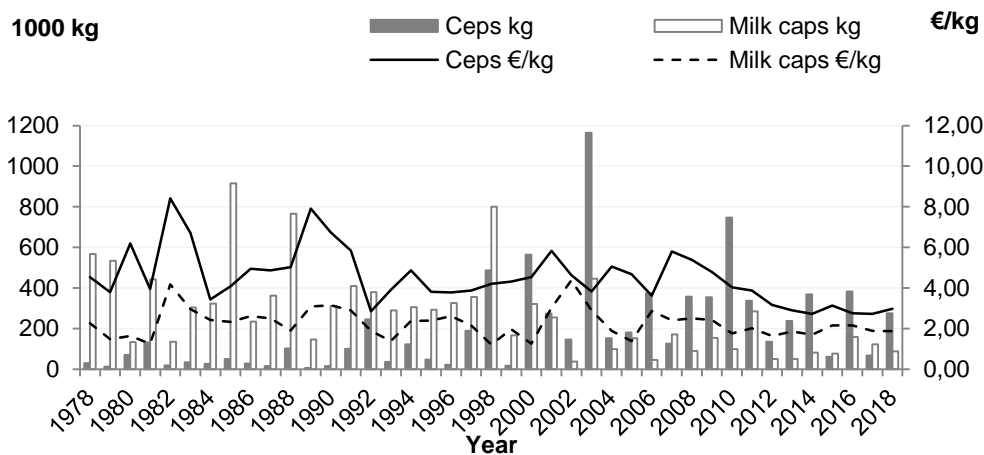
It is estimated that there are over 200 edible mushroom species in Finland (Jäppinen 1988), from which roughly 30 are used as food (Salo 1995). The most important marketed mushrooms in Finland are *Boletus edulis* Bull. (market statistics also include *B. pinophilus* Pilát and Dermek), *Cantharellus cibarius* Fr. and *Lactarius* spp. (including *L. trivialis* Fr., *L. rufus* [Scop.] Fr. and *L. torminosus* [Schaeff.] Pers.) (MARSİ 2018). However, other species are also used and traded in Finland (Figure 1). The wholesalers are buying mushrooms from pickers, and it is estimated that the supply chain of mushrooms provides jobs worth around 600 full-time equivalents (FTEs) (Ristioja 2018). The value added in the mushroom supply chain is low, as most of the mushrooms are exported fresh and frozen.

The raw material scarcity and instability are noted as hindering factors at the markets of wild edible mushrooms in Finland (Rämö et al. 2013).

Due to the strong history of berry and mushroom use, the prices and quantities of marketed mushrooms have been well-documented in Finland since the 1970s (MARSI 2018). Around half a million kilos of mushrooms are picked annually for sale in Finland, which generates an income of more than a million euros for mushrooms pickers. There is a lot of variation in the annual quantities of mushrooms traded in the organized trade and industry, as well as in the prices paid to the pickers (Figure 2). Instability in the supply of raw material is likely to cause instability in the whole supply chain. Although Finnish non-wood forest product markets are rather well documented, the knowledge of factors affecting the supply of marketed mushrooms is still inadequate.



**Figure 1.** Supply chains of marketed mushrooms in North Karelia (Tahvanainen et al. 2016).



**Figure 2.** Annual quantities (1000 kg/yr) and deflated prices (€/kg) of ceps and milk caps bought by organized trade and industry in Finland in 1978–2018.

## 1.2 Availability of marketed mushrooms to mushroom supply chains

Marketed mushrooms belong to the fungi kingdom, and the most important marketed mushroom species are ectomycorrhizal mushrooms, which form symbiotic associations with host plants (Smith and Read 1997), primarily trees. Currently, the marketed mushroom yields remain largely unutilized (Ohenoja 2005), and forest management aims at timber production. However, climate change, carbon sequestration and loss of biodiversity are affecting the discussions and policies concerning the use of forest resources (State of Europe’s Forests 2015). Most forest owners in Finland declare themselves as multipurpose forest owners (Hänninen et al. 2011). Multiple-use forestry is a growing trend, and hence, practical models and methods for forest management and mushroom production are needed.

The possibility of producing ectomycorrhizal mushrooms by cultivation has been studied, but so far, only a few species have been successfully cultivated (Boa 2004; Wang and Hall 2004). Production models are one way to include the NWF’s production in silviculture. In mushroom production, the term “mycosilviculture” is used (Savoie and Largeteau 2011). In recent decades, NWFs have also received attention in forest management (Kurttila et al. 2014; Wolfslehner et al. 2014).

### 1.2.1 Yields of marketed mushrooms

Climatic factors have an influence on the yields of marketed mushrooms. In particular, precipitation positively influences the fruit body production of mycorrhizal mushrooms (Ohenoja 1993; Straatsma et al. 2001; Martínez de Aragón et al. 2007; Krebs et al. 2008; Parladé et al. 2017). According to Ogaya and Peñuelas (2005), drought irrigation (reducing soil water by 15%) resulted in a decrease in mushroom yields in Spain. Similarly, in a Swedish study, water irrigation had a positive effect on mushroom production in general (Wiklund et al. 1995). The monthly mean precipitation and accumulated monthly mean

evapotranspiration of the fruiting season (September and October) and the monthly mean minimum soil temperature in August were used to estimate the annual sporocarp production of ectomycorrhizal and edible forest fungi in Spain (Martínez de Aragón et al. 2007). Temperature also influences the fruiting body production of mushrooms. Straatsma et al. (2001) found that the temperatures in July and August correlated with the fruit body appearance of mushrooms in Switzerland. Ohenoja (1993) estimated that temperature and precipitation explained 19–42% of the annual variation in the biomass of mycorrhizal mushrooms in different forest types in Finland. Studying the effect of climatic factors with the stand variables on mushroom yields is essential since forest density creates special microclimatic conditions.

The yields of mushrooms have been studied in Finland since the first half of the 20<sup>th</sup> century (Rautavaara 1947). Later, the mushroom yields were studied more in Finland based on the fruit body production (kg/ha/yr) of the mushrooms (Ohenoja and Metsänheimo 1982; Ohenoja 1984; Väre et al. 1996). According to the Finnish national forest inventory data from 1985–1986, the annual yields were 19.3 kg/ha for *Lactarius rufus*, 6.6 kg/ha for *L. torminosus*, 6.4 kg/ha for *L. trivialis* and 6.1 kg/ha for *Boletus edulis* in mineral soil forests (Salo 1993). However, the yields vary remarkably between stands and years.

### 1.2.2 Forest management and production of marketed mushrooms

Forest management affects the yields of wild edible mushrooms, and the effects of forest management operations on the mushroom yields have been studied in different countries (Ohenoja 1988; Luoma et al. 2004; Durall et al. 2006; Pilz et al. 2006; Egli et al. 2010; Bonet et al. 2012; de-Miguel et al. 2014; Liu et al. 2016; Parladé et al. 2017). The host plants' photosynthetic activity is connected to the mushroom production of the stand (Kuikka et al. 2003; Bonet et al. 2010; Egli et al. 2010). Due to a symbiotic relationship of trees and fungi, the clear cut or dramatic reduction of host trees remarkably decreases the yields of mycorrhizal mushrooms (Ohenoja 1988; Norwell and Exeter 2004; Durall et al. 2006). Also the sporocarp production of mycorrhizal mushrooms seems to be higher in younger stands, where the wood volume growth is highest (Senn-Irlet and Bieri 1999; Bonet et al. 2008; Egli et al. 2010).

The reactions of mushroom yields to thinnings on the other hand depend on numerous factors, e.g., thinning intensity, tree species composition and stand age (Tomao et al. 2017). For example, in a study of Canadian *Tsuga heterophylla* and *Thuja plicata* stands, the response of ectomycorrhizal mushroom production after partial cuttings was studied, and the yields reacted differently depending on the stand structure and tree vigor after stand management operations (Kranabetter and Kroeger 2001). According to Palahí et al. (2009) the thinning of pine stands in Spain first reduced the yields and later increased them, because the stand basal area was reduced to a favorable level for mushrooms. In a Swedish study, the yields of *L. rufus* increased right after thinning (Kardell and Eriksson 1987). A similar result was found with *L. deliciosus* in Spain in *Pinus pinaster* stands (Bonet et al. 2012). Medium thinnings were favorable for *B. edulis* yields in fir stands in Italy (Salerni and Perini 2004).

