Supplementary material

Appendix I

After conducting an initial test simulation, several challenges were identified, particularly concerning the limitations of some submodels. The original submodels were calibrated using data from the Spanish National Forest Inventory plots (Alberdi et al., 2010, 2016), which have distinct characteristics in terms of tree size and stand types compared to the data used in this study. This discrepancy was especially notable in the mortality (Adame et al., 2010a) and ingrowth (Adame et al., 2010a), submodels, where the range of values was narrower than those obtained in our simulations. Furthermore, the original model did not account for the effect of climate. To address these issues, both the mortality and ingrowth submodels were replaced with new mathematical rules that incorporate climate variables, thereby overcoming the limitations of the original models.

The new submodels are rule-based and tailored to the conditions of both trees and stands. Each submodel operates using a threshold value that determines when the submodel should be activated, followed by a deterministic value that dictates the amount of mortality or ingrowth to be applied. The threshold value acts as a reference point: if exceeded, the submodel is triggered, calculating the mortality (or ingrowth) to be applied. If the threshold is not surpassed, it is assumed that no mortality occurs, or there is no ingrowth. This framework follows the methodology proposed by Rodríguez de Prado et al. (2023) and relies on Reineke's Stand Density Index (SDI) (Reineke, 1933) and the Maximum Reineke's Stand Density Index (SDImax). SDI serves as an indicator of the current stand condition, while SDImax establishes the maximum carrying capacity of the stand, influenced by both stand and climate conditions.

The new mortality submodel is activated when the current SDI exceeds SDImax multiplied by an adjustment factor (i), where *i* is a variable between 0 and 1. This adjustment extends the conditions under which mortality occurs by modifying the original SDImax value. For the deterministic mortality value, the average mortality from Adame et al. (2010a), set at 11.18%, is used as a baseline and adjusted by another variable, *j*. This *j* variable, also ranging from 0 to 1, allows further adjustment of mortality severity based on stand characteristics. In this way, *i* adjusts the threshold, while *j* adjusts the intensity of the applied mortality. The final mortality submodel operates as follows:

$$\text{if } \mathbf{SDI > SDImax} * \boldsymbol{i}, \text{ then } \mathbf{expan = expan - m} * \boldsymbol{j}$$

where:

SDI: Reineke's Stand Density Index (trees/ha)

SDImax: Maximum Reineke's Stand Density Index (trees/ha)

expan: tree expansion factor, used to scale plot-level data to per-hectare values

m: average mortality value, fixed at 11.18% (Adame et al., 2010b)

i: threshold adjustment value, set at 0.90, 0.85, 0.80, or 0.75 for each corresponding *j* value

j: mortality adjustment value, set at 1, 0.75, 0.50, or 0.25 for each corresponding *i* value

This new approach allows the model to account for stand dynamics more flexibly, incorporating both stand density and climate effects, and providing a more accurate representation of mortality and ingrowth in the simulated stands.

The new ingrowth submodel follows a similar structure to the mortality submodel, but it is triggered when the current SDI is less than SDImax multiplied by an adjustment factor (*i*). Here, *i* is a variable between 0 and 1, which extends the conditions under which ingrowth can occur by modifying the original SDImax value. For the deterministic ingrowth value, the average ingrowth from Adame et al. (2010b), set at 27.21%, is used as a reference. This value is adjusted by another variable, *j*, which also ranges from 0 to 1, allowing for the adjustment of ingrowth severity based on stand characteristics, similar to the adjustment in the mortality submodel. The final ingrowth submodel operates as follows:

$$\text{if } \mathbf{SDI > SDImax} * \boldsymbol{i}\text{, then } \mathbf{expan = expan - m * j}$$

where:

SDI: Reineke's Stand Density Index (trees/ha)

SDImax: Maximum Reineke's Stand Density Index (trees/ha)

expan: tree expansion factor, used to extrapolate plot-level calculations to the hectare level

m: average ingrowth value, fixed at 27.21% (Adame et al., 2010a)

i: threshold adjustment value, set at 0.75, 0.80, 0.85, or 0.90 for each corresponding *j* value

j: ingrowth adjustment value, set at 0.25, 0.50, 0.75, or 1 for each corresponding *i* value

Appendix II

This appendix includes a table summarizing the silvicultural paths already published in different Spanish regions for managing Pyrenean oak stands for different purposes.

Table S1. Summary of the silviculture paths proposed in different regions of Spain to manage pure Pyrenean oak stands. The "status" column is referred to the scenarios included in this work.

	Silvicultural path code	**Objective product**	**Silviculture summary**	**Status**
Asturias	QP1	Firewood	Clearcut in 2 steps with 20-25% seed-trees	Not included
	QP2	Firewood	Clearcut in stand surfaces < 0,2 ha	Not included
	QP3	Saw and firewood	Uniform shelterwood	Not included
Cantabria	QP01	Biomass – firewood	Selective thinning creating 2 tree layers	Not included
Castile-and-Leon	Madera de calidad	Saw, veneer, staves	Medium/smooth thinning reaching Hart Index values between 27 and 30	Not included
	Múltiple	Veneer and/or staves	Thinning with harder intensities than previous case	Not included
	Cortas intensivas	Firewood/biomass	Clearcut with selective thinning, without selective thinning and preserving small groups of trees	Not included
	Adehesado	Grazing	Strong and selective thinning	Not included
	Irregular	Saw, veneer, staves	Improvement thinning	Included
Catalonia	QPY01	Wood and firewood in regular stand	Selective thinning followed by preparatory, seeding and final thinning	Not included
	QPY02	Wood and firewood in irregular stand	Selective thinning each 20-25 years	Not included
	QPY03	Wood and firewood in semirregular stand	Selective thinning each 25-30 years	Not included
Galicia	QP1	Leñas	Clearcut with selective thinning	Not included
	QP2	Multifunction (firewood, wood, fungi, grazing, hunting)	Continuous thinning and selective thinning	Included

Appendix III

This appendix summarizes the silvicultural paths applied on SIMANFOR simulator (Bravo et al., 2025), whose results were shown at the core of this article and metrics at both tree and plot levels are available in the complementary data attached to this study. Tables are split by the inventory used on each case (SG02, SO02 and both irregular plots SG02* and SO02*), showing just thinning information and excluding projections (10 years each) to promote understandability. Information is shown as follows:

- Inventory name: inventory name (irregular includes both SG02* and SO02* inventories)
- Scenario name: name provided to the scenario
- Scenario age: average stand age when the action was realized (years)
- Harvest type: details about the thinning process applied on the stand
- Harvest criteria: reference value used to apply certain thinning intensity. ‘Density’ refers to plot density; ‘Volume’ refers to the total plot volume including bark; ‘Basal area’ refers to the plot basal area
- Harvest severity: thinning intensity degree according to the metric selected in the previous step (%)
- Trees to preserve: when future trees are preserved through the thinning, a percentage of the bigger trees in the plot can be selected to be preserved (%)

Table S2. Summary of silvicultural scenarios applied in this study. Notice that projection was not included in the table to save space and facilitate its understanding; all the projections were based on 10 years-period for the proper use of the model.

