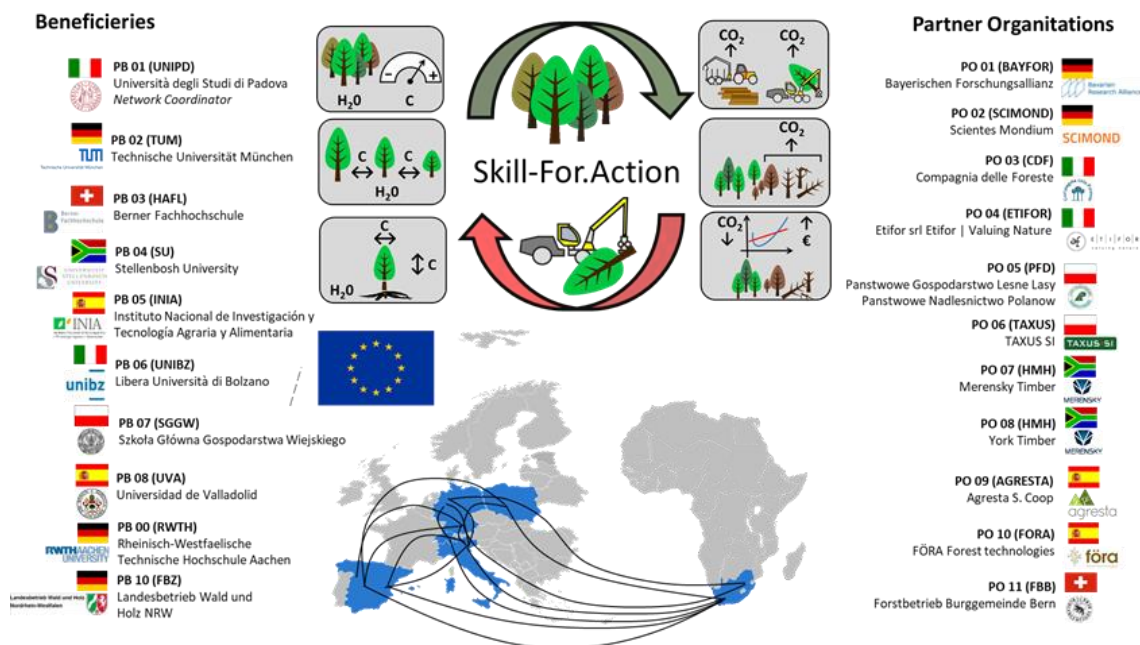


Deliverable	D 3.4	Improved and tested forest growth models
Responsible partner	INIA	Marta Pardos, Rafael Calama.



GA 956355
27.09.2024 | Version 1.0

CLASSIFICATION | PU | Public

The project has been received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement 956355



Contents

1. Background to the report and main objectives	4
2. Review on current existing models	4
2.1. Introduction.....	4
2.2. Answers to the questionnaire.....	4
2.3. Main limitations.....	5
2.4. Main potentialities.....	7
3. Review of forest growth models used in the ESRs.....	10
3.1. Questionnaire.....	10
3.2. Answers to the Questionnaire.....	11
3.2.1. Which are the pre-existing models that you have been using in the framework of S4A in order to estimate C capture?.....	11
3.2.1.1. ESR01- UVa (Spain).....	11
3.2.1.2. ESR02-TUM (Germany).....	11
3.2.1.3. ESR03- SGGW (Poland).....	13
3.2.1.4. ESR04- INIA (Spain).....	14
3.2.1.5. ESR05- SU (South Africa).....	15
3.2.1.6. ESR06- University of Bolzano (UNIBZ, Italy).....	16
3.2.2. Have you detected any shortcoming or limitation in the previously existing models which difficult you to make C capture estimation in your case studies?	17
3.2.2.1. ESR01- UVa (Spain).....	17
3.2.2.2. ESR02-TUM (Germany).....	18
3.2.2.3. ESR03- SGGW (Poland).....	19
3.2.2.4. ESR04- INIA (Spain).....	19
3.2.2.5. ESR05- SU (South Africa).....	20
3.2.2.6. ESR06- University of Bolzano (UNIBZ, Italy).....	20
3.2.3. Have you made any improvement in order to deal with the previous shortcomings?.....	20
3.2.3.1. ESR01- UVa (Spain).....	20
3.2.3.2. ESR02-TUM (Germany).....	20
3.2.3.3. ESR03- SGGW (Poland).....	21
3.2.3.4. ESR04- INIA (Spain).....	22
3.2.3.5. ESR05- SU (South Africa).....	25



3.2.3.6.	ESR06- University of Bolzano (UNIBZ, Italy).....	26
3.2.4.	Have you obtained any output related with this topic?.....	26
3.2.4.1.	ESR01- UVa (Spain).....	26
3.2.4.2.	ESR02-TUM (Germany).....	26
3.2.4.3.	ESR03- SGGW (Poland).....	27
3.2.4.4.	ESR04- INIA (Spain).....	28
3.2.4.5.	ESR05- SU (South Africa).....	28
3.2.4.6.	ESR06- University of Bolzano (UNIBZ, Italy).....	28



1. Background to the report and main objectives

The idea behind this deliverable is first to produce a technical report that integrates a short review on the state of the art of current existing forest growth and yield models in Europe. This review aims to identify the potential shortcomings and restrictions that limits the use of these models for accounting carbon sequestration capacity of European forests, under a general framework of climate change and adaptive management. In a second part of the deliverable we will specifically focus on the forest growth models used in the ESRs, including improvements made in existing models, new models, recommendations on how to use them and their application or implementations.

2. Review on current existing models

2.1. Introduction

The objective of this review was to identify potential capacities and constraints of the current existing growth and yield models in determining biomass and atmospheric C fixation under different conditions of climate, management and current state of the forest. To this aim we launched a questionnaire among different European research groups involved in Skill 4 action project and other close-in-topic European initiatives. These groups were selected as responsible for designing, developing and implementing forest growth & yield models currently in use by different forest managers.

The questionnaire focused on the following topics:

- *General characteristics of the model:*
 - Name and acronym
 - Process based or empiric
 - Basic unit of simulation (tree level, stand, cell...)
 - Temporal step of simulation
 - Spatial explicit or not?
 - Sensitive to climate?
 - Primary outputs of the models
 - How site properties are considered?
 - Do the model represent regeneraiont?



- *Parameterised species*
 - Which species are represented?
 - Validity for simulating mixed stand, and how mixture is considered
- *Management options*
 - Which are the treatments, actions or decisions that can be simulated by your model?
 - Can one configure species-specific preferences of treatment in your model?
 - Can one adjust parameters of the self-thinning limit in your model?

