
Forest biodiversity and structure modulate human health benefits and risks

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REFERENCES

FIGURE S1

Introduction

This documentation complements the paper: “*Forest biodiversity and structure modulate human health benefits and risks*”, and the respective Bayesian Belief Network (BBN) that underpins the results. As full access to the actual BBN is only possible after installing Netica, the software that was used, this document is appended to ensure maximal transparency and model interpretability.

Here, one will find a general methodological summary, followed by an overview of common nodes (i.e. variables in BBNs), each submodel, and the reasoning behind choices related to every of its constituting nodes, causal links and state thresholds.



This synthesis integrates data from a set of studies conducted under the banner of **Dr.FOREST** (*‘Forest diversity affecting human health and wellbeing’*) an international project that ran from 2020 to 2024.

For additional information, including the raw data and logbooks with further details and discarded variables, please contact Loïc Gillerot: loic.gillerot@ugent.be

Pictures were taken during the forest experiment on mental wellbeing and thermal comfort.



Simplified methodology

BBN development started in January 2021 in parallel to ongoing research on the multiple forest-health pathways studied in Dr.FOREST. As new data, results and insights were generated, submodels were updated. Model development was partitioned into three phases that were centered around Dr.FOREST's annual meetings, when protocols for each phase were presented and discussed.

During the second annual meeting (February 2022), the common dendrometric nodes (p. 11) and their range and state thresholds were defined during a group discussion involving all partners, representing a group of experts in forest ecological interactions.

Phase I: Conceptualising submodels

- Based on the Ecosystem Services Cascade framework (p. 6), partners developed submodels for their respective pathway based on current theoretical knowledge.

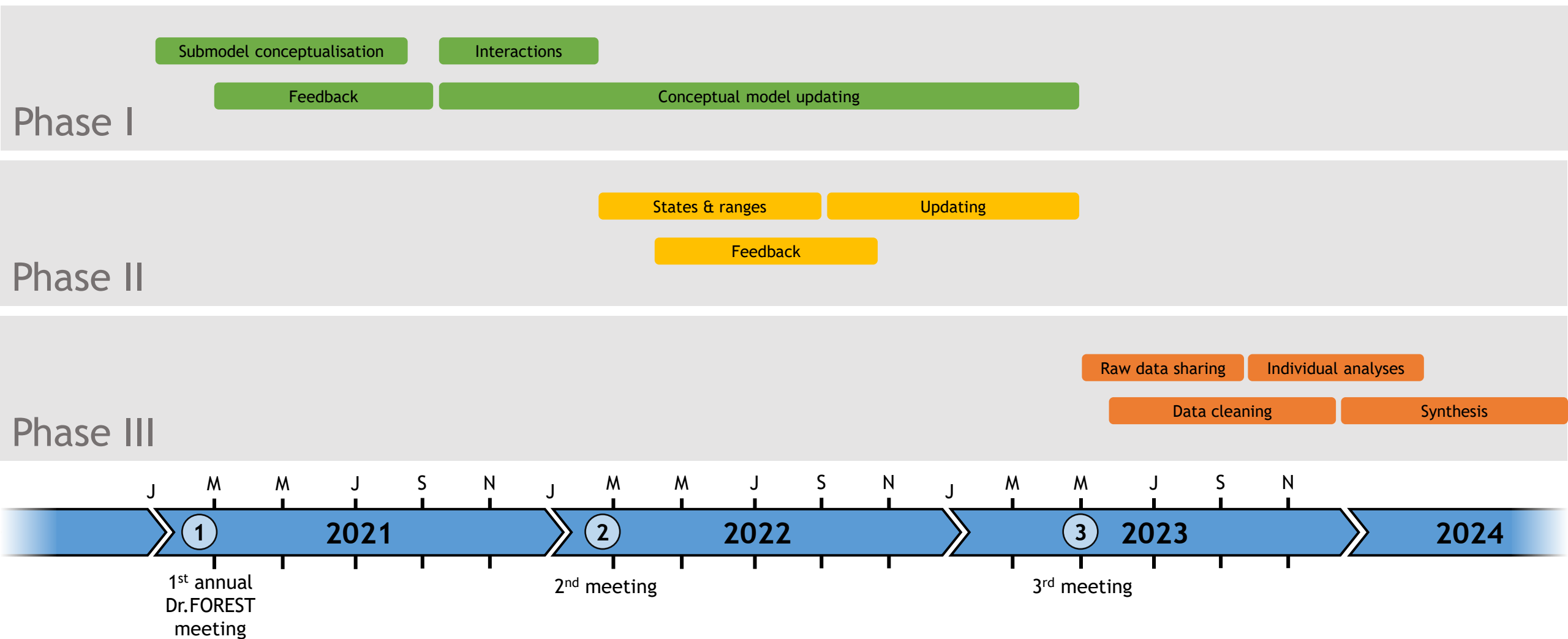
Phase II: Quantifying node states and ranges

- During group discussions, partners were encouraged to explore potential interactions among submodels.
- Based on incoming empirical data, partners updated their conceptual model, defined the potential node ranges and the possible states they could reach (p. 7).
- State thresholds were ideally based on management guidelines, key figures from literature or logical argumentation.

Phase III: Quantifying probabilities

- Per node, partners defined adequate data types using the decision tree to guide their choice (page 8). Partners then formatted and shared respective data types to quantify probabilities.
- Submodels were joined together, paying particular attention to the interactions among models.

Simplified timeline

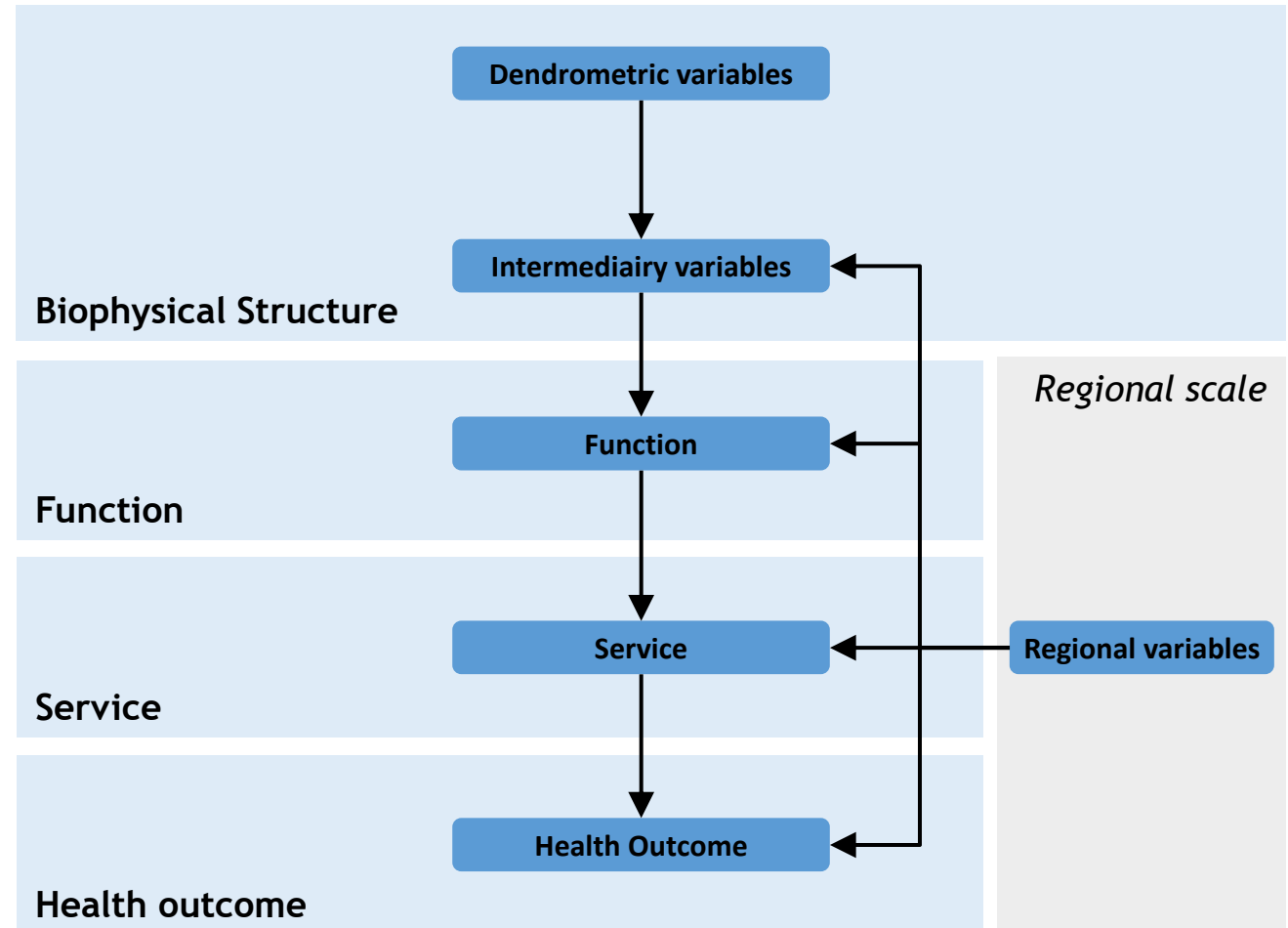


Phase I: conceptual framework

The framework that was used to disentangle forest-health associations into causal, mechanistic pathways is the Cascade Model by Haines-Young et al. (2010), which was adapted in the context for BBNs by Landuyt et al. (2013) and then specified for health outcomes in the context of the current study.

This adapted model is illustrated on the right. It states that variables related to the biophysical structure of the ecosystem (description of ecological characteristics) will influence the variables defining its functioning (capability of the ecosystem to do something potentially useful to people), which will determine its (dis-)services (does not exist in isolation from people's need), which will ultimately defining health outcomes (measurable impact on human health). We further distinguish variables acting at the forest stand scale (blue) from the regional, non-forest variables (grey).

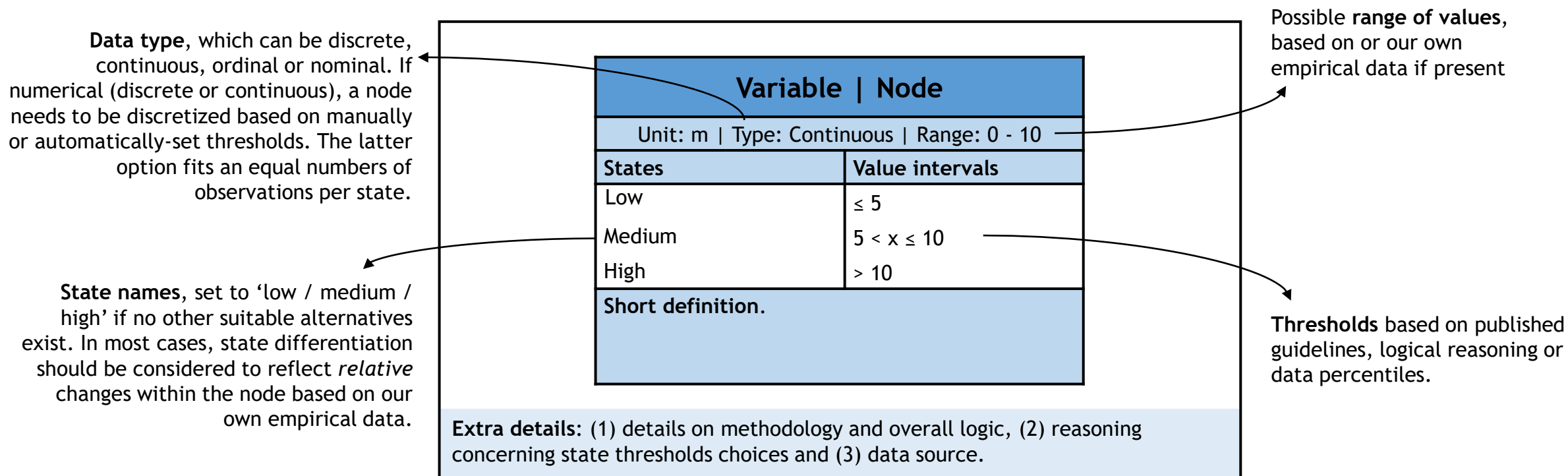
The different model stages should be considered as aids to disentangle mechanisms rather than clear-cut categories. In some cases, especially the distinction between functions and service is slightly ambiguous.



Phase II: states & ranges

In BBNs, the variables constituting the model are called nodes. Nodes have different states they can be in, which can be categorical, ordinal or discretized continuous. Underlying Conditional Probability Tables (CPTs) determine the probabilities of the node being in one of the given states.

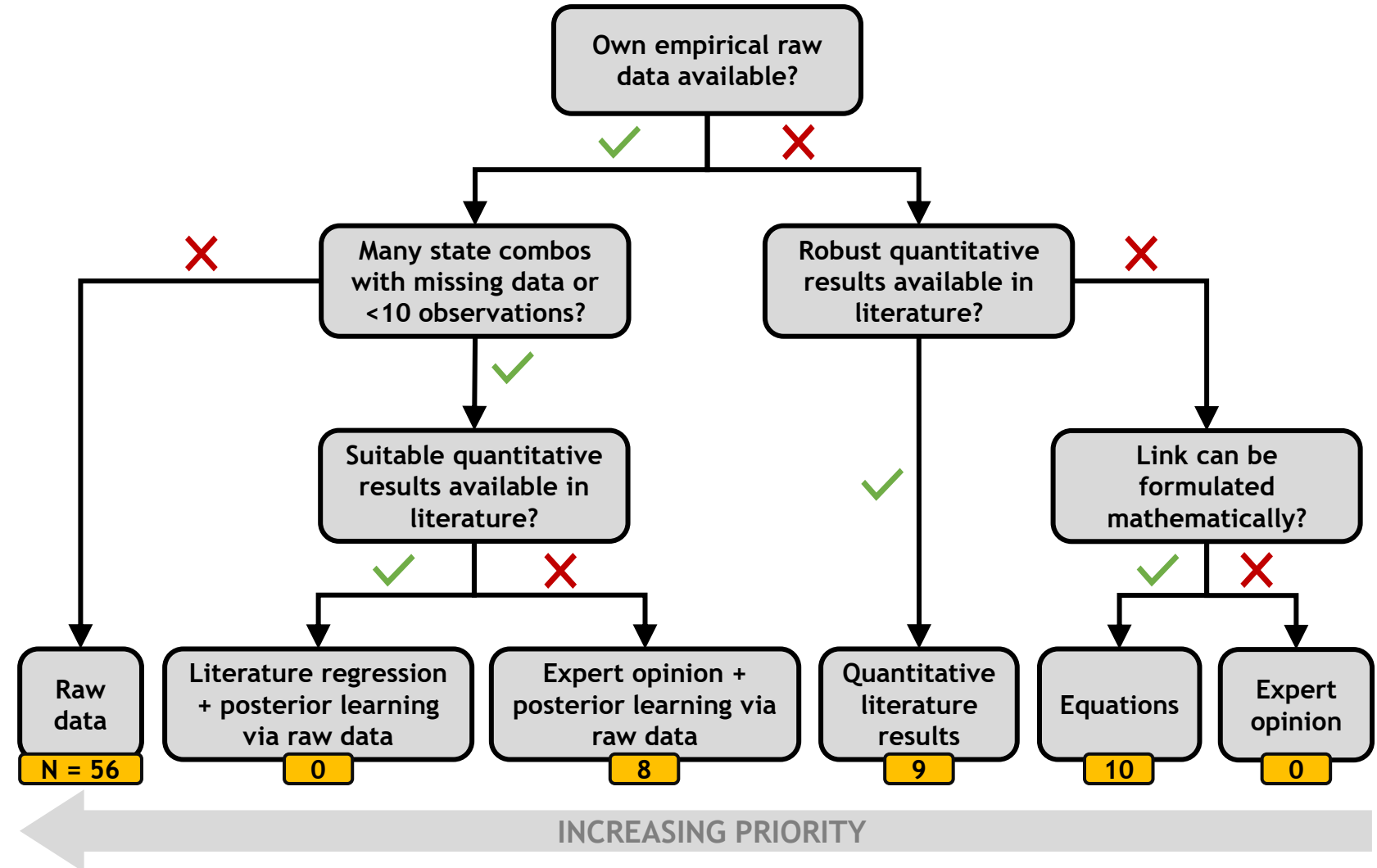
Shown below is a fictitious node to explain the format used throughout this document:



Phase III: decision tree

Partners were asked to follow the decision tree to identify the most suitable data source for each node in their submodel. Whenever possible, priority was given to our own empirical data, which represents the vast majority of nodes in the final model. Yet, when empirical data was not robust enough, it could be combined with results from literature or with expert opinion. When empirical data was not available at all, probability quantification could rely on literature regressions, key figures, logical equations or expert opinion alone.

In the yellow boxes is the number of nodes per category in the final model. The total number of nodes is 83.

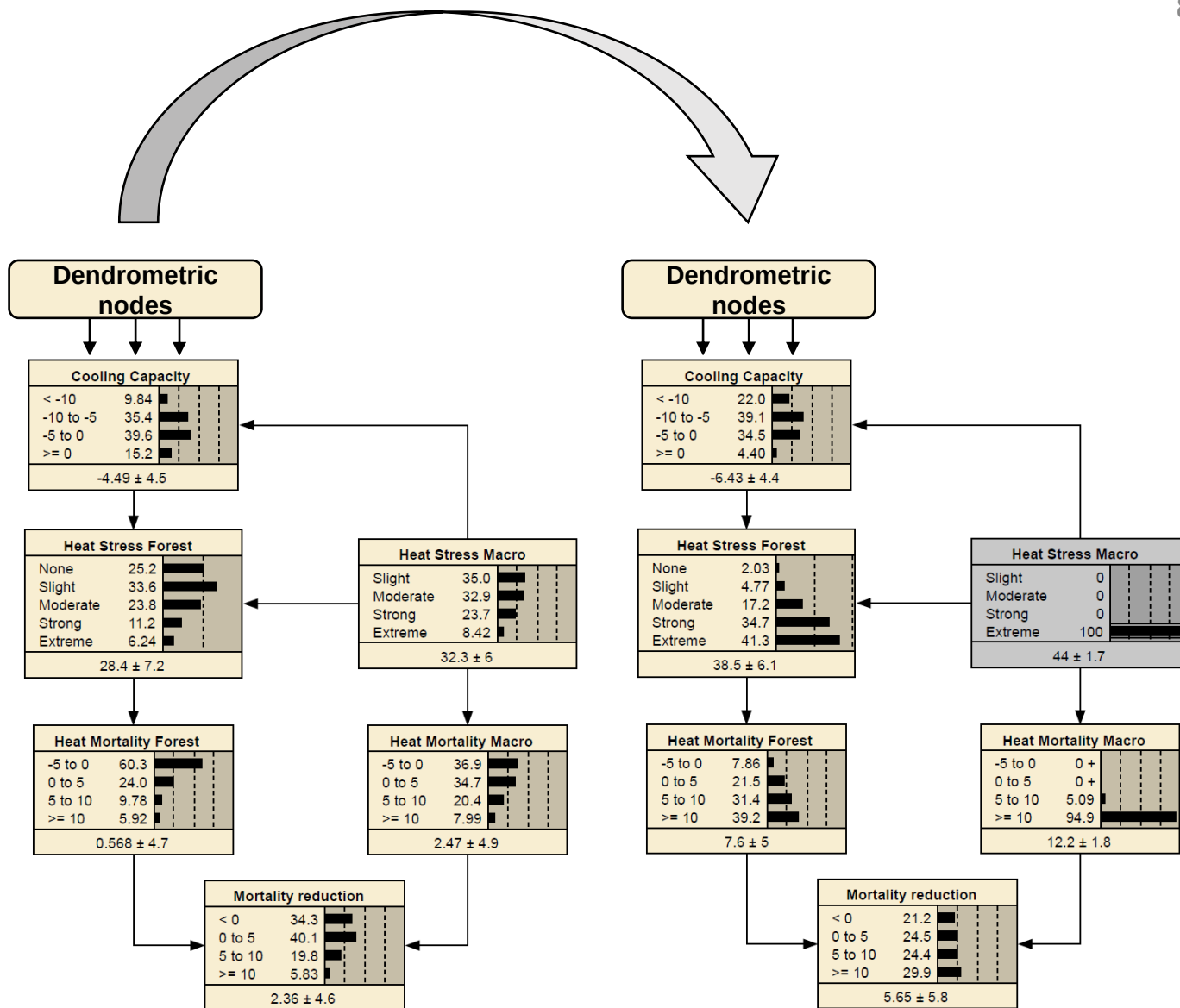


Example in Netica

Here is a concrete example from a simplified BBN submodel on forests and human heat stress. Pale yellow boxes are the nodes, connected by causal links. Each node has multiple states. The reasoning behind state thresholds is given later in this document. Each node has a certain probability distribution, represented by black bars and percentages, which always add up to 100%.