The current forest planning systems are timber production oriented, but there are some decision support systems (DSSs) developed for NWFPs too (Pukkala 2002). So far, yield models are formulated, for example, for the production of berries (Miina et al. 2009; Turtiainen et al. 2013) and stone pine cones (Calama et al. 2008), but also for mushrooms, such as wild mushrooms in pine stands in Spain (Bonet et al. 2008; Bonet et al. 2010), *L.*

group *deliciosus* and *B. edulis* in pine stands in Spain (Martínez-Peña et al. 2012), mycorrhizal mushrooms and *B. edulis* in *Cistus ladanifer* scrublands in Spain (Hernández-Rodríguez et al. 2015) and *L. deliciosus* and *L. salmonicolor* in Turkey (Kucuker and Baskent 2015). The models can be included in the simulators to produce management schedules and information on the future yields and profitability of the co-production of timber and NWFPs. The stand management optimizations for the co-production of timber and NWFPs have been produced, for example, for berries in Finland (Miina et al. 2016) and mushrooms in Spain (Palahí et al. 2009). It has been shown that changing stand management to produce NWFPs in addition to timber can create additional income for forest owners (Alexander et al. 2002; Palahí et al. 2009; Aldea et al. 2012; De-Miguel et al. 2014; Leonardi et al. 2017).

### 1.2.3 Mushroom picking

The public right of access and the right to extract goods from privately owned forests varies significantly from one country to another. In Europe the everyman's rights apply in the Northern European countries, but similar rights are practiced in other countries in relation to some NWFPs, too (Nichiforel et al. 2018). In some areas, the picking pressure of NWFPs can be very high, namely, in household and commercial use, which causes conflict among land-owners, local people and pickers. Organized commercial picking has raised questions about the limits of the everyman's rights in Finland (Viljanen and Rautiainen 2007; Peltola et al. 2014) and Sweden (Sténs and Sandström 2013) but also in Spain concerning the mushroom picking and property rights (Górriz-Mifsud et al. 2015). Based on earlier studies, the acceptability of picking was higher if the picker was local rather than non-local (Peltola et al. 2014; Górriz-Mifsud et al. 2015). The threat seems to be that some pickers overuse the resource or act otherwise unfairly, a phenomenon known as the tragedy of commons (Hardin 1968). Commonly-accepted rules on how to use the resources have been suggested as an answer to advance the sustainability of common pool resources (CPRs) (Ostrom et al. 1999).

Mushrooms have been used as food in Finland for decades and the picking culture is strong, especially in Eastern Finland (Jäppinen 1988; Sievänen et al. 2004). The marketed mushrooms are mainly picked for sale by domestic pickers in Finland (MARSİ 2018). Of Finnish people, approximately 40% pick mushrooms at least once a year (Sievänen and Neuvonen 2011) and around 1% of Finnish households were picking mushrooms commercially in 2011 (Turtiainen et al. 2012). The everyman's rights allow the picking of mushrooms and berries from forests without permission from the landowner, regardless of the picker's nationality or their reason for picking (Tuunanen et al. 2015). The income from selling mushrooms is tax-free for the pickers. Mushrooms are picked for sale opportunistically, meaning that they are not produced or cultivated. Some of the marketed mushrooms are now picked by organized commercial pickers too, although the majority are still picked by local mushroom pickers (MARSİ 2018).

Recreational and commercial picking also occurs on privately owned land. The good mushroom spots are visited several times a year, which means that, locally, the picking pressure can be high, especially near populated areas. There have been conflicts related to the everyman's rights between landowners and people practicing recreational or commercial activities in Finland (Lehtonen et al. 2007; Viljanen and Rautiainen 2007; Rantanen and Valkonen 2013; Rämö et al. 2013; Tuulentie and Rantala 2013; Peltola et al. 2014; Tuunanen et al. 2015). The conflict has mainly centered around organized

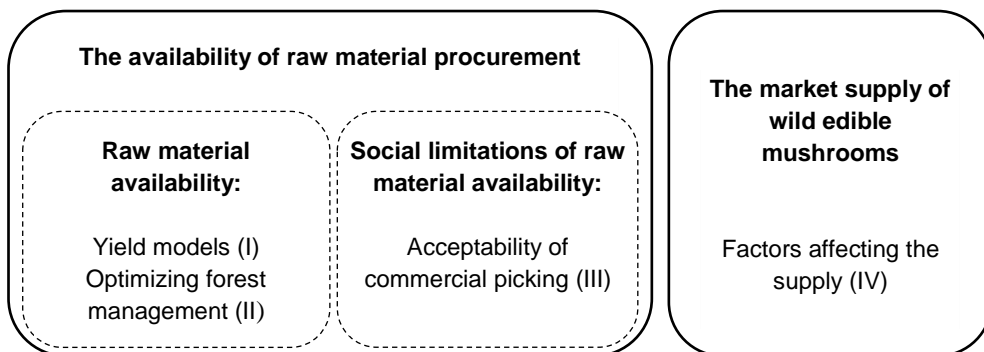
commercial berry picking, where a large group of foreign pickers pick berries from a forest area very efficiently. To avoid such problems and ensure that raw material procurement for mushroom supply chains is sustainable, it is essential to find out socially acceptable limitations for commercial mushroom picking.

### 1.3 Aim of the research

The aim of the dissertation was to study the availability of the raw material procurement and the market supply of wild edible mushrooms in Eastern Finland (Figure 3). The availability of mushroom yields was studied by:

- (I) formulating models for *Boletus edulis*, *Lactarius* spp. and all marketed mushrooms using stand and climate variables as predictors,
- (II) using yield models to optimize the forest management for the joint production of timber and marketed mushrooms: *B. edulis*, *Lactarius* spp. and both *B. edulis* and *Lactarius* spp. and
- (III) investigating the limitations of raw material availability through a forest owner survey to study the socially acceptable limits for mushroom picking on private land. The supply of marketed mushrooms was studied by:
- (IV) formulating models for the marketed quantities of *Boletus* spp., *Lactarius* spp. and *Cantharellus cibarius* as a function of climatic and economic factors.

Overall the study provides novel information on possibilities for multiple use forestry by providing methods of integrating mushroom production into forest management. Developing methods, which can facilitate the raw material harvest, and knowing the socially acceptable limits of picking enable a more stable and sustainable raw material supply to the mushroom supply chains.



**Figure 3.** The aim of the thesis and research topics.

## 2 MATERIALS AND METHODS

### 2.1 Yield models and optimizations of stand management

#### 2.1.1 Sample plot network and mushroom inventory

The sample plot network was established in Eastern Finnish *Picea abies* forests located in the North Karelia (N=52) and Savonia (N=4) regions. It included 56 sample plots from which 50 sample plots were established in 2010 and the network was completed in 2011, 2012 and 2014. Sample plots were located at the boreal coniferous zone (effective temperature sum during the growing season is 1100–1300 d.d. on average, and average rainfall is 340–360 mm) (Finnish Meteorological Institute 2015). The sample plots were 20 m × 20 m (400 m<sup>2</sup>) in size. They were chosen to represent variety in stand variables and management history, but few sample plots were known potential mushroom forests, and a few sample plots were approaching the first commercial thinning (Figure 1, **Article I**).

The stand and tree variables were measured from the sample plots at the time of establishment. They included: stand basal area (m<sup>2</sup>/ha), number of stems per ha by tree species, basal area median tree diameter (cm) and height (dm), biological age (years), site type class, and time since last cutting (1, 2, 3, 4, 5, 6–10, 11–15, 15–20, 21–30 and 30 years or more). Tree characteristics, the number and mean diameter of stumps, and the distance between the nearest extraction road and the center of the sample plot were measured after the thinnings.

