woodValuationDE: A consistent framework for calculating stumpage values in Germany (technical note)

(With 5 Figures and 2 Tables)

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Holzerlöse; Holzbewertung; Holzerntekosten; Mitteldurchmesser; R-Paket; Qualität; Gelände; Ernteverfahren; Schadereignis; Kalamität.

1. INTRODUCTION

Wood production is the most relevant source of income for larger forest enterprises (>200 ha) in Germany (Ermisch et al., 2015). The generation of income from wood production is, among multiple other goals, a relevant aspect in forest management decisions (e.g. v. Arnim et al., 2021; Feil et al., 2018). To represent and quantify this income goal, forest economists commonly use indicators such as the Net Present Value, the Land Expectation Value (Faustmann, 1849), or the land rent as its annuity (Möhring et al., 2006). These all require the calculation of the net revenues of the trees to be harvested at specific points in time. Indicators based on net revenues are widely used in the fields of forest economics and forest planning, e.g., for the assessment of the economic outcome of uneven-aged forests (Hanewinkel et al., 2014), for the identification of sylvicultural strategies that balance different ecosystem services (Knoke et al., 2020), or for the selection of optimal rotation ages under biotic and abiotic risks (Staupendahl and Möhring, 2011). In contrast, interdisciplinary studies, focusing on trade-offs among multiple forest ecosystem services, often use the wood volume (e.g. Mina et al., 2017; Pardos et al., 2017) or biomass (e.g. Gamfeldt et al., 2013) as indicators of wood production and income. Using these indicators to describe provisioning services implicitly assumes wood to be a homogeneous good (Paul et al., 2020). This, however, ignores the fact that in most regions, including Central Europe, wood prices depend on tree species, tree diameter, and wood quality. For example, the volume share of sawlog assortments of high quality usually increases with the tree diameter (e.g. Offer and Staupendahl, 2018). The monetary value of trees therefore tends to increase disproportionately to their volume (see e.g. 'dimension effect' in Koster and Fuchs, 2022). Simplified, volume-based indicators thus fall short in fully describing the degree to which wood production meets income goals.

Accounting for wood as a heterogeneous good and deriving net revenues requires in-depth knowledge and data on wood grading rules, price relations of different assortments, and harvest costs. In addition to this, the specific values depend on a variety of stand characteristics, such as tree species, mean diameter of the harvested trees, stand quality, and accessibility for logging operations.

For Germany, such data is in principle available. For instance, the German federal states publish forest valuation guidelines, which describe a framework for the valuation of volumes and diameters derived from yield tables. However, this procedure usually requires extensive calculations based on numerous tables (e.g. WBR 2020, NMELV, 2019: at least 6 tables); for a given combination of species

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and mean diameter, assortment tables divide the wood volume to be harvested into harvest residues, sawlogs of distinct mid-diameter classes, and pulp wood. A second table further divides the sawlog volumes into log quality classes, ranging from A (highest quality incl. veneer quality) to D (lowest quality, incl. pallet timber). A third table, the wood price matrix, provides wood prices for all quality and mid-diameter classes of the logs relative to the price of a reference assortment. The revenues are calculated as the volume-weighted mean wood price of the different assortments multiplied with the recent wood price for this reference assortment. Subtracting the harvest costs, which depend on species, mean diameter, and accessibility of the stand, provides the net revenues.

More recent approaches to derive wood assortment compositions for valuation purposes apply single-tree forest growth and yield software. Simulation results of, for example, WEHAM (BÖSCH et al., 2016), TreeGrOSS (HANSEN and NAGEL, 2014), or SILVA (PRETZSCH et al., 2002) are used to estimate the assortment composition of each harvested tree by means of taper functions (e.g. KUBLIN et al., 2013). While such approaches are generally more flexible for deriving the assortment composition based on user-defined grading systems, they still require wood price tables, as well as many assumptions and user-settings, e.g., regarding single-tree information, simulation settings, and the definition of the assortments for the taper function.

The forest valuation approach often builds on data sources differing in their covered temporal and spatial origin. For example, the Lower Saxonian guideline (NMELV, 2019) combines West German sawlog grading data from SCHÖPFER and DAUBER (1989) from the 1980s in the assortment table with wood prices from 2017 to 2019 provided by the forest enterprise of Lower Saxony (in Northwest Germany). Although some of these disadvantages can be overcome by approaches based on taper functions, where users can implement their own assortment definitions, both approaches share, to varying degrees, several limitations for simple applications in bioeconomic modeling. Users have to link several tables and carefully account for relative and absolute values and different volume units. They require an in-depth knowledge of the often region-specific wood grading, logging, and trading systems for correct interpretation. Given that this information is exclusively published in German impedes access for international scholars. Hence, carrying out a comparably trivial calculation of revenues minus costs turns into a time-demanding and error-prone exercise. In addition, several applications would benefit from functional relationships between stand characteristics and net revenues, for example, to avoid discontinuities in closed-form but also non-linear optimizations.

We perceive that the described complications often prevent scholars, particularly in interdisciplinary and international research communities, to use more realistic economic indicators, which consider wood as a heterogenous good and situation-specific revenues and costs. Many interdisciplinary research questions require plausible estimates for income from wood production at the stand level for different stand types or management regimes, while the exact net revenues for specific logs or trees are less relevant. Here, simple-to-apply functional relationships providing net revenues for a set of stand characteristics may be a helpful tool. This might enable a more realistic valuation of provisioning services, but also trade-offs between ecological and economic functions.

We therefore strive to make the existing empirical findings and data-bases accessible to a broad and international audience by contributing an easily applicable wood valuation framework. We compile a set of existing assortment tables, wood revenue and harvest cost models, and estimates for losses in net revenues after disturbances into one software package allowing for the calculation of stumpage values. This valuation framework `woodValuationDE` *should (i) be simple to apply and to integrate into bioeconomic simulations, (ii) provide continuous functions of harvest quantities, revenues, and costs over the stand's mean diameter, (iii) consider the key drivers of net wood revenues, including disturbances, and (iv) be based on consistent and recent empirical data sets.*

`WoodValuationDE` returns net wood revenues as a function of characteristics of the stand and harvest activity, such as tree species, mean diameter of the harvested trees, stand quality, logging method, and accessibility for logging operations. Net wood revenues are defined as the revenues obtained from selling raw logs at the roadside minus the harvest costs. While the model parameters currently refer to the data of a large state forest enterprise in Hesse, Germany, the fundamental concept with the implemented data structure and interrelations can be well transferred to other regions and applications.