The BBN on the left reflects the empirical raw data and literature data used to quantify it. An example interpretation: ‘given average probability distribution in all nodes based on the raw data, the expected mortality reduction is $2.36 \pm 4.6\%$ ’.

The BBN on the right illustrates what happens if a node is set on a particular state (‘instantiated’). Now the interpretation becomes: ‘conditional on extreme macroclimatic heat stress and average probability distributions in other nodes, the mortality reduction is $5.65 \pm 5.8\%$ ’. In other words, the warmer it gets outside the forest, the stronger the buffering effect of the forest and the higher the mortality reduction. Notice that this change in one node changes the probability distributions of all other connected nodes.



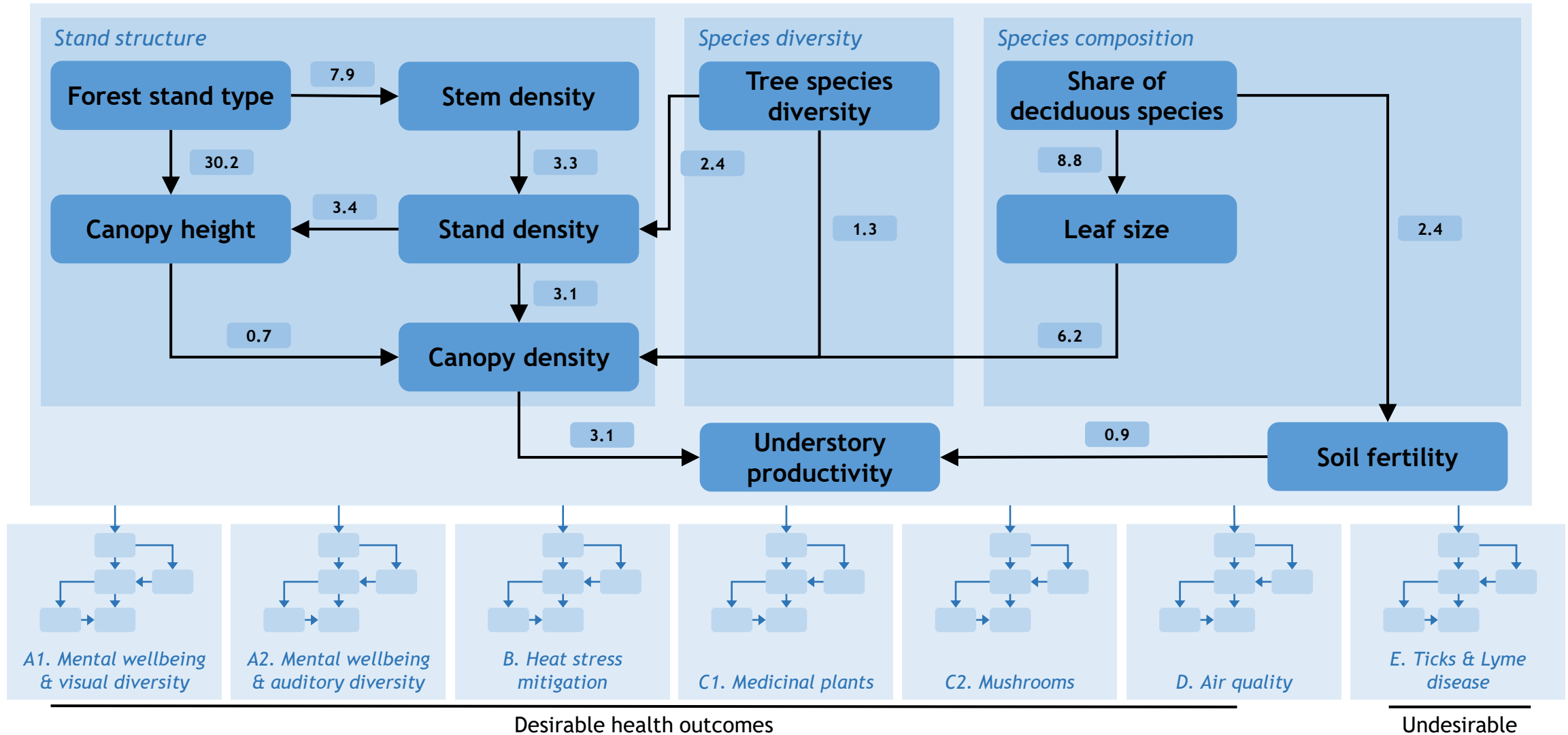


MODEL OVERVIEW

& biophysical nodes shared by multiple models

Common nodes

This common structure, its constituting nodes, causal links and state partitioning, are based on group discussions with forest ecology experts and represent current knowledge in forest ecological interactions. These 10 nodes are all exclusively operationalised using empirical raw data. Data from the Dr.FOREST network was complemented with data from similar international forest networks: FORMICA (n = 225 plots; Vanneste et al. 2024) and TREEWEB (n = 53; De Groote et al. 2017). Numbers represent the share of variance explained by a given relationship, expressed in %.



Submodel overview

Below is an overview of each of the seven submodels, and the group of experts that developed them. Put simply, each model represents the essence of a doctoral research. We then estimate the relative complexity of submodels compared to the most complex one (E) and the proportion of own empirical data. At last, we list the nodes that are at least partly based on expert opinion data. NTFP = Non-Timber Forest Product.

Model	Experts (^a = PhD student, ^b = supervisor)	Complexity	Proportion own empirical data	Nodes with expert opinion-based priors
A1. Mental health - visual diversity	Kevin Rozario ^a , Rachel Oh, Melissa Marselle, Aletta Bonn ^b	●●●●○	●●●●○	Δ Positive Affect, Δ negative Affect, Δ anxiety
A2. Mental health - auditory diversity	Taylor Shaw ^a , Kevin Rozario, Sandra Müller, Michael Sherer-Lorenzen ^b	●●●○	●●●●●	
B. Thermal comfort	Loïc Gillerot ^a , Pieter De Frenne ^b , Dries Landuyt ^b , Bart Muys ^b , Kris Verheyen ^b	●●●●○	●●●●○	
C1. NTFPs - Medicinal plants	Katarzyna Stojek ^a , Bogdan Jaroszewicz ^b	●●○○○	●●●●○	Plot-level polyphenol content
C2. NTFPs - Mushrooms	Katarzyna Stojek ^a , Bogdan Jaroszewicz ^b	●●○○○	●●●●○	Mushroom species diversity
D. Air quality	Matthias Steinparzer ^a , Daniela Haluza, Bart Muys, Douglas Godbold ^b	●●●●●	●●●●○	
E. Ticks & Lyme disease	Audrey Bourdin ^a , Tosca Vanroy, Hervé Jactel ^b	●●●○	●●●●○	Deer & mouse abundance, DON & NIP correction factors

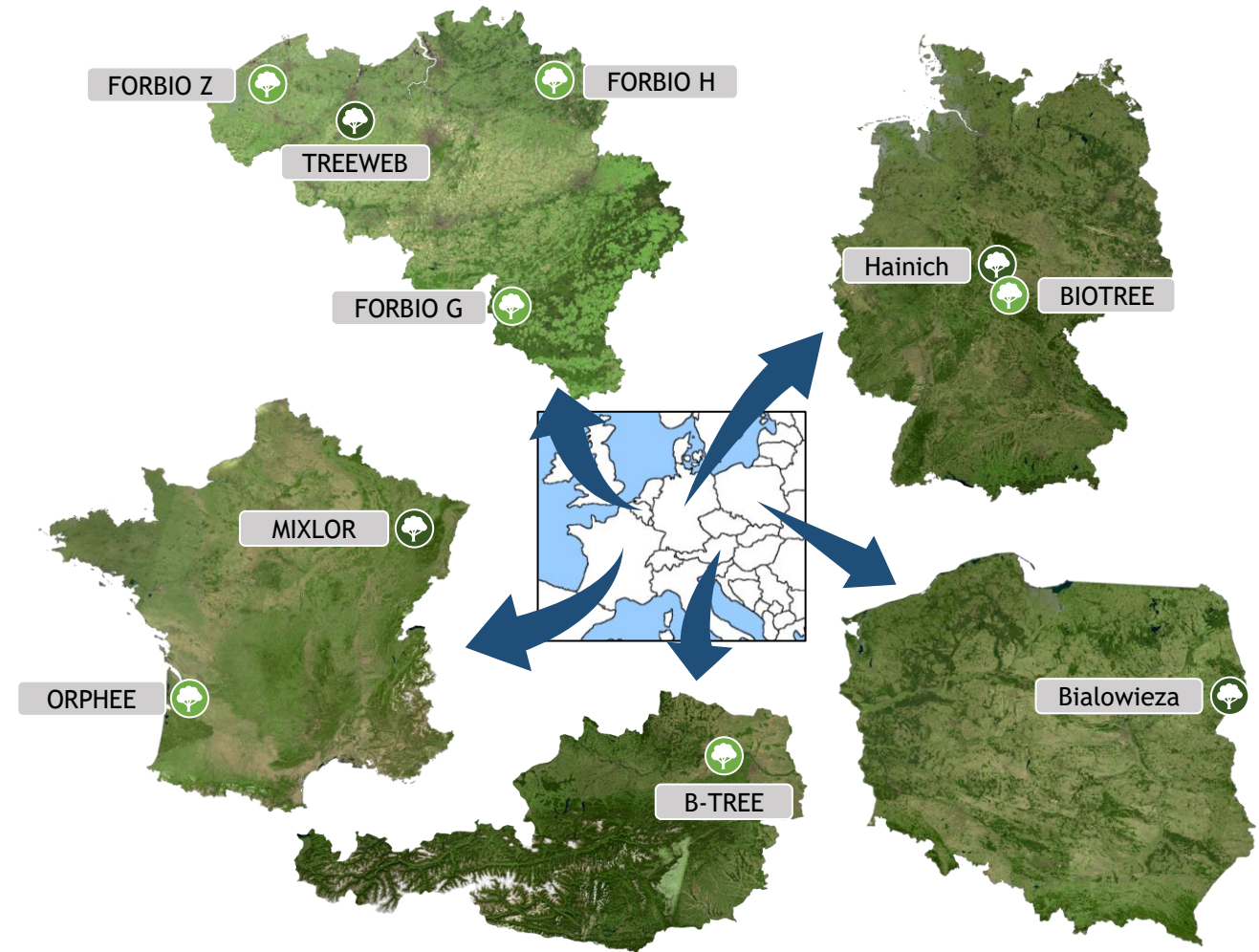
Tree species diversity

Tree species diversity	
Unit: Unitless Type: Continuous Range: [1, 6.9]	
States	Value intervals
Monospecific stand	≤ 1.4
Polyspecific stand	> 1.4
Definition: Shannon diversity index based on species-specific shares of the total basal area within plots. The index is then scaled to a 'true' diversity index <i>sensu</i> Jost (2006), generating values that directly reflect the number of species present.	

Methodology & logic: Compared to commonly used species richness values, a Shannon diversity index has the advantage of reflecting relative abundances of each species. Richness values give equal weight to species whether they are present as a single small tree, or as the dominant species. In contrast, our approach would concede very little weight to the single tree. **State thresholds:** The threshold represents a forest stand where a single species contributes to 80% of the basal area or more. We chose a very simplified state distribution for multiple reasons. Most importantly, this reflects the Dr.FOREST study design centered around contrasts between one- and three-species stands. It also facilitates comparison across disciplines. See for example Wolf et al. (2017) for an environmental psychology study with an analogous study design (1 vs. 4 species). The large range in tree diversity among European regions also makes a further partitioning of polyspecific stands potentially confounding with regional effects. At last, results from biodiversity-ecosystem functioning (BEF) research most often suggest asymptotically flattening trends with increasing diversity and yield relatively small effect sizes. In other words, contrasts are often only clearly visible between mono- and polyspecific stands. This is not always the case. In BEF-China research, for example, tree species diversity did have a strong effect beyond two-species mixtures (Huang et al. 2018). The distinction between mono- and polyspecific varies from country to country (e.g. 10 % in Poland), but is most often around 20%. **Data source:** empirical.

Forest stand type

Forest stand type	
Type: Nominal	
States	
Mature & natural	
Young & planted	
Definition: Forest stand type with regards to age and origin.	



Methodology & logic: Besides ensuring an equal amount of mono- and polyspecific forest stands per site, the Dr.FOREST study design also included a combination of two complementary forest site types from international networks. FunDivEUROPE (Baeten et al. 2013) comprises a network of mature, natural stands, being representative of natural conditions while still minimizing confounding environmental factors (e.g., soil, topography and disturbances). The similar forest stands of the TREEWEB (De Groot et al. 2017) site were added to this category. In contrast, TreeDivNet (Paquette et al. 2018) is a network of young experimental forest plantations designed for BEF research, with the advantage of accounting for, e.g. edaphic conditions, stand size and the spatial arrangement of tree species and individuals. In total, Dr.FOREST included four ‘mature & natural’ [i.e. Bialowieza (PT), Hainich (DE), MIXLOR (FR), TREEWEB (BE)] and six ‘young & planted’ [i.e. B-TREE (AT), BIOTREE (DE), FORBIO-Hechtel-Eksel & -Gedinne & -Zedelgem (BE), ORPHEE (FR)] sites, for a total of 164 forest plots. **Data source:** empirical.

Stem density

Stem density	
Unit: n / ha Type: Discrete Range: [50, 12200]	
States	Value intervals
low	≤ 500
medium	$500 < x \leq 2500$
high	> 2500
Definition: Number of stems per hectare.	

Methodology & logic: The stem density is related to stand development stage. With increasing age, the stand biomass will increase until a point where individuals start competing with each other, which will be typically followed by thinning (natural or artificial via silvicultural interventions), which reduces the stem number (Den Ouden et al. 2010). At one extreme, plantation forests can start with very high densities (~ 10000 / ha). At the other extreme, mature tree stands with large crown diameters have very low (up to 50-60 individuals) stem numbers. However, an analogous spruce forest, which tends to have narrower crowns, may have many more individuals. **State thresholds:** based on numbers estimated to reflect developmental stages. **Data source:** empirical.

Dominant canopy height

Dominant canopy height	
Unit: m Type: Continuous Range: [0, 45]	
States	Value intervals
Medium (pole stage)	≤ 20
High (tree stage)	> 20
Definition: Average crown height of the most dominant trees in subplots.	

Methodology & logic: Generally, canopy height was measured for three dominant trees in three spread out directions starting from the center of subplots (radius of 10m).
State thresholds: A canopy height of 20m represents a transition from the 'pole' to 'tree' developmental stage. The 20m threshold also approximately differentiates the 'young & planted' from the 'mature & natural' forest stands that are included in the Dr.FOREST site selection. Note also that a 5m threshold was also considered, as this represents the transition from the 'thicket' to the 'pole' phase in forests. However, only a fraction of plots (n = 10) had a dominant canopy height below 5m. **Data source:** empirical.

Basal area

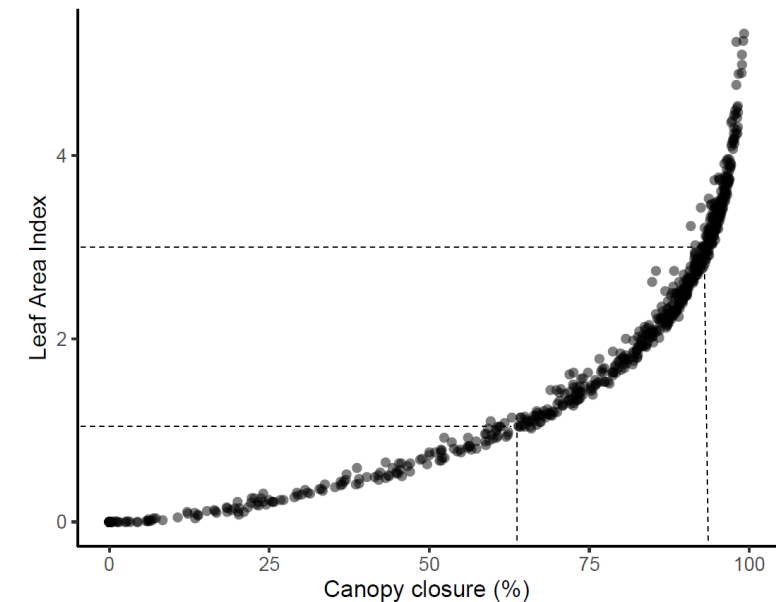
Basal area	
Unit: m ² / ha Type: Continuous Range: [0, 50]	
States	Value intervals
Low	≤ 20
High	> 20
Definition: Cross-sectional area of tree stems at breast height (1.3m) per hectare.	

Methodology & logic: Basal area is one of the most common ways to describe forest stand density, by both researchers and practitioners. **State thresholds:** In stands with a basal area above 15-20, the regeneration of light-demanding tree species will be strongly impeded and is therefore commonly used as a relevant ecological cutoff. **Data source:** empirical.

Leaf Area Index (LAI)

Leaf Area Index (LAI)	
Unit: m^2/m^2 Type: Continuous range: [0, 7.2]	
States	Value intervals
Low	≤ 1
Medium	$1 < x \leq 3$
High	> 3
Definition: The total one-sided green leaf area per surface area of forest floor, representing the density of the canopy layer.	

Relationship between canopy closure and LAI



Methodology & logic: LAI is considered to be the most widely used canopy closure indicator and has been applied for multiple ecosystem services, especially those related to heat mitigation, understory productivity and air filtering. In the figure on the right is the relationship between canopy closure and LAI, both based on the same hemispherical photographs of Dr.FOREST plots (including control plots without trees). Note that LAI could be complemented with Fractal Dimension (FD), which also accounts for the spatial arrangement (clumping) of leaves. This may be important in the filtering role of the forest for air quality, for example, where canopies that are more homogeneously distributed would be more efficient as capture particulate matter. Here, we focus on LAI only as it is more commonly used and easily interpretable. **State thresholds:** Stands with $\text{LAI} < 1$ are very open stands, while stands with $\text{LAI} > 3$ can be considered completely closed (see graph). **Data source:** empirical.

Share of deciduous species

Share of deciduous species	
Unit: % Type: Continuous Range: [0, 100]	
States	Value intervals
Mixed or evergreen-dominated	≤ 80
Deciduous-dominated	> 80
Definition: Share of the total basal area constituted of deciduous species.	

Methodology & logic: The distinction between evergreen and deciduous species represents a lot of different functional traits, including tree shape and leaf size, shape and type. In the case of included species, most evergreen species are also conifers, which is another categorization that could have been used - yielding similar results. The distinction between conifers and broadleaves is also partly captured by the leaf size variable. Stands that are mixed or evergreen-dominated were pooled because deciduous trees were overrepresented over Dr.FOREST, TREEWEB and FORMICA plots. In fact, 84.2% of plots fall in the deciduous-dominated category. **State thresholds:** Analogous to the distinction between mono- and polyspecific stands, a stand is deciduous-dominated when more than 80% of the basal area is made up by deciduous trees. **Data source:** empirical.

Leaf size

Leaf size	
Unit: mm ² Type: Continuous Range: [18, 10500]	
States	Value intervals
Small	≤ 1500
Medium	$1500 < x \leq 3000$
Large	> 3000
Definition: Leaf surface area of the average individual leaf constituting the canopy of the whole plot.	

