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Optimizing the joint production of timber and marketed mushrooms in *Picea abies* stands in eastern Finland

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A B S T R A C T

There is a notable potential for utilizing marketed mushrooms in Finnish forests. The most marketed mushrooms in Finland are *Boletus edulis* and *Lactarius* spp. To improve preconditions for the use of this potential the stand management was optimized separately for joint production of (1) timber and *B. edulis*, (2) timber and *Lactarius spp*. and (3) timber and both *B. edulis* and *Lactarius* spp. in even-aged *Picea abies* stands in eastern Finland. In optimizations soil expectation value (SEV) with a 3% discount rate was maximized and picking costs and mushroom prices were included in calculations. The optimal two-thinning management schedule for timber only consisted of a rotation length of 96 years and heavy thinnings from above. The optimal stand management schedules for joint production were very similar to that of timber, because mushroom yields are at their highest just before the first commercial thinning. When management was optimized for mushroom production only, the optimal rotation lengths were shorter, and for *B. edulis* the thinnings were lighter. Management optimal for *Lactarius* spp. did not include thinning treatments. The production of timber and marketed mushrooms were mostly in synergy, mushroom harvesting creating significant additional income to forest owners.

Introduction

The global trend towards local and more natural food products is reflected in increased use of mushrooms (Wong and Prokofieva, 2014). Picking wild forest mushrooms is popular also in Finland, where, in 2010, 40% of population picked and 76% knew how to pick mushrooms (Sievänen and Neuvonen, 2011). Picking mushrooms for sale generates extra income though Finns engage in mushroom picking rather for leisure than for income (Cai et al., 2011). Due to the increased interest towards wild forest mushrooms, forest owners are keen to know whether they could generate additional income from managing their forests for both timber and mushroom production (cf. Palahí et al., 2009) and whether there are trade-offs between timber and mushroom production in their forests. Such knowledge on the joint production of timber and mushrooms is however limited.

According to the statistics on mushrooms bought by organized trade and industry *Boletus edulis* and *Lactarius trivialis* are the two most marketed mushroom species in Finland, but also *L. rufus* and *L. torminosus* are popular marketed mushrooms (MARSI, 2016). In the average mushroom year 2016 383 tons of *B. edulis*, 114 tons of *L. trivialis*, 43 tons of *L. rufus* and 2 tons of *L. torminosus* were picked for sale corresponding to an income of approximately 960 400 € from *B. edulis* and 312 400 € from *Lactarius* spp. paid for pickers (MARSI, 2016). In good years the revenues from *B. edulis* for pickers can be a few million euros. *B. edulis* and several *Lactarius* species are also appreciated at the international markets (Boa, 2004; Sitta and Davoli, 2012; Vidale et al., 2014). *B. edulis,* collected for sale in Finland, is principally exported to Europe, whereas *Lactarius* species are used domestically. However, domestic use of *B. edulis* in Finland is growing too (MARSI, 2016).

B. edulis, *L. trivialis* and *L. torminosus* are mycorrhizal fungi growing in spruce forests, whereas *L. rufus* prefers pine (Salo et al., 2006). According to the national inventory data from 1985 to 1986 the estimations about an annual average yield of *B. edulis* in mineral soil forests is 6.1 kg ha^{-1}, *L. trivialis* 6.4 kg ha^{-1}, *L. rufus* 19.3 kg ha^{-1} and *L. torminosus* 6.6 kg ha^{-1} (Salo, 1993). The mushroom yields vary greatly between years and stands (e.g. Ohenoja et al., 2005; Tahvanainen et al., 2016). Some of the variation in mushroom yields can be explained by climatic factors (e.g. Ohenoja, 1993; Wiklund et al., 1995; Ogaya and Peñuelas, 2005; Martínez de Aragón et al., 2007; Tahvanainen et al., 2016; Parladé et al., 2017). It has been suggested that climatic conditions are affecting the mycorrhizal mushroom yields both directly, by providing affordable conditions to mushroom for sporocarp production, and indirectly through the photosynthesis of the host tree providing the mushroom with carbohydrates (e.g. Krebs et al., 2008; Primicia et al.,

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2016). Also, the joint effects of climatic and stand variables and thinning operations on mycorrhizal mushroom yields are obvious but not well-known (Bonet et al., 2012; Tahvanainen et al., 2016).

Forest management changes the stand characteristics, which affects the yields of mushrooms due to their symbiotic relationship with trees (Ohenoja, 1988; Laiho, 1990; Luoma et al., 2004; Renvall et al., 2005; Pilz et al., 2006; de-Miguel et al., 2014a; Parladé et al., 2017). The effect of thinning varies depending on the species, thinning method or observed response period (e.g. Kropp and Albee, 1996; Kranabetter and Kroeger, 2001; Pilz et al., 2006; Palahí et al., 2009; Savoie and Largetea, 2011; Tomao et al., 2017). In Sweden the yields of *L. rufus* increased immediately after thinning (Kardell and Eriksson, 1987) and so did *L. deliciosus* yields in *Pinus pinaster* stands in Spain (Bonet et al., 2012). Salerni and Perini (2004) observed that medium thinnings in fir stands in Italy were beneficial for yields of *B. edulis*. In a mixed-forest in Switzerland the photosynthetic activity of the trees and the mushroom production improved a few years after the thinning (Egli et al., 2010). The positive thinning reactions and findings of higher yields of mycorrhizal fungi in younger stands (Taye et al., 2016) may reflect a tight connection between the photosynthetic activity of the trees and mycorrhizal fungal dynamics (including mushroom productivity).