We built this framework on the assortment tables from OFFER and STAUPENDAHL (2018) and the wood revenue and harvest cost models from v. BODELSCHWINGH (2018). Both were consistently derived based on data of HessenForst, the public forest service of the Federal State of Hesse in Germany, which manages a forest area of about 326,320 ha (Thünen-Institut, 2015). We added missing interfaces and estimated smooth, continuous variable dependencies by means of regression analyses. In addition to this, we implemented a set of assumptions on the effects of disturbances on wood revenue and harvest costs, which allow the user to

simulate disturbance scenarios. We provide the framework as an R (R Core Team, 2020) package (https://cran.r-project.org/package=woodValuationDE) on CRAN and additionally as an example with the main functionalities in MS Excel (https://doi.org/10.5281/zenodo.6796526). While the models can be useful for several scientific and also practical applications, they are not intended for official forest valuation problems, which require, among other considerations, long-term stable and officially recognized estimates of assortment compositions and prices. Users seeking precise estimates of revenues and costs for specific conditions should carefully review the data sources and assumptions used in our simplified assessment framework. However, we expect our approach to be helpful for a broad community of researchers and practitioners who want to include empirically reasoned, general estimates for wood revenues in their studies or calculations. We explicitly invite fellow researchers to adapt the general concept of our framework and to share parameter sets for other regions and countries.

Our publication has a technical focus to introduce the scientific background of the valuation framework for future applications. This should illustrate the framework's features but also highlight important limitations, since the drawback of the simplification is that it becomes, in a sense, a black box. Therefore, we here focus on the description of the general framework, the applied models and the assumptions underlying the valuation framework. For user instructions of the `R` package with details on all available user arguments, the implemented model parameters, and example codes, we refer the reader to the package's README (https://github.com/Forest-Economics-Goettingen/woodValuationDE#readme). Section 2 gives an overview of the main modules with user inputs and model outputs, while Section 3 provides further details on the underlying models and available parameterizations. Section 4 exemplifies the application of `woodValuationDE` using established yield table data and Section 5 discusses some important limitations of the suggested approach. We present the valuation framework in English to provide international colleagues the opportunity to apply the model or adapt the general framework. However, we recognize that some terms are very specific to the value chain examined and therefore also provide the respective technical terms in German.

2. WOOD VALUATION FRAMEWORK

2.1. Main modules of woodValuationDE

`WoodValuationDE` estimates the net wood revenues[1)] per cubic meter wood over bark. For this purpose, it builds on two main modules and one optional module (see *Figure 1* for the implemented models). The user provides inventory data referring to the mean diameter and the volume over bark[2)] of standing trees to be harvested, as usually provided by yield tables or forest simulators (module forest stand information).

2.1.1. Harvest quantities

The module 'harvest quantities' enables a direct monetary valuation of the user-provided volume. Since not the entire volume over bark is skidded and sold, we derived quantity conversion factors depen-

[1)] Also known as net stumpage value. In German: holzwerbungskostenfreier Holzerlös, Deckungsbeitrag I, Abtriebswert.

[2)] In German: Vorratsfestmeter mit Rinde (Vfm m.R.).

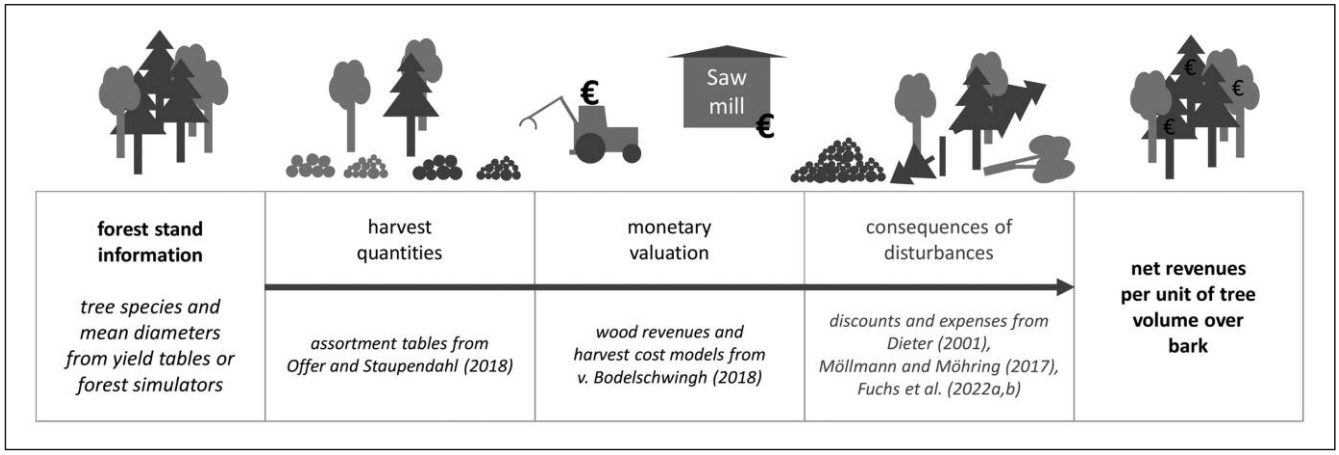

Fig. 1

Modules (upper line) and models (lower line) applied in `woodValuationDE` to derive net revenues per cubic meter wood over bark. The gray module is optional.

Module (obere Zeile) und Modelle (untere Zeile), die in `woodValuationDE` verwendet werden, um Nettoerlöse pro Vorratsfestmeter herzuleiten. Das graue Modul ist optional.

dent on species, mean diameter, and logging method (see Section 3.1) based on the assortment tables of OFFER and STAUPENDAHL (2018).

The *salable volume* is the share in the volume over bark that is actually sold as pulp wood, sawlogs, or for private fuel wood use[3]. It is calculated by converting the volume over bark to the volume under bark[4] and subtracting all other harvest residues[5] that remain in the forest, e.g., due to fixed assortment length or minimum diameters at the small end (*Figure 2*).

The *skidded volume* is the share in the salable volume that is delivered to the forest road or the salable volume minus the private fuel wood, respectively. Total costs of harvesting and skidding refer to this volume under bark[6]. Our framework thus assumes that the forest enterprise is responsible for the supply chain up until the forest road for pulp wood and sawlogs. In contrast, it is assumed that the private fuel wood is processed in the stand and hauled by the buyers themselves – it is relevant for the revenues, but not for the costs.

Both the share of salable and the share of skidded volume are expressed as proportions of the standing wood volume over bark (*Figure 2*).

