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

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Abstract

KNEIFL MICHAL, KADAVÝ JAN, KNOTT ROBERT, ADAMEC ZDENĚK, DRÁPELA KAREL. 2015. An Inventory of Tree and Stand Growth Empirical Modelling Approaches with Potential Application in Coppice Forestry (a Review). *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, 63(5): 1789–1801.

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, 2005; Gondard *et al.*, 2006; Van Calster *et al.*, 2007, 2008; Szymura, 2010). 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 (Bufka, 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 (Trnka *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), Philippot (1996), Tome (1996), Dickmann (2006), Jebaraj and Iniyan (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 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

The first simple empirical growth models, so-called yield tables for coppices, were developed concurrently, or with a slight delay, with forests of generative origin tables. In Europe, coppice yield tables were published by Schneider and Pfeil (1843), Groos (1953) in Germany, Fekete (1946), Redei and Gal (1986), Beky (1991) in Hungary, Castellani (1982), Marziliano *et al.* (2013) in Italy, Dimitrov and Stiptsov (1991) in Bulgaria, Crockford and Savill (1991) in Great Britain, Cabrera and Ochoa (1997) in Spain and Feistmantel (1854), Korsuň (1947, 1954, 1966, 1969), Řehák (1981) in the Czech Republic.

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

I: *Dendrometric variables of coppices*

No.	Variable	Unit	Description	Citation
1	diameter	[cm]	diameter at different heights of tree	Ducrey and Toth (1992), Covone and Gratani (2006), Adame *et al.* (2008)
2	height	[m]	height of tree	Ducrey and Toth (1992), Giovannini *et al.* (1992), Logli and Joffre (2001), Covone and Gratani (2006), Adame *et al.* (2008), Nachtmann (2011), Marziliano *et al.* (2013)
3	number	[pcs]	number of stumps, shoots, stools or shoots per stool per unit area	Ducrey and Boisserie (1992), Ducrey and Toth (1992), Giovannini *et al.* (1992), Retana *et al.* (1992), Logli and Joffre (2001), Giudici and Zingg (2005), Covone and Gratani (2006), Adame *et al.* (2008), Marziliano *et al.* (2013)
4	basal area	[cm^2]	the cross section area of the stem or stems of a plant or of all plants in a stand	Ducrey and Toth (1992), Giovannini *et al.* (1992), Logli and Joffre (2001), Adame *et al.* (2008), Nachtmann (2011)
5	leaf area index	dimensionless	index, which expresses the ratio between the one sided green leaf area and ground area	Joffre *et al.* (1996), Damesin *et al.* (1998), Covone and Gratani (2006)
6	volume	[m^3]	volume of all living trees in a given area of forest or wooded land that have more than a certain diameter at breast height	Marziliano *et al.* (2013)
7	biomass	[t]	the total quantity or mass of organic material produced by woody plants in a particular area, at a given time	Hoff *et al.* (2002), Gautam *et al.* (2010), Menéndez-Miguélez *et al.* (2013)
8	increment	[dx/dt]	the process of increasing of the biometric variable in the time	Nachtmann (2011), Marziliano *et al.* (2013)
9	mortality	[pcs]	the ratio of stool or shoots deaths in an area to the population of that area	Giovannini *et al.* (1992), Retana *et al.* (1992), Giudici and Zingg (2005), Gould *et al.* (2007), Pyttel *et al.* (2013)
10	competition		competition between stools or shoots, in which the fitness of one is lowered by the presence of another	Ducrey and Toth (1992), Logli and Joffre (2001), Adame *et al.* (2008), Nachtmann (2011)
11	stools morphological variability		variability of coppice stool environmental and morphological parameters	Joffre *et al.* (1996), Logli and Joffre (2001)
12	ingrowth	[pcs]	newly established seedlings or trees that passed the minimum size for measurement since the previous measurement	Adame *et al.* (2010)
13	resprouting probability	[%]	the probability of new shoots regrowth from the stump after the parent tree has been cut	Johnson (1977), Weigel and Peng (2002), Gould *et al.* (2007), Moreira *et al.* (2008), Matula *et al.* (2012), Splichalova *et al.* (2012), Pyttel *et al.* (2013)