Methodology & logic: Based on data from the TRY Plant Trait Database (Kattge et al. 2020, see full reference list in Gillerot et al. 2022). First obtained at the species-level and then upscaled at the stand-level using species-specific canopy cover estimations. Smaller leaves are generally associated to both stronger heat reduction (Rahman et al. 2020) and better filtration of particulate matter (Model E; see also Steinparzer et al. 2023). **State thresholds:** Chosen to ensure a good partitioning of observations and to differentiate between leaf types. Leaves of *Larix*, *Pinus*, *Picea* and *Abies* (i.e. conifers) species are all below 1500 mm², where *Betula pendula* approximately marks the transition to the next state. *Tilia cordata* leaves mark the transition to the largest state, with *Quercus rubra* has the largest leaves. **Data source:** empirical.

Understory productivity

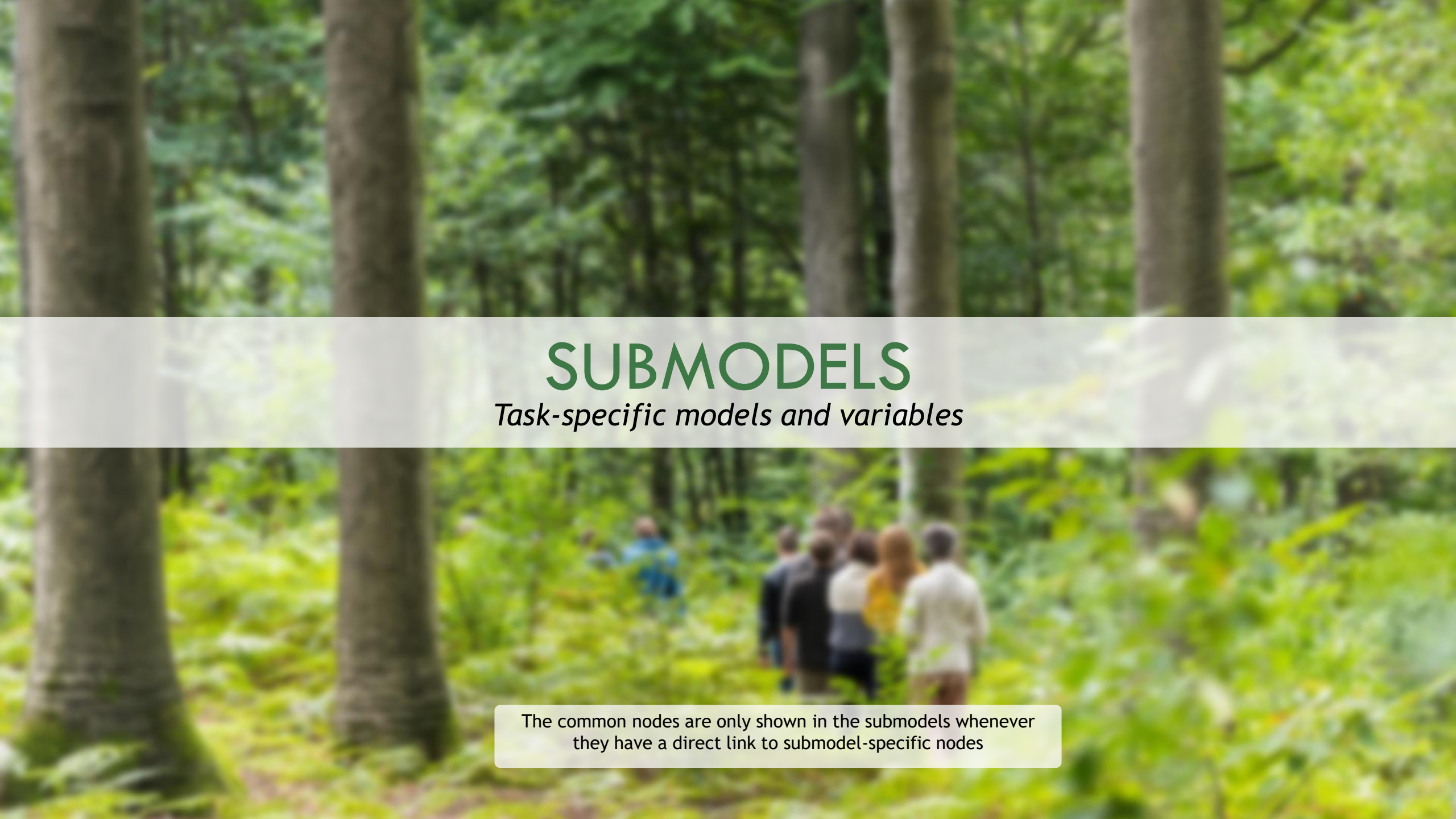
Understory productivity	
Unit: % Type: Continuous Range: [0, 100]	
States	Value intervals
Low (B-B classes < 3)	≤ 25
Medium (B-B classes 3 and 4)	$25 < x \leq 75$
High (B-B class 5)	> 75
Definition: Share of forest floor covered by understory vegetation.	

Methodology & logic: The higher the share of forest floor covered by the vegetation, the higher the considered productivity. This is strongly related to the light regime that is defined by the canopy: the denser the canopy, the lower the light availability for understory vegetation. **State thresholds:** Based on the Braun-Blanquet (1932) method for vegetation surveys. **Data source:** empirical.

Soil fertility

Soil fertility	
Unit: C/N ratio Type: Continuous Range: [9.4, 26.0]	
States	Value intervals
Mull (most fertile)	≤ 15
Rich Moder	$15 < x \leq 20$
Low Moder or Mor (least fertile)	> 20
Definition: The ratio between C and N as a proxy for soil fertility, where higher proportions of N indicate higher fertility.	

Methodology & logic: Soil properties are primarily influenced by the geological bedrock. From the biotic point of view, however, the proportion of conifers is a main driving factor of interest by playing a disproportionate role in acidifying the soil and hence affecting nutrient availabilities. **State thresholds:** Adapted from the most common soil fertility categories (Weil et al., 2017). Normally, this would imply C/N thresholds of 15 and 25, but because very few infertile soils were present ($C/N > 25$; Mor), a finer subdivision was necessary to ensure a sufficient amount of observations per state. **Data source:** empirical.



SUBMODELS

Task-specific models and variables

The common nodes are only shown in the submodels whenever they have a direct link to submodel-specific nodes

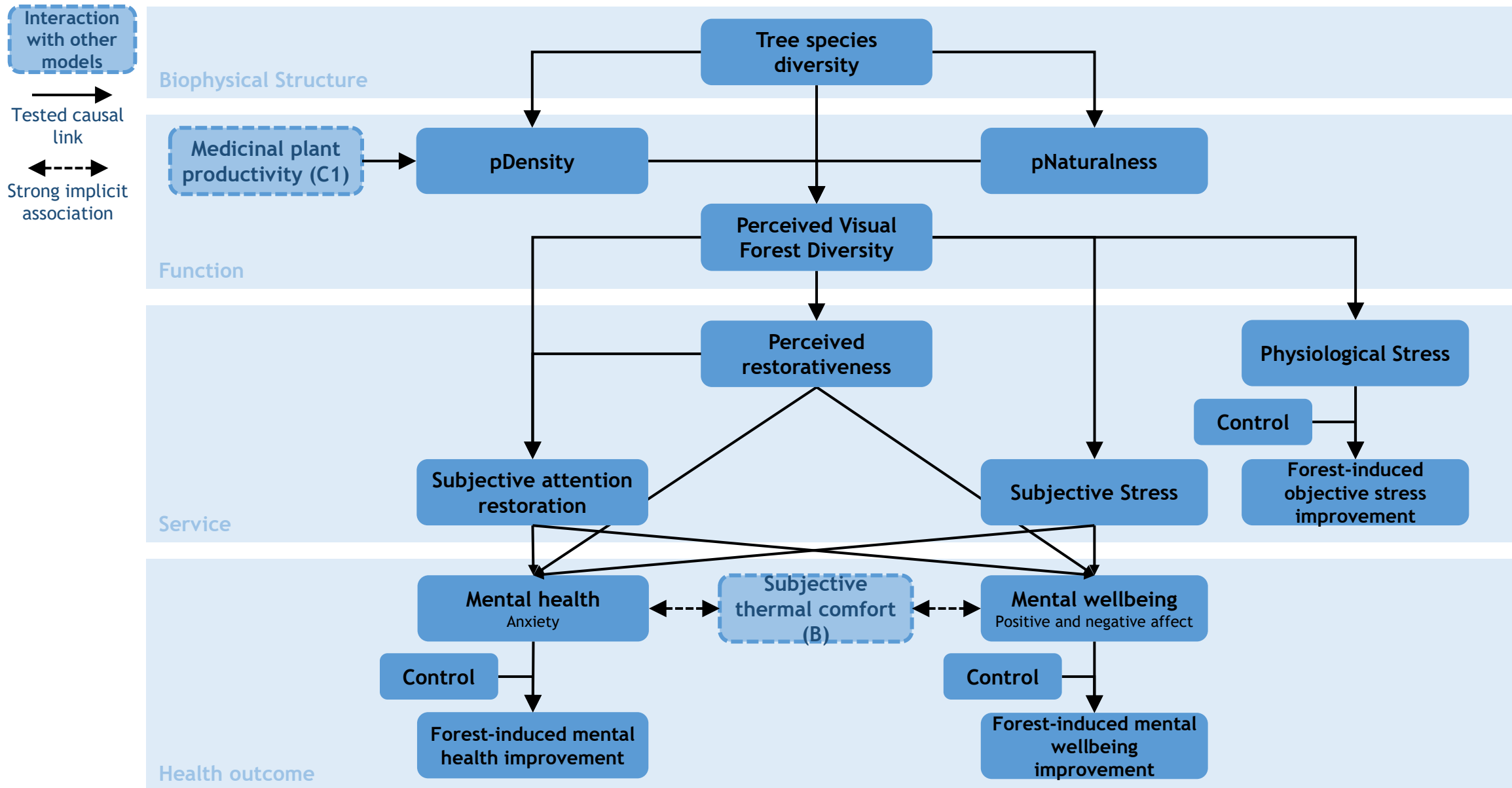
MODEL A1

Mental health - visual stimuli

Experts: Kevin Rozario, Rachel Oh, Melissa Marselle, Aletta Bonn



MODEL A1: Mental health - visual stimuli



Model conceptualisation

General information

The overall model outline is inspired by the conceptual framework of Marselle et al.¹. It incorporates three studies^{2,3,4}.

The first study covers most of the variables and was an *in situ* experiment with 223 participants in peri-urban forests of three cities. Participants were exposed to non-forest control conditions and then one of different forest stands varying in, among others, tree diversity. Under both conditions, participants filled in standardized scales to obtain various mental health and wellbeing indices.

The second study³ is a lab-based electroencephalography (EEG) experiment (n = 52 participants). Here, similar scales were used to assess subjective indices, but EEG theta-wave activity was also monitored to obtain a physiological measure of stress.

The third study⁴ was a picture-sort experiment, where participants ranked forest pictures according to their perceived biodiversity. These results were mainly used to investigate possible causal pathways. Empirical data of this study was not included here.

Overall, the main finding is that forest biodiversity indicators as commonly sampled by forest ecologists have little effect on mental health and wellbeing. Rather, it is forest characteristics as subjectively perceived that drive variation, with perceived density, naturalness and biodiversity having substantial effects. Furthermore, forests in general have a large effect compared to urban control conditions, which is highlighted by added nodes related to the overall improvement in mental wellbeing by the forest.

In sum, forests in general, and how people perceive them, seem to be important, while actual ecological qualities do not.

Limitations

Relatively few different forests were tested, limiting the range of ecological qualities that was statistically investigated. This is due to the inherent complexity of such experiments: participants could only be subjected to a limited number of forests.

Multiple forest ecological qualities were sampled and tested, including variables related to horizontal and vertical structure, the understory vegetation density and diversity, and the volume of deadwood. For simplification reasons, the least influential variables were left out of the model and we focused on a single index for perceived biodiversity (BEI).

In some contexts, forests could represent fear-inducing environments due to risks of, e.g. falling branches, wild animal encounters and contracting Lyme disease. This is not included in this model, but may be of limited importance in the relatively safe European forests we studied. Yet, this may be different in forests where attacks of wildlife and criminal activity are more common.

Interacting variables

The 'understory density' variable is correlated to the 'medicinal plant productivity' variable of Model C1. It is also possible that the 'medicinal plant diversity' has an additional influence on mental states, though this was not tested.

Thermal comfort (Model B) can influence mental wellbeing, and vice-versa. This interaction was explicitly studied in a paper centred around heat stress⁵.

Dr.FOREST papers

¹ Marselle et al. 2021 *Env Int*

² Rozario et al. 2024 *Peop & Nat*

³⁻⁴ Rozario et al. *In prep.*

⁵ Gillerot et al. 2024 *Land & Urb Plan*

Perceived Naturalness and density

Perceived Naturalness	
Unit: mm Type: Discrete Range: [0, 100]	
States	Value intervals
Low	> 25
Medium	$10 < x \leq 25$
High	≤ 10
Definition: How natural or artificial the environment participants sat in was perceived to be.	

Perceived Density	
Unit: mm Type: Discrete Range: [0, 100]	
States	Value intervals
Low	≤ 50
Medium	$50 < x \leq 70$
High	> 70
Definition: How dense the surrounding vegetation was perceived to be.	

Methodology & logic: Quantified using a single item, where participants indicated how natural they perceived the environment to be on a Visual Analogue Scale (VAS) that ranged from 0 (“natural”) to 100 mm (“artificial”); or how dense the perceived to vegetation to be on a VAS that ranged from 0 (“not at all”) to 100 mm (“very much so”). Perceived naturalness has been tested in a similar way before (Marselle et al. 2016), as are related vegetation density indices (An et al. 2004; Chiang et al. 2017). **State thresholds** are based on the 33rd and 66th percentiles and rounded. **Data source:** empirical.

Perceived visual forest diversity

Perceived visual forest diversity	
Unit: Unitless Type: Discrete Range: [1, 5]	
States	Value intervals
Low	≤ 2.5
Medium	$2.5 < x \leq 3.5$
High	> 5
Definition: How biodiverse the environment participants sat in was perceived to be.	

Methodology & logic: Values are scores rated by participants on the Biodiversity Experience Index (BEI) (Gyllin & Grahn 2005) during an outdoor experiment in peri-urban forests. The BEI is a multi-item scale that includes perceptions of plant and animal diversity and environment wildness and variation. Participants could choose between five options ranging from ‘a little’ to ‘much’. A score of 5 represents a maximally diverse forest stand as perceived by participants. Noteworthy is that the BEI correlated very poorly to the actual indicators of forest ecological qualities as commonly sampled by forest ecologists such as the horizontal and vertical structure and the amount of deadwood - though the Shannon diversity of tree species yields a relatively better association. Furthermore, variation in the BEI can be explained by the perceived naturalness and perceived density. Perceived colourfulness had a relatively small effect. Another single item scale related to overall biodiversity was also tested, but found to have less explanatory power. **State thresholds** are based on the 33rd and 66th percentiles and rounded. **Data source:** empirical.

Perceived restorativeness

Perceived restorativeness	
Unit: Unitless Type: Discrete Range: [0.6, 9.6]	
States	Value intervals
Low	≤ 4.5
Medium	$4.5 < x \leq 5.5$
High	> 5.5
Definition: How restorative the environment participants sat in was perceived to be. Positive values indicate increased perceived restorativeness, on a score ranging from 1 to 10.	

Methodology & logic: Values are scores rated by participants on the Perceived Restorativeness Scale (PRS) (Hartig et al. 1997) during the outdoor experiment in peri-urban forests. The PRS is a 16-item scale with items related to fascination (e.g. ‘This place has fascinating qualities’), the sense of being away (e.g. ‘This place gives me a good break from my day-to-day routine’), extent (e.g. ‘it is chaotic here’) and compatibility (e.g. ‘I have a sense of oneness with this setting’). For the EEG study, we adapted the 5-item PRS scale (Berto, 2005) to make items eligible for photographs (that do not necessarily show environments or places). **State thresholds** are based on the 33rd and 66th percentiles and rounded. **Data source:** empirical.

Subjective attention restoration

Δ Subjective attention restoration	
Unit: Unitless Type: Continuous Range: [-9, 13]	
States	Value intervals
Decrease	≤ 0
Small increase	$0 < x \leq 4$
Large increase	> 4
Definition: Attention restoration based on subjective questionnaires. Positive values indicate increased attention restoration.	

Methodology & logic: Difference value (post - pre) of a 7-item questionnaire on momentary directed attention (adapted from the attentional focusing subscale of the Attentional Control Scale by Derryberry & Reed (2002)). The pre condition is a baseline environment that is neither entirely urban nor entirely natural (see Rozario et al. 2023). Negative values mean that attention restoration decreased in the forest compared to the baseline, while positive values reflect increasing attention restoration. For the EEG study we used a single item to test perceived attention restoration on a visual analogue scale (VAS) ranging from 0 - 100 (high perceived concentration). **State thresholds** ensure the differentiation between decreases and increases and a similar number of observations among the two increasing states. **Data source:** empirical.

Subjective & physiological stress

Δ Subjective stress	
Unit: Unitless Type: Continuous Range: [-67, 59]	
States	Value intervals
Increase	> 0
Small decrease	$-10 < x \leq 0$
Large decrease	≤ -10
Definition: Difference value (post - pre) of a single item on perceived (momentary) stress on a VAS, obtained during the <i>in situ</i> experiment. Values range from 0 ('not stressed at all') to 100 ('extremely stressed') (Schebella et al. 2019).	

Δ Physiological stress	
Unit: dB/Hz Type: Continuous Range: [-1.48, 2.3]	
States	Value intervals
Increase	≤ 0
Small decrease	$0 < x \leq 1$
Large decrease	> 1
Definition: Mean spectral power of theta waves, obtained as a biomarker for stress during the lab-based EEG experiment. These are baseline-corrected per condition.	

Methodology & logic: Concerning the *in situ* experiment, the pre condition is a baseline environment that is neither entirely urban nor entirely natural (see Rozario et al. 2023). For the lab-based EEG study, the baseline is the situation prior to showing participants forest scenery pictures, or a scrambled control version. The interpretation of both variables is slightly different. In the case of subjective stress, positive values reflect increasing amounts of stress in the forest compared to the baseline. In the case of objective stress, positive values reflect a decrease in stress because higher theta wave activity mirrors a more relaxed state. **State thresholds** ensure the differentiation between decreases and increases and a similar number of observations among the two decreasing states. **Data source:** empirical.

Positive affect (+ control)

Δ Positive affect forest	
Unit: Unitless Type: Discrete Range: [-17, 15]	
States	Value intervals
Decrease	≤ 0
Small increase	$0 < x \leq 4$
Large increase	> 4
Definition: Difference value (post - pre) of the multi-item Positive and Negative Affect Schedule (PANAS) (Watson et al. 1988). Values range from 10 to 50, with higher values indicating higher positive affect.	

Δ Positive affect urban control	
Unit: Unitless Type: Discrete Range: [-35, 8]	
States	Value intervals
Large decrease	≤ -8
Small decrease	$-8 < x \leq 0$
Increase	> 0
Definition: Difference value (post - pre) of the multi-item PANAS at the urban control condition (Watson et al. 1988). Values range from 10 to 50, with higher values indicating higher positive affect.	

Methodology & logic: Positive and negative affect (mood or emotional state) are separated as they are often not correlated, including in our own data. Positive values reflect improved affect in the forest compared to the baseline. Three quarters of participants were subjected to one of different forests, while one quarter was subjected to an urban control condition. The urban control ensures that potential non-forest-related fluctuations in mental variables are accounted for, and that the forest effect can be compared to an urban environment. Generally, positive affect increased for participants who were subjected to forests while it decreased for those who were subjected to the urban control. Positive and negative affect represent a proxy for mental wellbeing. Since the ' Δ Positive affect' variable had three parent nodes, it needs at least $n = 10 \times 3 \times 3 \times 3 = 270$ observations. Because of a lack of sufficient observations, an Expert Opinion Table constitutes the first layer of data. **State thresholds** ensure the differentiation between decreases and increases and a similar number of observations among the two increasing/decreasing states. **Data source:** empirical.