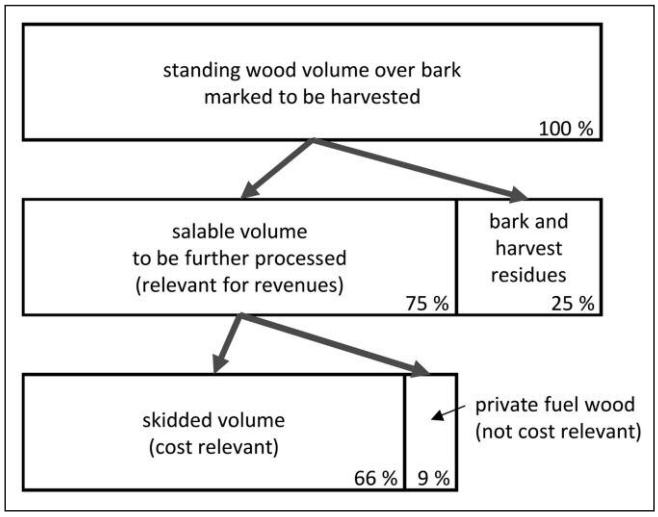

Fig. 2

Exemplary illustration of the derived harvest quantities share of salable wood volume and share of skidded wood volume, expressed relative to the standing wood volume. The arrows represent the application of species-, diameter-, and quality-sensitive volume conversion factors. Bar width and percentage values represent the quantities for beech stands with a mean diameter of 40 cm and a moderate stand quality.

Beispielhafte Darstellung der hergeleiteten Anteile verkaufsfähigen bzw. gerückten Volumens, relativ zum stehenden Volumen. Die Pfeile stellen die Anwendung baumart-, durchmesser- und qualitätsabhängiger Volumenumrechnungsfaktoren dar. Balkenbreite und Prozentangaben repräsentieren die Anteile für Buchenbestände mit einem mittleren Durchmesser von 40 cm und durchschnittlicher Bestandesqualität.

2.1.2. Monetary valuation

For the monetary valuation, we applied the wood revenue and harvest cost functions according to *v. Bodelschwingh* (2018). The wood revenues provide the average revenues of all assortments weighted by their estimated volume proportions for a given mean diameter, species, logging method, and stand quality (definitions in Section 2.2). They can therefore be multiplied directly with the salable volume without applying an additional, explicit assortment module. The harvest costs include both harvesting as well as skidding[7] and are applied to the skidded volume.

2.1.3. Consequences of disturbances

Users can choose between different parameter sets for the consequences of disturbances on net wood revenues, taken from literature sources. We recommend the use of the data set of FUCHS et al. (2022b) since it also refers to Hessian data. It provides estimates for higher harvest costs and distinguishes between two effects on revenues, the oversupply at the wood markets and actual quality losses.

2.2. User input

The obligatory user inputs are the quadratic mean diameter[8] and the tree species (*Figure 3*). Calculating total net revenues additionally requires the volume over bark. Other inputs that allow for a more detailed specification of the stand, logging method, and market situation are optional.

`species:`

The harvest quantity and wood revenue functions were parameterized for a broad set of species: alder (*Alnus glutinosa* (L.) Gaertn.), ash (*Fraxinus excelsior* L.), beech (*Fagus sylvatica* L.), birch (*Betula pendula* Roth), Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco), larch (*Larix decidua* Mill.), oak (*Quercus robur* L., *Qu. petraea* (Mattuschka) Liebl.), pine (*Pinus sylvestris* L.), poplar (*Populus nigra* L.),

[3]) In Hesse, and many other regions in Germany, parts of the harvested volume are not sold as skidded logs at the roadside but in the stand for private fuel wood use. In German: Selbstwerber-Brennholz.

[4]) In German: Erntefestmeter ohne Rinde (Efm o.R.).

[5]) 'Nicht verwertbares Derbholz' (NVD), often also separated into NVD and X-Holz. We assume that private fuel wood is a separate assortment and is not obtained from these harvest residues.

[6]) The skidded volume is expressed as volume under bark, with the bark usually being removed at the saw mill.

[7]) Other costs, e.g., for coordination, the selection of the trees to be harvested, or the sale of the wood, are not considered.

[8]) It is calculated as the diameter corresponding to the mean single-tree basal area at breast height, often referred to as *QMD*, D_q, or D_g (see e.g. CURTIS and MARSHALL, 2000). In German: Durchmesser des Grundflächenmittelstamms.