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.*, II: *Evaluation of empirical growth models designed for coppices*

Model type	**Evaluated models**	**Variables**												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Edd-tree	SIBYLA – Fabrika (2005)	yes	yes	yes$_{b}$	yes		yes	yes	yes$_{g, h}$	yes$_{l}$	yes$_{o}$			
	SORTIE – Pacala *et al.* (1996), Murphy (2012)	yes	yes	yes$_{b, c}$	yes		yes	yes	yes$_{g, h, i}$	yes$_{l}$	yes$_{o}$		yes	
	SILVA – Pretzsch (1992), Pretzsch *et al.* (2002)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h}$	yes$_{l}$	yes$_{o}$		yes	
	Newnham (1964)	yes		yes$_{b}$	yes				yes$_{g, i}$	yes$_{l}$	yes$_{o}$			
	Lee (1967)	yes	yes	yes$_{b}$	yes		yes			yes$_{l}$	yes$_{o}$			
	Arney (1972)	yes	yes	yes	yes		yes		yes$_{g, h, i}$	yes$_{l}$	yes$_{o}$			
	DRYMOS – Spyroglou and Chatziphilippidis (2005), Chatziphilippidis and Spyroglou (2006)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h}$	yes$_{l}$	yes$_{o}$			
	MOSES – Hasenauer (1994), Hasenauer *et al.* (2006)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h}$	yes$_{l}$	yes$_{o}$		yes	
Edi-tree	Forest Vegetation Simulator – Dixon *et al.* (2002)	yes	yes	yes$_{b,d}$	yes		yes	yes	yes$_{g, h}$	yes$_{l}$	yes$_{o}$		yes	yes
	Prognosis – Stage (1973)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, i}$	yes$_{l}$	yes$_{o}$		yes	
	Stand Prognosis model – Wykoff *et al.* (1982)	yes	yes		yes		yes		yes$_{g, h, j}$	yes$_{l}$	yes$_{o}$			
	STAND – Pukkala and Miina (1997)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h}$	yes$_{l}$				
	PROGNAUS – Sterba *et al.* (1995), Ledermann (2006)	yes	yes	yes$_{b}$	yes		yes		yes$_{h, i}$	yes$_{l}$	yes$_{o}$		yes	
	BWIN – Nagel (1996, 2011)	yes	yes	yes$_{b}$	yes		yes	yes	yes$_{g, h}$	yes$_{l}$	yes$_{o}$		yes	
E-stand	Simon *et al.* (1993)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, j}$					
	STAOET – Franz (1968)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, j}$					
	DFSIM – Curtis *et al.* (1981)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, i, j}$	yes$_{l}$				
	DFIT – Bruce *et al.* (1977)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, j}$	yes$_{l}$				
	Zach (1991)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, j}$					

Legend: yes – model contains the desired variable; yes + letter – model contains the desired variable in more detailed variants; 1 – Diameter: a – including shoot basal diameter; 2 – Height; 3 – Number: b – of individuals, c – of stumps, d – of sprouts, e – of shoots, f – of stools; 4 – Basal area; 5 – LAI; 6 – Volume; 7 – Biomass; 8 – Increment: g – dbh, h – height, i – basal area, j – volume, k – biomass; 9 – Mortality: 1 – individuals, m – stools, n – shoots; 10 – Competition: o – between individuals, p – between stools, q – within stools; 11 – Stools morphological variability; 12 – Ingrowth; 13 – Resprouting probability; Edd-tree – empirical distance-dependent tree model; Edi-tree: empirical distance-independent tree model; E-stand: empirical stand model. Numbers of variables correspond with Tab. I

2013) and the decline in number of shoots per hectare in relation to age (Retana *et al.*, 1992). All of the published tree submodels use a distance-independent model.

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-Migueléz *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.