Climatic variables were used for modeling. The data were based on measurements from the meteorological stations of the Finnish Meteorological Institute. The monthly precipitation sums and mean temperatures during 2009–2014 were used as predictors, as well as; effective temperature sum and minimum and maximum daily temperatures.

Marketed mushrooms were inventoried from sample plots during 2010–2014 at the fruiting season approximately once a week until the first frosts (July–September). The mushroom sporocarps of 19 marketed mushroom species were collected, counted and converted into fresh-weight biomass using species-specific conversion factors (Salo 1988; K. Salo, unpublished data). Annual mushroom production (kg/ha/yr) was calculated for each species. Separate models were fitted for *B. edulis*, *Lactarius* spp. (*L. trivialis*, *L. torminosus* and *L. rufus*) and all marketed mushrooms. The measured mean annual yields were 5.4 kg/ha for *B. edulis*, 16.4 kg/ha for *Lactarius* spp. and 28.3 kg/ha for all marketed species. The variation between years and sample plots was high.

#### 2.1.2 Models for marketed mushrooms

The annual mushroom yields were modeled as a function of year effects and stand and/or climatic variables. Because of the annual climatic conditions, observations for the same year were cross-correlated, which is why the fixed year effects were used. In total, three yield models were fitted for: *B. edulis*, *Lactarius* spp. and all marketed mushrooms (including *B. edulis* and *Lactarius* spp.). A non-linear mixed-effect modeling (NLMM) approach was used to account for between-plot and between-year variations in mushroom yields (Searle et al. 1992). The model for mushroom yields can be written in a general form:

$$y_{ij} = \exp\{f(x_1, x_2, \dots, x_n) + u_i\} + e_{ij} \quad (1)$$

where  $y_{ij}$  is the mushroom yield of plot  $i$  in year  $j$  (kg/ha/yr),  $f(\cdot)$  is the fixed part of the model,  $x_1, \dots, x_n$  are fixed predictors (i.e., year effects, stand and/or climatic variables), and  $u_i$  and  $e_{ij}$  are the random plot effect and the residual, respectively (normally distributed with a mean equal to zero).

For the three different mushroom yields (*B. edulis*, *Lactarius* spp. and all marketed mushrooms), three types of models were fitted by including only the fixed year effects (Model 0 as reference), including the fixed year effects and stand variables (Model 1) and including stand and climate variables as predictors (Model 2) (Tables 3–5, **Article I**). The sources of variation in mushroom yields were examined by comparing these three models.

### 2.1.3 Stand management optimization for timber and mushrooms

Stand management was optimized by maximizing the soil expectation value (SEV) from mushrooms and timber, timber only and mushrooms only. The mushroom species were *B. edulis* and *Lactarius* spp. and models for predicting mushroom yields (**Article I**) were used. Stand development was simulated in 5-year time steps using the individual-tree models (Pukkala 2009; 2013). The stand with good mushroom yields was used in calculations as it was assumed that they would more likely be managed for mushroom production. The stand was made as a good mushroom stand so that the 90<sup>th</sup> percentile of the distribution of the random stand effect was added to the yield predictions. Additionally, it was assumed that 90% of the *B. edulis* yield and 75% of the *Lactarius* spp. yield was picked. Mushrooms were not picked if the picking cost exceeded the selling price. A yield reduction was added after the regeneration felling, because the models overestimated the mushroom production after regeneration. The yield reduction was decreased linearly from regeneration felling until 15 years after it.

In optimization, the initial stands represented a *Myrtillus*-type mesic heath site in North Karelia (Finland). The empirical models used for mushrooms were based on *Myrtillus*- and *Oxalis-Myrtillus*-type stands (**Article I**). The stand age was 10 years at the beginning of the simulations, and pre-commercial thinning was assumed to be done. The non-linear programming algorithm of Hooke and Jeeves (1961) was used. The optimization problem was solved 10 times with different randomly generated initial values of decision variables. For each direct search run, 200 random combinations of decision variables were generated and the best combinations (highest SEV) were used as initial solutions of each direct search. When calculating the SEV, all future costs and incomes in timber and mushroom production during the simulated rotation period to infinity were included. The costs and incomes were discounted using a 3% discount rate to the beginning of the rotation. Planting, soil preparation, tending, final cuttings and 0–4 thinnings were included in optimization calculations. The decision variables defining the stand management were as follows: number of years since regeneration (first thinning) or previous thinning (other thinnings), removal percentage in each tree cohort, and number of years between the last thinning and the final cut, type and intensity of thinning.

The costs of operations and prices of wood assortments were obtained from national statistics (<http://stat.luke.fi/en/metsa>). The prices for mushrooms were based on statistics of wild edible mushroom sales in Finland (MARSII 2014). The mushroom picking costs



included harvesting and travel costs. It was assumed that the picker (forest owner) would drive 10 km per each picking trip and 4 picking trips were done per season. The travel cost was 0.40 €/km. At each picking trip, an average area of 7 ha was covered, resulting in an annual travel cost of 2.29 €/ha. The harvesting cost was calculated using a 6 €/h salary, and with a yield of 15 kg/ha, the harvesting would take 2 h/ha, resulting in a harvesting cost of 12 €/ha. With a higher yield, the harvesting cost increased so that it was doubled when the yield was as high as 60 kg/ha. If the picking cost was higher than the selling price, the mushrooms were not collected.

## **2.2 The social acceptability of picking**

### *2.2.1 The forest owner survey*

Private forest owners were asked their opinion on picking mushrooms and berries for household and commercial use in a mail survey in 2015. The survey was sent to 2000 forest owners from the North Karelia (50%) and Kainuu regions (50%). The forest owners were systematically selected from the Finnish Forestry Center contact list based on their forest holding size. Half the questionnaires were about mushroom picking and half were about berry picking. In the survey information about the respondent's sociodemographic background, forest holding, relationship to forest holding and picking behavior were asked. The everyman's rights from the point of view of picking mushrooms and berries in their different forms were assessed. In detail, the questions addressed the acceptability of household and commercial picking of mushrooms and berries for different picker profiles. The forest owner was asked if picking had caused some troubles or if some forms or effects of the picking disturb them and if they feel the need to restrict picking somehow. The questions were likert-scale, multiple choice and open questions. The non-response analysis was done as a phone survey (N=60) to detect systematic differences in respondents that could cause bias.

The final sample size was 1977 forest owners, and the response rate was 48% (N=953). From the responses, 51% were berry- and 49% mushroom-oriented and about half were from North Karelia (51%) and half from (49%) Kainuu. According to the non-response analysis, forgetting to answer was the most common reason not to answer.

### *2.2.2 Forest owners' backgrounds*

The forest owner profile was compared to the Finnish Forest Owner 2010 survey (Hänninen et al. 2011) and the non-response survey. The forest owners were mainly 60 years or older (64%) and male (70%). Around half of the respondents were retired (52%), and one-third were working. The most common form of forest ownership was family forest owner (70%). The profile of forest owners was significantly different from the Finnish Forest Owner 2010 results (Hänninen et al. 2011): in this study, the number of women and the forest owners' average age were higher, and the share of family and co-operative forest ownership was less common. According to the non-response analysis, the younger forest owners were not reached, the share of agricultural entrepreneurs was lower and the share of retired forest owners was higher. About half of the forest owners had a summer house at the forest holding, which was more than in the Finnish Forest Owner survey (30%), but there were fewer people living on their forest holding (30%) than in Finland on average (48%). The

total size of the forest holding in a study area was 54 ha on average, and the distance to the nearest population center averaged 20 km.

The picking activity of the forest owners who replied to the survey was higher than in the non-response survey. Altogether, 92% of forest owners' households picked berries and 70% mushrooms and 10% picked berries and 4% mushrooms to sell. Most forest owners estimated that their forest stands were annually used for berry (79%) and mushroom picking (67%) at least a little, and that the berry yields in their forests were good and their mushroom yields poor. The respondents of the study were participating in mushroom and berry picking more than respondents of the non-response survey.

