AN INVENTORY OF TREE AND STAND GROWTH EMPIRICAL MODELLING APPROACHES WITH POTENTIAL APPLICATION IN COPPICE FORESTRY (A REVIEW)

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Abstract


We examined currently available empirical growth models which could be potentially applicable to coppice growth and production modelling. We compiled a summary of empirical models applied in coppices, high forests and fast-growing tree plantations, including coppice plantations. The collected growth models were analysed in order to find out whether they encompassed any of 13 key dendrometric and structural variables that we found as characteristic for coppices. There is no currently available complex growth model for coppices in Europe. Furthermore, many aspects of coppice growth process have been totally ignored or omitted in the most common modelling approaches so far. Within-stool competition, mortality and stool morphological variability are the most important parameters. However, some individual empirical submodels or their parts are potentially applicable for coppice growth and production modelling (e.g. diameter increment model or model of resprouting probability). As the issue of coppice management gains attention, the need for a decision support tool (e.g. coppice growth simulator) becomes more actual.

Keywords: competition, dendrometric variables, mortality, resprouting, shoots, short-rotation forestry, stools, structural variables

INTRODUCTION

In the past, European forests were managed using traditional methods involving coppices or coppices-with-standards (Hochbichler, 1993; Peterken, 1993; Szabó, 2010). Records on coppice management date back to the 12th century, demonstrating that this method of forest management was previously virtually universal in some regions of Europe (Rackham, 1980). Throughout their history, coppices provided firewood and building materials for houses and fences, and their importance as a source of charcoal for metallurgy and the glass industry gradually increased. Oak (Quercus L.) coppices additionally provided tanbark (Evans, 1992). During the 20th century, coppices in central Europe have been transformed into high forests (Kadavý et al., 2011) or they became abandoned due to the declining use of wood and charcoal as energy sources. Abandoning of this traditional forest management method has resulted in a high density of unmanaged tree coppices, without generative regeneration, stand disintegration and the disappearance of their ecological, economic and social contributions (Cañellas et al., 2004).

Currently mainly biologists advocate for an increase in open forest area (Buckley, 1992; Harmer and Howe, 2003) because the decline in contemporary high-forest biodiversity is allegedly significant (Ash and Barkham, 1976; Gondard et al., 2001; Gondard and Romane, 2003; Gondard et al., 2006; Van Calster et al., 2007, 2008; Szymura,
Coppicing promotes a diverse community of ground vegetation, invertebrates and birds; the subsequent creation of a mosaic of clear-cuts of various ages, a high structural complexity and a temporal continuity of habitat types (Buckley, 1992; Peterken, 1996; Harmer and Howe, 2003) enhances the diversity.

A similarly valid argument for enhancing biological diversity, which supports the contemporary reintroduction of coppices in central Europe, is the production of firewood, or biomass, for energy production in short rotations (firewood or biomass for energy production is main assortments in coppice). Currently, the renewable energy source is used to produce electricity and, more importantly, for household heating, which is illustrated by the growth of firewood prices over the past two decades (Buľka, 2012).

Apart from the traditional use of coppices, short rotation forestry (SRF) with fast growing woody plants is utilized for the production of biomass on the arable land (Trnková et al., 2008). Short rotation coppice (SRC) where coppice grows as an energy crop also belongs to SRF. A quality tool to support decision making in coppice management is lacking. Growth models could facilitate search for solutions in the management of coppice stands, where growth often justifies investment in silvicultural measures (Adame et al., 2008).

So far, many reviews on forest growth modelling have been published; most of them focused on seed-origin high forests (HF) (Peng, 2000; Porte and Bartelink, 2002; Monserud, 2003; Soderbergh and Ledermann, 2003; Hasenauer, 2006; Sun et al., 2007). Modelling the growth and production of fast growing (energy) tree plantations has been examined in a number of studies. Some of these publications were reviews or were similar to reviews. The following studies: Ceulemans (1996), Ceulemans et al. (1996), Isebrands et al. (1996), Philipot (1996), Tome (1996), Dickmann (2006), Jebraj and Inyian (2006), Vanclay (2010), Aosaar et al. (2012), Surendran Nair et al. (2012) but without modelling of coppice growth (on forest land).

For this reason, we focused on the review of existing empirical growth models applicable in coppice forests in the condition of central Europe. We primarily analysed models addressing the growth process of coppices. Also, most important models of high forest and SRF were also analysed.