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

Area of application	Type – level of model	Model name or citation
HF	Edd-tree	Newnham (1964), Lee (1967), Arney (1972), FOREST – Ek and Monserud (1974), SILVA – Pretzsch (1992), Pretzsch *et al.* (2002), MOSES – Hasenauer (1994), Hasenauer *et al.* (2006), SORTIE – Pacala *et al.* (1996), Murphy (2012), SIBYLA – Fabrika (2005), DRYMOS – Spyroglou and Chatziphilippidis (2005), Chatziphilippidis and Spyroglou (2006)
	Edi-tree	Prognosis – Stage (1973), Stand Prognosis model – Wykoff *et al.* (1982), STAND – Pukkala and Miina (1997), PROGNAUS – Sterba *et al.* (1995), Ledermann (2006), BWIN – Nagel (1996, 2011), Forest Vegetation Simulator – Dixon *et al.* (2002)
	E-stand	STAOET – Franz (1968), DFIT – Bruce *et al.* (1977), DFSIM – Curtis *et al.* (1981), Zach (1991), Simon *et al.* (1993)
SRF	Edd-tree	Tome and Burkhart (1989), Tome (1990, 1996), Tahvanainen (1996), Perez-Cruzado *et al.* (2011)
	Edi-tree	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)
	E-stand	-

Legend: HF – high forest, SRF – short rotation forestry (including SRC – short rotation coppice), Edd-tree – empirical distance-dependent tree model, Edi-tree – empirical distance-independent tree model, E-stand – empirical stand model

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-dependent models, the following broadly use same variables: SILVA (Pretzsch, 1992; Pretzsch *et al.*, 2002), MOSES (Hasenauer, 1994; Hasenauer *et al.*, 2006), 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 Tahvanainen (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).

Stool and shoot mortality is used in studies by Tome and Burkhart (1989), Tome (1990, 1996), Garcia and Ruiz (2003), Trnka *et al.* (2008) and Perez-Cruzado *et al.* (2011). Stool and shoot competition is applied in studies by Tome and Burkhart (1989), Tome (1990, 1996) and Tahvanainen (1996). Studies by Garcia and Ruiz (2003) and Trnka *et al.* (2008)

IV: *Evaluation of high forest empirical growth models*

Model type	**Evaluated models**	**Variables**												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Edd-tree	SIBYLA – Fabrika (2005)	yes	yes	yes$_{b}$	yes		yes	yes	yes$_{g, h}$	yes$_{l}$	yes$_{o}$			
	SORTIE – Pacala *et al.* (1996), Murphy (2012)	yes	yes	yes$_{b, c}$	yes		yes	yes	yes$_{g, h, i}$	yes$_{l}$	yes$_{o}$		yes	
	SILVA – Pretzsch (1992), Pretzsch *et al.* (2002)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h}$	yes$_{l}$	yes$_{o}$		yes	
	Newnham (1964)	yes		yes$_{b}$	yes				yes$_{g, i}$	yes$_{l}$	yes$_{o}$			
	Lee (1967)	yes	yes	yes$_{b}$	yes		yes			yes$_{l}$	yes$_{o}$			
	Arney (1972)	yes	yes	yes	yes		yes		yes$_{g, h, i}$	yes$_{l}$	yes$_{o}$			
	DRYMOS – Spyroglou and Chatziphilippidis (2005), Chatziphilippidis and Spyroglou (2006)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h}$	yes$_{l}$	yes$_{o}$			
	MOSES – Hasenauer (1994), Hasenauer *et al.* (2006)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h}$	yes$_{l}$	yes$_{o}$		yes	
Edi-tree	Forest Vegetation Simulator– Dixon *et al.* (2002)	yes	yes	yes$_{b,d}$	yes		yes	yes	yes$_{g, h}$	yes$_{l}$	yes$_{o}$		yes	yes
	Prognosis – Stage (1973)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, i}$	yes$_{l}$	yes$_{o}$		yes	
	Stand Prognosis model – Wykoff *et al.* (1982)	yes	yes		yes		yes		yes$_{g, h, j}$	yes$_{l}$	yes$_{o}$			
	STAND – Pukkala and Miina (1997)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h}$	yes$_{l}$				
	PROGNAUS – Sterba *et al.* (1995), Ledermann (2006)	yes	yes	yes$_{b}$	yes		yes		yes$_{h, i}$	yes$_{l}$	yes$_{o}$		yes	
	BWIN – Nagel (1996, 2011)	yes	yes	yes$_{b}$	yes		yes	yes	yes$_{g, h}$	yes$_{l}$	yes$_{o}$		yes	
E-stand	Simon *et al.* (1993)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, j}$					
	STAOET – Franz (1968)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, j}$					
	DFSIM – Curtis *et al.* (1981)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, i, j}$	yes$_{l}$				
	DFIT – Bruce *et al.* (1977)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, j}$	yes$_{l}$				
	Zach (1991)	yes	yes	yes$_{b}$	yes		yes		yes$_{g, h, j}$					