Inventory name	Scenario name	Scenario age (years)	Harvest type	Harvest criteria	Harvest severity	Trees to preserve
SG02	*cyl*	50	Systematic thinning with future trees	Density	20	-
		50	Thinning from above with future trees	Density	10	-
		60	Systematic thinning with future trees	Density	20	-
		60	Thinning from above with future trees	Density	10	-
		80	Thinning from above with future trees	Density	10	-
		80	Systematic thinning with future trees	Density	10	-
		90	Thinning from above with future trees	Density	10	-
		90	Systematic thinning with future trees	Density	10	-
		110	Thinning from above with future trees	Density	10	-
		110	Systematic thinning with future trees	Density	10	-
		120	Thinning from above with future trees	Density	10	-

		120	Systematic thinning with future trees	Density	10	-
		140	Thinning from above with future trees	Density	10	-
		140	Systematic thinning with future trees	Density	10	-
	mix	50	Thinning from below	Density	25	-
		50	Systematic thinning with future trees	Density	10	40
		70	Thinning from below	Density	25	-
		70	Systematic thinning with future trees	Density	10	40
		90	Systematic thinning with future trees	Density	15	40
		110	Systematic thinning with future trees	Density	15	40
		130	Systematic thinning with future trees	Density	15	40
	gal	50	Thinning from below	Density	20	-
		60	Thinning from below	Density	20	-
		80	Thinning from below	Density	10	-
		100	Thinning from below	Density	10	-
		120	Thinning from below	Density	10	-
		140	Thinning from below	Density	10	-
SO02	*cyl*	50	Systematic thinning with future trees	Density	10	-
		50	Thinning from above with future trees	Density	10	-
		60	Systematic thinning with future trees	Density	10	-
		60	Thinning from above with future trees	Density	10	-
		80	Thinning from above with future trees	Density	10	-
		80	Systematic thinning with future trees	Density	10	-
		90	Thinning from above with future trees	Density	10	-
		90	Systematic thinning with future trees	Density	10	-
		110	Thinning from above with future trees	Density	10	-
		110	Systematic thinning with future trees	Density	10	-
		120	Thinning from above with future trees	Density	10	-
		120	Systematic thinning with future trees	Density	10	-
		140	Thinning from above with future trees	Density	10	-
		140	Systematic thinning with future trees	Density	10	-
	mix	50	Systematic thinning with future trees	Density	10	30
		70	Thinning from below	Density	10	-
		70	Systematic thinning with future trees	Density	10	30
		90	Thinning from below	Density	10	-
		90	Systematic thinning with future trees	Density	10	30
		110	Thinning from below	Density	10	-
		110	Systematic thinning with future trees	Density	10	30
		130	Thinning from below	Density	10	-
		130	Systematic thinning with future trees	Density	10	30
	gal	50	Thinning from below	Density	10	-
		60	Thinning from below	Density	10	-
		80	Thinning from below	Density	20	-
		100	Thinning from below	Density	20	-
		120	Thinning from below	Density	20	-
		140	Thinning from below	Density	20	-

irregular	*cyl*	70	Systematic thinning with future trees	Density	10	30
		70	Thinning from above	Volume	10	-
		90	Systematic thinning with future trees	Density	10	30
		90	Thinning from above	Volume	10	-
		110	Systematic thinning with future trees	Density	10	30
		110	Thinning from above	Volume	10	-
		130	Systematic thinning with future trees	Density	10	30
		130	Thinning from above	Volume	10	-
	mix	70	Thinning from below	Density	5	-
		70	Systematic thinning with future trees	Density	5	30
		70	Thinning from above	Volume	10	-
		90	Thinning from below	Density	5	-
		90	Systematic thinning with future trees	Density	5	30
		90	Thinning from above	Volume	10	-
		110	Thinning from below	Density	5	-
		110	Systematic thinning with future trees	Density	5	30
		110	Thinning from above	Volume	10	-
		130	Thinning from below	Density	5	-
		130	Systematic thinning with future trees	Density	5	30
		130	Thinning from above	Volume	10	-
	gal	70	Thinning from below	Density	10	-
		70	Thinning from above	Volume	20	-
		90	Thinning from below	Density	10	-
		90	Thinning from above	Volume	20	-
		110	Thinning from below	Density	10	-
		110	Thinning from above	Volume	20	-
		130	Thinning from below	Density	10	-
		130	Thinning from above	Volume	20	-

Appendix IV

Graphical summary of stand evolution over the 100-year simulation for both case studies. In all included graphs, the labels refer to:

- A: SG02 plot for stand structure transformation
- B: SO02 plot for stand structure transformation
- C: SG02* plot for irregular stand management
- D: SO02* plot for irregular stand management

Graphs are shown in the following order:

- Stand density (trees/ha)
- Stand basal area (m^2/ha)
- Stand biomass (squared dots) and carbon (circular dots) (t/ha)
- Standing volume (squared dots) and accumulated volume (standing + extracted; circular dots) (m^3/ha)
- Accumulated big saw volume (size: 1.5m x 30cm) (m^3/ha)
- Accumulated saw volume (size: 2.0m x 25cm) (m^3/ha)
- Accumulated staves volume (size: 1.0m x 40cm) (m^3/ha)
- Accumulated bottom staves volume (size: 0.6m x 40cm) (m^3/ha)
- Accumulated wood panels and "other uses" volume (size: 2.5m x 30cm) (m^3/ha)
- Hart-Becking index (%)
- Shannon-Weaver index estimated for tree dbh; it was calculated using diametric classes grouped in 5 cm intervals
- Biodiversity Index based on Deadwood (BID) based on stand basal area
- Biodiversity Index based on Deadwood (BID) based on stand volume