## 2.3 The supply of raw material to markets

### 2.3.1 Statistics on marketed mushrooms and climate

The annual data on mushroom market prices (€/kg) and quantities (kg) (1978–2016) were obtained from statistics on the annual quantities of berries and mushrooms bought by organized trade and industry (MARSİ 2018). The most marketed mushroom species *B. edulis*, *Lactarius* spp. and *C. cibarius* were included in the analysis. The statistics on *B. edulis* also included *B. pinophilus* since these two species are traded as the same species. *Lactarius* spp. included *L. trivialis*, *L. rufus* and *L. torminosus* because *Lactarius* spp. are often mixed in markets for the same products (e.g., mushroom salad, soup and sauce). The deflated prices were used in modeling (1949 = 100). Additionally, statistics from the international trade of mushrooms were used in the study (EUROSTAT 2018). Climatic data were obtained from a Finnish Meteorological Institute interpolated dataset (Finnish Meteorological Institute 2018). The climatic data consisted of monthly precipitation sums, monthly mean temperatures, effective temperature sum (threshold value +5 °C) and minimum and maximum daily temperatures of the current and previous years.

### 2.3.2 Supply models

The species-specific supply functions for *B. edulis*, *Lactarius* spp. and *C. cibarius* were described as linear regression models. The dependent variable was the quantity of mushrooms in organized trade and industry in Finland and climatic and economic factors were used as independent variables.

## 3 RESULTS

### 3.1 Biological availability

#### 3.1.1 Yield models for marketed mushrooms

**Table 1.** Estimates of the parameters, variance components and fitting statistics of the yield models for *B. edulis* and *Lactarius* spp. Models are estimated using year effects and stand variables (Model 1) and stand and climate variables (Model 2). The number of observations was 255 in all models. The fitting statistics using both fixed and random effects are given in parentheses.

Variable	<i>B. edulis</i> kg/ha/yr		<i>Lactarius</i> spp. kg/ha/yr	
	Model 1	Model 2	Model 1	Model 2
Intercept	-1.9819	7.7339**	2.1243***	-0.8144
Year 2010 (ref. 2014)	0.4161	--	-2.5208***	--
Year 2011	1.8743***	--	0.3535***	--
Year 2012	0.6166*	--	-0.2483**	--
Year 2013	0.3267	--	0.0507	--
Stand basal area, m <sup>2</sup> /ha	0.1778	0.2727	-0.0179	-0.0255
Stand basal area <sup>2</sup> , m <sup>2</sup> /ha	-0.0049	-0.0068*	-	--
Stand basal area/(Age+5)	2.0907*	2.4462*	1.7435	1.4389
Precip. in Jul. mm	--	-0.0167***		0.0003
Precip. in Aug. mm	--	0.0102***		0.0178***
Mean temp. in Aug. °C	--	-0.6794***		0.1089
var(u)	0.6906	0.9218	0.5611	0.4831
var(e)	32.8	29.6	174.1	335.7
Log likelihood	-844.8	-837.3	-1062.3	-1131.5
R <sup>2</sup> , %	20.6 (72.4)	15.5 (75.2)	10.4 (86.4)	8.6 (72.7)
Bias, kg/ha/yr	1.21 (-0.01)	1.20 (0.10)	2.73 (-1.51)	1.61 (-1.91)
Bias%, %	28.7 (-0.2)	28.4 (1.9)	20.0 (-8.4)	10.9 (-10.4)
RMSE, kg/ha/yr	9.10 (5.37)	9.39 (5.08)	31.03 (12.11)	31.33 (17.13)
RMSE%, %	215.4 (98.6)	221.7 (95.2)	227.1 (67.7)	212.0 (93.6)

\*, \*\* and \*\*\* Significant at the 0.05, 0.01 and 0.001 levels, respectively.

Models were formulated for *B. edulis*, *Lactarius* spp. and all marketed mushrooms (including *B. edulis* and *Lactarius* spp.) using stand and climatic predictors (Tables 3–5, **Article I**). According to the model for predicting the yields of *B. edulis*, the yields were higher when the stand basal grew until it reached 25 m<sup>2</sup>/ha (at the stand age of 25–30 years) (Table 1). After that the yields started to decline. When the climatic variables were considered the model fit improved (Table 3, **Article I**). The precipitation sum in August had a positive effect on yields, and the precipitation sum in July and temperature sum in August negatively affected the yields of *B. edulis*. The proportion of explained variance was 20.6%. In the *Lactarius* spp. yield model, the optimal stand basal area was higher than for *B. edulis* (30 m<sup>2</sup>/ha), but the stand basal area and age were not significant predictors (Table 1). The proportion of explained variance was 10.4%. If climatic variables were taken into account, the precipitation sum in August positively influenced the yields (Table 4, **Article I**). In the model for all marketed mushrooms, the stand age and basal area were

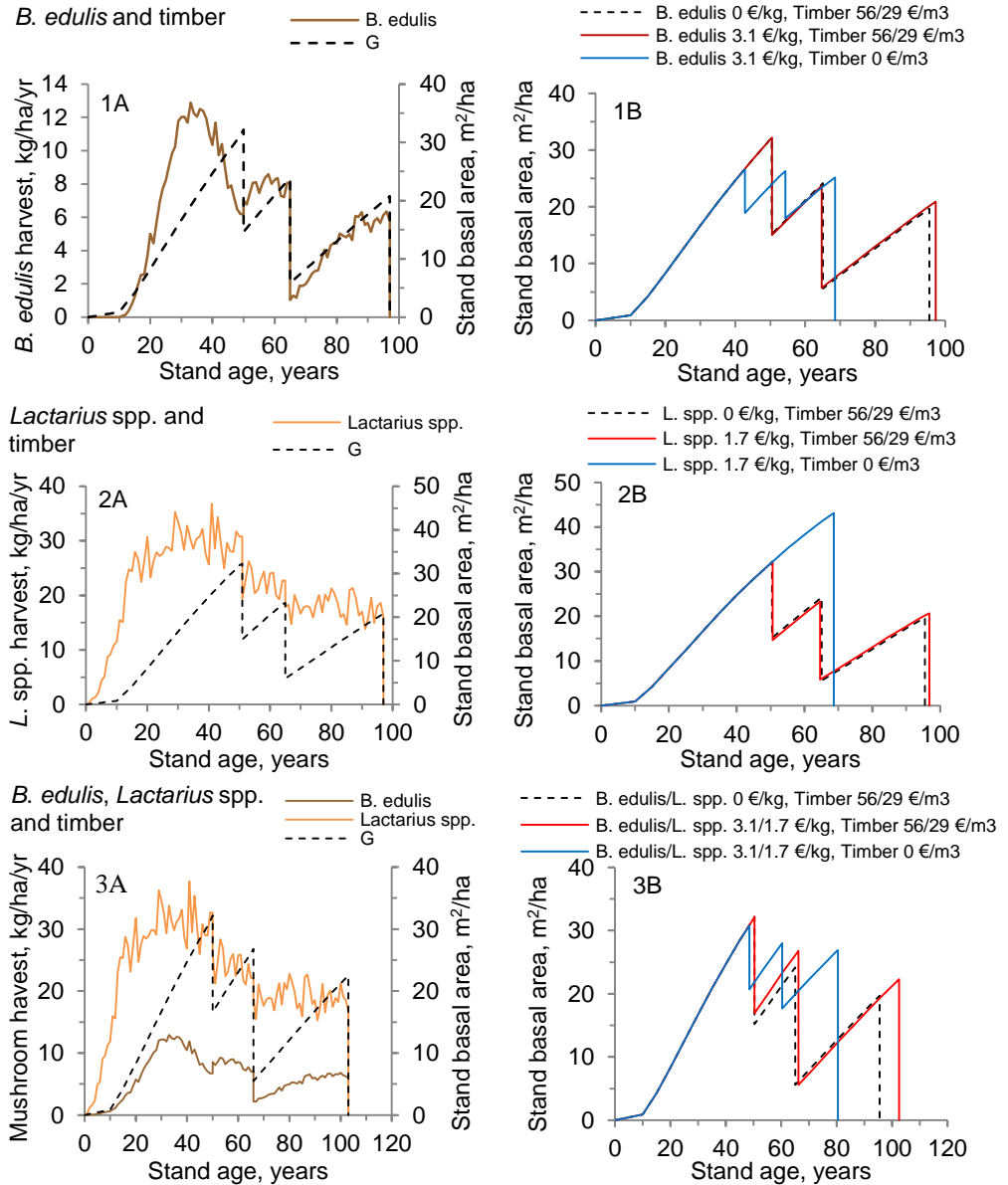
statistically significant predictors, and the optimal stand basal area was about 25 m<sup>2</sup>/ha (Table 1). The precipitation sum in August had a positive effect on the yields of all marketed mushrooms, and the precipitation sum in July and temperature sum in August had a negative effect (Table 5, **Article I**). Using climatic predictors instead of fixed year effects did not improve the model fit.