2.2. Answers to the questionnaire

Six research groups, responsible for the design of six forest growth and yield models, responded to the questionnaire. These groups and models are:

- BOKU – University of Applied Life Science (Austria): model PROGNAUS
- ICIFOR – INIA-CSIC (Spain): model PINEA_Mix
- UNITUS-CMCC_CNR (Italy): model 3D-CMCC-BGC
- CNRS (France): model For CEEPS
- IUFOR – University of Valladolid (Spain): model IBERO
- TUM Technical University of Munich (Germany): model SILVA3

A short resume of the responses to the questionnaire is shown in tables 1 – 3. From these questionnaires we have identified the main limitations and potentialities of the models to estimate biomass and atmospheric C fixation in the European Forests.

2.3. Main limitations

- *Empiricity of the models*

Five of the six revised models are empirical ones (3D-CmCC-BGC the exception), thus not including equations to represent processes that happen inside a tree, e.g. sap flow, transpirational flow, photosynthesis or nutrient cycles. This results a main limitation under an environmental changing conditions: while empirical models accurately represents and predicts



tree and stand evolution under current conditions, they fail to simulate the response under future changing climate or nutrient status conditions.

- *Non-spatial models*

Again, five of the six models (SILVA3 the exception) do not consider the spatial position of the trees in the model. Non spatial models present the advantage of simplicity, but at the expense of not being able to represent the real pattern of inter-tree competition. While this approach is largely valid for continuous and homogeneous monocultures (e.g. Eucalyptus plantations) may be invalid for heterogeneous mixed and uneven sized stands. Due to this limitation many of the models, though parameterised for the main part of the European species, are not valid for simulating mixed stands, or the simulations rely on very simple assumptions (assume a mixed stand as independent pure stands)

- *Unit of simulation*

While tree is the unit of simulation most commonly used in European forest growth&yield models, many processes occur at a within tree scale. Crown architecture and position, and root systems development have been identified as crucial factors for determining competition for light and nutrients

- *Temporal extent of the simulation steps*

Simulations are commonly carried in one to five-years steps. While this is a valid scale for practical forest management, and for models including as climate driver annual mean temperature or rainfall, is quite limiting to predict intra-annual processes linked to phenology, earlywood and latewood development and others.

- *Biomass estimates in the outputs*

Some of the models do not consider the tree or plot biomass stock as an output (PROGNAUS, SILVA), relying on estimates on volume. This can be a limitation given the difficulty observed in transforming volume into biomass, depending on Biomass Expansion factors. In addition, volume or biomass of standing dead trees, a main component of the stocks of C stored in the forests, is only considered in model SILVA 3.

- *Site properties*



While many models already include indicators of growth potential based on site attributes (as soil, climate and orography) others still rely on the traditional site index model for considering this. The limitation of the traditional site index model is its inflexibility to adapt to new conditions and the requirement for specific ground measurements, which limits its application at larger spatial scales.

- *Not consideration of the tree regeneration or mortality*

Regeneration is commonly not modelled or included in the models as a fixed heuristic value. In the case of mortality only self-thinning mortality is considered in the models, not including mortality and dieback processes associated with drought or other biotic factors.

2.4. Main potentialities

- *Climate and management sensitive*

The revised European forest growth & yield are mainly sensitive to changing climate and management conditions. This permit to carry out simulation under different climate and management scenarios, at least at a short or medium temporal extent. In addition, these climate and management sensitive models permit to simulate the application of silvicultural practices aiming to adapt forests to climate change.

- *Species parameterised*

Currently, the main part of the species in European forest are parameterised either in the revised forest growth and yield models, or in other models not included in the revision. This permits to have a broad overview on the expected future evolution of European forest ecosystems.

Table 1. General characteristics of the revised models

Model		PROGNAUS	PINEA_MIX	3D-CMCC-BGC	ForCEEPS	IBERO-Ps / IBERO-Pp	SILVA 3
Institution		Boku- University of Applied Life Science	INIA-CIFOR	UNITUS-CMCC- CNR	CNRS	IUFOR- University of Valladolid	Technical University of Munich
Country		Austria	Spain	Italy	France	Spain	Germany
Characte- ristics of the model	Represent processes	No	No	Yes	No	No	No
	Basic unit simulation model	Individual tree	Individual tree	Average tree	Individual tree	Individual tree	Individual tree
	Tree position	No	No	No	No	No	Yes
	Time of simulation	1-year	1-year	day	1-year	5-years	5-years
	Sensitive to climate	Partly	Yes	Yes	Yes	No	Yes
	Outputs	Individual tree size (dbh, height, crown) and volume Stand timber volume Harvested timber volume Bark peeling damage Rockfall damage Harvesting damage Wood quality	Individual tree size (dbh, height, crown) and volume Stand timber volume Harvested timber volume Annual cone production Stocking biomass on different compartments (roots , stem, branches,) and CO2	Growss Net Primaty Production	Individual tree size (dbh, height) Stand composition (relative abundance by species) Annual productivity (biomass increment) for each tree/stand level Stand timber volume and biomass Harvested timber volume	Individual tree size (dbh, height, crown) and volume at each step Stand timber volume Harvested timber volume, classified according end use Stocking biomass on different compartments (root, stem, branches) and fixed CO2.	Individual tree stem and crown size per time step, alive(yes/no), harvested (yes/no) Stand volume Stand volume increment Harvested volume Mortal volume
	Consider site properties	Individual site parameters	Site index Ecological stratification of the study region*	Individual site parameters	Individual site parameters: Bucket (water filled capacity), average nitrogen content in the soil Climatic variables Elevation, latitude, slope Browsing intensity (for tree regeneration)	Site index	Derives growth potential from (1) climate variables like temperature in vegetation period (2) from a moisture index and nutrition index
	Regeneration	Yes - ingrowth model	Not*	No	Yes*	No	Yes

Table 2. Species parameterised in the models

Model		PROGNAUS	PINEA_MIX	3D-CMCC-BGC	ForCEEPS	IBERO-Ps / IBERO-Pp	SILVA 3
Institution		Boku- University of Applied Life Science	INIA-CIFOR	UNITUS- CMCC-CNR	CNRS	IUFOR- University of Valladolid	Technical University of Munich
Country		Austria	Spain	Italy	France	Spain	Germany
(ii) Species paramet erised	Species represented	Picea abies Abies alba Larix decidua Pinus sylvestris Pinus nigra Pinus cembra Fagus sylvatica Quercus spp Other deciduous species	Pinus pinea (dominant) Juniperus thurifera (low proportion) Quercus ilex (low proportion) Quercus faginea (low proportion)	Fagus Sylvatica Pinus sylvestris Pinus nigra Picea abies Quercus cerris Pinus maritima Olea eruopaea Castanea sativa Larix decidua Quercus ilex	Abies alba Larix decidua Picea abies Pinus cembra Pinus uncinata Pinus sylvestris Taxus baccata Acer campestre Acer pseudoplatanu s Other 30 spp	Pinus sylvestris (IBERO-Ps model) Pinus pinaster (IBERO- Pp model)	Spruce Fir Pine Larch Beech Oak Douglas High broadleaved (ash, hacer,a.s.o) Remainder broadleaved (alder, birch a.s.o)
	Non- parameteris ed species/low proportion assigned to other species	Generalised: Quercus species as Quercus spp. Broadleaved species (except Fagus sylvatica & Quercus spp.)	Generalised: Quercus ilex and Quercus faginea as Quercus sp.	Not completely	No	No	Generalized: Quercus petraea and Quercus robur represented by oak Several species represented by gropus high quality broadleaved and remainder broadleaved
	Valid for simulating mixed stands	Yes	Yes	Yes	Yes	No	Yes
	Mixing effects	Independent model for each species Weighted mean for productivity	Interspecific tree level competition*	Interspecific tee-level competition/n eighboring indices Process based approach	Process-based approach: only light	Independent model for each species	Interspecific tree-level competition/n eighboring indices*