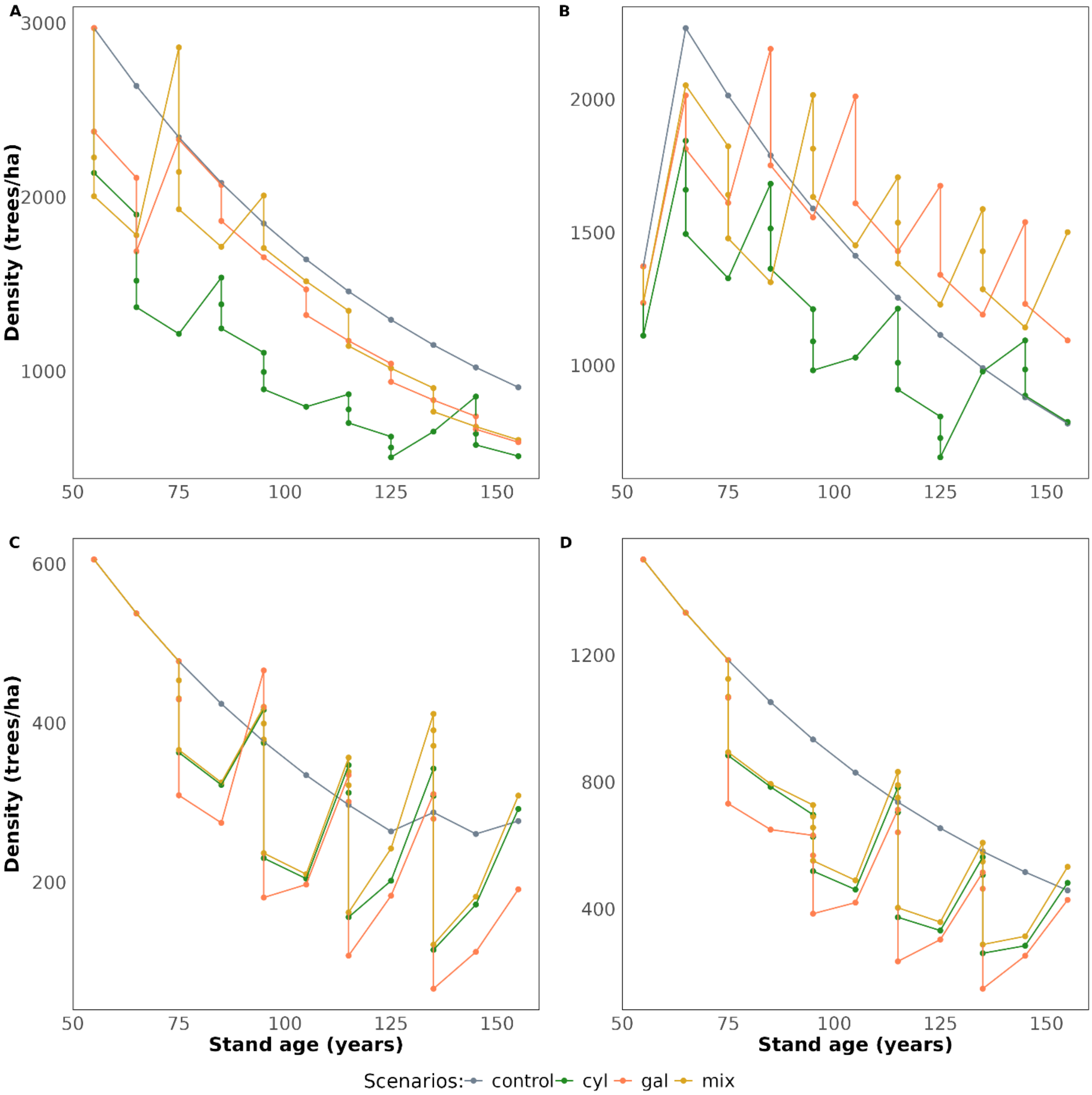

Figure S1. Summary of stand density evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

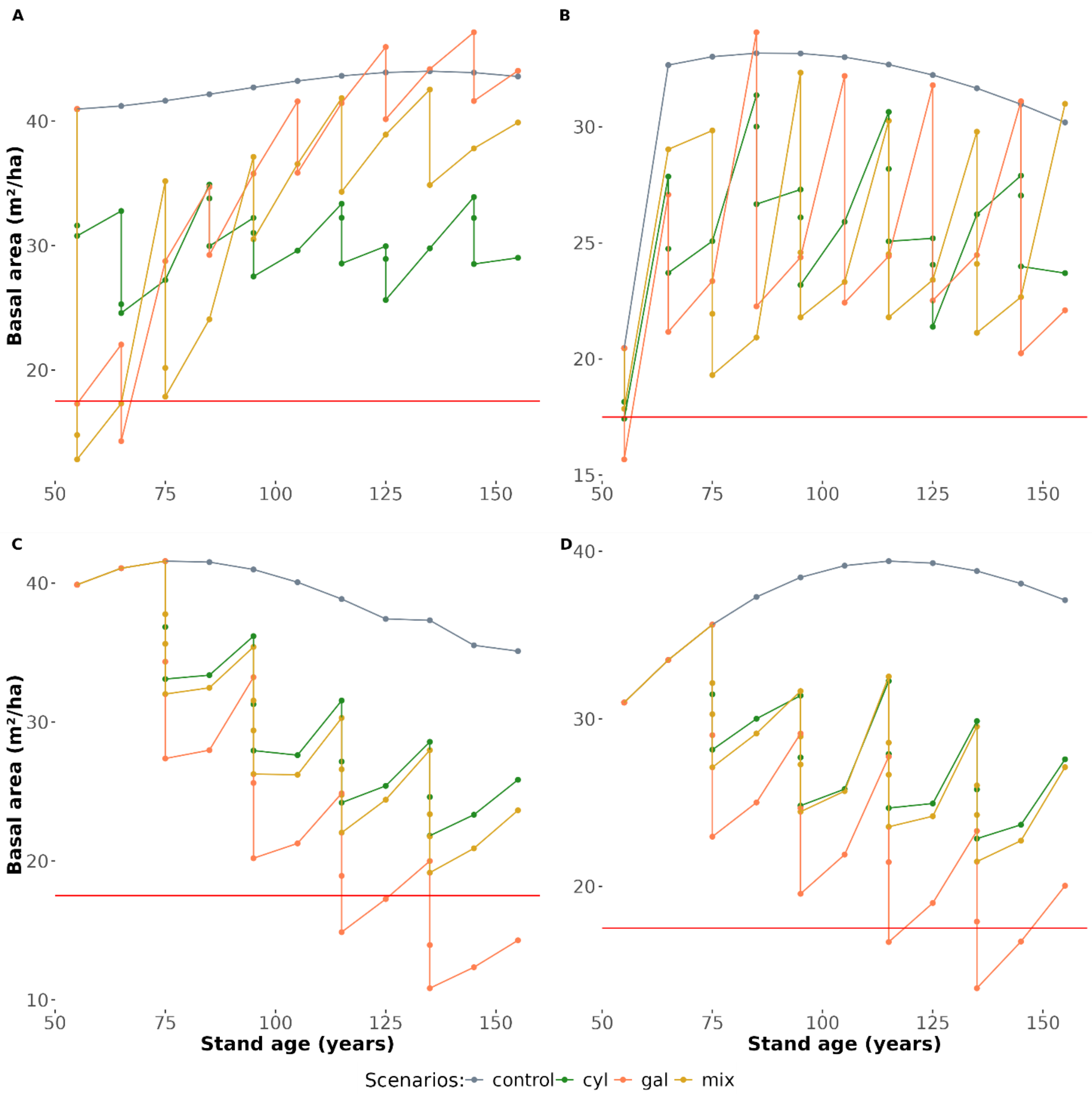

Figure S2. Summary of stand basal area evolution over the 100-year simulation. Red line refers to the reference value stablished in the methodology section. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