Stand management (e.g. number of thinnings, timing and intensity of thinnings, rotation length) affects the profitability of timber production (e.g. Valsta, 1992; Hyytiäinen and Tahvonen, 2002), but also mushroom yields in spruce stands (Tahvanainen et al., 2016). So far, the management of spruce stands has not been optimized considering simultaneously timber and mushrooms yields. However in earlier studies the joint production of timber and non-wood forest products (NWFPs) has been optimized: for mushrooms in Catalonian pine stands (Palahí et al., 2009) and for bilberries and cowberries in Finnish conifer stands (Miina et al., 2016) for example. Miina et al. (2016) found that modifying timber-oriented stand management for joint production was profitable only in good berry stands. In Catalonia the inclusion of mushrooms in the stand management was profitable especially in stands with good mushroom yields (Palahí et al., 2009). In Finland, due to the everyman's rights anyone can harvest berries and mushrooms also from privately owned forests. Hence, it can be assumed that managing forests for both timber and mushrooms is an attractive opportunity mainly in stands with good mushroom yields and where the owner could control the utilization of mushroom yields. According to Hänninen et al. (2011), 42% of Finnish forest owners live at their forest state and in addition 22% in the same municipality where their forest state is located. Furthermore, stand management aiming at joint production makes sense in recreational forests that are particularly managed for multiple-use purposes.

The aim of the study was to optimize even-aged management of Norway spruce (*Picea abies*) stands where timber and marketed mushrooms are co-produced. The mushroom species included in the calculations were *B. edulis* and *Lactarius* spp. (*L. trivialis, L. rufus* and *L. torminosus*) growing in spruce stands. The management schedules were optimized for spruce stands, which were assumed to produce good mushroom yields. The management was optimized separately for joint production of timber and *B. edulis*, timber and *Lactarius* spp. and timber and both *B. edulis* and *Lactarius* spp. In addition management was optimized for timber production only, *B. edulis* production only, *Lactarius* spp. production only, and for the production of *B. edulis* and *Lactarius* spp. The picking costs and market prices of mushrooms were included in the calculations.

Materials and methods

Simulations

The stand development was simulated using the individual-tree models presented by Pukkala et al. (2009, 2013). The model set included species-specific models for diameter increment, height, tree survival and ingrowth. The stand development was simulated in 5-year time steps. The taper models of Laasasenaho (1982) and the minimum top diameter of 15 cm for logs and 7 cm for pulp wood were used to calculate assortment volumes of removed trees.

The non-linear mushroom yield models of Tahvanainen et al. (2016) were used to predict the annual mushroom yield for *B. edulis*:

$$y = \exp\left\{-1.3351 + 0.1778G - 0.0049G^2 + 2.0907\frac{G}{T+5} + v + u\right\} \tag{1}$$

and for *Lactarius* spp.:

$$y = \exp\left\{1.6513 - 0.0179\,G + 1.7435\frac{G}{T+5} + v + u\right\} \tag{2}$$

where y is the annual mushroom yield of *B. edulis* or *Lactarius* spp. in the stand (kg ha^{-1} a^{-1}), G is stand basal area (m^2 ha^{-1}), T is stand age (years) and v and u are, respectively, normally distributed random year and stand effects with zero mean and variance equal to 0.4432 and 0.6906 for *B. edulis* and 1.2695 and 0.5611 for *Lactarius* spp, respectively. The sample means of the estimated year effects, i.e. 0.6468 and -0.4730 have been added to the intercepts of Eqs. (1) and (2), respectively. For each year, the mushroom yield was predicted 200 times by drawing the random between-year effects (v) from the normal distribution, and the annual mushroom yield was computed as the mean of the 200 outcomes.

A stand with good mushroom yields was used in calculations as the stands known or expected to be good for mushrooms are more likely to be managed for mushroom production. The stand was made a good mushroom stand by adding the 90 t h percentile of the distribution of the random stand effect u to the yield predictions: 1.06 for *B. edulis* (Eq. (1)) and 0.96 for *Lactarius* spp. (Eq.(2)). Not the entire total yield of the season was assumed to be harvested for sale (e.g. Alexander et al., 2002; Palahí et al., 2009), and thus the yield predictions for *B. edulis* and *Lactarius* spp. were multiplied by 0.90 and 0.75, respectively. Since only few species (*B. edulis* and *Lactarius* spp.) were included, a slightly higher multipliers were used, than in calculations of Palahí et al. (2009) and Alexander et al. (2002), who included edible mushrooms and marketed mushrooms (incl. several mushroom species in the calculations). A smaller multiplier was used for *Lactarius* because its sporocarps emerge gradually over long time making it difficult to harvest the whole production. For all years during the rotation period, it was assumed that no mushrooms were picked when their harvesting cost was higher than the selling price. The costs and incomes were calculated separately for each of the 200 stochastic yield predictions. Only those cases where picking was profitable were included in the mean harvest and income of a particular year.

The models overestimated the production of mushrooms after regeneration felling and therefore a yield reduction for this point was added. After the regeneration felling the mycorrhizal mushrooms are losing their host trees and therefore it is assumed that the yields collapse. It was presumed that immediately after regeneration felling, at the stand age of 0 years, no mushrooms are produced (Laiho, 1990; Kropp and Albee, 1996; Tahvanainen et al., 2016). The yield reduction was then decreased linearly until it was over in 15 years after regeneration.

Initial stand

An initial stand representing *Myrtillus* -type mesic heath site in North Karelia, Finland was used as the starting point for the simulations. The models used in this study (Tahvanainen et al., 2016), are based on empirical data from sample plots on mainly *Oxalis-myrtillus* and *Myrtillus*-type stands. In North Karelia, the total area of *Myrtillus*-type mesic heath sites is 479 000 ha (11th NFI). If we assume, that roughly half of this area is dominated by spruce, then 10% of spruce dominated stands i.e. 24 000 ha would be classified as "good mushroom stands". At the beginning of simulations the stand age was 10 years, and