Negative affect (+ control)

Δ Negative affect forest	
Unit: Unitless Type: Discrete Range: [-12, 15]	
States	Value intervals
Large decrease	≤ -2
Small decrease	$-2 < x \leq 0$
Increase	> 0
Definition: Difference value (post - pre) of the multi-item Positive and Negative Affect Schedule (PANAS) (Watson et al. 1988). Values range from 10 to 50, with higher values indicating higher negative affect.	

Δ Negative affect urban control	
Unit: Unitless Type: Discrete Range: [-10, 14]	
States	Value intervals
Decrease	≤ 0
Small increase	$0 < x \leq 2$
Large increase	> 2
Definition: Difference value (post - pre) of the multi-item PANAS at the urban control condition (Watson et al. 1988). Values range from 10 to 50, with higher values indicating higher negative affect.	

Methodology & logic: Positive and negative affect (mood or emotional state) are separated as they are often not correlated, including in our own data. Negative values reflect reductions in negative affect in the forest compared to the baseline (which is the desirable outcome). Three quarters of participants were subjected to one of different forests, while one quarter was subjected to an urban control condition. The urban control ensures that potential non-forest-related fluctuations in mental variables are accounted for, and that the forest effect can be compared to an urban environment. Generally, negative affect decreased for participants who were subjected to forests while it increased for those who were subjected to the urban control. Positive and negative affect represent a proxy for mental wellbeing. Since the ' Δ Negative affect' variable had three parent nodes, it needs at least $n = 10 \times 3 \times 3 \times 3 = 270$ observations. Because of a lack of sufficient observations, an Expert Opinion Table constitutes the first layer of data. **State thresholds** ensure the differentiation between decreases and increases and a similar number of observations among the two increasing/decreasing states. **Data source:** empirical.

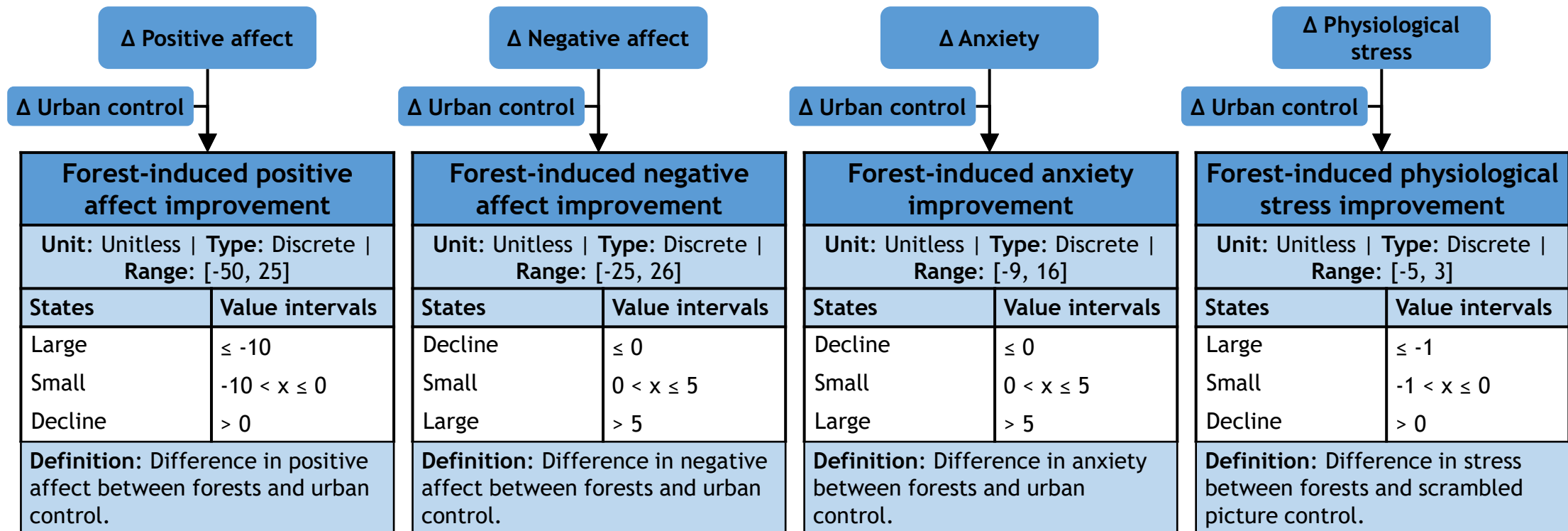
Anxiety (+ control)

Δ Anxiety	
Unit: Unitless Type: Discrete Range: [-8, 5]	
States	Value intervals
Large decrease	≤ -2
Small decrease	$-2 < x \leq 0$
Increase	> 0
Definition: Difference value (post - pre) of the state version of the multi-item State Trait Anxiety Inventory (STAI)(Spielberger et al. 1971). Values range from 20 to 80, with higher values indicating higher state anxiety.	

Δ Anxiety urban control	
Unit: Unitless Type: Discrete Range: [-4, 8]	
States	Value intervals
Decrease	≤ 0
Small increase	$0 < x \leq 3$
Large increase	> 2
Definition: Difference value (post - pre) of the multi-item STAI at the urban control condition. Values range from 20 to 80, with higher values indicating higher state anxiety.	

Methodology & logic: Negative values reflect reductions in anxiety in the forest compared to the baseline. Three quarters of participants were subjected to one of different forests, while one quarter was subjected to an urban control condition. The urban control ensures that potential non-forest-related fluctuations in mental variables are accounted for, and that the forest effect can be compared to an urban environment. Generally, anxiety decreased for participants who were subjected to forests while it increased for those who were subjected to the urban control. Anxiety is a proxy for mental health. Based on a STAI score of 40, a subdivision can be made between sub-clinical and clinical cases (where clinical cases have scores > 40). However, since these cases represented only 2 people out of 223 participants, making it an inadequate reason to define state cutoffs. Since the ' Δ Anxiety' variable had three parent nodes, it needs at least $n = 10 \times 3 \times 3 \times 3 = 270$ observations. Because of a lack of sufficient observations, an Expert Opinion Table constitutes the first layer of data. **State thresholds** ensure the differentiation between decreases and increases and a similar number of observations among the two increasing/decreasing states. **Data source:** empirical.

Mental health and wellbeing improvement in forests vs. urban controls



Methodology & logic: Based on the equation: Urban control - forest. The addition of these variables allows to compare the magnitude of forest effects compared to an urban control (*in situ* experiment) or a scrambled control version of forest scenery photographs (EEG study). Photographs were scrambled to retain an equal colour palette compared to the forest photographs. In general, inter-forest effects are rather small, whereas these variables reflect the larger forest vs. urban effects. Note that, in case of positive affect and physiological stress, negative values signify that the pre-to-post change is more positive in forests compared to the urban/scrambled condition - which is the desirable outcome. The opposite holds for negative affect and anxiety. In all cases, the forest has more beneficial effects than detrimental ones, which are most consistent for anxiety. **State thresholds** ensure the differentiation between decreases and increases and a similar number of observations among the two increasing/decreasing states. **Data source:** Equation.

MODEL A2

Mental health - auditory stimuli

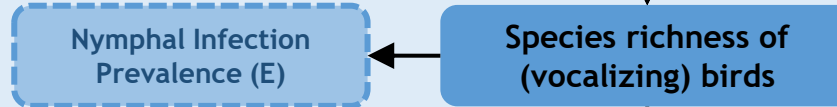
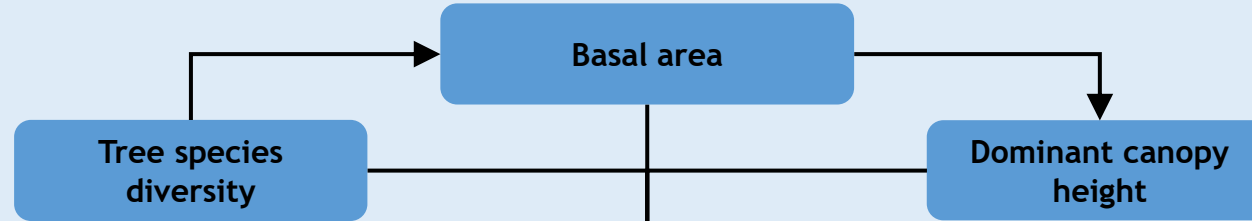
Experts: Taylor Shaw, Sandra Müller, Ana Gabriela Cuentas Romero, Kevin Rozario, Michael Scherer-Lorenzen



MODEL A2: Mental health - auditory stimuli

Interaction
with other
models

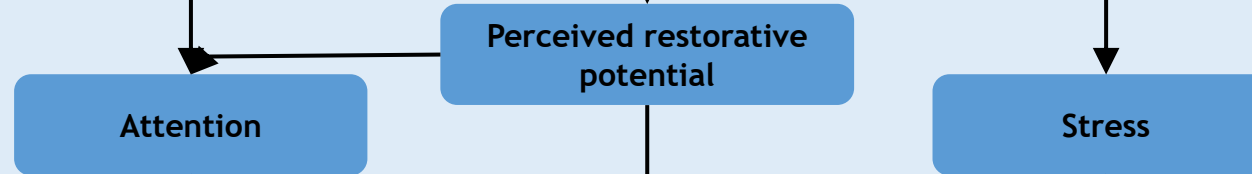
Biophysical Structure
Stand-scale



Biophony

Perceived acoustic diversity

Function



Service

Mental wellbeing inside forest
Positive and negative affect

Health outcome

Model conceptualisation

General information

This model is based on two main studies. A first study sampled acoustic (i.e. soundscapes) and dendrometric parameters at 126 plots pertaining to eight different Dr.FOREST sites to determine forest effects on songbird diversity and the resulting biophony¹.

The second study is a lab-based experiment where participants were asked to listen to previously recorded sound fragments². Mental wellbeing variables were quantified via scales that are analogous to those used in the studies of Model A1³. Even though the scales are distinct, the same model outline was adopted for the mental component.

Overall, we observe a moderate-to-high sensitivity of bird diversity to dendrometric parameters, but this effect is quickly diluted by the biophony and perceived acoustic diversity variables. Causes may be technical (see limitations), but also reflect experimental findings. Indeed, mental wellbeing benefits are tightly associated to what participants subjectively perceived than to multiple objectively measurable acoustic diversity indices^{1,2}.

Limitations

Potentially important variables were not added to the model, including stand structural complexity, tree functional traits (e.g. seed production) and deadwood. To keep the overarching model simplified, we retained the most easily obtained variables that experts estimated to be most influential. Other dendrometric variables that are included in the common part of the overall model were tested but removed because of their small effect sizes.

Bird diversity was little sensitive to dendrometric parameters, because the small scale of sampled subplots (circular with 9m radius) and experimental stands (30m x 30m) matches poorly with the very mobile nature of birds. Accordingly, data at a 1ha scale from another project ([ConFoBi](#)) was incorporated, substantially enhancing the sensitivity of bird diversity levels to dendrometric variables.

Biophony indices are available for all studied stands, but the related mental wellbeing experiment could only be conducted with four contrasting sound fragments. This simplification weakens the link between dendrometric variables and mental outcomes a lot, but this also reflects the state-of-the-art (i.e. few psychological studies have included a wide and well-replicated gradient of birdsong diversity).

Although recorded anthropogenic noise may also have strong mental health effects (WHO 2011), little anthropophony was recorded and we found little variation among forest stands. The variable was therefore excluded for simplicity.

Interacting variables

The diversity of vocalizing bird species is related to model E, where it will be strongly associated to general bird diversity. In that model, bird diversity is influencing the nymphal infection prevalence (NIP). The direction (vocalizing bird diversity → bird diversity) was chosen in this direction for technical reasons: i.e. the model A2 node has already three parents and insufficient replications to take a fourth one. However, technically, the two nodes are made equivalent to each other, with the causal direction having no implications for results.

Dr.FOREST papers

¹ Shaw et al. *In prep.*

² Cuentas Romero et al. *Under review.*

³ Rozario et al. 2023 *Peop & Nat*

Species richness of vocalizing birds

Species richness of vocalizing birds	
Unit: n species / plot Type: Discrete Range: [4, 25]	
States	Value intervals
Low	≤ 10
Medium	$10 < x \leq 15$
High	> 15
Definition: Number of species recorded with audiloggers during the Spring season.	

Methodology & logic: Recorders (Audiomoths) were set up for one month during each of the four seasons, where two-minute recordings were triggered every 15 minutes. This happened at 126 forest stand plots of eight Dr.FOREST sites. Because of limited bird vocalisations during all seasons except Spring, only the latter period was used to study contrasts between forest stands. Species were identified by an expert based on recordings. The number of species identified based on audio fragments matched an in-field visual assessment (point-count data) at two of the sites conducted in mid May and early June. A major limitation is that the size of subplots used to sample dendrometric parameters poorly fits the highly mobile nature of birds. This is why a related dataset of the ConFoBi project (confobi.uni-freiburg.de) was added as an extra layer (n plots = 80), where dendrometric parameters were obtained for 1 ha stands together with bird species richness data. This reduced uncertainty in the CPT for the link between tree species diversity and bird species richness. **State thresholds** are based on the 33rd and 67th percentiles and rounded. **Data source:** empirical.

Biophony

Mid-Frequency Cover Biophony	
Unit: Unitless Type: Continuous Range: [0.01, 0.09]	
States	Value intervals
Little diverse	≤ 0.019
Intermediate	$0.019 < x \leq 0.025$
Highly diverse	> 0.025
Definition: The fraction of noise-reduced spectrogram cells that exceed 3 dB in the mid-frequency band (1000-8000 Hz).	

Bird Biophony per Day	
Unit: Unitless Type: Continuous Range: [0.43, 0.91]	
States	Value intervals
Silence prevails	≤ 0.73
Intermediate	$0.73 < x \leq 0.81$
Biophony prevails	> 0.81
Definition: Number of files that include bird vocalisations divided by total number of audiofiles per plot, per spring.	

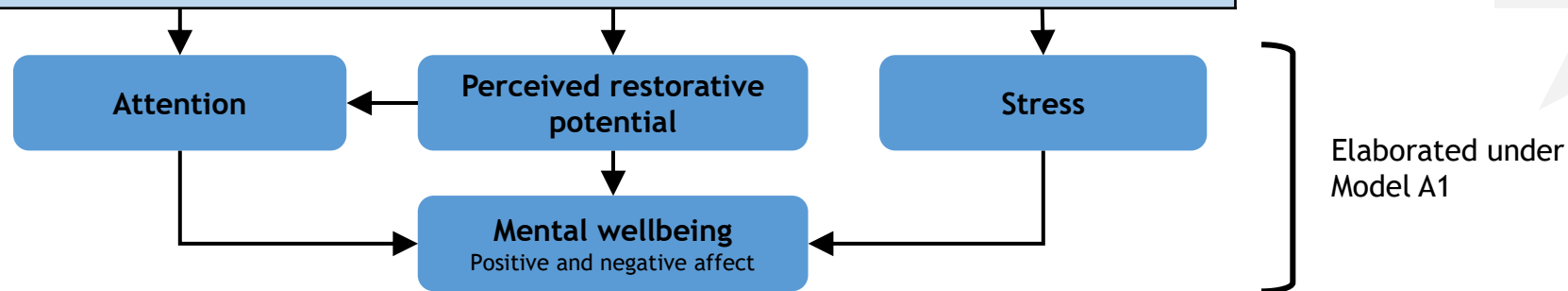


Methodology & logic: Obtained via Audiomoths and reflecting birdsong diversity during Springtime. The Mid Frequency Cover reflects the diversity in bird song when it is present. Bird Biophony per Day reflects the absolute presence of bird song within a day. As such, both variables are thus complementary and provide different information. The latter, however, co-determines the former because birdsong needs to be present before its diversity can be assessed in the first place. Other acoustic indices were tested, including 'Events Per Second', 'Acoustic Complexity Index' and Entropy of Co-variance Spectrum' for biological sources of noise (= biophony, in contrast with geophony and antropophony). However, these variables were either too strongly co-varying with the Low Frequency Cover (which related to antropophony and wind) or too little with the dendrometric variables. **State thresholds** are based on the 33rd and 67th percentiles. **Data source:** empirical.

Perceived Acoustic Diversity and mental wellbeing

Perceived Acoustic Diversity	
Unit: n species Type: Discrete Range: [1, 5]	
States	Value intervals
Low	1
Medium	2
High	≥ 3
Definition: How diverse the sound recordings participants perceived to be.	

Mental wellbeing variables were assessed using scales analogous to those applied in the studies underlying Model A1. These were: a) the Perceived Restorative Soundscape Scale (PRSS; Payne et al. 2018, Uebel et al. 2021), b) a single item on perceived concentration for the 'Attention' node, c) the Scale of Positive and Negative Experience (SPANE; Diener et al. 2010 in *Soc Indic Res*) for negative and positive affect. Stress was operationalized using the same single item scale as in Model A1.



Methodology & logic: Based on a lab-based experiment, where 195 participants were asked to estimate the bird species diversity based on four contrasting sound recordings. Analogous to the model based on visual stimuli, mental wellbeing parameters were found to be driven by what participants subjectively perceived rather than the diversity quantified by objective indices. Both are nonetheless moderately associated based on sensitivity analyses. Values are based on questionnaires where participants were asked to estimate the number of bird species they heard. The subsequent mental wellbeing variables are based on the same scales used in model A1. Note that they are expressed as difference values, where scores are subtracted from those obtained before exposing participants to forest sound fragments (i.e. Pre/Post measures). **State thresholds** were chosen to ensure equal numbers of observations per state. **Data source:** empirical.

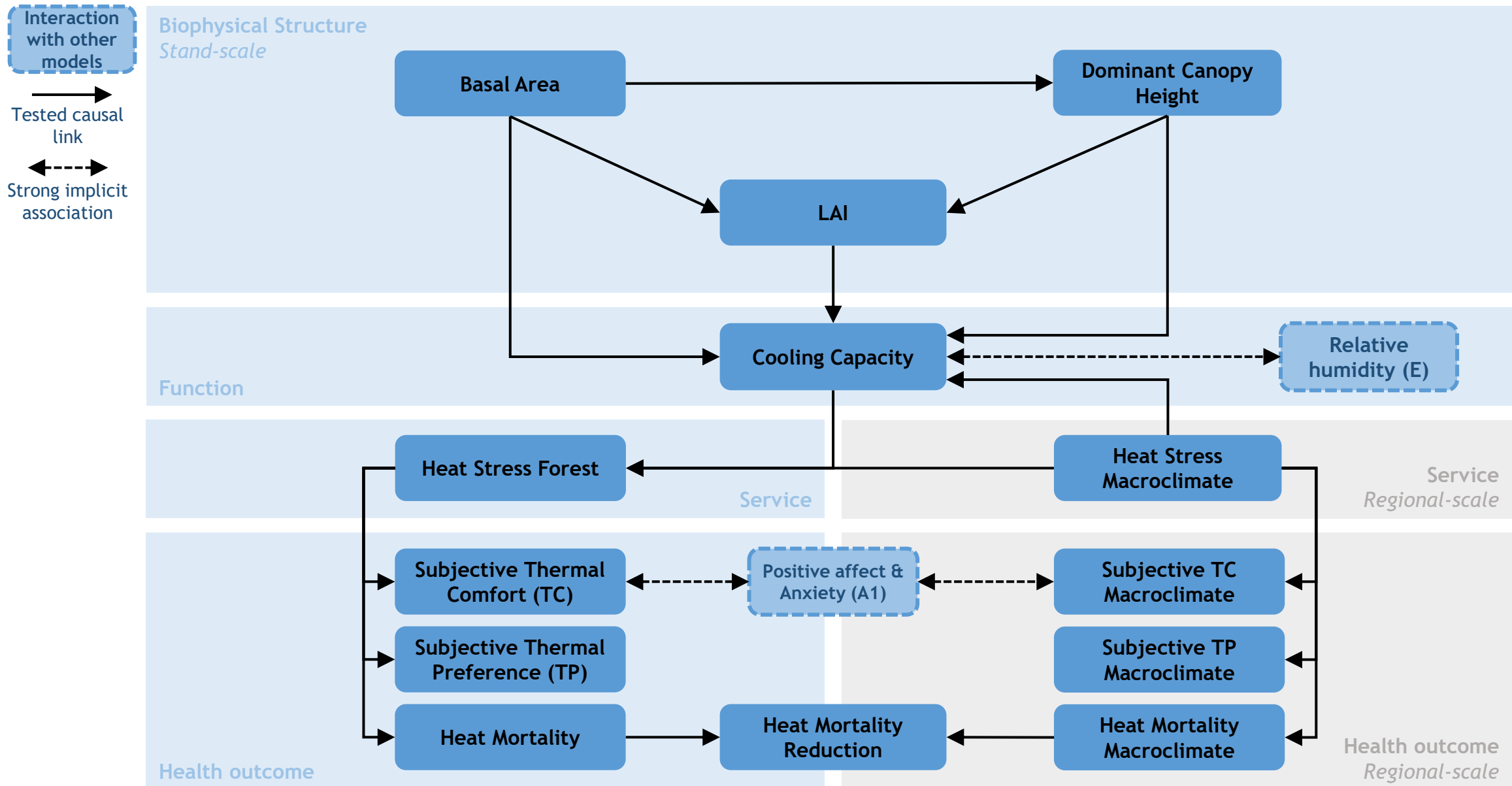
MODEL B

Thermal comfort

Experts: Loïc Gillerot, Dries Landuyt,
Pieter De Frenne, Bart Muys, Kris Verheyen



MODEL B: Thermal comfort



Model conceptualisation

General information

The model outline is primarily based on a published Structural Equation Model fitted on 14 months of microclimate data from 131 plots over eight Dr.FOREST sites¹. Measured parameters included the air temperature and humidity, the grey globe temperature and wind speed, which are needed to obtain the Physiologically Equivalent Temperature (PET) – a thermal stress index (Höppe 1999). The focus is on PET maxima, as heat has stronger public health relevance than cold in Europe (Baccini et al. 2008), especially considering anticipated climate warming (Forzieri et al. 2017).