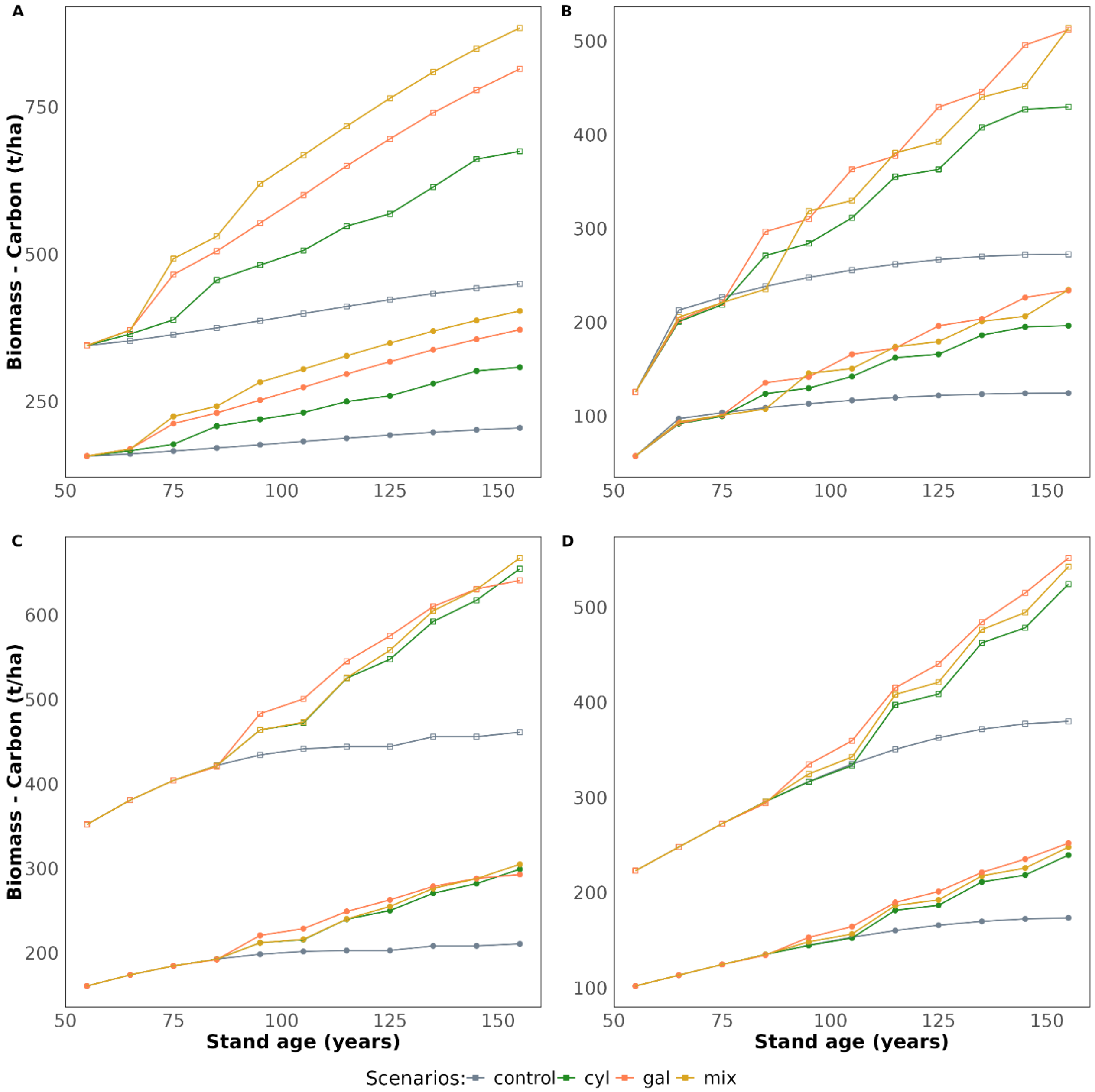

Figure S3. Summary of stand biomass (squared points) and carbon (circular points) evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

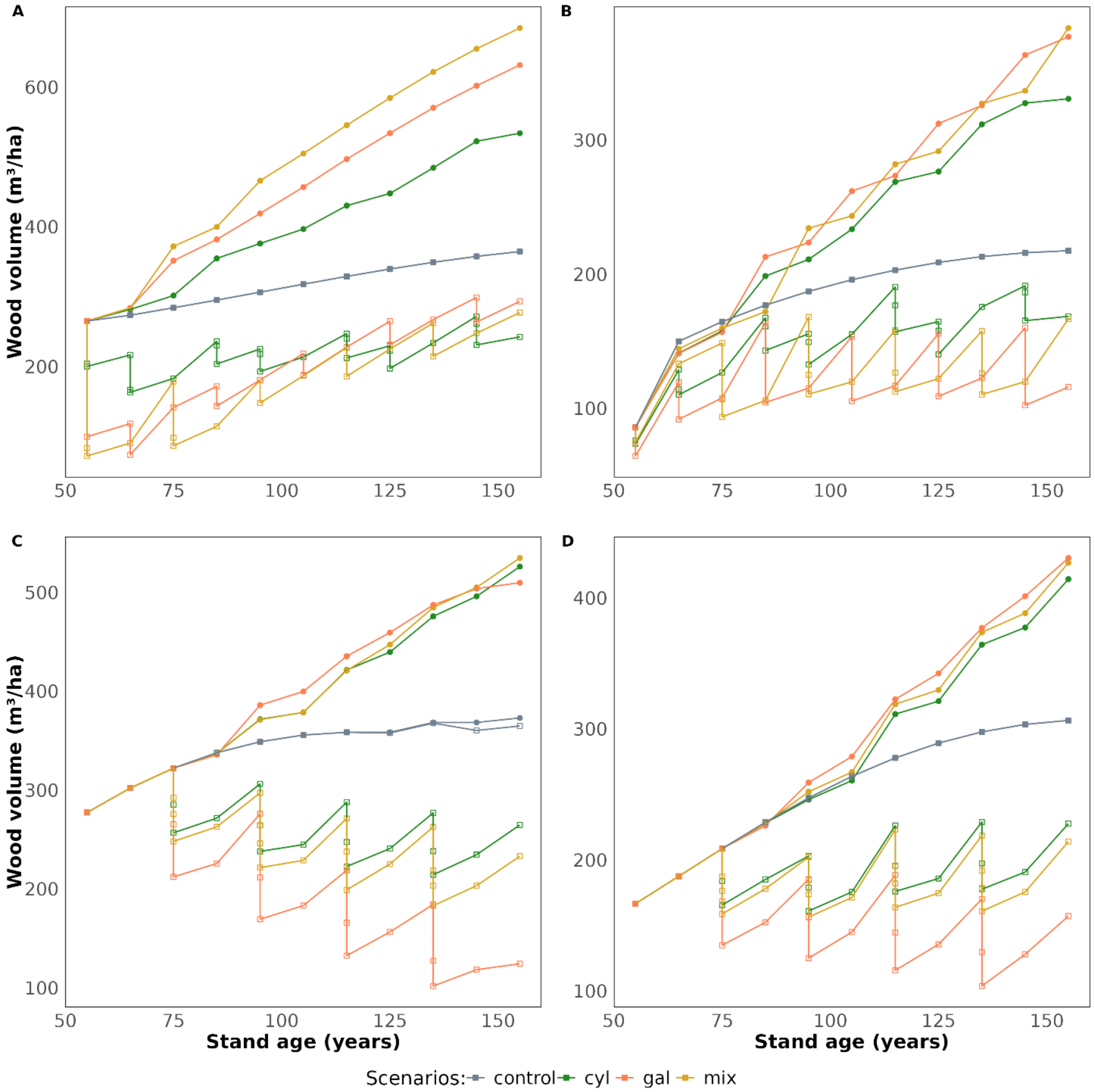

Figure S4. Summary of stand standing (squared points) and accumulated (circular points) volume evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