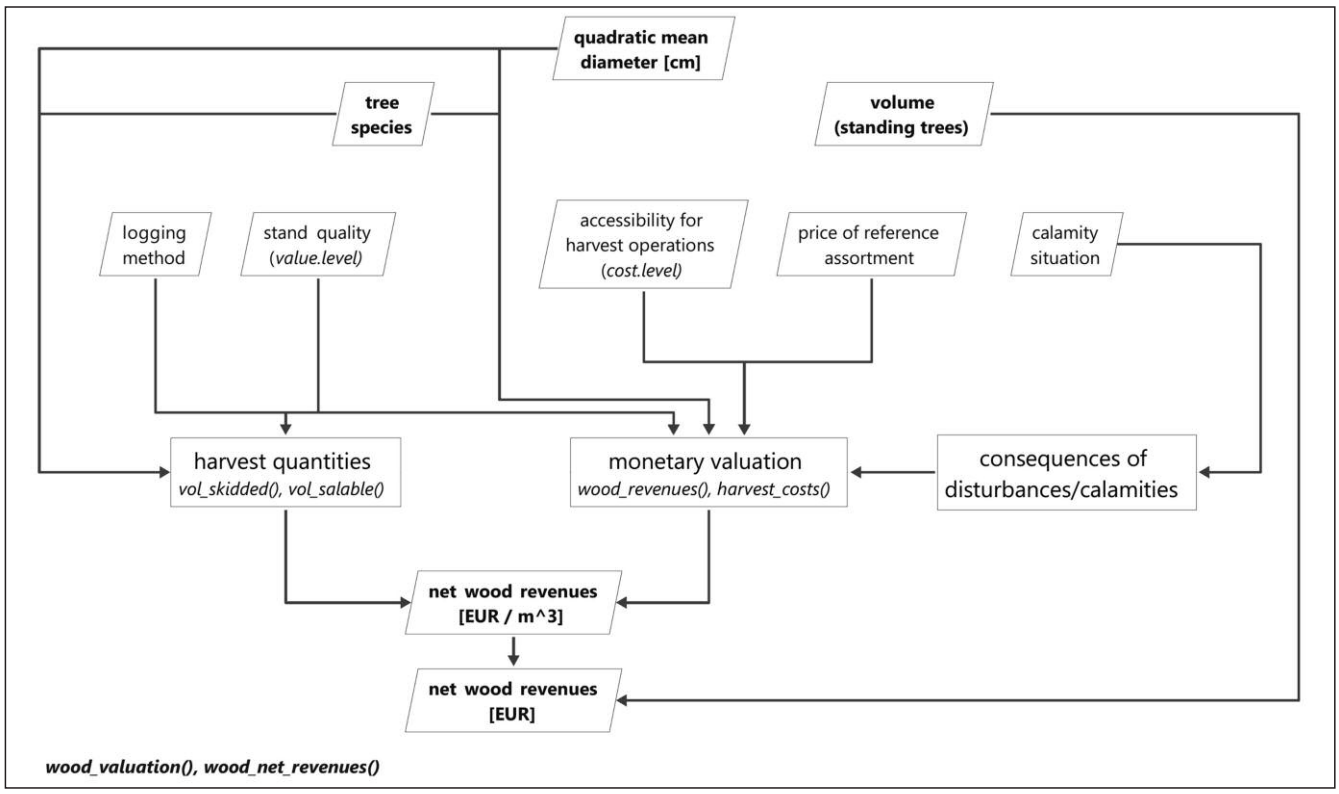

Fig. 3

Structure of the wood valuation framework. Parallelograms: user input or output, rectangles: main modules, in bold: obligatory input without predefined standard parameters and output variables.

Aufbau des Holzbewertungsmodells. Parallelogramme: Nutzereingaben und -ausgaben, Rechtecke: Hauptmodule, fett gedruckt: Obligatorische Nutzereingaben ohne voreingestellte Werte sowie wichtigste Ausgabevariablen.

and spruce (*Picea abies* (L.) H. Karst.). The harvest costs were derived for the species groups commonly found in practice: beech, oak, pine, and spruce. For the other species, and several others for which both models were not parameterized separately, assignments to the parameterized species are supplied.

`diameter.q` *(quadratic mean diameter):*

Based on the quadratic mean diameter at breast height, the models implicitly consider changes in the assortment compositions with increasing tree dimensions as well as lower harvest costs per cubic meter.

`logging.method:`

The user may select among three logging methods: `'manually'`, `'harvester'`, and `'combined'`. Choosing between manual logging with a chain saw (`'manually'`) and highly mechanized logging with forest harvesters (`'harvester'`) affects the assortment compositions (OFFER and STAUPENDAHL, 2018). For example, logging with forest harvesters tends to cut fixed-length sawlogs of mixed qualities (e.g. B/C) more frequently. We also derived harvest quantities and wood revenues for a 'combined' method and recommend it for most applications. It assumes highly mechanized logging for small mean diameters ($d_q \leq 20$ cm) and an increasing share of logging with a chain saw with increasing diameters. This is in line with the logging methods assumed for the harvest cost model (V. BODELSCHWINGH, 2018) and avoids extrapolation, as the assortment tables do not cover highly mechanized logging for deciduous species at $d_q \geq 40$ cm. Such a combination of two distinct logging methods may be unrealistic for a single logging operation, but a reasonable choice at the enterprise level.

`value.level` *(stand quality):*

For the stand quality, three levels are available for user selection: 1 for an extraordinarily high quality with high shares of wood suitable for furniture or other high valued usages, 2 for a moderate quality, and 3 for a low quality (see V. BODELSCHWINGH, 2018; OFFER and STAUPENDAHL, 2018).

`cost.level` *(accessibility for logging operations):*

The accessibility for logging operations distinguishes between harvest costs for standard conditions with a full accessibility for logging vehicles (1), moist sites or slopes between 36 % and 58 % where the logging vehicles rely on additional technical sup-

port (2), and slopes > 58% where special logging techniques, such as cable logging, are required (3) (see V. BODELSCHWINGH, 2018).

`price.ref.assortment` *(prices for reference assortments):*

User-provided prices for reference assortments allow for the updating of the revenue model to current market conditions. By defining the current market prices for the species-specific reference assortments commonly used in Germany (e.g. logs of quality B and a mid-diameter of 25–29 cm for spruce, see package README), the revenue model, which refers to reference prices in Hesse from 2010 to 2015, is updated to the new price level (details below). Time series of price indices reflecting the price developments of reference assortments are, for example, published by the Federal Statistical Office of Germany (DESTATIS).

`calamity.type:`

The optional calamity type specifies whether or not it is a salvage harvest and which literature-based assumption on the consequences of disturbances is used. This allows for a differentiation between different disturbance agents or spatial extents. The users can also specify their own parameterizations.

2.3. User output

The most relevant functions of the `R` package are `wood_valuation()` and `wood_net_revenues()`, which wrap all other functions and perform the entire calculation in one function. `wood_valuation()` returns a table with the results of all calculation steps and `wood_net_revenues()` the resulting vector of net revenues in Euro for the entire volume over bark (*Table 1*).

3. MODELS AND DATA

One of the strengths of our valuation framework lies in its consistency, which can be seen in the underlying empirical data sets. All models are based on, or at least validated against, data of HessenForst. In this section, we shortly present the main characteristics of the models implemented in each module of `woodValuationDE`. In addition to this, we provide further details on the fitted continuous functions for harvest quantities over the mean diameter and the `'combined'` logging method. For the detailed, more technical definitions of all user inputs and their options, we refer the reader to the `R` package's README at https://github.com/Forest-Economics-Goettingen/woodValuationDE#readme. All parameters of the implemented models are provided by the `R` command `woodValuationDE:::params.wood.value`.

Tab. 1

Functions of `woodValuationDE` and their return values.

Funktionen in `woodValuationDE` und ihre Rückgabewerte.