The first study covers everything but a health outcome. For this, we applied two complementary approaches. Firstly, we added subjective thermal comfort data from our multicenter experiment, where 223 participants were interviewed under forest and non-forest baseline conditions². However, obtained Thermal Sensation Votes have limited health implications because the experiment excluded the hottest conditions. To complement this, we also linked PET to heat mortality data from existing literature (instead of morbidity because heat mortality is much better reported) (Muthers et al. 2010).

Least influential links with dendrometric variables were omitted to avoid a high number of parent nodes. The final model very accurately reflects results of the two published studies. This includes a central role of the Leaf Area Index (LAI), and a very large modulating effect of the macroclimate on the cooling capacity.

Tree canopies were also confirmed as primordial drivers for heat stress mitigation in urban environments by a third Dr.FOREST study³.

Limitations

Crown depth could be better related to cooling capacity than crown height, given that it reflects the thickness of the insulating canopy layer. Yet, this is partly indirectly covered by the LAI. According to the first study¹, canopy openness was a better predictor than LAI, but this would reduce compatibility with other models.

The main limitation concerns the health outcomes. Our own subjective thermal comfort data accurately represents reality, but health implications do not reach beyond mere discomfort. However, the link with heat mortality implies an important assumption; the individual is subjected to the forest microclimate in similar amounts than the population studied by Muthers et al. was subjected to the study's urban environment.

Interacting variables

Forests with high thermal buffering capacity also tend to remain more humid, which creates a favourable environment for ticks (model E). This is indicated as an implicit association because PET is based on many more factors than humidity, which would reduce its explanatory power for humidity, leading to a dilution of effects.

The physical microclimate only explains about half of the variation in subjectively thermal comfort, with psychological and physiological factors driving remaining variation (Nikolopoulou et al. 2003, Lai 2020). Interactions with the mental wellbeing (A1) were explicitly tested in our second study², where we found a forest-induced synergy between thermal comfort and positive affect and anxiety.

Dr.FOREST papers

¹ Gillerot et al. 2022 *Glob Chang Biol*

² Gillerot et al. 2024 *Land & Urb Plan*

³ Gillerot et al. 2024 *Urb For & Urb Green*

Cooling capacity

Cooling capacity	
Unit: °C PET Type: Continuous Range: [-23, 10]	
States	Value intervals
None - Warming	≥ 0
Weak	$0 > x \geq -5$
Moderate	$-10 > x \geq -5$
Strong	> -10
Definition: Expressed as 'offsets' (see De Frenne et al. 2021), which is the difference between the forest and the open-field control (Forest PET - Control PET). Negative values indicate cooler temperatures inside the forest.	

Methodology & logic: These values are based on daily maxima in the forest vs. controls. Negative values mean that the forest microclimate is colder than the macroclimate. We focus on maxima, given that heat mortality studies commonly use them as indicators (Baccini et al. 2008; Muthers et al. 2010). However, other indicators could also be used, where nightly temperatures can be very influential as well by disrupting sleep quality (Obradovich et al. 2017). Perceived temperature is proxied by the Physiologically Equivalent Temperature, which is based on a physiological model that considers the heat exchanges between the physical environment (air temperature and humidity, mean radiant temperature and wind speed) and the human body (Höppe 1999). **State thresholds** are based on the 25th, 50th and 75th percentiles, and rounded. **Data source:** empirical.

Parent node selection was based on the original SEM (Gillerot et al. 2022), after which variables with least predictive power were removed one-by-one until reaching the maximal number of nodes allowed by the number of observations at hand. This resulted in a model where only stand structure variables (LAI, canopy height and basal area) were left over. This exactly matches our previous conclusions that stand structure is largely more influential than species composition and tree species diversity (Gillerot et al. 2022). The cooling capacity does not only depend on the forest characteristics, but also on the macroclimate (De Frenne et al. 2021). The hotter the conditions outside of the forest, the stronger the cooling. We also found that the relative importance of individual dendrometric variables increases with increasing macroclimate temperature.

Heat stress forest & macroclimate

Heat stress forest	
Unit: °C PET Type: Continuous Range: [-13.5, 49.1]	
States	Value intervals
No heat stress	≤ 23
Slight heat stress	$23 < x \leq 29$
Moderate heat stress	$29 < x \leq 35$
Strong heat stress	$35 < x \leq 41$
Extreme heat stress	> 41
Definition: Heat stress within the forest stand, quantified by PET.	

Heat stress macroclimate	
Unit: °C PET Type: Continuous Range: [-9.6, 50.7]	
States	Value intervals
Slight heat stress	$23 < x \leq 29$
Moderate heat stress	$29 < x \leq 35$
Strong heat stress	$35 < x \leq 41$
Extreme heat stress	> 41
Definition: Idem.	

Methodology & logic: Not to be confused with the offset (cf. cooling capacity), these are the temperatures as perceived by an average human body (i.e. PET) in the forest (left) or under macroclimatic control conditions - as measured in open fields (right). The probabilities assigned to each interval are based on the proportion of days with PET maxima falling within each category, based on the monitoring of minimum 14 continuous months at eight Dr. Forest sites inside 131 forest plots and in adjacent open-field control plots. Only timestamps where macroclimatic conditions of slight heat stress or more ($PET > 23^{\circ}\text{C}$) were selected, explaining why the macroclimate node does not have a 'no thermal stress' state. Because of the forest cooling capacity, 'no heat stress' conditions ($PET \leq 23^{\circ}\text{C}$) are of course possible inside of the forest at the same time, and are even common. **State thresholds** are based on heat stress categories as defined by Matzarakis et al. (1999). **Data source:** empirical.

Subjective thermal comfort

Subjective thermal comfort forest	
Unit: Unitless Type: Ordinal Range: [1, 6]	
States	Score
Cold	1
Cool	2
Slightly cool	3
Neutral	4
Slightly warm	5
Warm	6
Definition: ASHRAE seven-point scale 'Thermal Sensation Vote', used as in Chow et al. (2016).	

Subjective thermal comfort macroclimate	
Unit: Unitless Type: Ordinal Range: [2, 7]	
States	Score
Cool	2
Slightly cool	3
Neutral	4
Slightly warm	5
Warm	6
Hot	7
Definition: Idem.	

Methodology & logic: In Gillerot et al. (2024), participants were surveyed for their thermal comfort in different forest types and under non-forest baseline conditions. The latter serves as the macroclimate control, allowing for within-individual comparison of subjective thermal comfort inside and outside the forest. None of the forest participants felt 'hot' (score = 7) in forests while none felt 'cold' (score = 1) under non-forest baseline conditions. **State thresholds** relate to the ordinal scoring system of the ASHRAE scale. **Data source:** empirical.

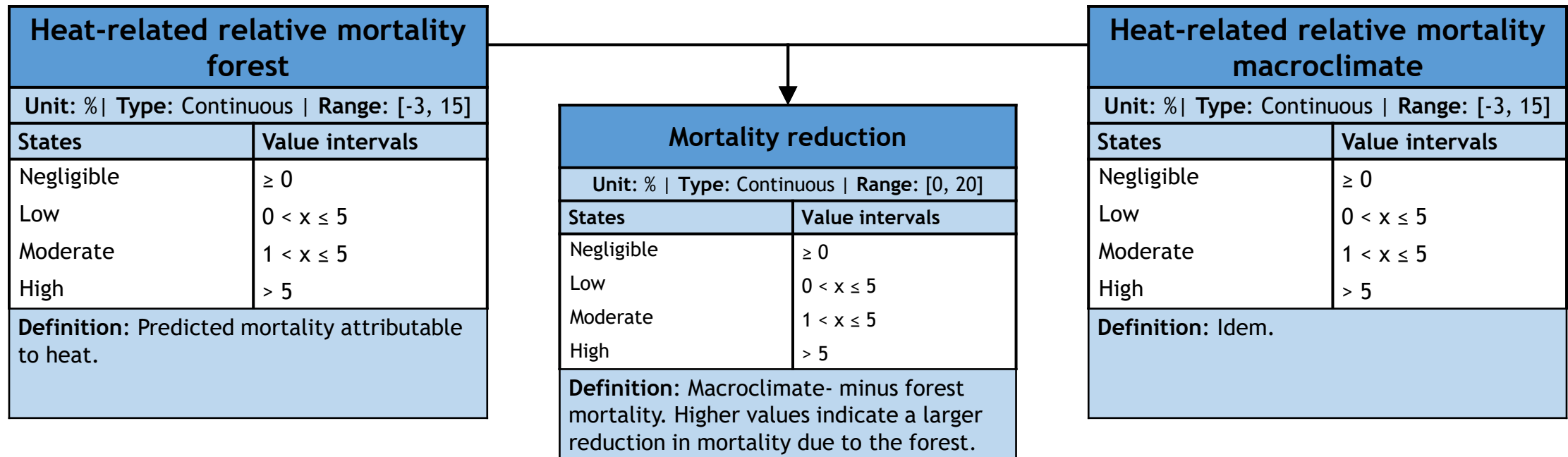
Subjective thermal preference

Subjective thermal preference forest	
Unit: Unitless Type: Ordinal Range: [1, 3]	
States	Score
Warmer	1
No Change	2
Colder	3
Definition: Thermal Preference Vote, used as in Chow et al. (2016). The question participants were asked is “For the current spot you are at now, would you like it to be...?”	

Subjective thermal preference macroclimate	
Unit: Unitless Type: Ordinal Range: [1, 3]	
States	Score
Warmer	1
No Change	2
Colder	3
Definition: Idem.	

Methodology & logic: In Gillerot et al. (2024), participants were surveyed for their thermal comfort in different forest types and under non-forest baseline conditions. The latter serves as the macroclimate control, allowing for within-individual comparison of subjective thermal comfort inside and outside the forest. **State thresholds** simply relate to the ordinal scoring system of the used scale. **Data source:** empirical.

Heat-related mortality & mortality reduction



Methodology & logic: Based on the associations between different PET heat stress categories and mortality levels observed in Vienna for the most recently studied period (2001-2006) in Muthers et al. (2010). Values are relative to baseline mortality rates for the region. This approach entails two important assumptions that need to be considered. Firstly, it assumes that the individual of population in question spends a similar amount of time within the case environment (forest or control) compared to the Viennese population studied in Muthers et al. (2010). The latter study adopts a daily resolution, where day-to-day mortality is related to daily maximum heat. In other words, these exact mortality reductions would only be valid for a population inhabiting the given forest stand. Nonetheless, under extreme heat a forest visitor may also experience a drastic reduction in their chance in short-term health impacts (e.g. heat stroke). Second, it assumes that the mortality rates in Vienna for the studied period can be extrapolated to our study region (Austria, but also Belgium, France, German and Poland). Yet, acclimatization, adaptation and mitigation at the individual- or population-level are known to vary spatio-temporally. As Europe-wide data or equivalent meta-analyses linking PET to mortality are not published yet to our knowledge, we chose the study in Vienna for its robust results that are presented per PET heat stress category and include error estimations. Less adequate but similar studies exist for regions that are further away: Croatia (Zaninović et al. 2013), Finland (Ruuhela et al. 2017) and Czech Republic (Urban et al. 2019), all suggesting similar mortality predictions. In sum, our mortality results should be considered *relative* predictions, not *absolute* ones. **State thresholds** are inspired by the predicted mortality distribution in Muthers et al. (2010). **Data source:** Quantitative literature results and equation (mortality reduction).

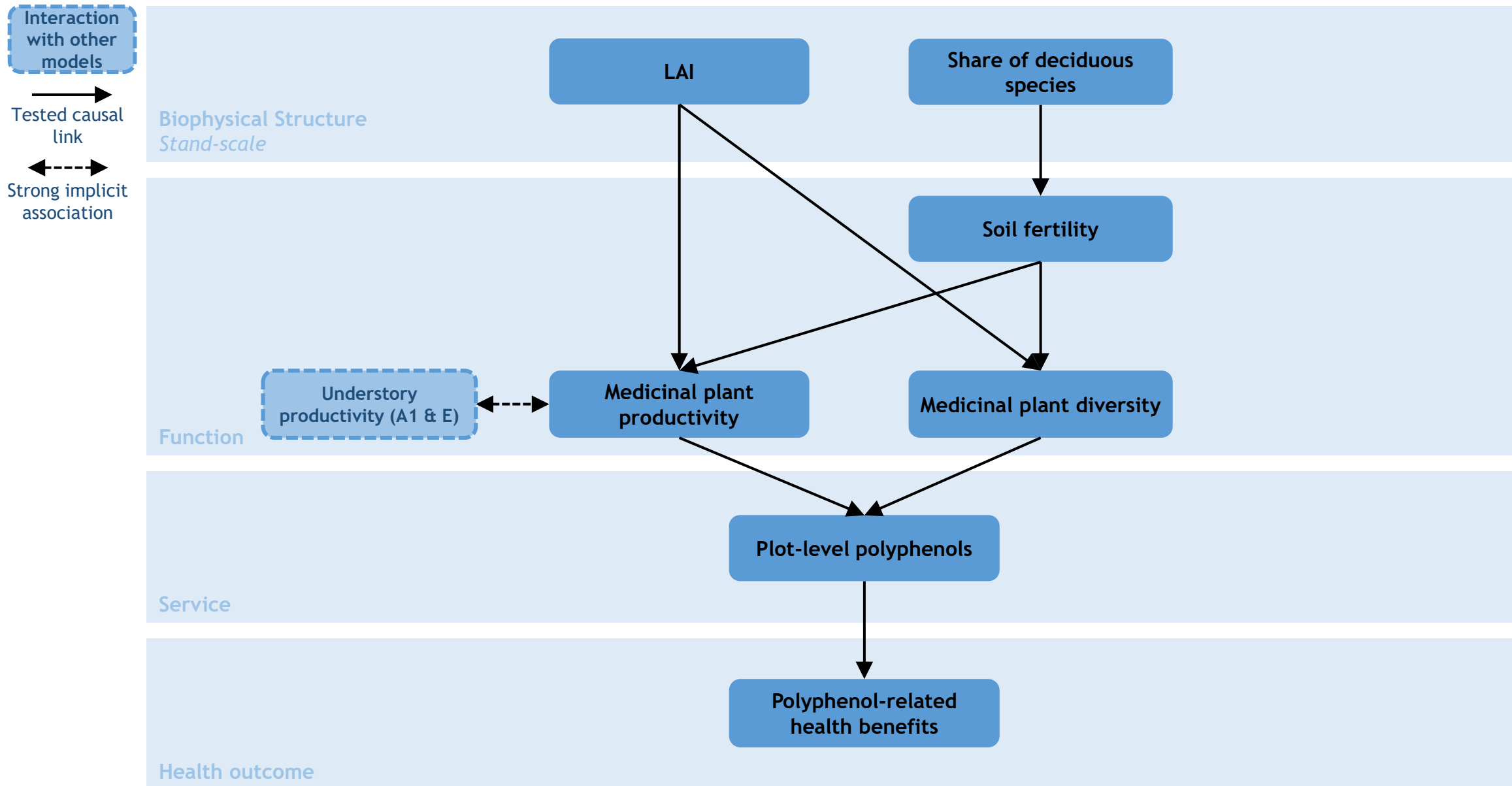
MODEL C1

NTFPs - Medicinal plants

Experts: Katarzyna Stojek, Bogdan
Jaroszewicz



MODEL C1: NTFPs - medicinal plants



Model conceptualisation

General information

Except for the health outcome category (polyphenol-related health benefits), the outline and all variables are based on our own empirical data that were sampled on 119 plots over eight Dr.FOREST sites.

Dendrometric variables are assumed to determine medicinal plant productivity and diversity via canopy cover (LAI) and soil fertility (C/N ratio).

Three medicinal plants were selected based on their occurrence over all sites and their potential health benefits. These are *Rubus fruticosus*, *Galium aparine* and *Urtica dioica*. Their productivity and diversity have been averaged per plot and together determine the polyphenol content one could find at the plot-level.

Plot-level polyphenol (biologically active substances, incl. multiple compounds such as flavonoid and tannins) content then determines the health benefits one can expect from consuming the medicinal plants.

Limitations

In the European context, the consumption of medicinal plants for human health is of limited direct relevance at the population-level. Their relative contribution to overall health will be small compared to an average person's diet and conventional medicine usage. Additionally, a large quantity of medicinal plants should be consumed before health benefits will be observable. Therefore, some stringent assumptions have to be made before interpreting the model (analogous to model C2 on mushrooms):

- 1) The model assumes a person practices the harvesting of medicinal plants and consumes the totality of medicinal plants growing in one hectare of the studied stand.
- 2) These forest medicinal plants are their only source of polyphenols.
- 3) The person does this consistently over the timescale of years.

Mental wellbeing outcomes arising from the act of harvesting plants and the physical contact with nature are also likely, but the evidence is too weak and anecdotal to substantiate the relationship.

There is a strong species identity effect (e.g. *R. fruticosus* has much higher polyphenol content), which was not modelled to avoid additional complexity. However, the presence and abundance of specific species are important determinants for plot-level polyphenol content, and they are driven by a multitude of deterministic and stochastic processes that are not reflected in this model. However, identity effects are partly taken into account in the formula to calculate plot-level polyphenol content.

Interacting variables

Medicinal plant productivity has multiple links to the tick model (E) via 'understory productivity', where higher understory cover has a direct effect on the questing nymph abundance and an indirect effect via rodent and ungulate abundances. There is also a link to the 'perceived density' node (model A1), where higher understory cover increases the perceived density, which increases the perceived biodiversity. However, remark that the medicinal plants only represent a fraction of the total understory cover, making these links rather weak.

Dr.FOREST papers

Stojek et al. *Under review*.

Medicinal plant diversity

Medicinal plant diversity	
Unit: n species / m ² Type: Continuous Range: [0, 0.8]	
States	Value intervals
Low	≤ 0.1
Medium	$0.1 < x \leq 0.24$
High	> 0.24
Definition: Scaled diversity in medicinal plants in subplots.	