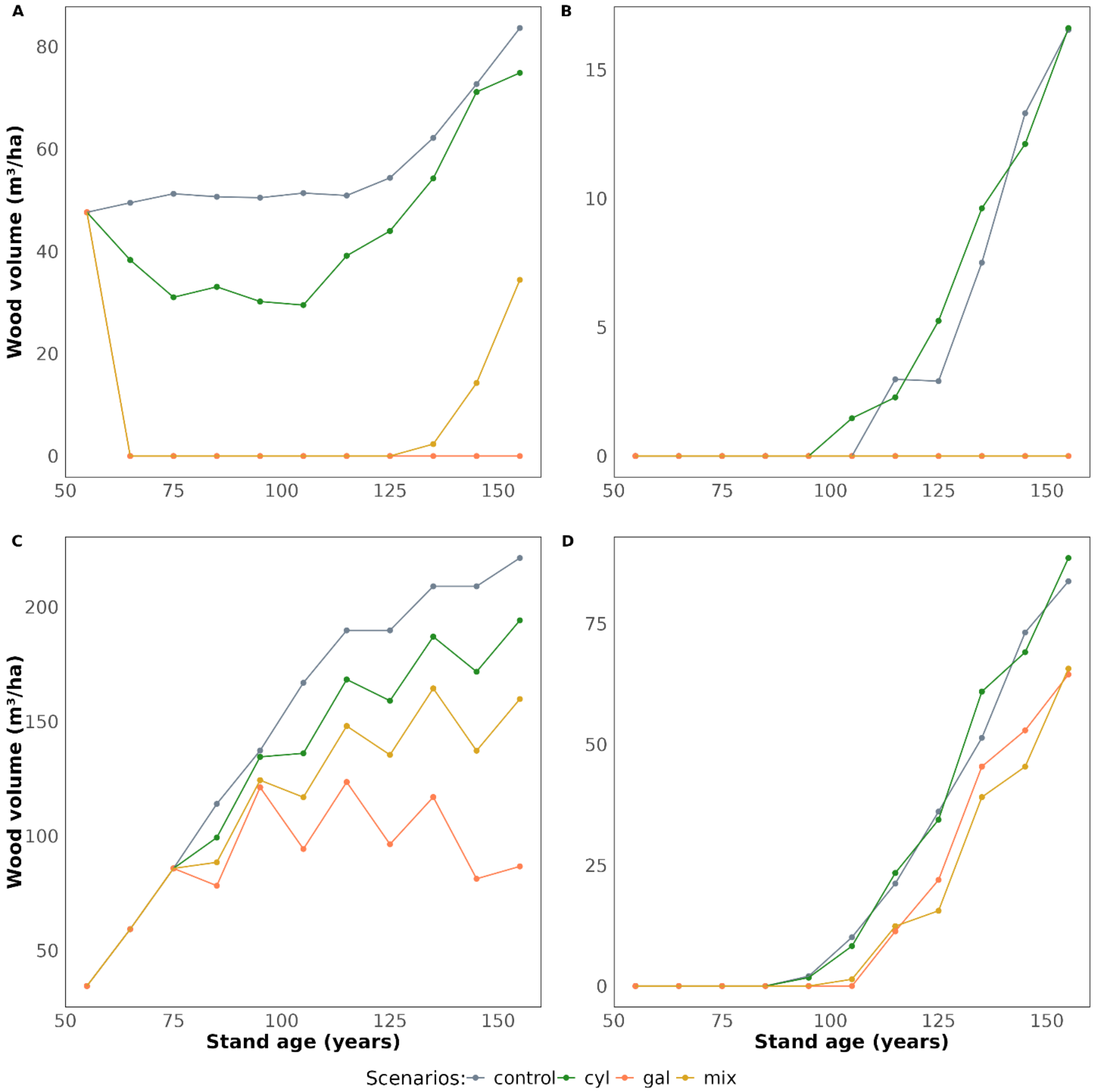

Figure S5. Summary of stand big saw volume evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