Function	User output
`vol_skidded()`	Vector with the relative share of the volume over bark that is delivered to the forest road
`vol_salable()`	Vector with the relative share of the volume over bark that is sold as sawlogs, pulp wood, or fuel wood
`wood_revenues()`	Vector with the average revenues over all assortments in Euro per cubic meter salable volume
`harvest_costs()`	Vector with the costs for harvesting and skidding to the forest road in Euro per cubic meter skidded volume
`wood_valuation()`	Table with all calculation steps of the valuation framework
`wood_net_revenues()`	Vector with the net revenues for the provided volume over bark

3.1. Harvest quantities

The harvest quantities depend on the mean diameter, species, quality, and logging method. We fitted the functions for the share of salable volume and share of skidded volume to the discrete assortment tables from OFFER and STAUPENDAHL (2018). These tables were derived for HessenForst using the software HOLZERNTE 7.1 (SCHÖPFER et al., 2003). The parameters relevant for the generation of the assortment tables were defined by experienced forest district officers and tested against logging and timber sale statistics of HessenForst. More details on the methodology underlying these tables can be found in OFFER and STAUPENDAHL (2008; 2009). We derived conversion factors from volume over bark to skidded or salable volume based on the tables' values: (i) conversion factor from volume over bark to volume under bark ('Faktor_VFM_EFM'), (ii) share of fuel wood ('EH'), and (iii) share of non-utilized wood, which remains in the forest ('NVD'). We then derived a continuous functional relationship between these harvest quantities and the mean diameter by fitting the Gompertz function to the discrete values, using the modified formulation according to FISCHER and SCHÖNFELDER (2017):

$$v_{skidded} = A \cdot \exp\left(-\exp\left(\frac{z_m}{A} \cdot \exp(1) \cdot \left(t_w - d_q\right)\right)\right), \qquad (1)$$

with the relative share of skidded volume $v_{skidded}$, the quadratic mean diameter d_q in cm as the explanatory variable, and the function parameters A, z_m and t_w. This curve was fitted to all combinations of species and value levels as well as for the shares of salable volume as the dependent variable (different sets of function parameters). We chose this modified Gompertz function since it guaranteed a reasonable behavior at both low and high diameters and the starting values for the non-linear regression could be easily derived.

Our harvest quantities thus already combine the conversion from volume over bark to volume under bark with the volume reductions due to additional harvest residues ('NVD'). For applications that require more detailed estimations, there are other, often region-specific functions estimating, e.g., only the bark thickness (see, e.g., STÄNGLE et al., 2017; STÄNGLE and DORMANN, 2018).

3.2. Monetary valuation

3.2.1. Wood revenues

The wood revenues s depend on the mean diameter, the species, stand quality, logging method, and price of the reference assortment. They are calculated applying the model from V. BODELSCHWINGH (2018), which uses a previous version of the Hessian assortment tables (OFFER and STAUPENDAHL, 2013) for the assortment compositions. Combined with a wood price matrix based on the revenues from timber sales of the public forests of Hesse managed by HessenForst from 2010 to 2015 (V. BODELSCHWINGH, 2018: Appendix 3), the average revenues over all assortments were derived. V. BODELSCHWINGH (2018) fitted the following function to these average revenues in € m^{-3}:

$$s = a \cdot d_q^4 + b \cdot d_q^3 + c \cdot d_q^2 + d \cdot d_q + e, \qquad (2)$$

with the quadratic mean diameter d_q in cm and the function parameters a to e. The function parameters depend on species, stand quality (`value.level`), and logging method. The revenues can be adjusted by the user to other market situations by specifying prices for reference assortments $p_{ref,user}$ (user argument `price.ref.assortment`, see README for further details and the required data structure). Assuming that changes in the price of the reference assortment are representative for the other assortments, the revenues are updated by:

Tab. 2

Assumed proportions of the harvest methods 'manually' and 'harvester' for the parameterization of the 'combined' harvest method.

Angenommene Anteile der Ernteverfahren 'manually' und 'harvester' für die Parametrisierung des Ernteverfahrens 'combined'.

Softwood species	Deciduous species
$d_q \leq 20$ cm: 100 % '`harvester`'	$d_q \leq 20$ cm: 100 % '`harvester`'
20 cm $< d_q <$ 50 cm: linear increase up to 50 % '`manually`'	20 cm $< d_q <$ 40 cm: linear increase up to 100 % '`manually`'
$d_q \geq 50$ cm: 50 % '`manually`'	$d_q \geq 40$ cm: 100 % '`manually`'

$$s_{updated} = \frac{p_{ref,user}}{p_{ref,model}} \cdot s_{model}. \quad (3)$$

The revenue model of v. BODELSCHWINGH (2018) provides parameters for logging with a chain saw (`'manually'`) or for highly mechanized logging (`'harvester'`). In contrast to this, the harvest cost model (v. BODELSCHWINGH, 2018) considers that the choice of the logging method usually depends on the diameter as well as the species group (softwood vs. deciduous). In order to provide a revenue model that is in line with the assumptions of the cost model, we refitted the revenue function for diameter-dependent combinations of both logging methods. For this `'combined'` method, we applied the assumptions of the harvest cost model according to v. BODELSCHWINGH (2018) (*Table 2*). This avoids extrapolation problems with unrealistic revenues for large diameters in `'harvester'` and provides a continuously applicable set of parameters.

3.2.2. Harvest costs

The harvest costs h according to v. BODELSCHWINGH (2018) are sensitive to the mean diameter, species, and accessibility of the stand. The harvest costs h in € m^{-3} are calculated as:

$$h = \begin{cases} a \cdot d_q^b + c, & if\ a \cdot d_q^b + c < h_{max} \\ h_{max}, & otherwise \end{cases} \quad (4)$$

with the quadratic mean diameter d_q in cm, the maximum harvest costs h_{max} in € m^{-3}, and the function parameters a to c. The function parameters depend on species and the stand's accessibility for logging operations (`cost.level`). V. BODELSCHWINGH (2018) derived the parameters based on diameter-sensitive harvest cost information for different logging methods published by the German Center for Forest Work and Technology (KWF, 2006) and the Working-Group of Forestry Contractors (AfL, 2014) and checked the plausibility against contracts of HessenForst in 2014.

3.3 Consequences of disturbances/salvage revenues

`WoodValuationDE` offers the opportunity to consider the consequences of natural disturbance events on the stumpage value. They are implemented as reductions in wood revenues (multiplicative factors) and increases in harvest costs (factors or additional, absolute harvest costs). The factors refer to changes in the immediate stumpage value (salvage harvest). Potential losses in the future if salvage harvesting is not performed must be accounted for in the user's model. Since these effects can differ between hardwood and softwood (FUCHS et al., 2022b), our framework allows users to set different factors for both tree species groups. Users may provide their own disturbance factors or choose between the following pre-implemented parameter sets taken from literature: (i) The net revenues from salvage harvests are reduced by 50 % (according to DIETER, 2001); (ii) Factors derived in a survey of forest professionals by MÖLLMANN and MÖHRING (2017) are implemented for decreases in revenues and increases in costs dependent on the disturbance agent, species, and disturbance extent; (iii) Factors for salvage harvests after infestations by *Ips typographus* are implemented (originally assumed in FUCHS et al., 2022a based on calculations using the assortment tables of OFFER and STAUPENDAHL, 2018); (iv) Results of an econometric time series analysis of data from HessenForst are implemented relating the reduction in wood revenues to the severity and extent of the disturbance event (FUCHS et al., 2022b).