### 3.1.2 Optimal stand management for co-production

The models in **Article I** (Table 1) were used to optimize the co-production of mushrooms and timber in even-aged *Picea abies* stands in Eastern Finland by maximizing the soil expectation value (SEV). In the optimization the good mushroom stand (90<sup>th</sup> percentile) and 3% discount rate were used. The optimal two-thinning schedule for the co-production of *B. edulis* and timber consisted of a rotation length of 97 years and two heavy thinnings (Figure 4). The first thinning was done after the peak in the yields of *B. edulis* and the second when the stand basal area reached 24 m<sup>2</sup>/ha. The total SEV was 655 €/ha. The optimal timber-oriented management schedule was similar to that of co-production, resulting in a total SEV of 652 €/ha if mushrooms were picked for sale. If only the mushroom production was maximized, the rotation length was considerably lower (69 years), and the thinnings were light, aiming at keeping the stand basal area between 18 and 27 m<sup>2</sup>/ha. The yields peaked at the stand age of 33 years (Figure 1, **Article II**).

In the optimal two-thinnings schedule for the co-production of *Lactarius* spp. and timber, the heavy thinnings from above were done and the rotation length was 97 years (Figure 4). The first thinning was done after the peak in *Lactarius* spp. yields (41 years, basal area 25 m<sup>2</sup>/ha) (Table 2, **Article II**). The optimal management schedules for co-production and timber production were very similar. The optimal management schedule for mushrooms only, resulted in a shorter rotation length (69 years) and no thinnings. Although the total SEV was highest in the management schedule with two-thinnings (total SEV 1066 €/ha), the additional SEV from mushrooms was highest with no thinnings (Table 3, **Article II**).

When the co-production of both *B. edulis* and *Lactarius* spp. and timber was maximized, the optimal two-thinning management schedule was similar to the ones with *B. edulis* and timber and *Lactarius* and timber (Figure 4). Only the rotation length was longer (103 years) and the total SEV higher (1539 €/ha), because it included income from both: *B. edulis* and *Lactarius* spp. (Table 4, **Article II**). The timber-oriented management schedule was otherwise similar but had a slightly shorter rotation length. In the optimal mushroom oriented management schedule the thinnings were lighter and done earlier and rotation length was shorter (81 years) (Table 4, **Article II**).



**Figure 4.** Predicted *B. edulis* (1A), *Lactarius* spp. (2A) and *B. edulis* and *Lactarius* spp. (3A) harvests and development of stand basal area (G) in the optimal two-thinning management schedules of the spruce stand with good mushroom yields and the timber prices at 56/29 €/m<sup>3</sup>, *B. edulis* 3.1 €/kg and *Lactarius* spp. 1.7 €/kg. And the effect of mushroom and timber prices and forest management costs on the optimal two-thinning management schedule of the same stand for *B. edulis* (1B), *Lactarius* spp. (2B) and *B. edulis* and *Lactarius* spp. (3B). When the timber price was 0 €/m<sup>3</sup>, the stand regeneration and forest management costs were also zero.

### 3.2 The supply of marketed mushrooms

The supply of *B. edulis* was positively influenced by the precipitation in August (Table 2). The price effect was negative, and the internationalization of markets in the late 1990s (Dummy) caused the price effect to diminish. The climatic and economic variables explained 54% of the variation in annually marketed *B. edulis* quantities.

The marketed *Lactarius* spp. quantities were positively dependent on the precipitation in August (Table 2). The price effect turned negative and was statistically significant in the second half of the study period (1999–2016). Overall, 33% of the variation in annually marketed *Lactarius* spp. quantities was explained by climatic and economic variables. The precipitation in June and July positively influenced the supply of *C. cibarius* (Table 1). The effect of the price was negative and turned even more negative due to internationalization of the markets (1999–2016). Climatic and economic variables explained 35% of the variation in annually marketed quantities, but the first-order autocorrelation of the residuals was positive and statistically significant, suggesting that the variables were not able to explain the between-year variation well enough.

**Table 2.** Coefficients of supply models for the annual quantities of ceps, milk caps and chanterelle (1000 kg) bought by organized trade and industry in Eastern Finland. The data covered 1978–2016, with 39 total observations.

Variable	Ceps	Milk caps	Chanterelle
$\beta_0$ Intercept	4.8329***	4.9926***	2.8160***
$\beta_1$ Precipitation in June and July (mm)	--	--	0.0058**
$\beta_2$ Precipitation in August (mm)	0.0087*	0.0064*	--
$\beta_3$ Price (€/kg)	-0.3598**	0.0886	-0.1775**
$\beta_4$ Dummy <sup>1</sup> • Price (€/kg)	0.3158***	-0.4811***	-0.0479
$\sigma_v^2$ Error variance	0.8686	0.5050	1.1131
$\rho$ Autocorrelation coefficient	-0.0023	0.1380	0.6015***
Log likelihood	-58.9	-47.5	-55.9
Snowdon's bias correction ratio	1.3618	1.1948	1.3667
R <sup>2</sup> (%)	53.9	32.5	34.6
RMSE (1,000 kg/year)	133.5	158.7	8.0
RMSE% (%)	76.5	62.2	63.5

\*, \*\* and \*\*\*: significant at the 0.1, 0.05 and 0.01 level, respectively.

<sup>1</sup>Dummy = 1 in 1999–2016, otherwise dummy = 0.

### 3.3 The social acceptability of picking

#### 3.3.1 Forest owners' opinions on the everyman's rights

Most of the forest owners were content with the everyman's rights in picking berries and mushrooms in general (Table 3). Of the forest owners who replied to the mushroom-oriented survey, 14% had experienced some problems related to mushroom picking and everyman's rights, and 18% experienced mushroom competition in their forest holdings (Table 4, **Article III**).

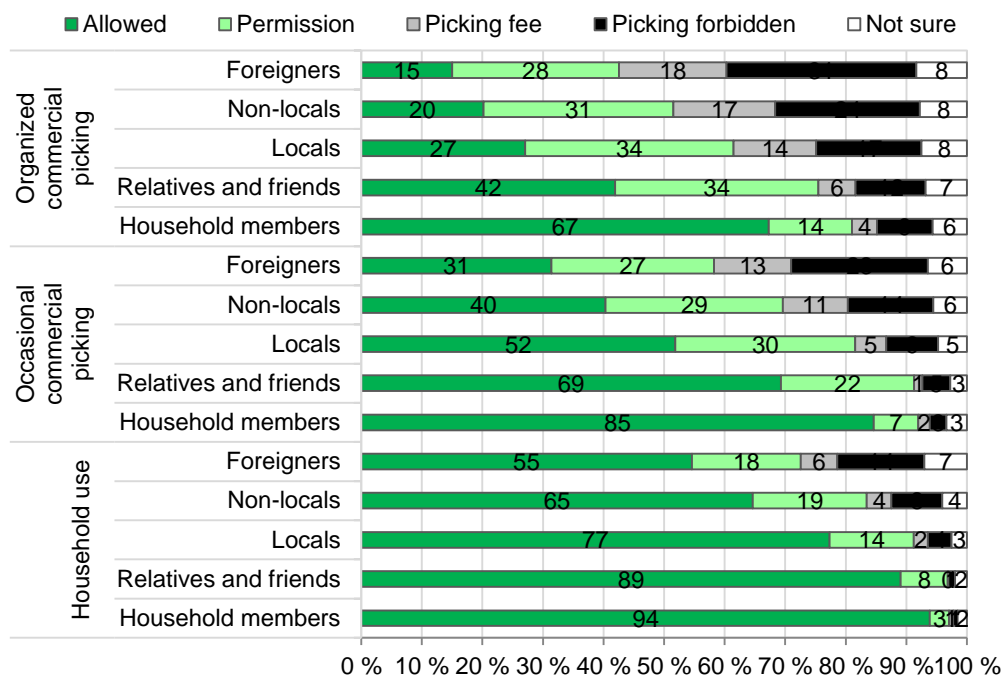
The forest owners were asked to assess some attributes and effects of picking (Figure 1, **Article III**) based on how disturbing they consider them. The most troubling ones were leaving trash, picking close to houses, leaving marks of picking in nature and leaving traffic and physical markings in nature. Forest owners thought that the most effective ways of advancing the acceptability of picking were: asking permission (73%), negotiating the picking places with forest owner (69%) and informing the forest owner of picking places and times (65%) (Figure 2, **Article III**).