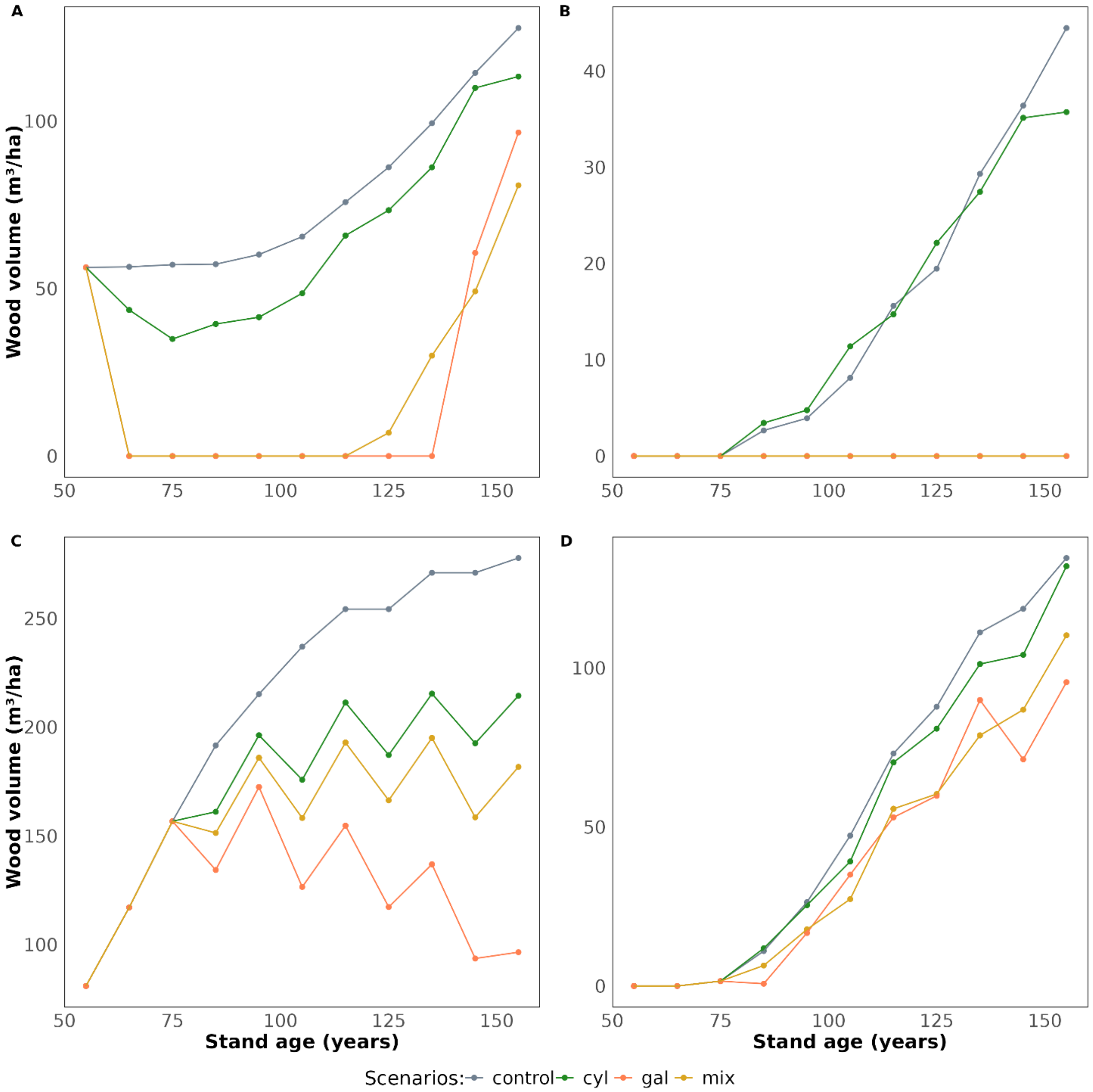

Figure S6. Summary of stand saw volume evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

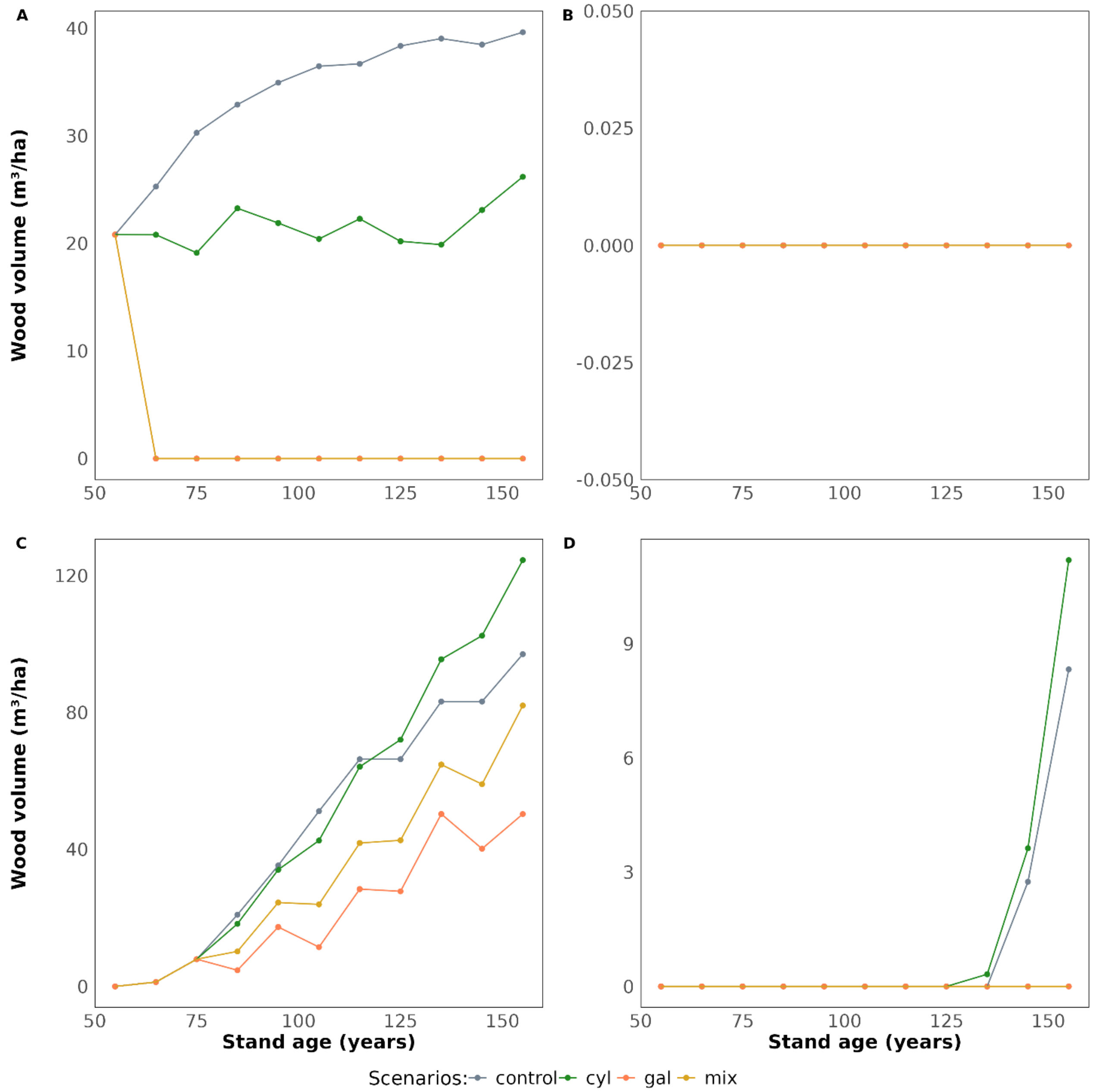

Figure S7. Summary of stand staves volume evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