This review’s objectives were:

i) to select and describe the basic variables applicable to coppice growth modelling,

ii) to revise the empirical models and modelling approaches that are applied or are potentially applicable in coppice growth modelling,

iii) to analyse potentially applicable empirical growth models and approaches to modelling coppice growth with respect to their content of basic coppice variables.

**METHODOLOGICAL APPROACHES**

Based on former research of coppices, the essential dendrometric variables for their growth and production were defined before the analysis of existing models. Tab. I summarises 13 essential variables that characterize coppice growth and structure including important citation references.

Our review is structured in the following sections:

i) Existing empirical models of coppices were listed.

ii) The modelling approaches and growth models that were applied in coppices (apart from yield tables) were analysed focusing on previously defined variables. Variables used for evaluation (Tab. I) were supplied with indices defining various levels of particular variables with respect to how they were published (for instance number of individuals, stumps, sprouts, shoots or stools, etc.).

iii) The modelling approaches in high-forest and SRF (including short rotation coppices) growth models were analysed focusing on previously defined variables despite differences in growth dynamics, structure and management among the mentioned management approaches. Models of high forest or SRF were analysed the same way as models of coppices. We focused on papers that directly used variables essential for coppice growth modelling.

**Empirical Models of Coppices**


Apart from yield tables, most simple empirical growth models describing the development of one or more stand variables were created for coppice modelling on an empirical basis. Models based on studies that were not intended for yield table construction may be divided into two basic categories: models published as part of studies that did not focus on coppice growth modelling (1), and models that were developed independently and may be applicable as the future submodels of growth simulator (2).

Papers on the growth of stools or their parts may be included in the first group of empirical coppice growth sub-models (Ducrey and Toth, 1992; Retana et al., 1992). Papers concerning biomass or dry matter development for one or more factors may be included as well (Seidel et al., 2012; Suchomel et al., 2012). The group also includes resprouting
probability models for stool regeneration after fire or felling (Johnson, 1977; Weigel and Peng, 2002; Gould et al., 2007; Moreira et al., 2008; Matula et al., 2012; Šplíchalová et al., 2012; Pyttel et al., 2013).

The second group of models includes the studies by Adame et al. (2008) that model shoot diameter using a mixed linear model that includes competition. Adame et al. (2010) also published a model of ingrowth probability using logistic regression and frequency using multiple non-linear regression. Nachtmann (2011) published a tree model of shoot height and basal area growth for a specifically formulated competition index. The model is not position-dependent and uses the robust linear model and the improved linear mixed model. Menéndez-Miguélez et al. (2013) published allometric equations for calculating the biomass of individual tree components for tree, stool and stand levels. The equations do not consider competition and are position-independent.

**Models of Particular Variables of Coppice Growth and Production**

Most of the studies published on empirical models of coppice growth and production (Tab. II) focus on the tree level. At the stand level, they focus only on the modelling of ingrowth (Adame et al., 2010), biomass (Menéndez-Miguélez et al.,...
Almost all of the published studies on dendrometric variables analyse diameter or use it as an input. The less frequently used variables include height, number and basal area. The smallest number of studies focus on the biomass and ingrowth variables. Only few papers addressed structure of particular variables. Structure of dbh was used in studies by Adame et al. (2008) and Nachtmann (2011) and the structure of biomass in two studies by Suchomel et al. (2012) and Menendez-Miguélez et al. (2013).

Resprouting probability is addressed in papers by Johnson (1977), Weigel and Peng (2002), Gould et al. (2007), Moreira et al. (2008), Matula et al. (2012), Šplíchalová et al. (2012) and Pyttel et al. (2013). Only two studies focus on stool and shoot competition, namely Adame et al. (2008) and Nachtmann (2011). The only study focuses on ingrowth modelling (Adame et al., 2010). The highest number of variables used together are found in models by Adame et al. (2008), Nachtmann (2011) and Menendez-Miguélez et al. (2013).

No distance-dependent model has been published, although it is essential to validate sprout number reduction.

Models of High Forests and SRF (Including Short Rotation Coppices)

In spite of the fact that forest of generative origin (high forests) are prevailing in central Europe most of the published empirical models focused on high forest growth. We analysed empirical models for generative-origin stands; models of SRC were also included.