Table 3. Management options implemented in the models

Model	PROGNAUS	PINEA_MIX	3D-CMCC-BGC	ForCEEPS	IBERO-Ps / IBERO-Pp	SILVA 3
Institution	Boku- University of Applied Life Science	INIA-CIFOR	UNITUS- CMCC-CNR	CNRS	IUFOR- University of Valladolid	Technical University of Munich
Country	Austria	Spain	Italy	France	Spain	Germany

(iii) Manage ment options in the model	Treatments, actions, decisions, simulated	Any harvesting / thinning treatment*	Thinning from below Selective thinning (theoretically) Systematic thinning Regeneration cut Planting	Systematic thinning Pruning Selection cut Planting	Thinning form below Thing from above Selective thinning Systematic thinning Planting	Thinning from below Thinning form above Systematic thinning	Thinning from above Selective thinning Regeneration cut Planting Other: fostering of future crop trees, selection cut combined with fostering through selective thinning
	Treatment through species- specific preferences	Yes	Yes	Yes	Yes*	No	Yes
	Self-thinning limit adjustment	Yes	Yes	Yes	No*	No	Yes
	Self-thinning limit adjustment per-species basis	Yes	No. Self- thinning only for dominant species (Pinus pinea)	Yes	No	No	Yes

3. Review of forest growth models used in the ESRs

3.1. Questionnaire

Six ESRs (SGGW, UNIBZ, TUM, INIA, UVa, SU) responded to the following questionnaire:

- 1) Which are the pre-existing models that you have been using in the framework of S4A in order to estimate C capture?
- 2) Have you detected any shortcoming or limitation in the previously existing models which difficult you to make C capture estimation in your case studies? (e.g. model not sensitive to climate, mixtures cannot be accurately programmed or simulated, no specific C equations, no mature ages are considered, etc.)
- 3) Have you made any improvement in order to deal with the previous shortcomings (include climate sensitive functions, include specific competition indices taking into account neighbour species, expansion of the models to cover older ages, etc)?
- 4) Have you obtained any output (article, report, congress presentation, software, etc) related with this topic?

3.2. Answers to the Questionnaire

3.2.1. Which are the pre-existing models that you have been using in the framework of S4A in order to estimate C capture?

3.2.1.1 .ESR01- UVa (Spain)

At UVa they have worked on the integration of variables obtained with LiDARS sensors into growth and yield models. They have evaluated advanced methods for mapping tree structural attributes to create detailed baselines for forest carbon biomass. They specifically investigate the combined use of mobile sensors (hand-held laser 25 scanning, HLS) and airborne (unmanned laser scanning, ULS), to estimate biomass and carbon stocks in a Mediterranean mixed forest.

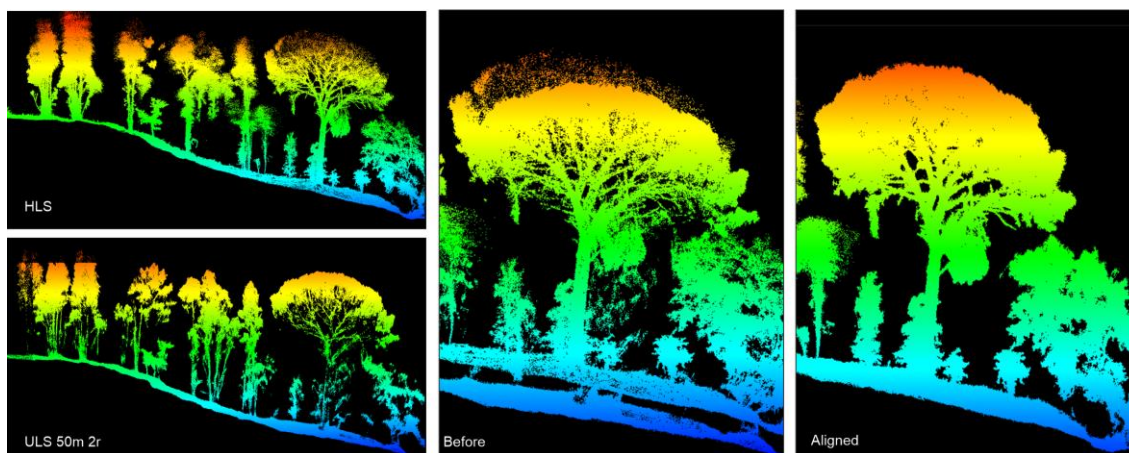


Figure 1. Example of fused point cloud data combining Hand-held Laser Scanning (HLS) and Unmanned Laser Scanning (ULS). The showcase point cloud alignment between ULS and HLS, and for the fused point cloud. (From Tupinambá-Simões et al. 2024).

3.2.1.2 ESR02-TUM (Germany)

In the framework of S4A, the models developed for estimating carbon capture are new models rather than pre-existing growth models. These models were specifically designed to incorporate high-resolution 3D crown structure data into the estimation of tree growth, using tree-ring data to better understand carbon capture dynamics at the individual tree level.

Thus, TUM has focused on developing novel methodologies to more accurately estimate tree growth and carbon capture by integrating advanced forest structure data (e.g., crown shape) and spatial dynamics (e.g., competition) into models.