4. APPLICATION TO YIELD TABLES

We illustrate the application of the valuation framework and its general behavior by showing the relationship between the most important user inputs and model outputs. We highlight the developments of harvest quantities, wood revenues, and harvest costs over the stand's quadratic mean diameter for the four most important tree species in Germany. In addition, we illustrate the sensitivity of revenues and costs to stand quality, accessibility of the forest stand, and consequences of disturbance events. We used the yield tables collected in SCHOBER (1995) as a simple growth model. In order to represent current growth conditions and management regimes, the quadratic mean diameters from the yield tables were updated using the approach of WOLLBORN and BÖCKMANN (1998).

4.1. Results for the most important tree species

Figure 4a illustrates the species-specific increase in the share of salable and skidded volume with the stand's mean diameter. Even though the functional pattern of a strict increase is similar for all species, the harvest quantities differ remarkably between the species groups. The softwood species spruce and pine reach shares > 50 % earlier than beech and oak. For the latter, the share of salable volume is comparatively low, even for larger mean diameters (> 40 cm). The difference between salable volume and skidded volume should be considered, especially for beech and oak, where the production of fuel wood is more common.

Figure 4b shows the development of harvest costs and wood revenues over the stand's quadratic mean diameter. With increasing single-tree volume, accounted for by the diameter at breast height, harvest costs per cubic meter decrease. At the same time, wood revenues per cubic meter increase since the proportion of higher valued wood assortments

increases with the tree dimension. The net revenues per tree therefore increase necessarily with the tree dimension. This increase in revenues is particularly pronounced for oak, as oaks in higher dimensions allow for the sale of the highest valued wood assortments, i.e., those used for furniture and veneer.

4.2. Influence of stand quality and accessibility

Figure 5 illustrates the effect of the stand quality (a) and accessibility for logging operations (b) on the net stumpage value. We calculated net stumpage values based on the yield tables' volumes and diameters. The difference in net revenues between stands of low (3) and high (1) quality is comparably small for pine, but reaches about 32,000 € ha^{-1} for 160-year-old oak stands. In contrast, the effect of the accessibility of the stand is more pronounced for both spruce and beech. The difference between an unrestricted accessibility (1) and moist stands or those with slopes between 36 and 58 % (2) is considerably smaller than the difference to the next cost level (3), where cable logging systems are assumed to be necessary. The corresponding difference in the net stumpage value reaches about 11,000 € ha^{-1} for spruce at age 100. This underlines the importance of taking both the stand quality and the suitable logging method into account when deriving net wood revenues.

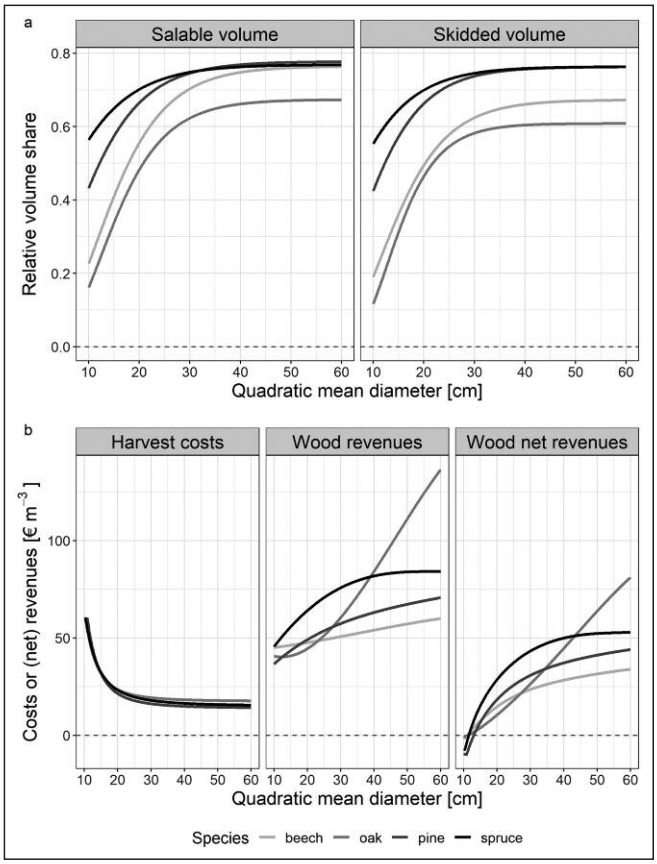

Fig. 4

Development of harvest quantities (a), harvest costs, wood revenues, and net revenues (b) over the mean diameter; calculated for the four most important tree species in Germany. Please note that the harvest costs refer to the skidded volume, the revenues to the salable volume, and the net revenues to the volume over bark. We assumed a moderate quality (value level 2) and no restriction in the accessibility of the stand (cost level 1).

Entwicklung der Erntevolumenanteile (a), Erntekosten, Holzerlöse und Nettoerlöse (b) über dem mittleren Durchmesser; berechnet für die vier wichtigsten Baumarten in Deutschland. Zu beachten: Während die Erntekosten sich auf das gerückte und die Holzerlöse auf das verkaufsfähige Volumen beziehen, werden die Nettoerlöse direkt für das Volumen in Vorratsfestmetern ausgegeben. Wir haben eine mittlere Qualität (Wertklasse 2) und eine uneingeschränkte Befahrbarkeit des Bestandes (Kostenstufe 1) unterstellt.