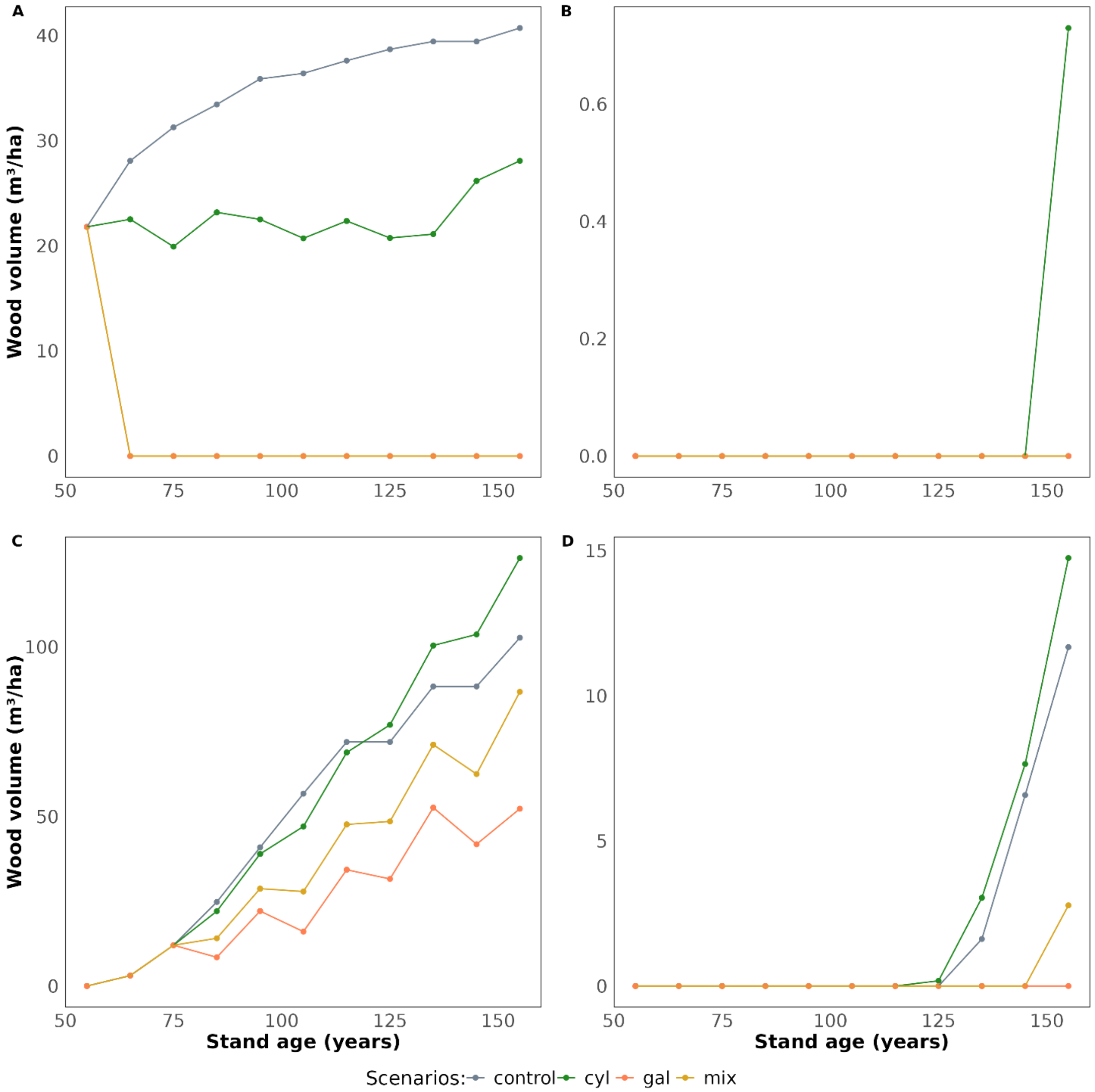

Figure S8. Summary of stand bottom staves volume evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

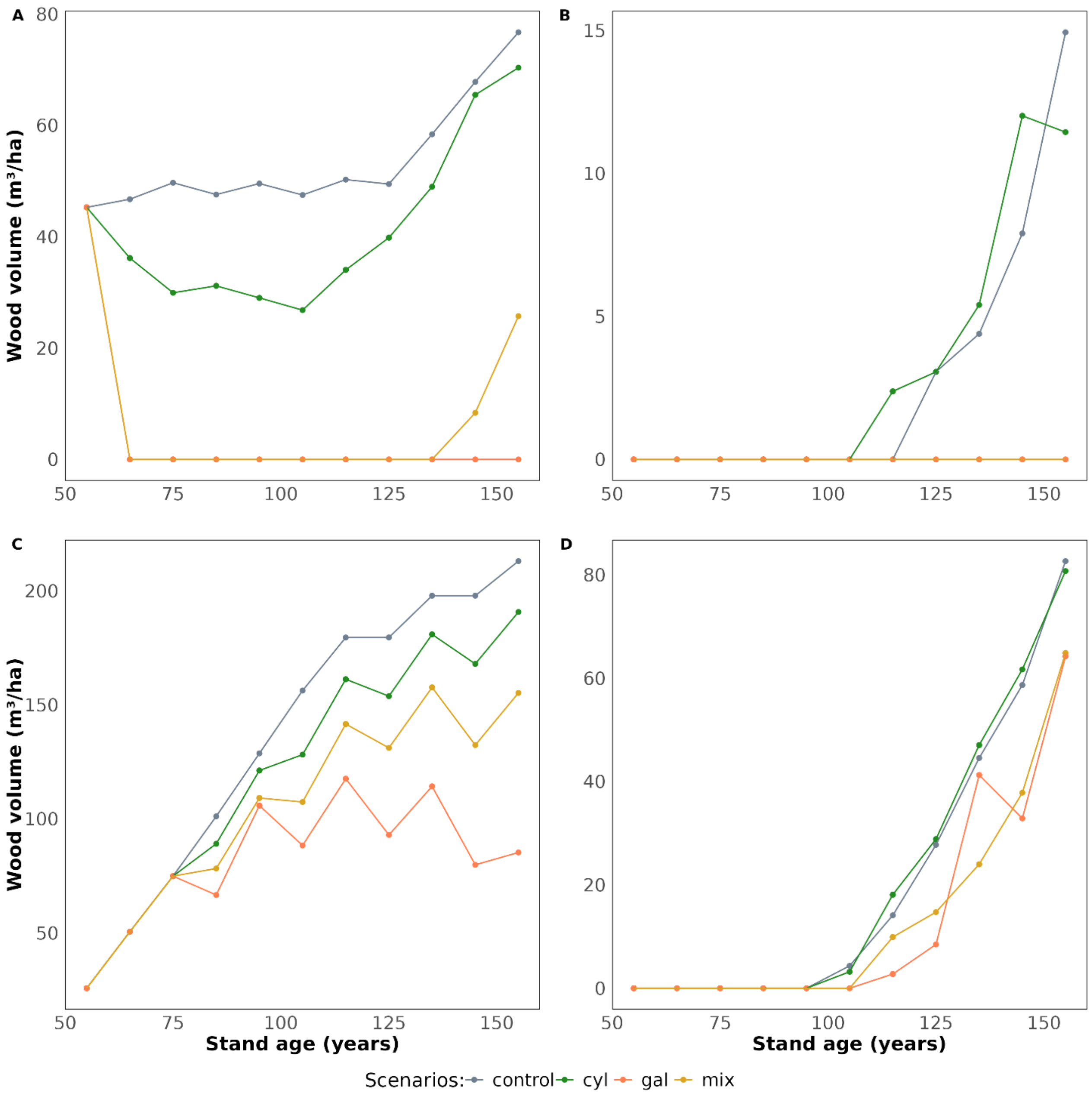

Figure S9. Summary of stand veneer volume evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