### II: Evaluation of empirical growth models designed for coppices

<table>
<thead>
<tr>
<th>Model type</th>
<th>Evaluated models</th>
<th>Variables</th>
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</tr>
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<td></td>
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<tr>
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<td>Newnham (1964)</td>
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<td>Lec (1967)</td>
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<td>Arney (1972)</td>
<td>yes yes yes yes yes yes yes yes yes yes yes</td>
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<tr>
<td>DRYMOS – Spyroglou and Chatziphilippidis (2005), Chatziphilippidis and Spyroglou (2006)</td>
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<tr>
<td>Edi-tree</td>
<td></td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13</td>
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<tr>
<td>E-stand</td>
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<td>Simon et al. (1993)</td>
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<tr>
<td>STAOET – Franz (1968)</td>
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<td>DFSIM – Curtis et al. (1981)</td>
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<tr>
<td>DFIT – Bruce et al. (1977)</td>
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<tr>
<td>Zach (1991)</td>
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</table>

III: Growth models for high forests and SRF, including short rotation coppices

<table>
<thead>
<tr>
<th>Area of application</th>
<th>Type – level of model</th>
<th>Model name or citation</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>NITGRO – Candy (1997), Fang et al. (1999), Garcia and Ruiz (2003), Specht and West (2003), Nordh and Verwijst (2004), Trnka et al. (2008), Bohm et al. (2011), Cañellas et al. (2012)</td>
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<td>E-stand</td>
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</table>


**High-forest Models**

Originally, only stand models were used for the empirical modelling of high-forest growth (forests of generative origin), but were later replaced by single tree models (Tab. III). The dominance of such approach has been most evident in the past twenty years. The use of distance-dependent and distance-independent tree models is roughly equal. Most of the evaluated models, regardless of their type, dealt with following variables: diameter, height, number, basal area, volume and increment (Tab. IV). Based on this finding, we assume that those variables are representative and support best outcome of forest growth model. Only Dixon et al. (2002), Fabrika (2005), Nagel (2011) and Murphy (2012) used the biomass variable in their work. None of the evaluated models use LAI (leaf area index) variable.

Of the distance-independent models, the following broadly use same variables: SILVA (Pretzsch, 1992; Pretzsch et al., 2002), MOSES (Hasenauer, 1994; Hasenauer et al., 2006), PROGNAUS (Sterba et al., 1995; Ledermann, 2006), BWIN (Nagel, 1996, 2011), SORTIE (Pacala et al., 1996; Murphy, 2012) and SIBYLA (Fabrika, 2005). Of the distance-independent models, the following use this variables: STAND (Pukkala and Miina, 1997), Forest Vegetation Simulator (Dixon et al., 2002), PROGNAUS (Sterba et al., 1995; Ledermann, 2006) and BWIN (Nagel, 1996, 2011). In the stand model group, these dendrometric variables are used by STAOET (Franz, 1968), DFIT (Bruce et al., 1977) and DFSIM (Curtis et al., 1981).

Mortality and competition are the common modelled variables but are always used only on the level of individual trees. The mortality variable is used in all tree models and in DFIT (Bruce et al., 1977), a DFSIM (Curtis et al., 1981) from the stand model group. The competition variable is used only in tree model types. The ingrowth variable is the focus of Prognosis (Stage, 1973), SILVA (Pretzsch, 1992; Pretzsch et al., 2002), MOSES (Hasenauer, 1994; Hasenauer et al., 2006), PROGNAUS (Sterba et al., 1995; Ledermann, 2006), BWIN (Nagel, 1996, 2011), SORTIE (Pacala et al., 1996; Murphy, 2012) and the Forest Vegetation Simulator (Dixon et al., 2002). Only the Forest Vegetation Simulator model (Dixon et al., 2002) focused on the resprouting probability variable.

BWIN (Nagel, 1996, 2011), SORTIE (Pacala et al., 1996; Murphy, 2012), the Forest Vegetation Simulator (Dixon et al., 2002) and SIBYLA (Fabrika, 2005) are the most complex models in models of forest of generative origin (high forests) because they use most of all analysed variables.