Methodology & logic: Based on floristic in three subplots per Dr.FOREST plot, and then scaled to 1 m². Medicinal plants are here defined as species commonly used as medicinal plants, with properties being well-documented in the European Pharmacopoeia and by the European Medicines Agency. The unscaled medicinal plant richness ranged from 0 to 20 species per subplot and was assessed during May-June 2021. In mature forests, three subplots (5m x 5m) were sampled per plot. In BIOTREE, the plots were 6m x 6m in size. FORBIO plots were sampled in 2017-2018, with four subplots of 4.5m x 4.5m per plot. The number of medicinal species was counted in each subplot, and this count was divided by the area of the subplot. **State thresholds** are based on the 33rd and 67th percentiles. **Data source:** empirical.

Medicinal plant productivity

Medicinal plant productivity	
Unit: % cover Type: Continuous Range: [0, 100]	
States	Value intervals
Low	≤ 3.8
Medium	$3.8 < x \leq 15$
High	> 15
Definition: Cover of medicinal plants in subplots.	

Methodology & logic: Based on floristic inventories in three subplots per Dr.FOREST plot. Medicinal plants are here defined as species commonly used as medicinal plants, with properties being well-documented in the European Pharmacopoeia and by the European Medicines Agency. Since medicinal plants only represent a proportion of the total plant communities, covers are relatively low. The diversity of medicinal plants was assessed in subplots during May-June 2021. For mature forests, three subplots (5m x 5m) were sampled per plot. In BIOTREE, the plots were 6m x 6m in size. FORBIO plots were sampled in 2017-2018, with four subplots of 4.5m x 4.5m per plot. The cover [%] of separate and total medicinal species was estimated in each subplot, where the the total medicinal plant cover represents productivity. **State thresholds** are based on the 33rd and 67th percentiles. **Data source:** empirical.

Plot-level polyphenols

Plot-level polyphenols	
Unit: (mg / ha) / day Type: Continuous Range: [0, 6000]	
States	Value intervals
Low	≤ 34
Medium	$34 < x \leq 600$
High	> 600
Definition: Content of biologically active substances based on the content of polyphenols in <i>Rubus fruticosus</i> , <i>Galium aparine</i> and <i>Urtica dioica</i> as proxy species, in 2021.	

$$\frac{\sum_{i=1}^n [(Polyphenol\ Dry\ Mass_i \times Cover_i \times LMA_i) \times (1 + 0.01 \times Richness)] \times 10000m^2}{365\ days}$$

Methodology & logic: This variable is based on the formula above, which accounts for the plant polyphenol content per dry mass (mg/g), the canopy cover (%) and the LMA (Leaf Mass per Area in g/m²), used to obtain the polyphenol content per m². This is then summed over each medicinal plant species *i* in the plot. Species had to occur on at least 50% of the selected plots. Next, 1% is added to the obtained value times the total medicinal species richness. Here, the assumption is that most relevant medicinal plant species are covered with the selection of the three aforementioned species, but that the rarer species that were not measured for polyphenol content in the lab can still provide a modest contribution to the total content. At last, the obtained value is extrapolated to an hectare and divided per day, to obtain the daily polyphenol production of one hectare of forest stand. **State thresholds** are based on the 33rd and 67th percentiles. **Data source:** equation.

Polyphenol-related benefits

Polyphenol-related benefits	
Unit: Unitless Type: Continuous Range: [0, 1]	
States	Value intervals
Negligible	≥ 0.95
Low-to-Medium	$0.95 > x \geq 0.5$
High	< 0.5
Definition: Hazard Ratio (HR) for cardiovascular disease (CVD) associated to daily polyphenol intake.	

Methodology & logic: Polyphenols have been shown to potentially counteract a great variety in diseases, including neurodegenerative diseases, inflammation, cancer, cardiovascular health, type II diabetes and obesity (reviewed in Cory et al. 2018). However, a lot of uncertainty around health effects exists, since there are thousands of polyphenols which could all be associated to a specific physiological pathway and health effects (Cory et al. 2018). The best study we found, based on the wide relevance of the health outcome, the robustness of the sample and the match with our data, is by Tresserra-Rimbau et al. (2014) in *Nutr Metab Cardiovasc Dis* (see Table 2). Based on a multi-annual follow-up study involving 7172 participants, they reported HRs for CVD based on daily polyphenol intake. Concretely, a HR of 0.8 indicates a 20% lower probability for CVD. Since about two thirds of forest plots reared polyphenol contents below 600 mg/day, and that this threshold roughly corresponds to the lowest dose at which health benefits were observed, only the upper third of forest plots would actually leaf to substantial HR decreases. **State thresholds** have been chosen to reflect the contrasting patterns in the data, given that only daily intakes of > 600-700 mg reduced the risk of disease. **Data source:** Quantitative literature results.

MODEL C2

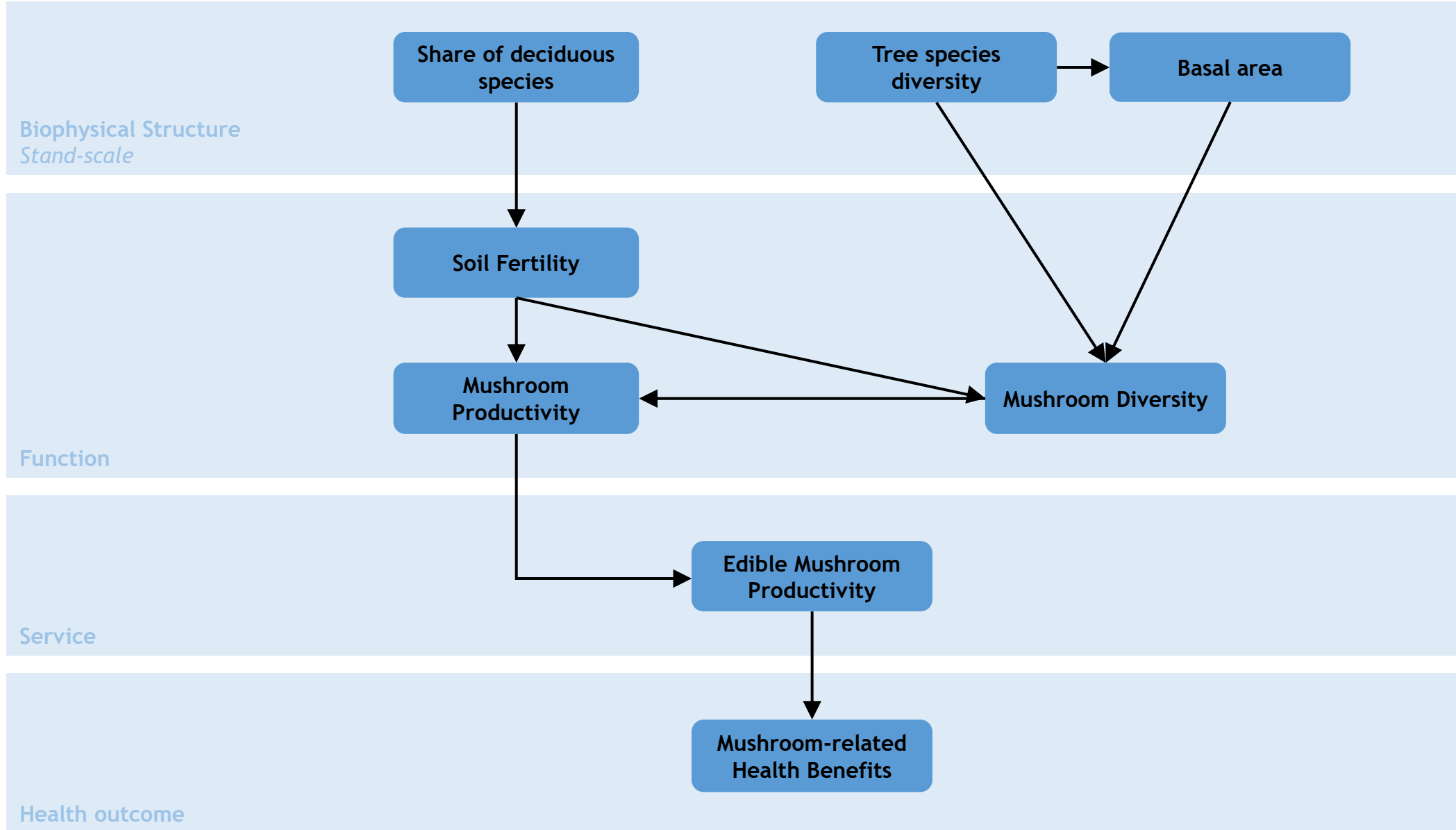
NTFPs - Mushrooms

Experts: Katarzyna Stojek, Bogdan
Jaroszewicz



MODEL C2: NTFPs - mushrooms

Interaction
with other
models



Model conceptualisation

General information

Except for the health outcome node, the model is based on our own currently unpublished and published¹ empirical observations. A first dataset includes 20 plots in Białowieża, Poland, which were entirely sampled every 10 days over two years (2020-2021) from mid-June to the end of October. The second dataset is based on a punctual sampling in 69 plots pertaining to five Dr.FOREST sites.

A forest stand will directly influence mushroom diversity and productivity through the diversity and composition of its constituting tree species, and its basal area. This is because most macroscopic mushrooms are mycorrhizal and therefore strongly associated to trees. The forest will also have an indirect influence through modification of soil fertility.

Mushroom diversity was found to be quite strongly determined by dendrometric variables. Based on the first study¹, it can also increase mushroom productivity. Yet, the relationship appears non-linear in the BBN model, and productivity seems little influenced by dendrometric characteristics. However, productivity, by itself, strongly determines the productivity of edible mushrooms specifically – as expected. In sum, changes in dendrometric characteristics appear to have little influence on the total edible mushroom biomass, which may be indicative of a strong identity effect (e.g. a few mushroom species determining the bulk of edible mushroom biomass).

At last, the model then relates the daily edible mushroom biomass production to cancer mortality estimations represented by hazard ratios based on long-term cohort data.

Limitations

The two datasets have contrasting time-scales, which required standardization based on logical assumptions (see next pages).

There are multiple assumptions that must be taken into account prior to interpreting outcomes, analogous to Model C1.

- 1) The model assumes a person practices mushroom picking and consumes the totality of mushrooms growing in a given 35m x 35m forest stand (plot size).
- 2) The person does this consistently over the timescale of years.

Mental wellbeing outcomes arising from the act of picking and the physical contact with nature are also likely, but the evidence is too weak and anecdotal to substantiate the relationship.

At last, some results might be quite region-specific. For example, mushroom diversity and production seemed not limited by precipitation based on our data, but might be in other regions like South Europe.

Interacting variables

An interaction that was removed because of negligible effect size is with the air quality model (D), mediated by the rainfall frequency and total volume. These are well-known drivers for mushroom productivity, but they also improve the air filtering capacity of leaves by cleaning and 'resetting' them, which is now represented by the 'accumulation days' node.

Dr.FOREST papers

¹ Stojek et al. 2022 *For Ecol & Man*

Mushroom diversity

Mushroom diversity	
Unit: n° of species / plot Type: Discrete Range: [0, 72]	
States	Value intervals
Low	≤ 15
Medium	$15 < x \leq 30$
High	> 30
Definition: Species richness of all mushrooms occurring in 35m x 35m plots, covering edible and non-edible species.	

Methodology & logic: Given that this node has three parent nodes, the minimal number of 10 observations per state combination was not reached. Accordingly, an expert opinion table was added and given equal weight to the empirical raw data. Notable is that mushroom diversity is much more affected by dendrometric variables than mushroom productivity (also when considering empirical data only). **State thresholds** are based on the 33rd and 67th percentiles. **Data source:** expert opinion + empirical.

Mushroom productivity

Mushroom productivity	
Unit: g fresh mass / plot / day Type: Continuous Range: [0, 400]	
States	Value intervals
Low	≤ 10
Medium	$10 < x \leq 80$
High	> 80
Definition: The total fresh biomass of all mushrooms occurring in 35m x 35m plots, divided by the amount of days covered by the sampling period. This covers all edible and non-edible species.	

Methodology & logic: The harvested fresh mushroom biomass within sampling plots (35 x 35 m), calibrated to daily production. Two datasets were combined to quantify this node. The first includes 20 plots (Bialowieza, PL) that were entirely sampled every 10 days for two years. The second includes 69 plots (five international sites) that were sampled once in September-October 2021. To combine them, only the observations of September-October 2021 of the Bialowieza dataset were selected to account for strong seasonal variation. Since only mushroom sporocarps (the sampled part) that would be harvested by a mushroom picker were sampled, and because of their very fast growth and degradation (within 10 days), we estimated that the biomass between plots that were only sampled once or every ten days are comparable. This was supported by comparing datapoint distributions and ranges of both datasets, and based on on-site monitoring. Biomass values were divided by ten days for a conservative estimate of daily mushroom production. The obtained values also correspond to other European studies (Alday et al. 2017, de Aragón et al. 2007). Notable is that mushroom productivity seems much less affected by dendrometric variables than mushroom diversity. **State thresholds** are based on the 33rd and 67th percentiles. **Data source:** empirical.

Edible mushroom productivity

Edible mushroom productivity	
Unit: g fresh mass / plot / day Type: Continuous Range: [0, 270]	
States	Value intervals
Low	≤ 4
Medium	$4 < x \leq 40$
High	> 40
Definition: The total fresh biomass of all mushrooms occurring in 35m x 35m plots, divided by the amount of days covered by the sampling period. This covers only edible species.	

Methodology & logic: The harvested fresh edible mushroom biomass within sampling plots (35 x 35 m), calibrated to daily production. Two datasets were combined to quantify this node. The first includes 20 plots (Białowieża, PL) that were entirely sampled every 10 days for two years. The second includes 69 plots (five international sites) that were sampled once in September-October 2021. To combine them, only the observations of September-October 2021 of the Białowieża dataset were selected to account for strong seasonal variation. Since only mushroom sporocarps (the sampled part) that would be harvested by a mushroom picker were sampled, and because of their very fast growth and degradation (within 10 days), we estimated that the biomass between plots that were only sampled once or every ten days are comparable. This was supported by comparing datapoint distributions and ranges of both datasets, and based on on-site monitoring. Biomass values were divided by ten days for a conservative estimate of daily mushroom production. The obtained values also correspond to other European studies (Alday et al. 2017, de Aragón et al. 2007). **State thresholds** are based on the 33rd and 67th percentiles. **Data source:** empirical.

Mushroom-related Health Benefits

Mushroom-related Health Benefits	
Unit: Relative Risk Type: Continuous Range: [0.2, 1]	
States	Value intervals
Low	≥ 0.8
Medium	$0.8 > x \geq 0.6$
High	< 0.6
Definition: The Relative Risk (RR) to developed cancer in function of daily mushroom consumption (in g/day), as reported by a recent meta-analysis (Ba et al. 2021).	

Methodology & logic: Mushroom consumption is associated to a wide array of health benefits, including “several chronic diseases, such as cancer, diabetes mellitus, cardiovascular and neurodegenerative diseases” as reviewed by Roncero-Ramos et al. (2017). Robust studies reporting dose-response relationships are rare and known cardiovascular benefits of mushroom consumption are poorly studied and probably weak (Krittanawong et al. 2021). We therefore prioritized data suitability and robustness, choosing the cancer-focused meta-analysis by Ba et al. (2021), which provides both a dose-response relationship and an error (see Fig. 6 in the publication). Results are expressed as a RR, where a RR of 0.8 indicates a 20% lower likelihood of cancer mortality attributable to a given amount of daily mushroom consumption compared to no mushroom consumption. **State thresholds** have been chosen to reflect the contrasting patterns in the data and to match our range in edible mushroom biomass values. **Data source:** quantitative literature results.

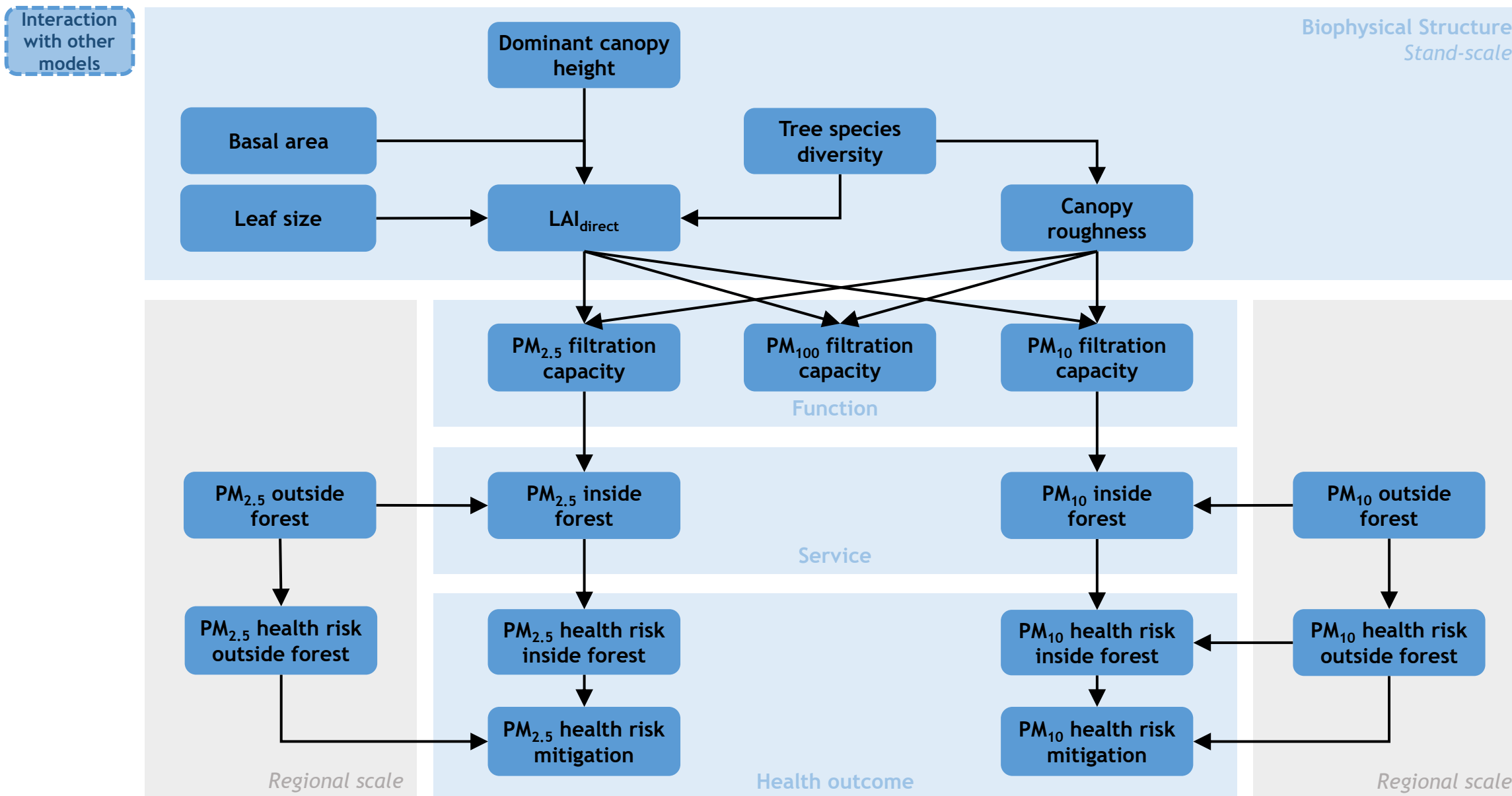
MODEL D

Air quality

Experts: Matthias Steinparzer, Daniela Haluza, Bart Muys, Douglas Godbold



MODEL D: Air quality



Model conceptualisation

General information

This model is based on insights from a meta-analysis¹, on partly published² empirical particulate matter (PM) data from 72 plots from four Dr.FOREST sites, and unpublished direct LAI measures at 140 plots from eight Dr.FOREST sites.

The forest functions as a filter that extracts more PM as it becomes more dense, thick and rough. The LAI represents both the canopy density and thickness, and is influenced by variables related to tree density (basal area), canopy height and tree diversity. The latter can influence canopy space filling by increased vertical stratification and crown plasticity (Pretzsch 2014; Jucker et al. 2015) and increases canopy roughness.