#### 3.3.2 Restricting the everyman's rights

Forest owners felt they should have the right to reserve picking sites for their own use for household picking (58%) or commercial picking for themselves (34%) or others (11%) (Table 6, **Article III**). The more distant the picker and the more organized the picking, the more the forest owners wanted to restrict the picking (Figure 5). The forest owners did not express a need to restrict traditional picking for household use; in fact, 55–94 % would allow it regardless of the picker. However, 31% would allow occasional commercial picking for foreigners and 40% for non-locals. For organized commercial picking, some restrictions were in demand, particularly if the picker was a foreigner or non-local. Not many forest owners were willing to receive money from picking fees.

**Table 3.** Forest owners' opinions on the everyman's rights in mushroom and berry picking (N=934).

Everyman's rights in berry and mushroom picking	%
Very bad practice	3.7
Quite a bad practice	7.7
Partly good, partly bad	24.3
Quite a good practice	38.7
Very good practice	25.6
Total	100



**Figure 5.** The opinion of forest owners on the appropriate rules of picking mushrooms and berries in their forest holdings according to the picker groups and purpose of picking. N= 869–917.

## 4 DISCUSSION

### 4.1 Evaluation of materials and methods

The methods used are commonly applied in analyses similar to those in this study. Empirical models were created to predict the annual yields of marketed mushrooms. The stand and tree data for modeling the yields of marketed mushrooms were obtained from Eastern Finnish *Picea abies* stands (**Article I**). The stands were even-aged, mostly planted spruce stands, which were managed mainly for timber production. Comparable data on unmanaged and old (over 100 years) spruce stands would improve the model. In the current data, the highest stand age is 95 years (**Article I**). To observe the effect of thinnings on mushroom yields, more sample plots with different thinning intensities at different stand development stages would be needed. Also, some stands were mixed-species, including birch and pine, until the first commercial thinning. This may have affected the yield response of some mushroom species to thinnings (e.g. pine preferring *Lactarius rufus*) (**Articles I–II**).

The models included climatic variables, which influenced the yields of marketed mushrooms together with stand variables. A more extensive inventory (e.g., observing



precipitation on the stands) would enable a more reliable study on the effect of climatic variables on mushroom yields and the joint effect of climatic variables and forest management operations on mushroom yields. Mushroom models were fitted using the non-linear mixed-effect modelling (NLMM) approach to account for the longitudinal data structure with observations correlated at the stand level and cross-correlated at the year level (Searle et al. 1992). According to yield models, the between-stand variation is high, which implies that some plot-level factors are not included (**Article I**). The list of marketed mushrooms considered in the study mainly consisted of ectomycorrhizal mushrooms, but also a few species that are not mycorrhizal. Logically, the species-specific models would be more precise. Although the market statistics for *B. edulis* also include *B. pinophilus*, because they are not separated in trade, the models are only prepared for spruce stands, where *B. edulis* grows. A similar inventory in pine stands would be needed.

The yield models were used to optimize the suitable stand management for the co-production of timber and mushrooms in Eastern Finnish spruce stands with good mushroom yields (**Article II**). The stand management was optimized with the simulation-optimization system, which finds the optimal combination of decision variables (timing, type and intensity of thinnings and rotation length) using the nonlinear programming algorithm of Hooke and Jeeves (1961). The calculations included timber prices, mushroom prices and all production and harvesting costs for timber and mushrooms. The study was unique in the sense that the mushroom picking cost function (picking and transportation costs) was included in the optimization calculations to obtain more realistic results. In the calculations, the good mushroom stands (90<sup>th</sup> percentile of the random plot effect) were used to see if the inclusion of mushroom incomes would affect the optimal stand management (**Article II**). Since the joint production-oriented stand management did not differ much from the timber-oriented management schedule, there is no need to optimize the management for average mushroom stands separately.

The data on annual quantities of berries and mushrooms bought by organized trade and industry in Finland are collected from statistics over 39 years (**Article IV**). However, the statistics do not include different quality classes (classes I, II and III) of ceps that all have different prices; also, the import and export statistics would most likely improve the supply models. Additionally, weekly or, at least, monthly data would be more suitable to detect the price-quantity relationships better. For example, in the Spanish study, weekly data were used (Alfranca et al. 2015). The linear regression models were prepared for the supply of mushrooms assuming the first-order autocorrelation of the residuals. The significant first-order autocorrelation coefficients implied that the climatic and economic factors could not describe the between-year variation in the quantities supplied, and that some predictors were still missing.

The mail survey was conducted to ask the opinions of private forest owners on picking mushrooms and berries for household and commercial use. A mail survey was used instead of an online survey (by email) because the average age of forest owners is high. In the forest owner survey the response rate was rather high (48%), and the total number of responses was high enough (N=953). However, compared to the non-response survey respondents, the respondents of mail survey were more likely pickers themselves, which likely affected the results regarding their willingness to restrict picking. In addition, the respondents were older on average than forest owners in general (Hänninen et al. 2011), and that may also have affected the results in a similar way because, according to the results, older forest owners were more eager to restrict picking in their forest holdings (**Article III**).

## 4.2 Biological yields of marketed mushrooms

The yields of marketed mushrooms are notable in even-aged eastern Finnish spruce stands but the yield variation between stands and years is high ranging from 28 kg/ha/yr to 298 kg/ha/yr. The average annual yield of *B. edulis* was 5.4 kg/ha/yr, *Lactarius* spp. 16.4 kg/ha/yr and the total yield 28.3 kg/ha/yr (**Article I**). The total yield of all marketed mushrooms mainly consisted of *Lactarius* spp. and *B. edulis*. Especially *Lactarius* spp. yields were lower than in the study of Salo (1993), but the yields of *B. edulis* were more similar: *B. edulis* to be 6.1 kg/ha (Salo 1993). The lower yields of *Lactarius* spp. in this study are possibly due to the fact that the abundant *Lactarius rufus* mostly prefers pine stands and not spruce, where the sample plots of this study were located. It has been estimated that, in Southern Finland, the average yields of mushrooms vary between 29 and 60 kg/ha/yr, and the share of edible mushrooms from that would be roughly 20–70% (Ohenoja 2005).

The highest yields of marketed mushrooms were obtained in stands with a stand age of 30–35 years and a stand basal area of around 25 m<sup>2</sup>/ha (**Article I**). Also, in a study of *B. edulis* yields in Spain, in *Pinus sylvestris* stands, the preferable stand basal area was not too high or too low (Martínez-Peña et al. 2012). Additionally, it was studied that in oak stands in the Netherlands, *B. edulis* preferred rather young and medium old stands (Keizer and Arnolds 1994). However, the tree species were different and, therefore, not directly comparable.