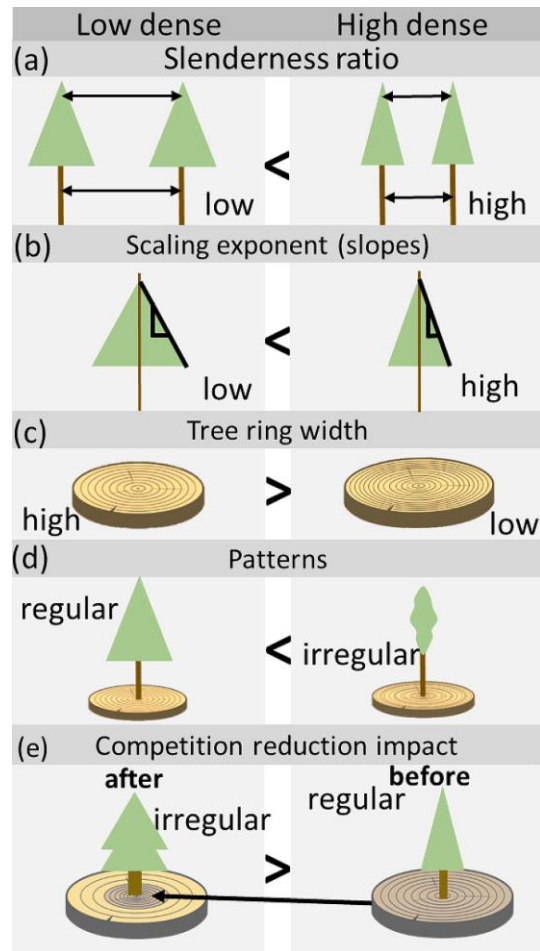


Figure 2. Conceptualized coniferous tree crown developments explain tree ring patterns by folding into polar coordinates, where the Gaussian tree crown growth curve transforms into several tree ring patterns across low-density or thinned and high-density or unthinned stands. (a) Impact of density or competition on crown shape and tree ring patterns (increasing density increases slenderness (cl/cr) coefficient value but decreases plumpness coefficient (cr/cl) and growth) [crown radius (cr) and crown length (cl)]. (b) Crown scaling exponent (slopes of sun exposed crown) components; (c) Ring width variations; (d) regular crown shape and tree ring patterns and irregular crown shape and tree ring patterns in low and high dense stands. A high coefficient of variation (cv) of crown radius (cr) and tree rings (trw) denotes higher irregularity, while a low cv value denotes lower irregularity, indicating more regular crown and tree ring patterns. (e) Competition reduction promotes crown and tree ring growth while creating more irregular patterns due to previous low and current high growth combinations. (From Ahmed and Pretzsch 2023).

3.2.1.3 ESR03- SGGW (Poland)

SGGW used the Polish empirical growth functions for C capture estimation by Jagodziński (2011), supplemented by some other functions for missing tree species such as aspen (Rock, 2007), ash, maple and lime (Bunce 1968, modified by Zianis et al. 2000). These models are based on the following two allometric equations, depending on the tree species (see also Forrester et al. 2017):

$$- \quad Y = a \times X^b \quad (\text{eq. 1}),$$

$$- \quad \ln(Y) = a + b \times \ln(X) \quad (\text{eq. 2}),$$

where,

Y – carbon stock (in kg) in living trees (above and below ground biomass),

X – diameter at breast height (cm),

a, b – species-specific function parameters.

All functions were implemented in the R environment and now serve as scripts for calculating C stock for the given tree and survey year (cf. Fig. 1).

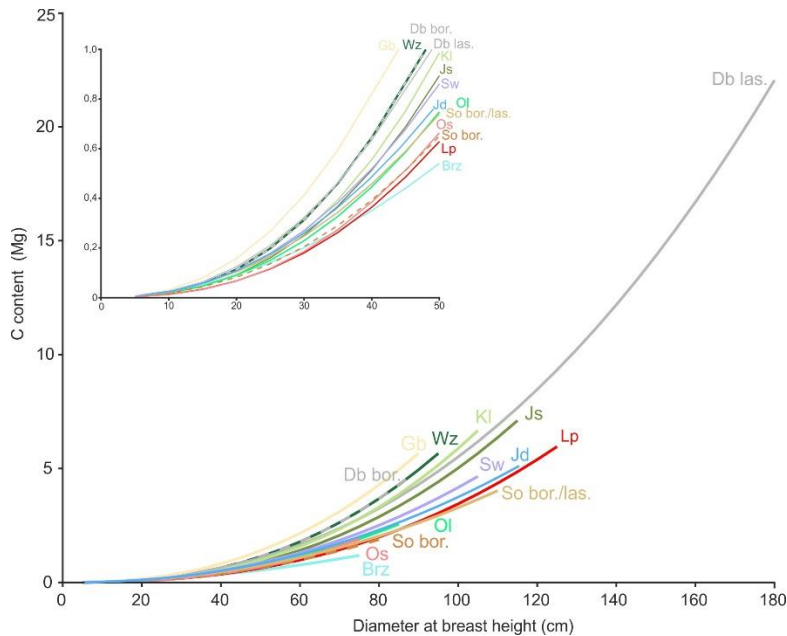


Figure 3. Graphical visualisation of allometric equations used to calculate carbon stock in living trees (above and below ground biomass) calibrated for tree species and soil fertility (pine and oak). Brz, Os, So, ...Db, Gb are Polish tree species abbreviations.

3.2.1.4 ESR04- INIA (Spain)

The main aim of ESR4 is to evaluate whether the adaptation capacity of a single species to compete for limited resources in a mixed forest can determine differences in species composition and distribution. Tree diversity may enhance growth and guarantee stability. However, it seems likely that environmental changes are modifying mixed stands dynamics. The ESR focuses on analysing the water stress and environmental patterns of tree species growing together in terms of radial growth. Results will facilitate improvement of growth and above-ground carbon stock models and simulations to support forest management.

PINEA_MIX, the calibrated version of PINEA model for its use on mixed stands (Calama et al. 2021, Forest Ecology and Management 481, 118782. <https://doi.org/10.1016/j.foreco.2020.118782>) is a tree-level distance independent model, working on annual steps, and climate and management sensitive, with geographic validity in the area of study. The model permits to forecast the evolution of a stand on time, providing outputs as individual tree size, tree volume, biomass, cone production and tree mortality. The model is

parameterised for pure stands of *Pinus pinea* and mixed stands of *P. pinea* (dominant species) with accompanying species *Quercus ilex* and *Pinus pinaster*.

3.2.1.5 ESR05- SU (South Africa)

Pre-existing models have not been used to estimate C capture in our study. Component biomass models have been developed for short rotation *Pinus radiata* stands in the Boland region, South Africa. The developed models have been validated against an independent study (van Zyl 2015 Unpublished) in the Garden Route that is of similar silviculture, age and site productivity, with good comparative results (Figure 5). Our models have also been compared to models developed in a study by van Laar (1978) for a *P. radiata* stand of higher productivity, DBH and age class. This comparison illustrated the extent to which component biomass are overestimated when equations developed for trees of higher productivity, DBH and age class are applied to sites of lower productivity, DBH and age class.