The filtration capacity itself is proxied by the amount of PM deposited on the leaves per day. How much PM is actually removed from the air depends also on the PM level outside of the forest.

Because both deposition dynamics and health consequences depend on PM size, a distinction is made between PM_{2.5} (particles < 2.5µm) and PM₁₀ (2.5µm < x < 10µm), with the former being more consequential for human health.

Limitations

Crown depth representing the filter's thickness might have been a better explanatory variable than dominant canopy height, because it is essentially the canopy that is going to do most of the air filtering (reflected by LAI), not the stem biomass. However, tree height data is more common and thus comparable to other models, and the thickness of the canopy layer is already reflected by the LAI. Adding crown depth would thus only yield small model improvements.

LAI measures are valuable and relatively rare in similar studies, yet we only used these for model E. The match between direct and indirect LAI data was mediocre. Potential reasons include different sampling points and dates. Still, we use direct measures here since PM deposition was directly measured on sampled leaves, making this link more straightforward.

The Fractal Dimension (FD) of the canopy layer could have replaced LAI, as it additionally represents how homogeneously the leaf mass is partitioned over the canopy space, with highly clumped leaves decreasing PM filtering. We chose LAI because it is more common in literature, more easily interpretable and overlapping with FD except that it does not reflect leaf clumping.

Leaf surface micromorphology and shape are also known drivers for PM deposition¹. Leaf shape had little effect based on the current model, and no data was available for the microstructure.

Due to unstable weather conditions in 2021, few periods were sufficiently dry for adequate PM deposition. This is why only four Dr.FOREST sites could be sampled.

Interacting variables

Leaf size is also shared with model B, where smaller leaves increase forest cooling. However, these leaf sizes are based on direct measures.

The canopy roughness could interact with model B, as it promotes turbulent airflow which can lead to a stronger evapotranspirative potential and thus stronger cooling, but also increased air mixing which could reduce temperature contrasts with macroclimatic conditions. This was not directly tested because of a lack of empirical data and existing literature.

Dr.FOREST papers

¹ Steinparzer et al. 2023 *Env Poll*

² Steinparzer et al. 2022 *Forests*

Canopy roughness

Canopy roughness	
Unit: % Type: Continuous Range: [0, 66]	
States	Value intervals
low	≤ 10
Medium	$10 < x \leq 19$
High	> 19
Definition: Coefficient of variation in tree heights at the stand scale as a proxy for canopy roughness. The higher the value, the more irregular and rough the canopy surface.	

Methodology & logic: Increased canopy roughness leads to enhanced turbulent airflow, which increases the deposition velocity of PM onto leaves (Oke et al. 2017 - p103; Rissanen et al. 2019). The coefficient of variation of tree heights was chosen instead of the SD because it is not influenced by the dominant canopy height, thereby avoiding a strong correlation. **State thresholds** are based on the 33rd and 67th percentiles. **Data source:** empirical.

Leaf Area Index via direct measuring

LAI _{direct}	
Unit: m ² / m ² Type: Continuous Range: [0.4, 8.7]	
States	Value intervals
low	≤ 1
Medium	$1 < x \leq 3$
High	> 3
Definition: The total one-sided green leaf area per surface area of forest floor, representing the density of the canopy layer.	

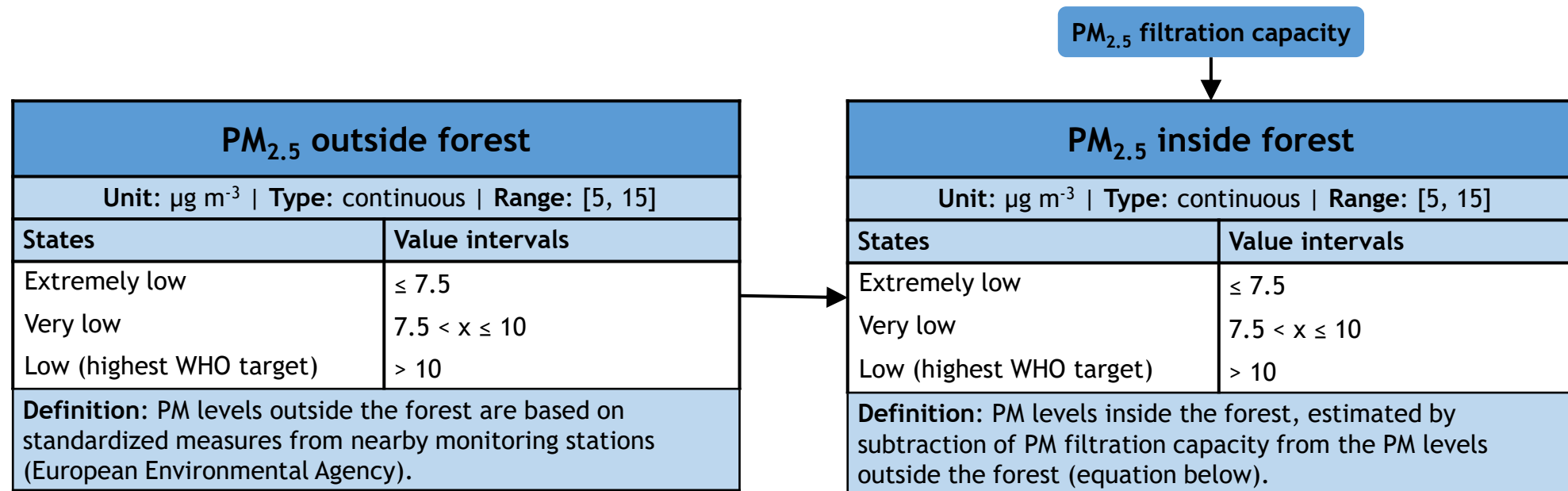
Methodology & logic: Based on data from eight Dr.FOREST sites. During the whole leaf-on period of 2021 until completion of leaf fall, leaves were collected using three or five buckets per forest plot in, respectively, mono- and polyspecific stands. Leaves were then sorted per species and their surface area was obtained through scanning. This was then extrapolated to 1 m² of forest floor, taking into account the surface area of the buckets. This is referred to as the 'direct' method for LAI, as opposed to the indirect method which uses proxies such as via hemispherical photography. In all models except model E, the indirect method is used because of relatively weak associations with the direct method. Possible reasons include different sampling points and periods. We preferred using the direct method in model E because of the straightforward link with the PM deposition loads that were obtained on these leaves, and because of the superior predictive power in the current submodel. **State thresholds** were chosen to match the direct method (p 18). **Data source:** empirical.

PM_{2.5}, PM₁₀ and PM₁₀₀ filtration capacity

PM _{2.5} filtration capacity		PM ₁₀ filtration capacity		PM ₁₀₀ filtration capacity	
Unit: g m ⁻² per day Type: continuous Range: [0, 1.7]		Unit: g m ⁻² per day Type: continuous Range: [0, 2.4]		Unit: g m ⁻² per day Type: continuous Range: [0, 6.4]	
States	Value intervals	States	Value intervals	States	Value intervals
Low	≤ 0.15	Low	≤ 0.27	Low	≤ 0.39
Medium	0.15 < x ≤ 0.36	Medium	0.27 < x ≤ 0.8	Medium	0.39 < x ≤ 1.1
High	> 0.36	High	> 0.8	High	> 1.1
Definition: Amount of PM deposition on leaf surfaces and upscaled to deposition (g) per forest floor area (m ²) via LAI.		Definition: Idem.		Definition: Idem.	

Methodology & logic: Based on empirical data from four Dr.FOREST sites. In each plot, a number of leaves was sampled, ensuring a total leaf area of approximately 300-400 cm² (Dzierzanowski et al. 2011; Łukowski et al. 2020; Popek et al. 2013). Leaves were obtained from three randomly selected dominant or co-dominant trees per species with healthy crowns around the plot's center, at east five days after the last rainfall event. PM deposited on these leaves was then washed off and quantified using gravimetrical mass analysis for the different PM size classes. Note that PM deposition is strongly determined by the frequency and intensity of rainfall events. This is taken partly compensated for by dividing the deposition values by the number of dry days preceding the sampling moment to obtain values at the daily scale. This is a pragmatic simplification of a complex process, where rainfall frequency and intensity will influence which PM size classes are washed off and how 'sticky' leaves become (discussed in Steinparzer et al. 2023). **State thresholds** are based on the 33rd and 67th percentiles. **Data source:** empirical.

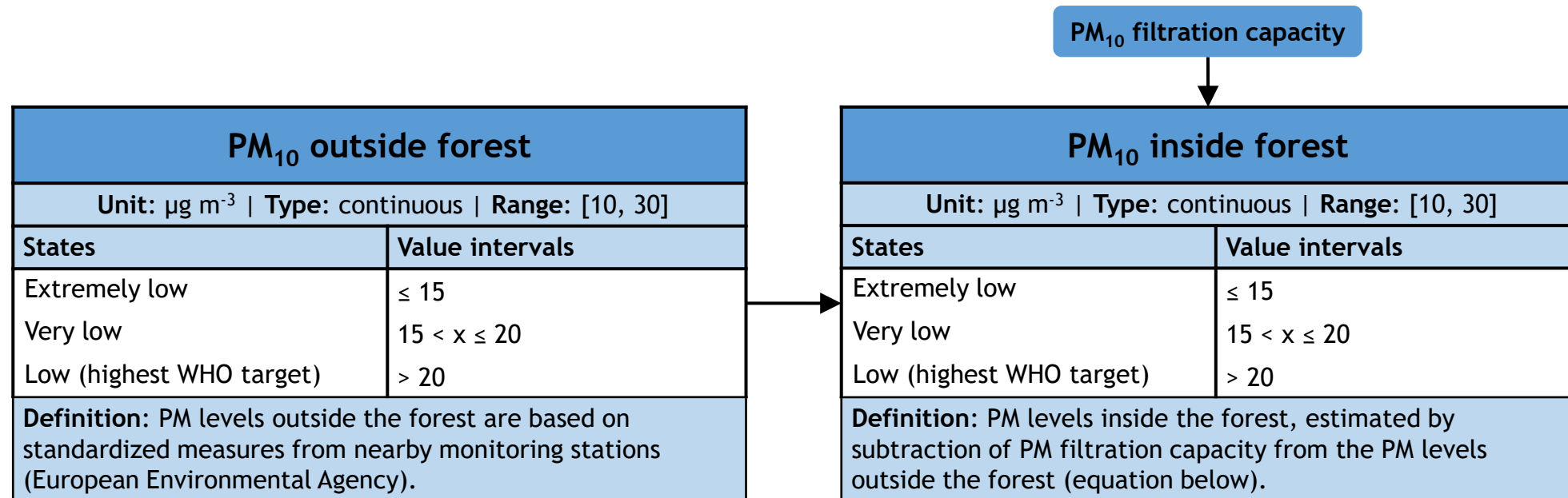
PM_{2.5} inside and outside forest



$$PM_{inside\ forest} = PM_{outside\ forest} - \left(PM_{filtration\ capacity} \times \left(\frac{24\text{gm}^{-2}\text{yr}^{-1}}{365\text{days}} \right)^{-1} \right)$$

Methodology & logic: PM levels inside the forest are calculated via a calculation that implies some assumptions. The major challenge is to extrapolate PM levels in 1m³ of air from filtration capacities expressed in gm⁻². For this, we relied on the large study by Nowak et al. (2013), whom found that, removal of 24 gm⁻²yr⁻¹ by trees was equivalent to a reduction of 1µgm⁻³ in PM_{2.5}, on average. First, the daily filtration capacity is multiplied by the filtration capacity that is equivalent to a 1µgm⁻³ PM reduction (Nowak et al. 2013), calibrated at the daily scale, to obtain the PM level reduction factor by the forest. This reduction factor is then subtracted from the PM levels outside of the forest to obtain the PM levels inside the forest. Note that we did not consider the role of the forest as a potential source of (ultrafine) particulate matter, which can comprise pollen, spores and plant fragments (Bignotti et al. 2022). **State thresholds** are based on the WHO (2021) air quality guideline levels and interim targets (annual average) for PM_{2.5}. The threshold of 10 µg/m³ already represents the most ambitious WHO air quality target. Studied forest were located in rural areas, hence the already high air quality. **Data source:** empirical (left node) and equation (right)

PM₁₀ inside and outside forest



$$PM_{inside\ forest} = PM_{outside\ forest} - \left(PM_{filtration\ capacity} \times \left(\frac{24gm^{-2}yr^{-1}}{365\ days} \right)^{-1} \right)$$

Methodology & logic: See explanation of PM_{2.5} inside and outside the forest. One limitation is that the filtration values by Nowak et al. (2013) refer to PM_{2.5} and not PM₁₀. By lack of an equivalent study, we used the same factor. This should, however, lead to conservative estimations as typically more PM₁₀ is deposited onto leaves than PM_{2.5}. **State thresholds** are based on the WHO (2021) air quality guideline levels and interim targets (annual average) for PM₁₀. The threshold of 20 µg/m³ already represents the most ambitious WHO air quality target. Studied forest were located in rural areas, hence the already high air quality. **Data source:** empirical (left node) and equation (right).

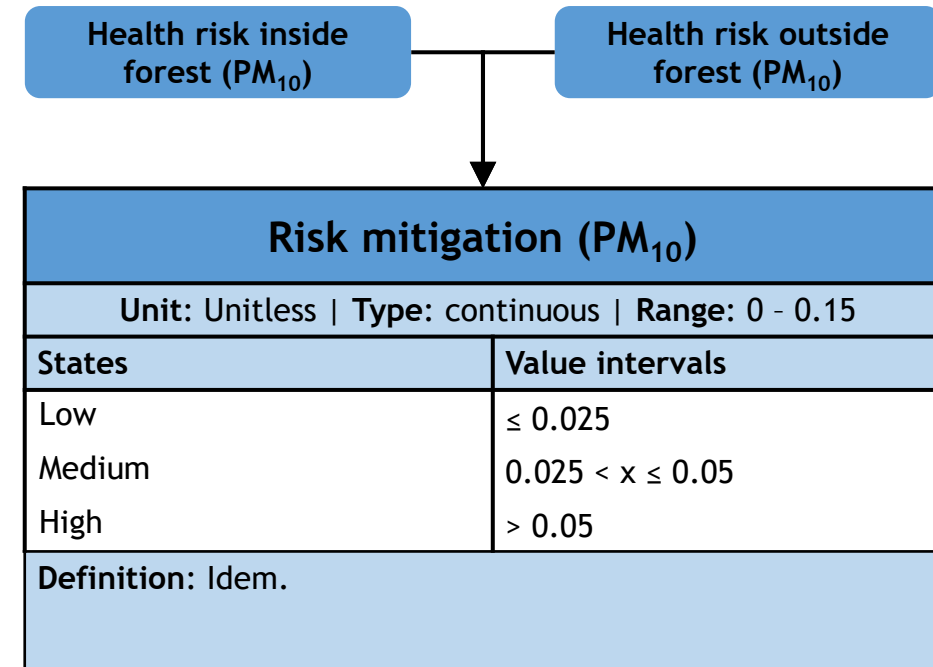
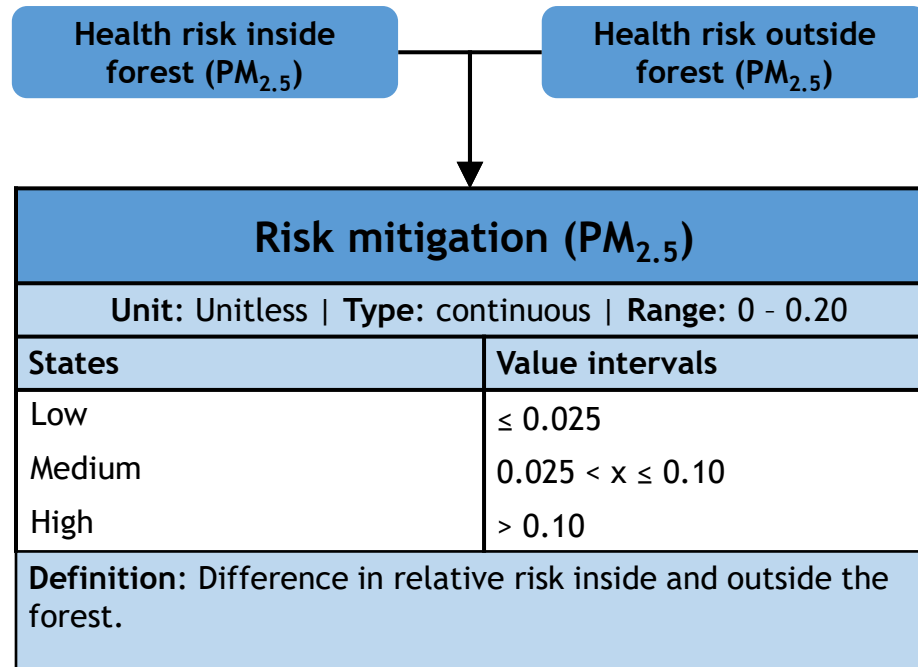
PM_{2.5} & PM₁₀ health risk inside/outside forest

Health risk inside/outside forest (PM _{2.5})	
Unit: Unitless Type: continuous Range: [1, 1.20]	
States	Value intervals
Low	≤ 1.10
Medium	$1.10 < x \leq 1.15$
High	> 1.15
Definition: Relative Risks (RR) of all-cause mortality, based on PM pollution levels.	

Health risk inside/outside forest (PM ₁₀)	
Unit: Unitless Type: continuous Range: [1, 1.15]	
States	Value intervals
Low	≤ 1.05
Medium	$1.05 < x \leq 1.10$
High	> 1.10
Definition: Idem.	

Methodology & logic: Values obtained from a meta-analysis of over 100 studies by Chen & Hoek (2020). Studies in the meta-analysis included health outcomes such as circulatory and respiratory diseases, cancer and natural-cause mortality in general. Results of the analysis explicitly compare WHO guidelines. Per 10 µg/m³ of PM_{2.5} and PM₁₀, the meta-analysis found a RR of 1.08 and 1.04, respectively. In other words, at PM_{2.5} levels of 20 µg/m³, one would expect a RR of $1.08^2 = 1.17$, or a 17% higher likelihood of natural-cause mortality. Note that the meta-analysis assumes that people are exposed to pollution for at least multiple years. **State thresholds** approximate the 33rd and 66th data percentiles, matching distributions both inside and outside the forest. **Data source:** quantitative literature results.

PM_{2.5} & PM₁₀ health risk inside/outside forest



Methodology & logic: Estimated by subtracting the RR outside the forest by the RR inside the forest. The higher the value, the stronger the risk mitigation by the forest. For example, if the RR outside the forest equals 1.15 and the RR inside the forest 1.10, the risk mitigation would be 0.05. Note that the meta-analysis assumes that people are exposed to pollution for at least multiple years. **State thresholds** were chosen to reflect contrasts in results and rounded. **Data source:** equation.