**SRF Models (Including Short Rotation Coppices)**

The studies on empirical models of SRF (Tab. III) primarily focus on the tree modelling level, while the stand level is not addressed. Most utilize predominantly distance-independent models. Most studies focus on diameter, height and number (Tab. V). Less attention is given to basal area and biomass, and only a small amount of publications focuses on increment and volume. Studies by Candy (1997), Fang et al. (1999) and Garcia and Ruiz (2003) are the most complex, as they use the most variables used in distance-independent models, whereas the studies by Talvainainen (1996) and Perez-Cruzado et al. (2011) are the most complex in the group of distance-dependent models, respectively. Moreover, these studies use the highest number of dendrometric variables for growth and production modelling. The least used dendrometric variable is LAI, which is only used in a study by Fang et al. (1999).

focus on these variables in distance-independent models, while works by Tome and Burkhart (1989), Tome (1990, 1996), Tahvanainen (1996) and Perez-Cruzado et al. (2011) apply them in distance-dependent models. None of the studies analysed here dealt with the stool morphological variability, ingrowth and resprouting probability variables in their models and modelling approaches to fast growing tree plantations.

**DISCUSSION**

Growth of a coppice is significantly different than that of a forest of generative origin, particularly during regeneration after disturbances (harvesting), when most parent trees survive the disturbance and regenerate via shoots (Rackham, 1980). Models and modelling approaches used in high-forest growth and production modelling were identified as valuable sources of information. A straightforward utilization of such models is problematic because of obvious differences in growth and structure of coppices as compared to high forests. Shoots grow very fast in the coppice, particularly in their initial development stage, which is facilitated by their developed root system containing a supply of nutrients and water (Castell et al., 1994; Crombie, 1997; Miller and Kaufman, 1998; Pallardy, 2008). The most frequently used variables in all analysed models were diameter and height. Information on diameter increment is important in forest management which allows the selection of tree species for logging or protection as well as the estimation of cutting cycles and the prescription of silvicultural treatments (Adame et al., 2008).

Radial growth of basal area of individual shoots is correlated with the basal area ratio of a given shoot within the total basal area of a given stool.

### Evaluation of high forest empirical growth models

<table>
<thead>
<tr>
<th>Model type</th>
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V. Evaluation of the empirical growth models designed for SRF, including short rotation coppices

<table>
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<th>Model type</th>
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<td>E-stand</td>
<td>Cañellas et al. (2012)</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13</td>
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(Nachtmann, 2011). Growth in shoot diameter may be influenced by a reduction of the other shoots within the stool (Ducrey and Toth, 1992). Height was used in 50% of analysed coppice growth models. Shoot height growth in coppice is correlated with the size of the parent stool prior to cutting, primarily with the quantity of supply nutrients in the roots. The rate of height growth is high in early phase of development and then declines quickly (Giovannini et al., 1992); the rapid growth at an early age is related to an early peak of the current height increment (Giovannini et al., 1992; Covone and Gratani, 2006; Marziliano et al., 2013). The current height growth increment peaks approximately 10 to 20 years earlier than in individuals of generative origin, and consequently declines faster after 20 to 30 years (Groos, 1953; Vyskot et al., 1978). Number of individuals and sprouts could be frequently found in papers addressing coppice growth. Number of individuals, stumps, shoots and stools are used in terminology of SRF. Most models of high forest growth use numbers of individuals. From this group of models, the model SORTIE (Pacala et al., 1996; Murphy, 2012) uses number of stumps and the Forest Vegetation Simulator (Dixon et al., 2002) uses number of sprouts. The stand density in coppices peaks in a relatively short time (Joffre et al., 1996; Damesin et al., 1998; Gondard and Romani, 2005; Covone and Gratani, 2006). The ensuing auto-reduction of stand density takes place primarily within the stools (polycormons), while the number of stools remains approximately the same (Covone and Gratani, 2006). The initially large number of shoots in the stools gradually decreases due to a number of factors, most important being the amount of nutrients in the soil and the available light and nutrients for further growth (Giovannini et al., 1992; Retana et al., 1992; Giudici and Zingg, 2005; Gould et al., 2007; Pyttel et al., 2013). Compared to forests of seed origin, the spatial structure of coppices may have several gaps if the initial number of stools is low. Generally, the number of shoots of the same age per unit area in a coppice is higher than the number of trees in a forest of generative origin (Ducrey and Toth, 1992).