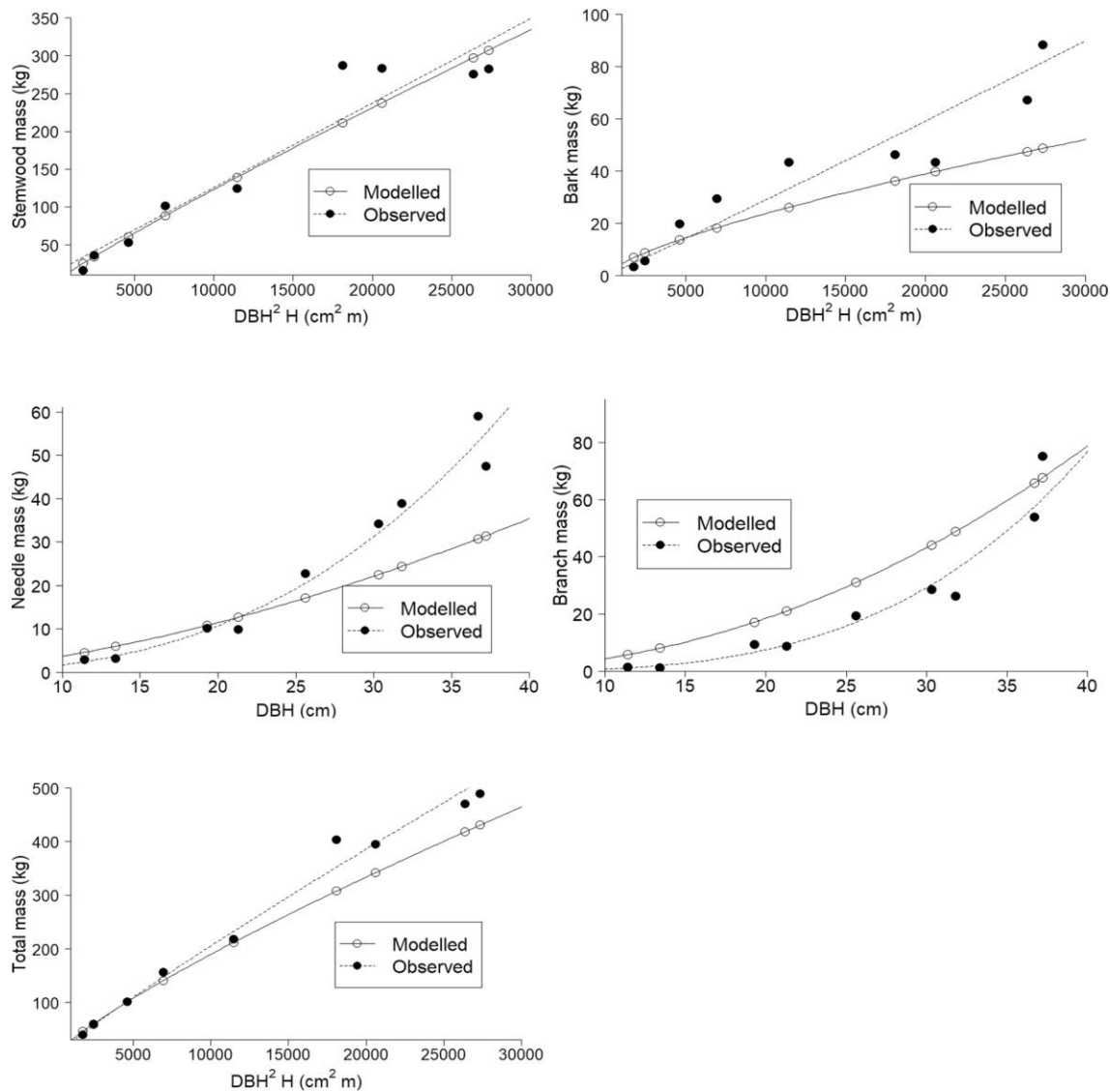


Figure 5. Relationships of the various biomass components of the current study (modelled) in comparison to the biomass components measured by van Zyl (2015) (observed in independent datasets emanating from the Garden Route, South Africa). (From Pienaar et al. 2024).

3.2.1.6 ESR06- University of Bolzano (UNIBZ, Italy)

UNIBZ used linear mixed models to assess the potential effects of elevated N availability on total ring width, mean ring density, and their corresponding earlywood and latewood fractions of

predominantly pure, even aged, Sessile oak (*Quercus petraea* L.) and European beech (*Fagus sylvatica* L.) forest stands, treated with either below or above canopy N fertilization.

Results for basal area increment (BAI) and biomass area increment (BAIden) trends for *Quercus petraea* and *Fagus sylvatica* are shown in Figure 6.

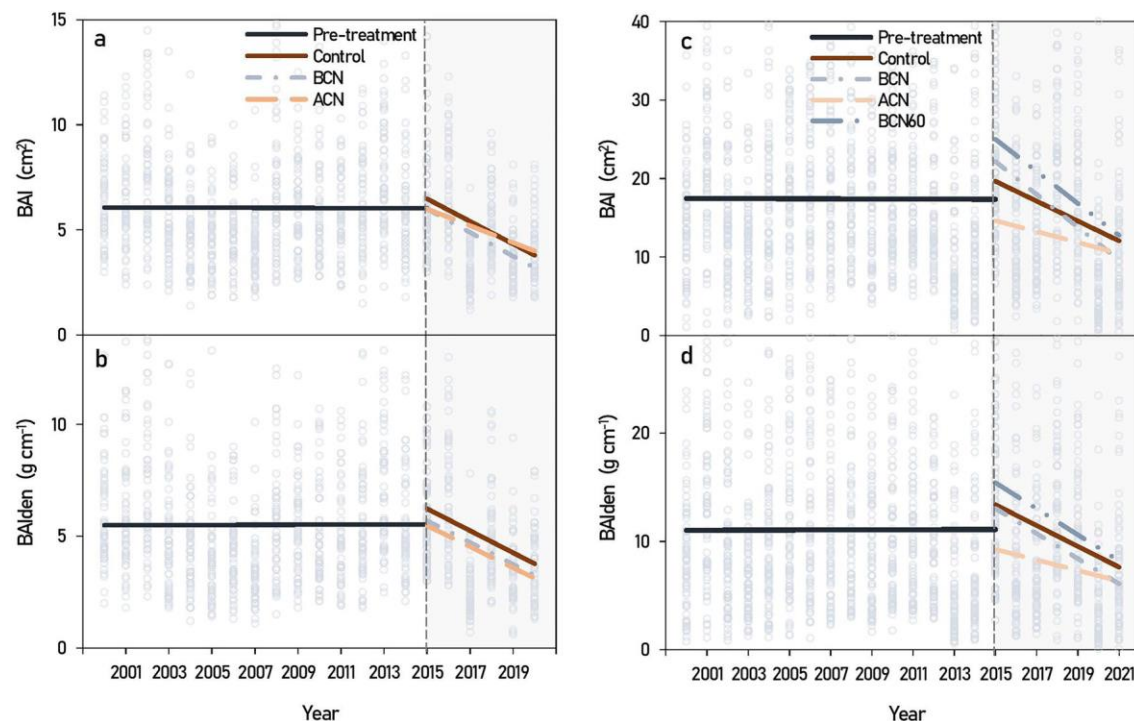


Fig. 6. Basal area increment (BAI) and biomass area increment (BAIden) trends for *Q. petraea* in Monticcolo (a, b), and *F. sylvatica* in Cansiglio (c, d). General patterns for pre-experiment years ($n = 54-60$), and patterns separated by treatment for post treatments years ($n = 16-18$). Dashed line indicates the experiment onset in 2015, with the light gray area thereafter indicating the post-treatment fertilization period (From Minikaev et al. 2024).