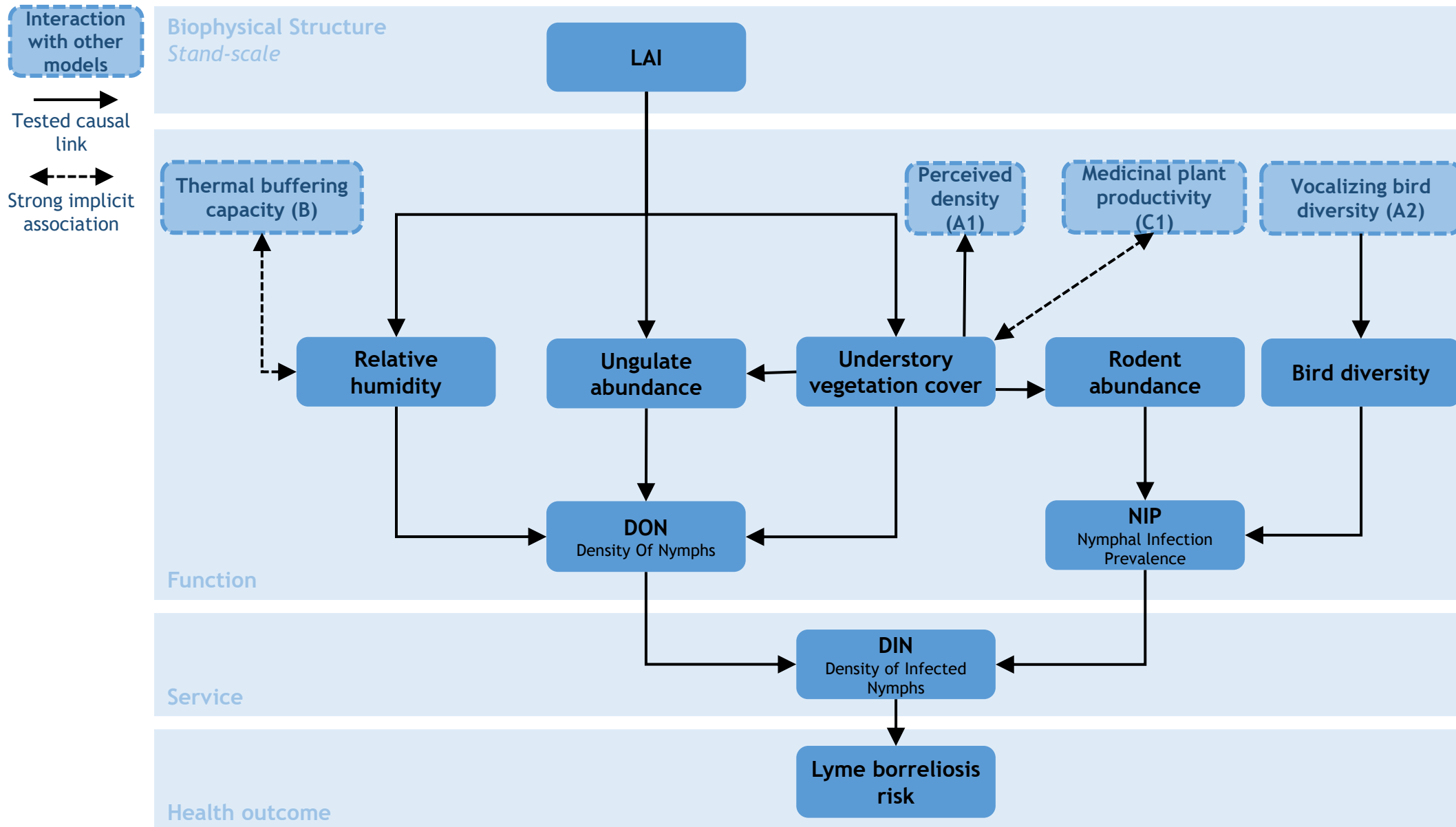
MODEL E

Ticks & Lyme disease

Experts: Audrey Bourdin, Tosca Vanroy,
Hervé Jactel



MODEL E: Ticks & Lyme disease



Model conceptualisation

General information

This model focuses on the prevalence of Lyme borreliosis disease and its spread by *Ixodes ricinus* ticks. The initial model outline is based on Fig. 1 of ref¹ and then modified according to patterns arising from our own empirical data¹⁻⁴. This covers 136 forest plots pertaining to seven Dr.FOREST sites. The forest characteristics will influence tick populations via three pathways: the humidity of the microclimate, the abundance of the understory vegetation and the vertebrate host community.

Ticks are mostly active under high air humidity conditions, and can use understory vegetation for reaching passing vertebrate hosts. Host effects are specific to the functional group. On the one hand, ungulate abundance will mainly increase the density of nymphs (DON), but they are incompetent hosts for *Borrelia* bacteria. On the other hand, rodents and birds, which are competent hosts, mainly determine the nymphal infection prevalence (NIP). The product of DON and NIP is the density of infected nymphs (DIN), which is used as a proxy for the risk of contracting Lyme disease.

How the vertebrate community modulates the risk therefore depends on the balance between ungulate effects on DON and rodent and bird effects on NIP. The dilution hypothesis (Schmidt et al. 2001) states that increasing tree diversity would reduce Lyme prevalence by increasing host diversity, thereby increasing the share of incompetent to competent (rodents, which are almost always present) hosts. However, according to our data, increasing ungulate abundance has a negative effect because of its disproportionate role in increasing DON, while rodent abundance has little effect on NIP.

Limitations

Other variables such as basal area, the share of conifers, canopy cover, leaf litter thickness and other bedding quality-related variables such as the pH were considered and tested as they impact the abundance of ticks. They were not retained as they were little influential.

Tick predators (e.g. ants, spiders and carabids) could have been included, but the relevant relationships are crucially understudied, according to a meta-analysis² (only four papers).

Our empirical data comes from two separate projects. The Dr.FOREST studies focus on the non-vertebrate pathways¹ and were therefore complemented with vertebrate data⁴ from 19 plots of the “Forester” project⁵. Because sampling took place at different sites, they are not directly comparable. To match these, we used correction factors.

The model focuses on Lyme borreliosis as the health outcome, yet other pathogens can be transmitted to humans (e.g. tick-borne encephalitis, spotted fever). Yet, Lyme remain the most common tick-borne disease in Europe so far and is better represented in literature.

Interacting variables

For relative humidity: see model B.

Higher understory cover is a driver for increased ‘perceived density’ in humans, which influenced perceived biodiversity (A1).

An increasing ‘understory vegetation cover’ increases the chance of a higher ‘medicinal plant productivity’, a variable in model C1.

Birds, especially ground-dwelling species, are hosts for ticks. There is thus an interaction between the ‘vocalizing bird species diversity’ variable of model A2 and the ‘bird diversity’ variable.

Dr.FOREST & Forester papers

¹ Bourdin et al. 2022 *Front Ecol Evol*

² Bourdin et al. 2023 *For Ecol & Man*

³ Bourdin et al. *under review*

⁴ Vanroy et al. 2024 *For Ecol & Man*

⁵ Catfolis et al. 2023 *Ecol Indic*

Understory productivity

Understory productivity	
Unit: % Type: Continuous Range: [0, 100]	
States	Value intervals
Low (B-B classes < 3)	≤ 25
Medium (B-B classes 3 and 4)	$25 < x \leq 75$
High (B-B class 5)	> 75
Definition: Share of forest floor covered by understory vegetation.	

Methodology & logic: The Braun-Blanquet scale was used in Bourdin et al. (2022), where high vegetation cover was associated with a reduction in nymph densities. This is also reflected in the current model. This may be counterintuitive, as ticks can use the understory for its favourable microclimate and to reach hosts. However, some studies found that locations with high understory covers might be less accessible to hosts, while they could also be less suitable for ‘dragflag’ sampling. This is discussed in Bourdin et al. (2022). The Braun-Blanquet scale was also used for the ‘medicinal plant productivity’ variable in model B1, though thresholds were much lower because of the small proportion of medicinal plants. **State thresholds** are based on the Braun-Blanquet (1932) method for vegetation surveys. **Data source:** empirical.

Relative humidity

Relative humidity	
Unit: % Type: Continuous Range: [0, 100]	
States	Value intervals
Unfavourable	< 80
Favourable	≥ 80
Definition: Relative humidity, averaged for a period of 48h prior to sampling ticks.	

Methodology & logic: Ticks are sensitive to dessication, especially during the questing phase. Results in Bourdin et al. (2022) also clearly indicate that the irrigated experimental forest plots housed greater numbers of nymphs. Relative humidity was monitored *in situ* for the microclimate model (B) and merged to the tick dataset. **State thresholds:** Favourable conditions have a relative humidity that “*does not fall below 80% for any length of time*” (Gray 1998). We chose this period of time to be 48h, inspired by experiments of McLeod (1935). When the average relative humidity of a forest fell above 80% for a timeframe of 48h, a forest was considered favourable for ticks. **Data source:** empirical.

Ungulate abundance

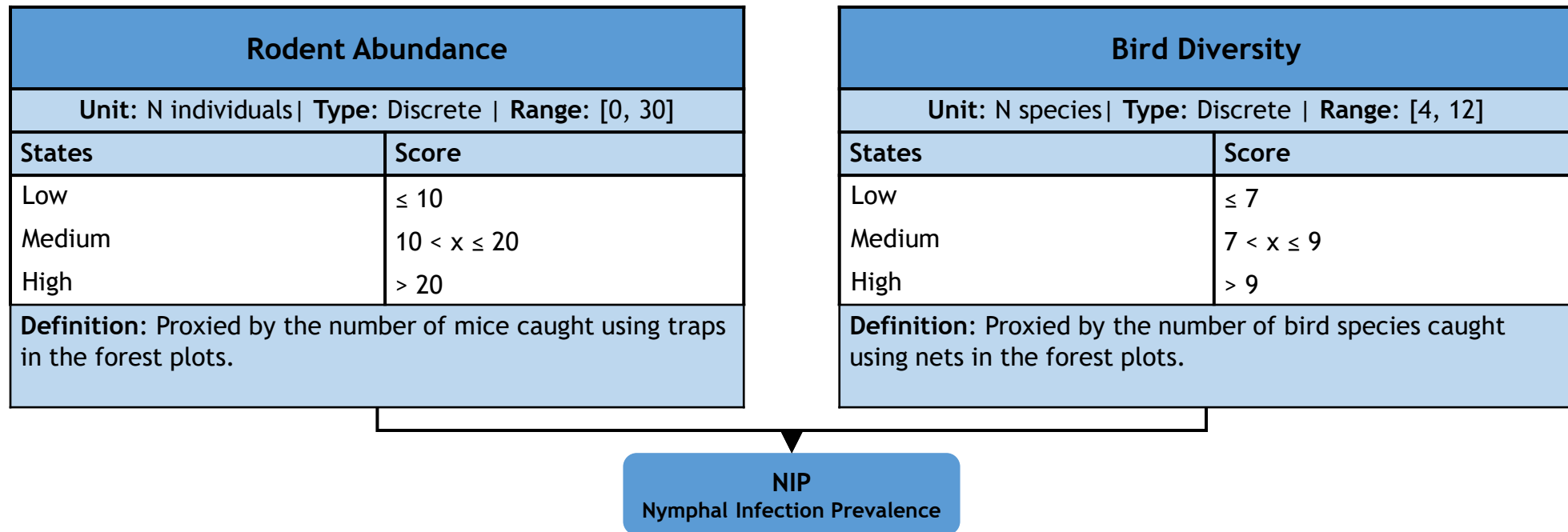
Ungulate abundance	
Unit: N deer nests Type: Discrete Range: [0, 8]	
States	Value intervals
Low	≤ 2
Medium	$2 < x \leq 4$
High	> 4
Definition: Number of deer nests observed at the forest plots, averaged for three different sampling periods.	

↓

DON
 Density Of Nymphs

Methodology & logic: Roe deer habitat selection is driven by a high canopy cover for sheltering on the one hand, and high understory canopy cover for browsing and for to shield them from forest visitors on the other hand (Mysterud et al. 1999; Van Gestel et al. 2024). Large vertebrates such as deer are ideal host for adult ticks, which produce eggs. Deer nesting sites are therefore hotspots for tick larvae and adults, strongly affecting DON. Deer absence would lead to very low tick influx. Yet, they are incompetent hosts for *Borrelia* bacteria that cause Lyme disease. Some studies (Schmidt et al. 2001; Vourc'h et al. 2016) therefore argue that forests attracting higher numbers of ungulates such as red deer will reduce Lyme prevalence (i.e. dilution hypothesis). Yet, based on the current model, the increase they cause in DON seems to strongly outweighs the reduction in NIP -as is found by some other studies as well (Vanroy et al. 2024, Ruiz-Fons et al. 2010, but see Perkins et al. 2006). **State thresholds** are based on the 33rd and 67th percentiles and rounded. **Data source:** The vertebrate-related variables are from another project ('Forester'), which required a first Expert Opinion datalayer because of the relatively small number of replications (n = 19 plots), followed by the empirical data.

Rodent abundance and bird diversity



Methodology & logic: Based on literature and our sensitivity analyses, the rodent abundance and bird diversity are the best predictors for NIP. Rodents prefer locations with high understory cover for hiding from predators but may forage in more open spaces. On the one hand, rodents represent competent host animals for *Borrelia* bacteria (*afzelii*, *spielmanii* strains), but only slightly affect NIP according to our own data and literature (LoGuidice et al. 2008). On the other hand, the effect of bird diversity is poorly studied and inconsistent. One study found NIP (*garinii*, *valaisiana* strains) to increase with bird diversity (Ostfeld and Keesing 2012), but based on a subset of ground-dwelling species - which are easily reachable by ticks and lead to higher pathogen loads (Marsot et al. 2012). Ground-dwelling birds are present in almost all 'Forester' plots, even the least species rich ones. In this case, adding bird species reduces the share of birds that contribute to higher NIP, which is also observed in our empirical data. **State thresholds** are based on the 33rd and 67th percentiles and rounded. **Data source:** A first Expert Opinion datalayer was required because of the relatively small number of replications (n = 19 plots), followed by empirical data.

DON and NIP

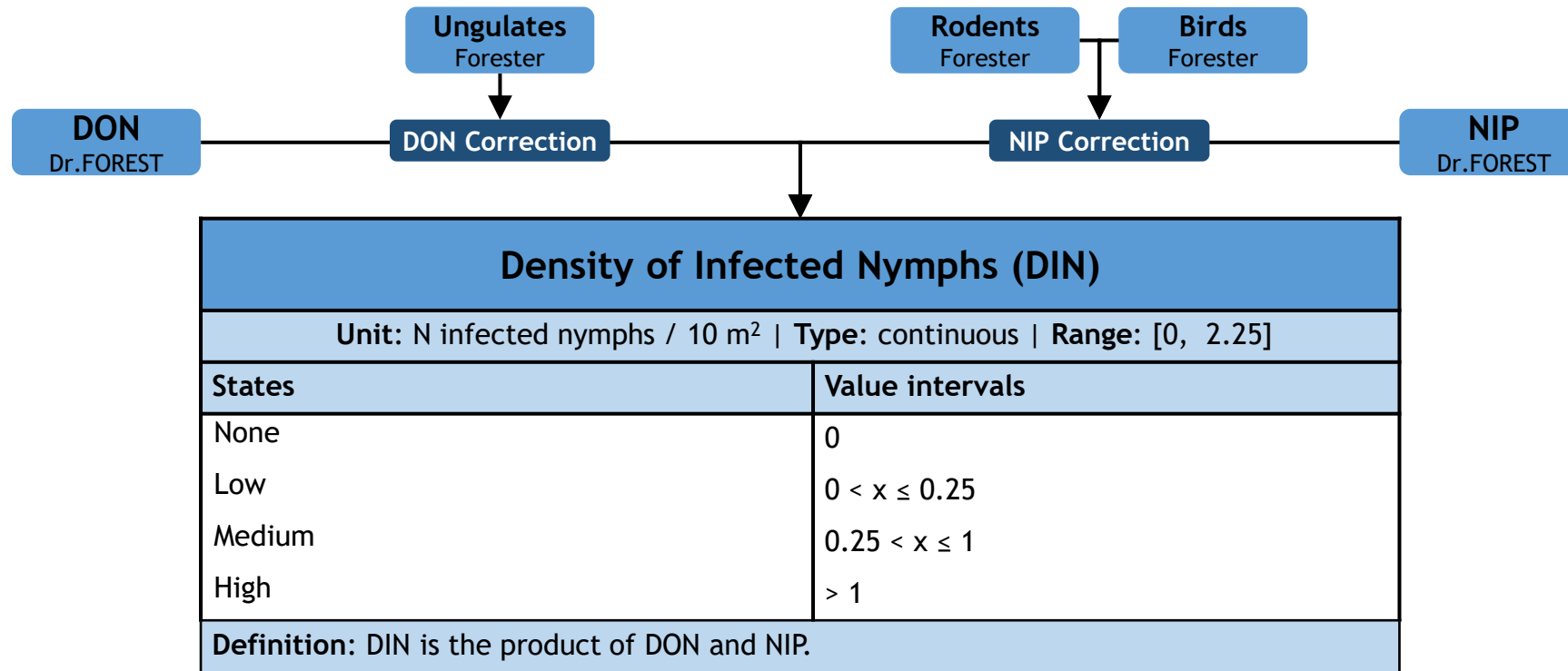
Density of Questing Nymphs (DON)	
Unit: Nymphs / 10 m ² Type: Continuous Range: [0, 14.3]	
States	Score
None	0
Low	$0 < x \leq 1$
Medium	$1 < x \leq 3$
High	> 3
Definition: Number of questing ticks per 10m ² transect.	

Nymphal Infection Prevalence (NIP)	
Unit: Unitless Type: Continuous Range: [0, 1]	
States	Score
Zero	0
Low	$0 < x \leq 0.5$
High	> 0.5
Definition: Share of sampled ticks infected with <i>Borrelia</i> bacteria.	



Methodology & logic: Left node: Based on dragflag sampling with a 1m² flag over four 10m transects per plot and averaged over the four transects. Right: Based on lab analyses of all sampled ticks. Ticks were screened for the bacterial complex *Borrelia burgdorferi* sensu lato, which also includes strains such as *B. garinii* and *B. afzelii*. **State thresholds** are based on data percentiles and rounded. There were sufficient observations to quantify the probability distribution for four states in DON. For NIP, however, a disproportionate amount of observations (61%) had a NIP of zero, rendering the contrasts in three additional states (analogous to DON) challenging. **Data source:** empirical.

Density of Infected Nymphs (DIN)



$$DIN = (DON + DON_{correction} \times DON) \times (NIP + NIP_{correction} \times NIP)$$

Methodology & logic: Vertebrate-related data was not sampled in Dr.FOREST, which is why it was complemented with data from a similar project called Forester. Even though the same technique was used (i.e. dragflag), these data are based on different sampling sites and sampling periods, which influences the absolute values of DON and NIP. Because we are interested in *relative* changes according to the vertebrate communities, we used a correction factor represented by a relative error = $(x - \mu)/\mu$, where x is an observation and μ is the mean value. By adding this correction factor to the calculation of DIN, standardized changes relative to the mean value of Forester data is also reflected in Dr.FOREST data. This pragmatic approach makes it insensitive to site effects and provides better harmonization to Dr.FOREST data. **State thresholds** ensure the possibility of a DIN of 0, which was the most common state. The remaining states are based on data percentiles and rounded. **Data source:** equation.

Lyme borreliosis risk

Lyme borreliosis risk	
Unit: N infected nymphs / 10 m ² Type: continuous Range: [0, 2.25]	
States	Value intervals
None	0
Low	$0 < x \leq 0.25$
Medium	$0.25 < x \leq 1$
High	> 1
Definition: Risk of contracting Lyme disease.	

Methodology & logic: The density of infected nymphs (DIN) is used directly as a proxy to estimate the risk of Lyme disease in a certain area, done as in Li et al. (2019). There are studies explicitly relating DIN to Lyme prevalence, like Pepin et al. (2012) whom sampled DIN over 36 states in the US. However, as in other similar studies, it is found that relationships are very site-dependent. This is because there is generally a mismatch in the very local DIN data and the regional-level incidence of Lyme. Accordingly, because local-scale data for Lyme incidence in our sampled forest is also not available, we preferred using the simpler approach of using DIN as a proxy for Lyme incidence directly. **State thresholds** ensure the possibility of a DIN of 0, which was the most common state. The remaining states are based on data percentiles and rounded. **Data source:** equation.

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Fig. S1

Synergies and trade-offs between forest-health pathways - extended version. Based on mutual information levels between nodes of different pathways. Mutual information is here defined as the reduction in entropy in one node, measured in computational bits, due to a finding in the other node (as defined in Norsys Software Corporation 1998). This represents a measure of interaction strength and was computed for ecosystem functions (a), ecosystem services (b) and health outcomes (c). This figure constitutes the basis for Fig. 3 in the main text, where full lines indicate interactions between submodels that are the strongest and visible until the health outcome level. In Fig. 2, dotted lines indicate that interactions between submodels were present at the function or service levels, but not the health outcome level.