The results suggested that the yields of marketed mushrooms in Eastern Finnish spruce stands are highest right before the first commercial thinning (**Article I**). The stand volume increment is peaking at the same time as the marketed mushroom yields of this study (Vuokila and Väliaho 1980). Similarly, it has been pointed out in several earlier studies that the yields of mycorrhizal mushrooms are high at the younger stands, where tree growth is also good (Senn-Irlet and Bieri 1999; Smith et al. 2002; Bonet et al. 2008; Egli et al. 2010; Tomao et al. 2017). Sporocarp production has also been found to be higher in young stands (20–30 years) in Finland (Hintikka 1988) and Estonia (Kalamees and Silver 1988). Especially the most abundant species, *Lactarius* spp. and *B. edulis*, seem to prefer younger stands. The peak of mushroom production at the time of maximal stand growth would support the photosynthate allocation theory, which suggests that the tree would primarily use the photosynthates to grow, and after that, it would allocate the photosynthates to its roots (Waring 1987; Egli et al. 2010). It seems apparent that sporocarp production is connected to carbohydrate production of the host tree (Kranabetter and Kroeger 2001; Pilz and Molina 2002; Sato et al. 2012; Primicia et al. 2016). On the contrary, *B. edulis* sporocarp production was higher in older stands in *Pinus sylvestris* forests in Spain (Martinez-Peña et al. 2012) and mature stands in Finland (Hintikka 1988). In French deciduous stands *B. edulis* was considered to be an early-stage fungi (Buée et al. 2011). However, the connections between tree growth, climatic conditions and sporocarp production are trivial and difficult to study or interpret due to the complexity of forest ecosystems (Collado et al. 2019).

Climatic factors influence the emergence of sporocarps: precipitation in the fruiting season in August promoted the yields of marketed mushrooms and the precipitation sum in July and mean temperature in August negatively affected yields (**Article I**). Also, Ohenoja (1993) discovered that precipitation favored the yields of mycorrhizal mushrooms in

Finnish heath forests. Also in the earlier literature, the precipitation in the fruiting season had a positive effect on the production of mycorrhizal mushrooms (Ogaya and Peñuelas 2005; Martínez de Aragón et al. 2007; Parladé et al. 2017). It has been suggested that climatic factors would affect the yields directly and indirectly through the host tree (Krebs et al. 2008; Primicia et al. 2016). Studying the effect of climatic factors on the phenology of marketed mushrooms would provide valuable information for example, to predict the appropriate picking times from the basis of weather.

### 4.3 Joint production of timber and mushrooms

According to the National Forest Inventory, the total area of spruce stands located on mineral soils in North Karelia that would be at the right stand development stage for producing marketed mushroom yields is 207 000 ha (Antti Ihalainen, Luke, personal comm.). This area of potential mushroom spruce stands excludes regeneration areas and young seedling stands. Thus, there is a notable potential for utilizing marketed mushrooms in North Karelian forests. To improve preconditions for the use of this potential the stand management was optimized for the joint production of timber and mushrooms.

The optimal management of timber only and the joint production of timber and *B. edulis* did not differ much (Table 2, **Article II**). Therefore, to produce *B. edulis* and timber, the management schedule of spruce stands would not have to be changed from that of timber-oriented. The reactions to thinnings, however, are less evident. In this study, the results suggested that thinning would promote the *B. edulis* yields so that they could recover after the thinnings and, more so after the first commercial thinning (Figure 4). A higher production of fruit bodies in medium thinned stands is also found in an Italian fir stands study (Salerni and Perini 2004). However, for reliable results on suitable thinning intensity for *B. edulis* yields, there should be more thinned sample plots and more diverse thinning intensities on the sample plot network.

The stand management for *Lactarius* spp. was more approximate, as the yield model included three species: *Lactarius* genus: *L. rufus*, *L. trivialis* and *L. torminosus*, each with their own habitat requirements. The optimal stand management for *Lactarius* spp. and timber was also similar to timber-oriented stand management, partly because the peak at *Lactarius* spp. yields is around the first thinning phase of the stand development (Figure 4) and partly because of the low value (€/kg) of *Lactarius* spp. The optimal stand basal area for the *Lactarius* spp. yield was about 30 m<sup>2</sup>/ha, which was somewhat higher than for *B. edulis* (**Article I**), and therefore, thinnings negatively affect the *Lactarius* spp. yields (Figure 4), and the optimal *Lactarius* spp. production-oriented stand management would be without thinnings. Conversely, in earlier studies the yields of *Lactarius rufus* have been observed to react positively in thinnings (Kardell and Eriksson 1987) and cuttings (to seed tree position) (Paulus et al. 1995). *Lactarius rufus* prefers *Pinus sylvestris* stands, and this has likely skewed the results of this study.

### 4.4 Factors affecting the supply of marketed mushrooms

As mentioned, climatic variables affect the marketed quantities of mushrooms, which indicates that their biological yield is an important factor in determining the mushroom

markets (Table 2). The total precipitation in August influenced the quantities of ceps and milk caps positively, and the total precipitation in June and July positively influenced the quantities of chanterelles entering the markets. The results are in line with the finding of the yield study: mushroom yields were promoted by precipitation during fruiting season (**Article I**). The results are also supported by other studies, in which precipitation positively influenced the yields of mushrooms (Ohenoja 1993; Krebs et al. 2008; Parladé et al. 2017). The biological availability of mushrooms for sale does, of course, also influence other factors, such as the stand variables (**Article I**) and climatic variables other than precipitation.

In addition, the availability of marketed mushrooms for sale is influenced by economic factors. According to the results, the market price of mushrooms affected their marketed quantities (**Article IV**). The price paid to pickers had a negative effect on the quantities of ceps and chanterelles (Table 2). Arguably, in years with high yields, the prices were lower, and in poor crop years, the wholesalers had to pay higher prices. In similar studies in Spain, the price effect on the weekly supply of wild edible mushrooms was positive (Diaz-Balteiro et al. 2013; Alfranca et al. 2015), but in a Finnish study, the annually aggregated supply of cowberries was negatively affected by price (Kangas 1999). The mushroom markets have been globalizing since the late 1990s, e.g., due to new member states joining the European Union. Competition in the mushroom and berry markets has also increased. The results suggest that a decrease in the effect of price on the marketed quantities of ceps in the second half of the study period (1995 – 2016) could be because the cep markets are in Southern Europe, and therefore, the price of ceps is no longer determined only in Finland, but rather elsewhere in Europe. Also, the price effect on marketed milk cap quantities was negatively affected by globalization, but the price effect of chanterelles was not affected, since its markets are largely domestic.

Clearly, a picker's willingness to pick mushrooms for sale is one of the factors that affect the supply, but in the case of mushrooms, there were no appropriate statistics on commercial pickers available. Also, factors other than price affecting the decision to sell mushrooms are unknown.

#### **4.5 Forest owners' roles and possibilities in mushroom markets**

Forest owners generally consider the everyman's rights as a good practice (Table 3). Based on earlier studies, the everyman's rights have strongly been supported in Finland (Viljanen and Rautiainen 2007; Silvennoinen and Sievänen 2011). On the other hand, the forest owners express the need to restrict organized commercial picking on private lands without permission (Figure 3). Organized commercial picking is clearly different than traditional occasional picking for commercial or household use. It might be that the forest owners do not consider organized commercial picking as part of the nature of the everyman's right (Peltola et al. 2014). According to the results, picking by local pickers was more acceptable than by non-local pickers or foreigners (Figure 3). Similar findings on local customary rules (Ostrom et al. 1999) of mushroom picking can be seen, for example, in Catalonia (Górriz-Mifsud et al. 2015). Following this rationale, the picker companies could increase the acceptability of organized commercial picking using rather light methods: asking permission or negotiating picking places and informing forest owners about picking times and places. Forest owners want to know what is happening in their forest holdings. According to the results, the forest owners were not willing to receive payment from

pickers for picking on their land (Figure 5). In a Spanish study, the mushroom picking fee was supported among forest owners who perceive mushrooms as their property, and the ones who perceive picking as a free-access activity did not want it restricted (Górriz-Mifsud et al. 2017).