3.2.2 Have you detected any shortcoming or limitation in the previously existing models which difficult you to make C capture estimation in your case studies?

3.2.2.1 ESR01- UVa (Spain)

The shortcomings are related the accuracy of laser scanning technologies in estimating above and below-ground carbon stocks.

3.2.2.2 ESR02-TUM (Germany)

Previous growth models for estimating carbon (C) capture indeed had several shortcomings and limitations that made them less applicable or useful for the specific requirements of recent case studies. For example, traditional growth models often relied on classic forest inventory data, such as tree diameter at breast height (DBH) and height, which offered limited insight into the finer structural details of individual trees. Important variables like crown architecture, branching patterns, or 3D crown structure were typically overlooked, even though they play a critical role in understanding tree growth, light interception, and carbon assimilation. This gap hindered the accuracy of carbon capture estimates, especially for species or stands where crown structure strongly affects growth. In addition, many older models required intensive fieldwork or destructive sampling to collect data, particularly for estimating growth rates, biomass, or carbon storage. For example, tree ring analysis and destructive sampling of biomass were often necessary for calibrating models, making the process both labour-intensive and time-consuming. This inefficiency posed a challenge when trying to apply these models to large forest landscapes or when aiming for frequent, real-time data updates. Besides, earlier models frequently lacked species-specific or context-specific carbon equations tailored to different forest types, ages, or management regimes. This made it difficult to estimate carbon capture accurately for a wide variety of ecosystems, particularly in heterogeneous landscapes with species-specific growth traits and carbon storage capacities. Most conventional models did not account for long-term growth variability or shifts in growth trajectories due to factors such as stand development, resource availability, or changes in competition dynamics. This resulted in less reliable projections for carbon capture over extended periods, particularly when forests matured or underwent significant structural changes.

These limitations necessitated the development of new models, like those in the framework of S4A, which incorporate high-resolution 3D crown structure data, more efficient data collection

methods (e.g., non-destructive approaches like TLidar), and an ability to handle more complex forest interactions such as species mixtures and the effects of competition. These advancements help produce more accurate and detailed estimates of carbon capture across different forest types and conditions.

3.2.2.3 ESR03- SGGW (Poland)

They have observed that the above functions overestimate C content for large trees. Such large trees are quite common in our data set. We have, for instance, silver fir with dbh up to 140 cm.

3.2.2.4 ESR04- INIA (Spain)

Several limitations prevent the use of PINEA_MIX for the aim of the research dealt in ESR4:

The case study of ESR04, “Mixed forests in Spanish Northern Plateau”, includes pure and mixed forests of the three mentioned species, together with *P. pinaster*. Current model PINEA_MIX do not take into account the main 4th species, *Pinus pinaster*.

PINEA_MIX was calibrated only using pure or mixed stands dominated by *Pinus pinea*, without special attention to pure stands of the *Quercus* or *Juniperus* species.

PINEA_MIX is not a spatially explicit model, but a distance independent one. This results in the impossibility for decomposing the competition suffered by a subject tree into the component of competition due to conspecific and the competition due to other species.

Detailed analysis of the use of resources by the different species and its allocation to growth and biomass increment require intra-annual measurements and predictions, permitting to identify patterns in the temporal occurrence of phenological stages as the spring and fall growth initiation, or summer and winter growth cessation.

3.2.2.5 ESR05- SU (South Africa)

There are currently no published allometric equations for short/mid rotation *P. radiata* stands. Previously published allometric equations are for *P. radiata* stands of a more mature age (29 years old) and higher site productivity and not appropriate to estimate biomass for stands of younger age.

3.2.2.6 ESR06- University of Bolzano (UNIBZ, Italy)

The lack of adequate attention to repeated measure/autocorrelation effects that seemed missing in many of the literature about dendrochronology in general, and nutrient related in particular. Additionally, the vast growth/C capture estimations in the literature that rely mostly on radial growth/BAI, and often leave out the outmost important intrinsic density measurements. Radial growth and wood density are not always coupled, therefore models relying only on BAI without taking density into account might result in under/over estimation of actual biomass changes/predictions.

3.2.3. Have you made any improvement in order to deal with the previous shortcomings?

3.2.3.1 ESR01- UVa (Spain)

Improving the accuracy of laser scanning technologies can benefit the estimation of structural properties on above and below-ground stocks. Thus, it is important to understand how varying flight altitudes and scanning modes of ULS can affect the accuracy and precision of biomass and carbon stock estimates in forests. The measurement error ranges for HLS in tree detection were investigated, along with these errors influence the overall biomass and carbon stock estimates.

3.2.3.2 ESR02-TUM (Germany)

They addressed previous shortcomings by developing non-destructive, 3D crown shape-based models that are less time-consuming and more accessible to key variables. Our models integrate stand-level and neighbourhood competition, account for long-term growth history, and include climate-sensitive functions. We incorporated specific competition indices that consider neighbouring species, improving the accuracy of growth predictions. Additionally, our models are expanded to cover different tree sizes, ages, species, social classes, and varied growth conditions, making them more versatile and suitable for a broader range of forest types, including older stands. These improvements result in more advanced and efficient growth models for carbon capture estimation.

3.2.3.3 ESR03- SGGW (Poland)

Based on a very broad dataset by Grundner and Schwappach tables (1952) consisting of full tree volume and merchantable volume for the same trees, we are going to fit the functions for expunction species-specific factors: full tree volume/ merchantable volume~ tree diameter and/or height. Then, use density and finally come to the biomass and by multiplying by 0.5 to C content. We observe that the allometry relationship between merchantable volume and full tree volume is very stable, and the Polish empirical growth functions work quite well also for large trees.

References

Bunce, R. G. H. 1968. Biomass and Production of Trees in a Mixed Deciduous Woodland: I. Girth and Height as Parameters for the Estimation of Tree Dry Weight. *Journal of Ecology*. Vol. 56 (3): 759-775.