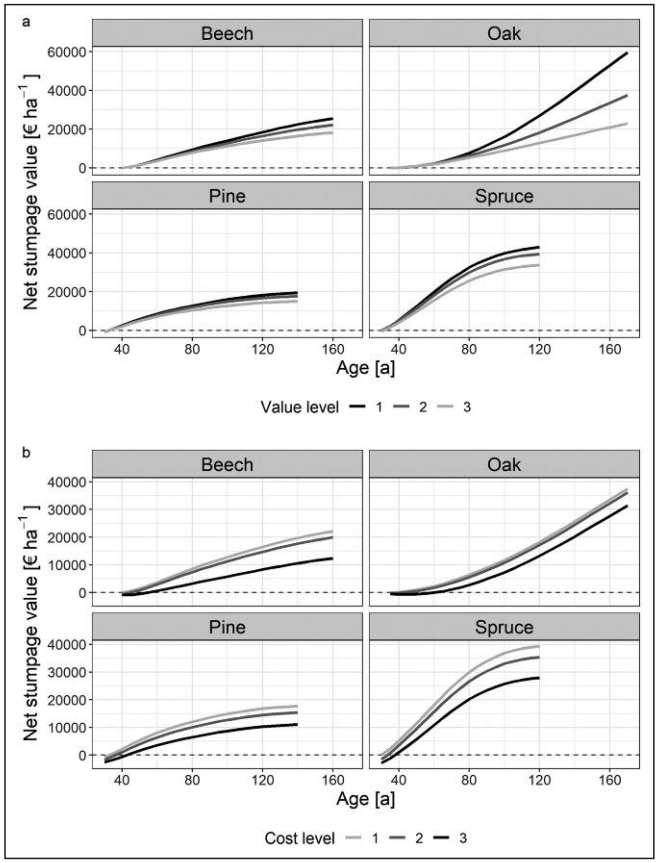

Fig. 5

Net revenues for the harvest of the entire stand volume over bark (stumpage values) calculated for the four most important tree species in Germany using the yield tables collected in SCHOBER (1995) with yield class I. The value level decodes the stand quality (a), and the cost level decodes the accessibility for logging operations (b).

Nettoerlöse für das gesamte Bestandesvolumen in Vfm (Abtriebswerte) berechnet für die vier wichtigsten Baumarten in Deutschland. Beispielhafte Anwendung auf die Ertragstafeln in SCHOBER (1995) mit Ertragsklasse I. Die Wertklasse (value level) repräsentiert die Bestandesqualität (a) und die Kostenstufe (cost level) die Befahrbarkeit (b).

4.3. Effect of different assumptions on the consequences of disturbances

Users should consider the remarkable differences in the influence of the pre-implemented assumptions on the consequences of disturbances on (net) wood revenues found in literature (DIETER, 2001; FUCHS et al., 2022a; FUCHS et al., 2022b; MÖLLMANN and MÖHRING, 2017). These factors, reducing the (net) revenues[9] by 10 % to 50 %, are based on different data sources and assumptions on the disturbance extent and the disturbance agent. For an 80-year-old spruce stand, the net stumpage value without disturbances is 29,967 € ha^{-1} while the corresponding net salvage revenues range between 6,640 and 24,709 € ha^{-1} for the different factors mentioned above. For beech, the net stumpage value for the undisturbed stand is 8,560 € ha^{-1} with corresponding net salvage revenues of 3,149 to 5,725 € ha^{-1}. Such wide ranges of net revenues from salvage harvests underline the fact that users should carefully select the assumed disturbance factors depending on the intended disturbance scenarios in their simulations.

5. DISCUSSION OF LIMITATIONS AND OUTLOOK

The application to yield tables illustrates the importance of considering species, diameter, stand quality, accessibility, and possible consequences of disturbances when deriving net wood revenues. The framework presented here provides parameters for a wide range of valuation problems in bioeconomic simulation modeling and combines models that consistently refer to Hessian data sets. It compiles numerous existing models and data sets while also providing continuous, functional relationships. This is particularly appealing for bioeconomic modeling since the functions can be implemented directly into other R models, are simple to apply, and avoid discontinuities of net revenues over the mean diameter. The latter omits a common source of model artifacts. Nevertheless, users should be aware of the underlying data sources and potential limitations of our approach, which may be of varying importance depending on the intended application.

The data from HessenForst represents the harvests and sales of forest management on 326,320 ha (THÜNEN-INSTITUT, 2015) in the center of Germany, ranging from the low mountains to the Rhine-Main plain. We thus consider the data sets underlying the `woodValuationDE` models to be also representative for forest enterprises in other regions of Germany and Central Europe which have similar production goals and wood supply chains. However, some considerations might limit the transferability to other regions in Central Europe, for example, the Hessian public forests in 2012 were mainly composed of beech (34 %) and spruce (21 %) (THÜNEN-INSTITUT, 2015). The models can be assumed to be representative for typical wood supply chains that depend predominantly on spruce and beech. In contrast, pine and oak covered only 10 % of the entire forest each. The lower volumes of pine are therefore often sold within spruce assortments. The cost and revenue conditions in regions where the economic focus lies on other species could therefore differ from the parameters of our package.

Concerning the harvest cost model, a parameter set for steep slopes is available. However, the assumed conditions might differ from more mountainous stands in the Alps and may not be applicable for costs in special situations such as helicopter logging (e.g. for sanitation fellings in Alpine forests, see FACCOLI et al., 2011). The model may be limited in situations with heterogeneous topographic conditions or stands with exceptionally large diameters. It probably underestimates the costs in diverse mixed stands where more assortments tend to increase the hauling costs. However, it is likely that the estimates are useful for a wide range of stand conditions in the lower mountain ranges. In general, the harvest costs refer to typical logging situations in Germany, usually thinnings and partial final harvests such as shelterwood cuttings. Our harvest costs most likely overestimate, for example, the costs for clear cuttings, where higher harvester productivities can be achieved (e.g. ELIASSON, 2000). Additionally, the costs are influenced by the German taxes[10] and social security payments, which limits the application to other countries.

OFFER and STAUPENDAHL (2018) underline that the assortment tables are designed for applications to entire stands. Strictly speaking, this may restrict applications of the derived functions to harvests of a limited number of trees, which are not representative for the diameter distribution of the entire stand. Practical experience from several comparisons between estimates using the assortment tables and post calculations of larger thinning operations suggests that the deviations are of minor practical relevance. However, particularly the valuation of single trees using our package is most likely biased and cannot be recommended. The average cost and revenue situation of a stand does not reflect the characteristics of each single tree. For example, the assortment tables estimate a composition of numerous assortments for the harvest while the number of different assortments per tree is obviously restricted by the number of logs. Concerning the quality, individual tree characteristics, such as branches, gain in

[9] Some studies refer to revenues, others to net revenues; see the package README for a detailed list.

[10] With regard to the VAT, the regular German rate is assumed in our framework (Regelbesteuerung statt Pauschalierung).

importance at the single-tree level. Thus, approaches based on single-tree simulations (e.g. HANSEN and NAGEL, 2014; PRETZSCH et al., 2002) and taper functions (e.g. KUBLIN, 2003; KUBLIN et al., 2013) may be the better alternative for studies with a higher spatial resolution than the stand level. Future studies based on laser scanning data with detailed information on quality-relevant single-tree characteristics (e.g. HÖWLER et al., 2017) could improve `woodValuationDE` and single-tree valuation models by directly relating the assortments according to the German standard (RVR, Deutscher Forstwirtschaftsrat e.V. and Deutscher Holzwirtschaftsrat e.V., 2020) to a more quantitative (single-tree) quality measure.