According to the results, at stands that produce good mushroom yields, if mushrooms are picked and sold, the total SEV is remarkably higher than the SEV without mushrooms (Table 4, **Article II**). The production of *B. edulis* was largely in synergy with timber production, competing only near the maximal yields (Figure 7, **Article II**). Similar results were found in a study regarding trade-offs at near-maximal production levels of several NWFPs (including mushrooms) and timber in Finland (Peura et al. 2016; Kurttila et al. 2018). These results were expected, because in the studies of Peura et al. (2016) and Kurttila et al. (2018), the model for *B. edulis* was the same or based on the same data as in this study. In the joint production of timber and mushrooms, the forest owner can prolong the picking period by up to 7 years without remarkably affecting the total SEV (Table 4, **Article II**). The first commercial thinning should not be done before the stand age of 25–30, which is the peak of mushroom yields (Figure 5). Of course, in this study, only *B. edulis* and *Lactarius* spp. were considered, but there can also be other marketed mushroom species producing yields (e.g., *Russula* spp., *Cantarellus* spp.). Accounting for NWFPs in forest management has also increased the total SEV from forests according to other studies as well (Palahí et al. 2009; De-Miguel et al. 2014; Miina et al. 2016), which makes it a desirable opportunity for forest owners.

In addition to commercial use, wild edible mushrooms are important as food picked and consumed directly in households. The recreational value of picking is very important, and the models can, for example, be used to produce information on potential picking places. This option could suit special forest owners such as the state, municipalities and other public actors, who want to provide services for citizens.

#### **4.6 Availability and supply of marketed mushrooms through SWOT analysis**

The purpose of a supply chain SWOT analysis is to summarize the results of this and earlier studies on the supply of marketed mushrooms from the point of view of a company operating in mushroom markets in Eastern Finland (Table 4). SWOT analysis consists of strengths, weaknesses, opportunities and threats that can be recognized in mushroom-related businesses in the light of this and other studies. The strengths are related to the existing structures and traditions that are beneficial for the mushroom markets, whereas the weaknesses consist of several issues mainly related to the profitability of mushroom picking and high competition in the markets. There are multiple opportunities in the markets due to a high and possibly growing demand of mushrooms and possibilities to enhance the profitability of mushroom raw material procurement. Issues related to decreasing sustainability and low competitiveness of mushroom businesses are still possible threats.

**Table 4.** SWOT-analysis summarizing the results of this and earlier studies on the availability and supply of marketed mushrooms from the point of view of a company operating in mushroom markets in Eastern Finland.

<b>Strengths</b>	<b>Weaknesses</b>
<p>-There are a lot of potential stands producing marketed mushrooms and the production of timber and mushrooms are largely in synergy (<b>Articles I-II</b>).</p> <p>-Forest owners do not want to restrict the occasional commercial picking of mushrooms (<b>Article III</b>).</p> <p>-The traditions in trading and utilizing mushrooms, especially <i>B. edulis</i>, are strong.</p> <p>-Selling mushrooms and berries is tax-free for the pickers and broad everyman's rights enable easy access to raw material.</p>	<p>-Only a few mushroom species have existing markets (MARSI 2018).</p> <p>-Between-year variation in mushroom yields is high and remains unexplained (<b>Article I</b>).</p> <p>-The market price for <i>B. edulis</i> is determined by European markets rather than domestic ones, and the picker price is considered low (<b>Article IV</b>).</p> <p>-Weak profitability of commercial picking due to low prices, high picking costs and high yield variation (<b>Articles I-II, IV</b>).</p> <p>-High recreational picking rate (Turtiainen et al. 2012) reduces possibilities for domestic markets (Sievänen and Neuvonen 2011).</p>
<b>Opportunities</b>	<b>Threats</b>
<p>-Yield models for mushrooms help in planning mushroom picking and enhancing mushroom production (<b>Articles I-II</b>).</p> <p>-More results on, e.g., the quality of ceps and the effect of thinning on mushroom yields enable more efficient stand management for joint production (<b>Articles I-II</b>).</p> <p>-Climatic effects on mushroom yields are known, which helps in planning the picking period (<b>Article I</b>).</p> <p>-Use of NWFPs in Europe is growing (Schulp et al. 2014).</p> <p>-There is interest among forest owners to participate in NWFP production (Tahvanainen and Kurttila 2017).</p> <p>-Profitability of picking can be increased by utilizing social media and evolving digital services to plan picking (e.g., mushroom maps).</p> <p>-Forest owners' goals are diversifying creating new possibilities for diversified production (Häyrinen 2019).</p>	<p>-Dialogue between forest owners and commercial pickers is needed if (organized) commercial picking becomes more popular (<b>Article III</b>, Górriz-Mifsud et al. 2017).</p> <p>-Sustainability of NWFP businesses can be neglected if forest owners and the local community are not involved in business (Hamunen et al. 2019)</p> <p>-Due to the everyman's rights, anyone can pick the mushrooms, so it is not profitable for the forest owner to contribute to mushroom production.</p> <p>-Climate change may further increase the yield variations (Büntgen et al. 2015; Kauserud et al. 2008; Kauserud et al. 2012), e.g., due to expected negative effects on Norway spruce growth caused by drought (Kellomäki et al. 2005).</p> <p>-The competitiveness of Finnish NWFPs is low compared to Eastern Europe, where production costs are lower and markets closer.</p>

## 5 CONCLUSIONS

This thesis provides novel information on the availability and supply of marketed mushrooms by producing yield models and optimal stand management for the co-production of timber and marketed mushrooms and by clarifying the socially sustainable limits for commercial mushroom picking. According to empirical yield models there are a lot of potential spruce stands producing mushrooms in Eastern Finland. Climatic variables, especially warm pre-season and wet conditions during the fruiting season (August), promoted the yields of marketed mushrooms. The highest *Boletus edulis* yields were obtained just before the first thinning and those of *Lactarius* spp. slightly later. The optimal stand management for both timber and *B. edulis* and timber and *Lactarius* spp. was similar to that for timber production only, and therefore, their production competes only near maximal yields. Consequently, with the current mushroom and timber prices, the production of timber and marketed mushrooms is largely in synergy. In stand producing good mushroom yields, the incomes from mushroom picking greatly increased the total SEV up to four times higher compared to the SEV of mere timber production. This makes it a low-threshold opportunity to consider mushrooms as part of the production matrix for the forest owner. The optimization calculations included the mushroom picking cost function, which was new in the field and enables more realistic calculations.

The biological yield of mushrooms, which is strongly dependent on climatic factors, affects the supply of marketed mushrooms in Eastern Finland. Precipitation during the yield season favored both the yield and supply. Surprisingly, the market price had a negative effect on the marketed quantities of ceps and milk caps. Apparently, when the biological yield is high, the wholesalers pay a lower price to the pickers. The NWFP markets have become more international since the late 1990s, and this has modified the price-quantity relationships of ceps and milk caps. The supply is affected by numerous factors, which were not included in the analysis. Export and import statistics, applying weekly or monthly data of marketed mushroom quantities and prices and considering the effects of storages would improve the understanding of the marketed mushroom supply in Finland. The quality of ceps also affects the prices paid to pickers and should be included in the supply analysis, as well as in the yield model.

To secure the acceptability of the mushroom businesses, it is important to consider the opinions and expectations of forest owners on matters concerning their premises. According to the forest owner survey, forest owners were not willing to restrict traditional picking to household use, whereas for organized commercial picking, some restrictions were in demand. The acceptability of commercial mushroom picking, however, could be improved by generating dialogue between land owners and berry and mushroom enterprises and also by distributing good picking practices, especially if commercial picking will increase.

The results improved the possibilities of taking mushrooms into account in forest management and, hence, contributed to advance multiple-use of forests. Knowledge of mushroom markets' behavior promotes a more stable supply chain of mushrooms in Finland. The models for the yields of marketed mushrooms enable the prediction of mushroom yields, along with the development of spruce stands. One application is to use the models to produce information on suitable picking sites, which can improve the

planning of mushroom picking. A future challenge is to distribute the findings to forest owners, actors in mushroom businesses and mushroom pickers.

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