- Forrester, D. I., Tachauer, I. H. H., Annighoefer, P., Barbeito, I., Pretzsch, H., Ruiz-Peinado, R., Sileshi, G. W. 2017. Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. *Forest Ecology and Management*, 396, 160–175.
- Jagodziński, A., 2011. Wyniki – retencja węgla w biomasie drzew i drzewostanów. W: Raport Końcowy z Realizacji Tematu Badawczego: Bilans Węgla w Biomasie Drzew Głównych Gatunków Lasotwórczych Polski. Kórnik.
- Jagodziński, A. M., Dyderski, M. K., Gęsikiewicz, K., Horodecki, P. 2019. Effects of stand features on aboveground biomass and biomass conversion and expansion factors based on a *Pinus sylvestris* L. chronosequence in Western Poland. *European Journal of Forest Research*, 138(4): 673–683.
- Grundner, F., Schwappach A. 1952. Massentafeln zur Bestimmung des Holzgehaltes stehender Waldbäume und Bestände. Verlag Paul Parey, Berlin
- Rock, J. 2007. Suitability of published biomass equations for aspen in Central Europe—Results from a case study. *Biomass and Bioenergy*: 31(5), 299–307.
- Zanne, A.E., Lopez-Gonzalez, G., Coomes, D.A., Ilic, J., Jansen, S., Lewis, S.L., Miller, R.B., Swenson, N.G., Wiemann, M.C., and Chave, J. 2009. Global wood density database. Dryad. Identifier: <http://hdl.handle.net/10255/dryad.235>.
- Zianis, D., Muukkonen, P., Mäkipää, R., Mencuccini, M., 2005. Biomass and stem volume equations for tree species in Europe. *Silva Fennica Monographs* 4: 1-64.

3.2.3.4 ESR04- INIA (Spain)

In the development of the activities linked with ESR04 objectives, we have made significant advances that can be easily implemented in order to improve previous existing models. To attain these advances first a net of plots in pure and mixed stands of the four tested species were installed, past annual increments were obtained through increment cores and band and

electronic dendrometers were installed in a sample of trees (see Jankowski et al. 2022 for more details into the experimental design). The main improvements made were:

a) Assessing the impact of competition – composition on growth and tree resistance to drought

The impact of intra- and inter-specific competition in growth and tree resistance to drought was assessed by the computation of Hegyi competition index, which represent the sum of the competition exerted by the n competing trees over the i th subject tree, and was computed for each tree and year for the studied period 1996-2021. The index was splitted into two components for consider inter and intraspecific competition. Generalized linear mixed models (GLMM) permitted to test different hypothesis aiming to evaluate how the response of trees in terms of growth depends on stand composition, species identity, the spatial position of the competitors and intensity of drought. A differential response was detected depending on the identity of the subject species and the identity of the competitors (Figure 7). The main finding indicates that *P. pinea* enhances growth and resistance to drought in mixtures, while the general performance of *P. pinaster* is aggravated when mixed with other species. Juniper is more resistant to drought if located in the understorey of pines, but its growth is inhibited. Finally, *Q. ilex* is largely indifferent to stand composition.

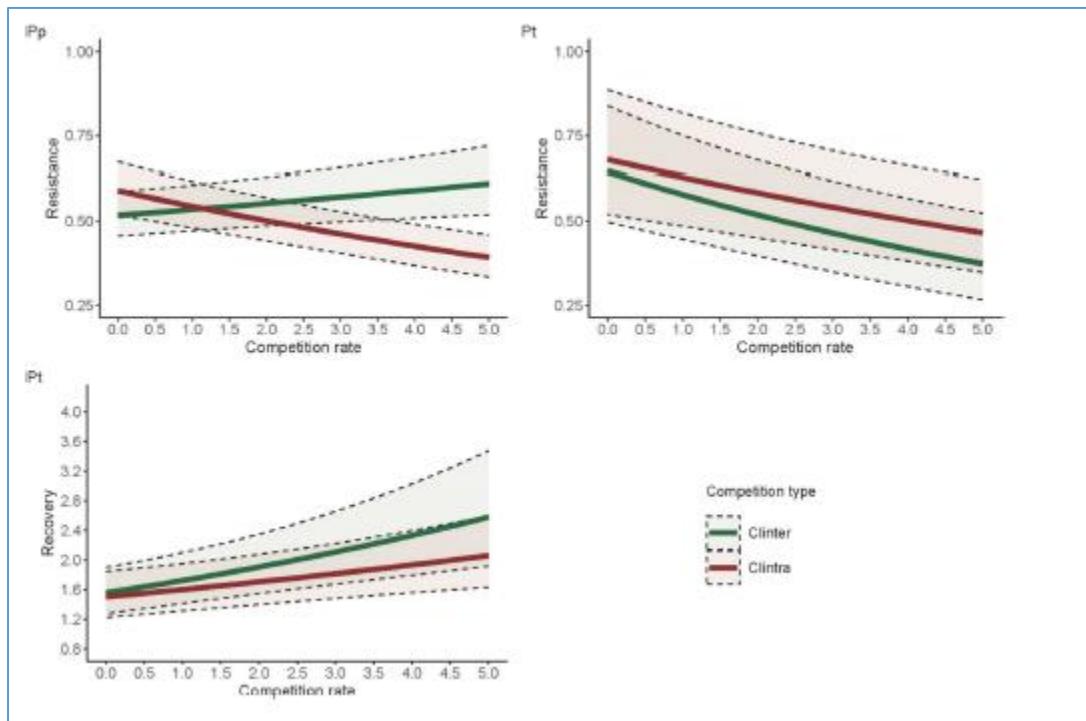


Figure 7. Impact of inter- and intra-specific competition on the resistance, resilience and recovery to growth for *Pinus pinea* (Pp) and *Pinus pinaster* (Pt). Source: Jankowski et al. 2024

b) Analysis of intraannual growth dynamics in pure and mixed stands

Classical forest growth and yield models, based on an annual step of simulation, do not succeed in capturing the typical Bi-modal pattern of intra-annual growth of the trees in the Mediterranean environments: growth in spring and autumn, constrained in summer and dormancy in winter. In the ESR04 research we have used data of girth increment from band dendrometers, recorded quarterly, to determine the impact of composition-competition-climate on seasonal growth, cumulative growth and phenology. Statistical approach is based on linear mixed models including daily radial increment as response variable. The main results point to an anticipated phenology and enhanced seasonal and cumulative growth in *P. pinea* when mixed with *P. pinaster* (Figure 8). Daily radial increment is associated with rainfall events (positively) and maximum temperatures (negative) occurring in the two previous weeks.

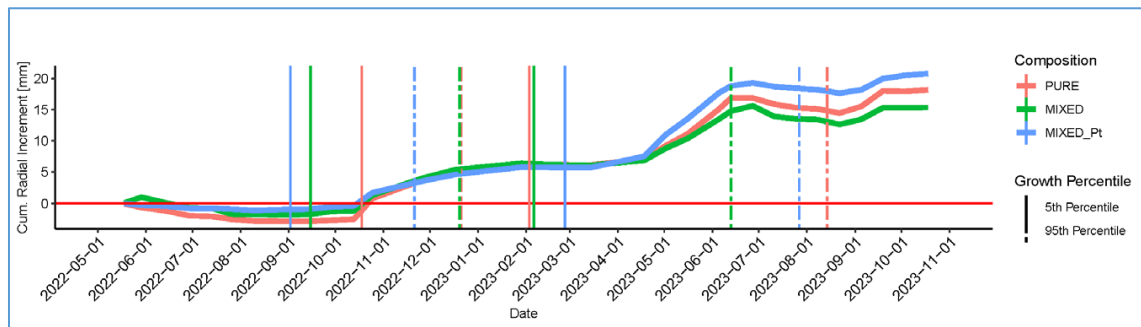


Figure 8. Cumulative annual growth for *P. pinea* growing on pure, mixed and mixed with *Pinus pinaster* stands. Source: Jankowski et al. 2023a.