The RVR also specifies how raw logs are measured and how volumes are calculated. For example, the actual length of a log has to be 1% (at least 10 cm) longer than the paid length. Such country-specific definitions of wood measurement most likely also affect the revenue model. In addition, users should consider that the actual specifications applied usually depend on the processing technology of the wood buyer, which may result in differences in the valuation standards.

While the applied models were parameterized based on historic data, forest economic simulations often refer to considerably long time periods in the future. Users should perform sensitivity analyses to study the influence of, for example, increasing oil prices, which would increase the fuel wood demand (HÄRTL and KNOKE, 2014) but also harvest costs, or warmer winters with limited accessibility of the stands (cf. RITTENHOUSE and RISSMAN, 2015), which may increase the harvest costs. For such sensitivity analyses, our framework provides the opportunity to change the revenues by updating prices for the reference assortments or to calculate revenues and costs separately. In addition, the `woodValuationDE` framework enables the future implementation of updated parameter sets that take into account current and future developments on the wood markets, e.g. related to increasing fuel wood prices, but also updated assortment tables (based on, a.o., the updated HOLZERNTE 8.2, FVA BW, 2020) and changes in assortment practice (e.g. less important quality differentiation with mixed qualities such as B/C).

Considering the aforementioned limitations and acknowledging that while our framework may provide plausible estimates, it may not cover each specific situation, we encourage the community to integrate this framework as a valuation module in future bioeconomic forest models. It accounts for numerous influences on realistic net revenues for wood, such as tree species, mean diameter, or stand accessibility. Combined with sensitivity analyses, it provides a sound framework, which simplifies the own model development to answer pressing questions on land-use and forest management while integrating realistic indicators for income from wood production – without having to assume rather simple, constant wood revenues per unit volume. The estimated net revenues could, for example, be implemented in Monte-Carlo simulations to estimate economic losses under changing disturbance regimes (KNOKE et al., 2021), to identify climate-adapted tree species portfolios (e.g. FUCHS et al., 2022a), or to improve the valuation of the heterogeneous good wood when deriving the utility provided by ecosystem services (e.g. PAUL et al., 2020). The framework provides a basis, for example, for quantitative assessments of possible effects of different carbon-related policies on land-use or harvest decisions (e.g. RAUTIAINEN et al., 2018) or to derive opportunity costs of management restrictions aiming at nature conservation (JACOBSEN et al., 2013). At the current state, we recommend the use of `woodValuationDE` mainly for scientific applications at the stand or enterprise level. Approaches based on taper functions, such as BDAT (KUBLIN, 2003; KUBLIN et al., 2013) provide an alternative for studies dealing with single-tree based information and official forest valuation problems may require the established, officially recognized estimates of the valuation guidelines (e.g. NMELV, 2019).

Besides the application of our framework, we invite interested researchers and practitioners to derive and contribute their own parameter sets for our functions to improve the applicability to other regions, such as those conditions found in Alpine areas.

6. DATA AND CODE AVAILABILITY

The wood valuation framework is available as the `R` package `woodValuationDE` at CRAN (https://cran.r-project.org/package=woodValuationDE). The newly derived model parameters as well as the parameters of the implemented models are provided by the command `woodValuationDE:::params.wood.value`. We further provide an example for the implementation of the most important functions and user inputs in MS Excel at Zenodo (https://doi.org/10.5281/zenodo.6796526).

7. SUMMARY

The `R` package and wood valuation framework `woodValuationDE` estimates averaged net wood revenues per cubic meter volume over bark based on data from HessenForst (*Figure 1*). In doing so, it simplifies the derivation of realistic wood revenues and harvest costs for Central German conditions and provides a basic module for applications in future bioeconomic forest modeling. Apart from tree species and the mean diameter of the harvested trees, the valuation is sensitive to the logging method, the stand quality, the accessibility for harvesting, market price developments, and conse-

quences of disturbance events (*Figure 3*). This flexibility makes it suitable for a variety of applications. This publication takes a technical perspective to introduce the framework and illustrate the main functions with an application to established yield table models (*Figure 4*, *Figure 5*).

8. ZUSAMMENFASSUNG

Titel des Beitrages: `woodValuationDE`**:** *Ein konsistentes Modell zur Abtriebswert-Berechnung in Deutschland (technischer Leitfaden)*

Das R-Paket und Holzbewertungsmodul `woodValuationDE` schätzt mittlere Nettoholzerlöse pro Vorratsfestmeter basierend auf Daten des Landesbetriebs HessenForst (*Figure 1*). Es vereinfacht damit die Herleitung realistischer Holzerlöse und Erntekosten für Zentraldeutschland und kann als grundlegendes Modul in zukünftige bioökonomische Waldmodelle integriert werden. Neben der Baumart und dem Durchmesser des Grundflächenmittelstamms ist es sensitiv in Bezug auf das Ernteverfahren, die Bestandesqualität, die Befahrbarkeit des Bestandes, Marktpreisentwicklungen und Auswirkungen von Schadereignissen (*Figure 3*). Mit dieser hohen Flexibilität ist es für verschiedenste Fragestellungen geeignet. Dieser Beitrag führt das Bewertungsmodul aus technischer Perspektive ein und wendet die Hauptfunktionen beispielhaft auf Ertragstafeldaten an (*Figure 4*, *Figure 5*).

9. RÉSUMÉ

Titre de l'article: *Un cadre cohérent pour le calcul les valeurs des coupe en Allemagne (note technique).*

Le paquet R et le module d'évaluation du bois `woodValuationDE` permettent d'estimer les recettes nettes moyennes du bois par mètre cube réel du capital sur pied en se basant sur les données du Centre forestier d'Etat du Land de Hesse (*Figure 1*). Cela simplifie ainsi la déduction de revenus du bois et de coûts de récolte réalistes pour l'Allemagne centrale et peut être intégré comme module de base dans de futurs modèles forestiers bioéconomiques. En plus de l'espèce et du diamètre du tronc moyen représentatif de la surface terrière, le module réagit à la méthode de récolte, à la qualité du peuplement, à la possibilité de rouler en véhicule dans le peuplement, à l'évolution des prix du marché et aux effets des événements dommageables (*Figure 3*). Avec cette grande flexibilité il peut répondre aux questions les plus diverses. Cet article présente le module d'évaluation d'un point de vue technique et utilise, à titre d'exemple, les données de tables de production pour tester les principales fonctions de ce module (*Figure 4*, *Figure 5*).

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