Except of one occasion, LAI was not used in any of the analysed models. LAI is only used in a study by Fang et al. (1999) (distance-independent model in group of SRF models). Nevertheless, LAI may be used as an indicator of responses of forest stand to treatment at canopy level. The variable is affected by management options and silvicultural practices which modify, according to different goals, the spatial distribution of the trees, competition levels and aboveground biomass (Cutini, 2001). Coppice production is usually expressed in terms of wood mass volume (Crockford and Savill, 1991; Marziliano et al., 2013) or, alternatively, in terms of biomass weight units (Hoff et al., 2002; Gautam et al., 2010; Menéndez-Miguélez et al., 2013). The total average volume increment in coppices peaks 20 to 30 years earlier than in high forests (Groos, 1953; Vyskot et al., 1978). From all analysed models, volume is most frequently used in high forest models. The variable biomass is most frequently used in SRF models. In coppice growth models, only Suchomel et al. (2012) and Menéndez-Miguélez et al. (2013) use both volume and biomass variables.
Although biomass production is an important role of coppices, timber volume and biomass are of rare occurrence in coppice growth models. The following variables proved to be key components in the coppice modelling as compared to other two groups of models (high forest and SRF): a) mortality, b) competition, c) stool morphological variability and d) resprouting probability. The degree of reduction of coppice density may be affected by the competition between stools and within them (Ducrey and Toth, 1992; Logli and Joffre, 2001; Adame et al., 2008; Nachtmann, 2011). While competition between individual polycormons has principally the same effect as in high forests, auto-reduction of shoot numbers within stools is complicated by the relationship between the plant’s roots and its aboveground parts as transferred through the stool (Ducrey and Toth, 1992). At the polycormon level, the shoot number reduction is compensated by the growth of surviving shoots (Retana et al., 1992). However, as Ducrey and Toth (1992) pointed out, individual groups of shoots may be completely independent within a single polycormon; in practice, this situation indicates that the removal of all of a given group's shoots does not increase the availability of trophic and hydric resources for the remaining shoots that originate in other bud groups. Shoot mortality in the coppice may be expressed by an exponential trend that has a rapidly decreasing tendency (Retana et al., 1992; Giudici and Zingg, 2005). From all analysed coppice models, only Nachtmann (2011) adopted within-stool competition. Similarly, only Tahvanainen (1996) and Trnka et al. (2008) used this approach for SRF models. In all remaining models, mortality and competition is addressed at level of interactions between individuals. Coppice structure is influenced by soil quality and competition (Joffre et al., 1996; Logli and Joffre, 2001) as well as by eco-physiological processes within polycormons (Damesin and Rambal, 1995; Damesin et al., 1998) and their architecture (Giovannini et al., 1992). Morphological variability of stools is therefore a very important variable that has to be dealt with in coppice growth modelling. However, none of the analysed models addressed this variable. An important variable that influences the start of a new life cycle of a coppice is resprouting probability. The size of the parent tree in coppice is negatively correlated with the probability of a successful regeneration after felling (Johnson, 1977; Weigel and Peng, 2002; Gould et al., 2007; Moreira et al., 2008; Matula et al., 2012; Šplíchalová et al., 2012; Pyttel et al., 2013) and with the average number of successive shoots (Ducrey and Boisserie, 1992; Retana et al., 1992; Logli and Joffre, 2001; Giudici and Zingg, 2005). Generative regeneration, which is a desired and common complementation of resprouting in coppices, follows similar rules as those of purely generative forests. However, the parameters of a potential model must be adjusted to its application in coppices (Adame et al., 2010).

CONCLUSION

The primary aim of the review was revision of empirical growth models that are potentially applicable in coppice growth and production modelling. To do so, we initially defined basic variables that characterize coppices. The empirical growth models of coppice were analysed to see whether the models encompass the listed variables. Empirical coppice growth models were not the only models used and analysed. The currently used high-forest models and short-rotation forestry (including short-rotation coppice) models may be an inspiration and potentially applicable as well. Our analysis revealed that there is a number of issues that are not completely covered and explained by existing works on growth modelling, within stool competition, within stool mortality and morphological variability of the stools being the most important ones. Currently, the authors are not aware of any practically used empirical models that are designed for coppice management, at least not to the extent specified by this review. However, individual empirical submodels or their parts are potentially applicable for coppice growth and production modelling. The future research should be focused on the highlighted problematic, or insufficiently addressed variables, that are, in our opinion crucial for coppice growth modelling.

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