c) *Synchrony of growth depends on climatic conditions differently across stand types*

While the classical growth models estimate the growth of single trees, species, etc. in absolute terms, they do not quantify how synchronous the reaction of single trees within pre-defined group (species, stand type, etc.) to external conditions was. That knowledge is extremely important, as more synchronous reaction to a stressor means higher susceptibility to disturbances. ESR04 developed GLMMs which uncovered, that the synchrony of studied Mediterranean species depends on winter-early spring water balance and autumn temperatures, that dependence being variable across stand compositions. The model showed that *Quercus ilex* and *Pinus pinaster* synchrony was decreasing faster in mixed stands along with improving spring's water balance. *Juniperus thurifera* and *Pinus pinea* showed the opposite pattern, their synchrony increasing faster in mixed stands with higher water supply during spring.

3.2.3.5 ESR05- SU (South Africa)

A range of component biomass models have been developed in our study, making use of a range of stand variables. The models developed in the study of van Laar (1978) make use of only DBH as independent variable, whereas the best models of our study include DBH and H, making them more transferable to other sites of different DBH and H allometry.

3.2.3.6 ESR06- UNIBZ (Italy)

No improvements have been reported.

3.2.4. Have you obtained any output related with this topic?

3.2.4.1 ESR01- UVa (Spain)

Tupinambá-Simões F, Pascual A, Guerra-Hernández J, Ordóñez C, de Conto T, Bravo F. Assessing the Performance of a Handheld Laser Scanning System for Individual Tree Mapping—A Mixed Forests Showcase in Spain. *Remote Sensing*. 2023; 15(5):1169. <https://doi.org/10.3390/rs15051169>

Tupinambá-Simões, F., Pascual, A., Guerra-Hernández, J. et al. Accuracy of tree mapping based on hand-held laser scanning comparing leaf-on and leaf-off conditions in mixed forests. *J. For. Res.* 35, 93 (2024). <https://doi.org/10.1007/s11676-024-01747-1>

Tupinambá-Simões, F., Pascual, A., Guerra-Hernández, J. et al. 2024. Combining Hand-Held and Drone-Based LiDAR for Forest Carbon Monitoring: Insights from a Mediterranean Mixed Forest in Central Portugal. *EJFR* (in press).

3.2.4.2 ESR02-TUM (Germany)

They have already produced four papers on this topic, with three published and one currently under review in very high impact journals. In addition, our research has been presented at various national and international conferences and meetings, showcasing its relevance and impact. To further advance the topic, we are now working on new hypotheses, aiming to deepen our understanding and refine our models for even greater accuracy in growth and carbon capture estimation.

Published and submitted papers:

Ahmed S, Hilmer T, Uhl E, Tupinambá-Simões, Bravo, F, del Rio M, Pretzsch H (2024). Crown structure as a predictor of long term tree rings growth: Coniferous species outperform broadleaves in European dominant species. *Science of The Total Environment* (Under review).

Ahmed S, Hilmers T, Uhl E, Jacobs M, Bohnhorst L, Kolisnyk B, del Rio M, Pretzsch H (2024). Neighborhood competition modulates the link between crown shape and tree ring variability in monospecific and mixed forest stands. *Forest Ecology and Management*, 560, 121839. <https://doi.org/10.1016/j.foreco.2024.121839>.

Ahmed, S., & Pretzsch, H. (2023). TLidar-based crown shape indicates tree ring pattern in Norway spruce (*Picea abies* (L.) H. Karst) trees across competition gradients. A modeling and methodological approach. *Ecological Indicators*, 148, 110116. <https://doi.org/10.1016/j.ecolind.2023.110116>

Pretzsch, H., Ahmed, S., Jacobs, M., Schmied, G., & Hilmers, T. (2022). Linking crown structure with tree ring pattern: methodological considerations and proof of concept. *Trees*, 36(4), 1349-1367. <http://dx.doi.org/10.1007/s00468-022-02297-x>

Conference paper and presentation:

Ahmed S, Enno, U, Bravo, F, Pretzsch H. Unveiling the internal patterns: Linking external crown shape and internal Wood traits of trees by using artificial intelligence. Conference on Artificial Intelligence and Ecosystems Management, Palencia, Spain (18th April 2023) (Presentation)

Ahmed S. ITN Researchers Mobility and S4A experience. ASFORCLIC conference, RMendel University in Brno, Czech Republic. 10th February 2022 (Online) (Presentation)

Quantifying the link between crown shape and tree ring patterns: Understanding the impact of competition. INIA, Madrid, Spain. 4th April 2023 (Invited talk)

3.2.4.3 ESR03- SGGW (Poland)

Not yet. This will be implemented and reported early next year.

3.2.4.4 ESR04- INIA (Spain)

Jankowski PA, Calama R, Madrigal G, Pardos M. 2022. Mecanismos de complementariedad temporal en distintas mezclas de especies en el ámbito mediterráneo. *Poster presentation*. II Simposio del Pino Piñonero. Valladolid (Spain), 1-2 June 2022.

Jankowski PA, Calama R, Madrigal G, García M, Pardos M. 2023a. Enhancing *Pinus pinea* intra-annual growth dynamics in mixed species stands on the Spanish Northern Plateau—preliminary results. PINEA SPOT congress. *Oral presentation*. Lisbon (Portugal) 21-23 November 2023.

Jankowski PA, Calama R, Madrigal G, García M, Pardos M. 2023b. Influencia de la complementariedad espacio-temporal en la respuesta interanual del crecimiento de árboles frente a la sequía en masas mixtas y puras de la Meseta Norte de España. XVI Congreso Nacional de la AEET (Asociación Española Ecología Terrestre). Almería (Spain). 16 - 20 October 2023.

Jankowski PA, Calama R, Madrigal G, Pardos M. 2024. Enhanced interannual drought resilience in mixed stands: unveiling possible complementarity effects between tree species of the Spanish Northern Plateau. *European Journal of Forest Research* <https://doi.org/10.1007/s10342-024-01685-x>

3.2.4.5 ESR05- SU (South Africa)

Pienaar, L.O., Calama, R., Olivar, J. et al. Allometric equations for biomass and carbon pool estimation in short rotation *Pinus radiata* stands of the Western Cape, South Africa. *Eur J Forest Res* (2024). <https://doi.org/10.1007/s10342-024-01730-9>

3.2.4.6 ESR06- University of Bolzano (UNIBZ, Italy)

Minikaev, D., Ventura, M., Tonon, G. et al. Canopy nitrogen application effects on *Quercus petraea* L. and *Fagus sylvatica* L. ring width and wood density. *Eur J Forest Res* (2024). <https://doi.org/10.1007/s10342-024-01693-x>