Legend: yes – model contains the desired variable; yes + letter – model contains the desired variable in more detailed variants; 1 – Diameter: a – including shoot basal diameter; 2 – Height; 3 – Number: b – of individuals, c – of stumps, d – of sprouts, e – of shoots, f – of stools; 4 – Basal area; 5 – LAI; 6 – Volume; 7 – Biomass; 8 – Increment: g – dbh, h – height, i – basal area, j – volume, k – biomass; 9 – Mortality: l – individuals, m – stools, n – shoots; 10 – Competition: o – between individuals, p – between stools, q – within stools; 11 – Stools morphological variability; 12 – Ingrowth; 13 – Resprouting probability; Edd-tree – empirical distance-dependent tree model; Edi-tree: empirical distance-independent tree model; E-stand: empirical stand model. Numbers of variables correspond with Tab. I

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 Kauffman, 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

V: *Evaluation of the empirical growth models designed for SRF, including short rotation coppices*

Model type	Evaluated models	Variables												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Edd-tree	Tome and Burkhart (1989), Tome (1990, 1996)	yes	yes	yes$_{b}$	yes					yes$_{l}$	yes$_{o}$			
	Tahvanainen (1996)	yes$_{a}$	yes	yes$_{c}$	yes			yes	yes$_{g}$		yes$_{p, q}$			
	Perez–Cruzado *et al.* (2011)	yes	yes	yes$_{b}$	yes		yes	yes		yes$_{l}$				
Edi-tree	Candy (1997)	yes	yes	yes	yes		yes		yes$_{g, i}$					
	Fang *et al.* (1999)	yes	yes	yes$_{b}$		yes		yes	yes$_{k}$					
	Garcia and Ruiz (2003)	yes	yes	yes$_{b}$	yes		yes		yes$_{j}$	yes$_{l}$				
	Specht and West (2003)	yes		yes$_{b}$				yes						
	Nordh and Verwijst (2004)	yes	yes					yes						
	Trnka *et al.* (2008)	yes$_{a}$	yes	yes$_{b,e}$				yes		yes$_{l, n}$				
	Bohm *et al.* (2011)	yes$_{a}$	yes	yes$_{c}$				yes						
	Cañellas *et al.* (2012)	yes$_{a}$	yes	yes$_{b, c, f}$	yes									
E-stand	-													

Legend: yes – model contains the desired variable; yes + letter – model contains the desired variable in more detailed variants; 1 – Diameter: a – including shoot basal diameter; 2 – Height; 3 – Number: b – of individuals, c – of stumps, d – of sprouts, e – of shoots, f – of stools; 4 – Basal area; 5 – LAI; 6 – Volume; 7 – Biomass; 8 – Increment: g – dbh, h – height, i – basal area, j – volume, k – biomass; 9 – Mortality: l – individuals, m – stools, n – shoots; 10 – Competition: o – between individuals, p – between stools, q – within stools; 11 – Stools morphological variability; 12 – Ingrowth; 13 – Resprouting probability; Edd-tree – empirical distance-dependent tree model; Edi-tree: empirical distance-independent tree model; E- stand: empirical stand model. Numbers of variables correspond with Tab. I

(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 Romane, 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 competititon. 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 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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