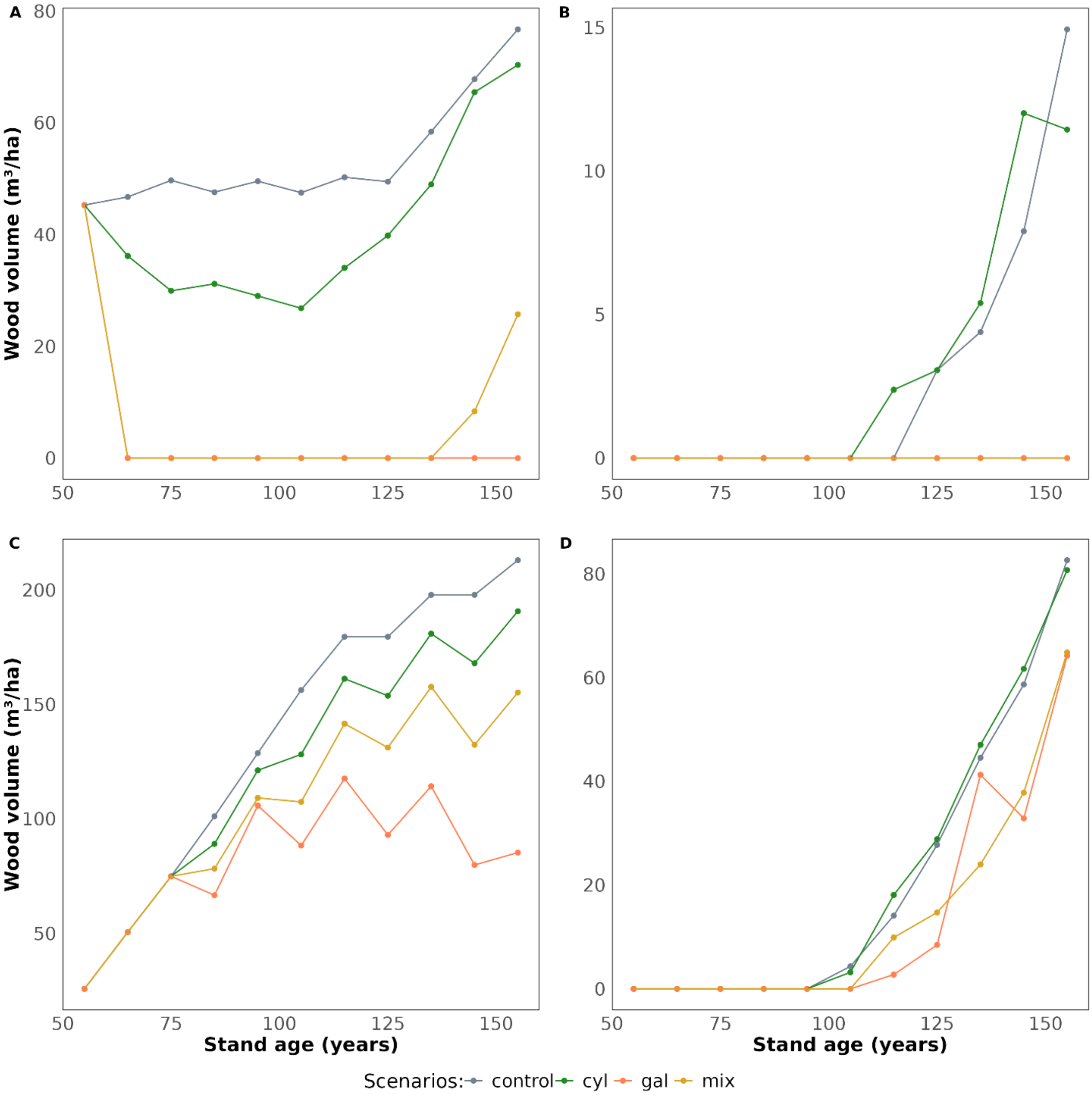

Figure S10. Summary of stand wood panels and “other uses” volume evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

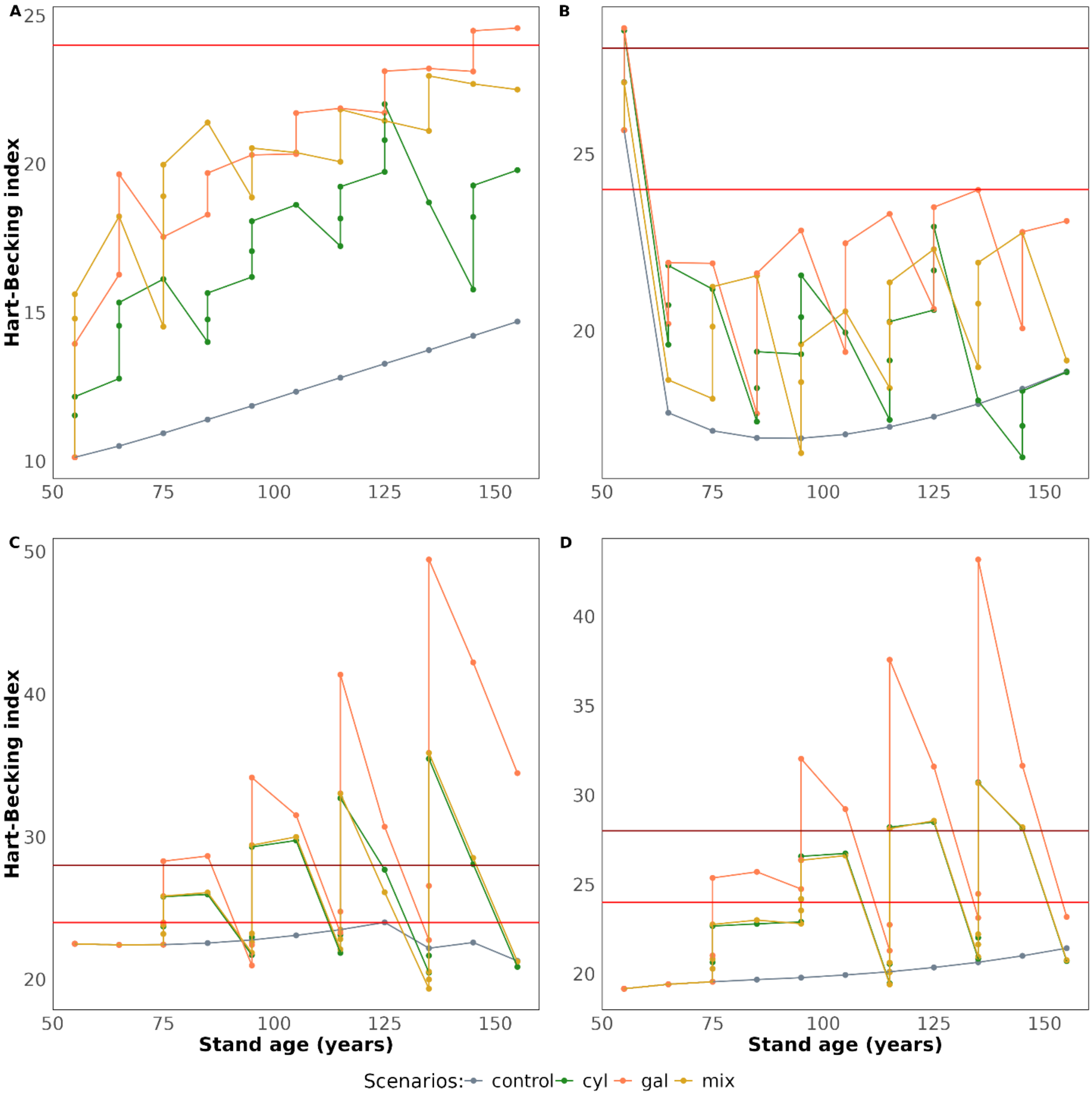

Figure S11. Summary of stand Hart-Becking index evolution over the 100-year simulation. Light and dark red lines refer to the reference values established in the methodology section. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

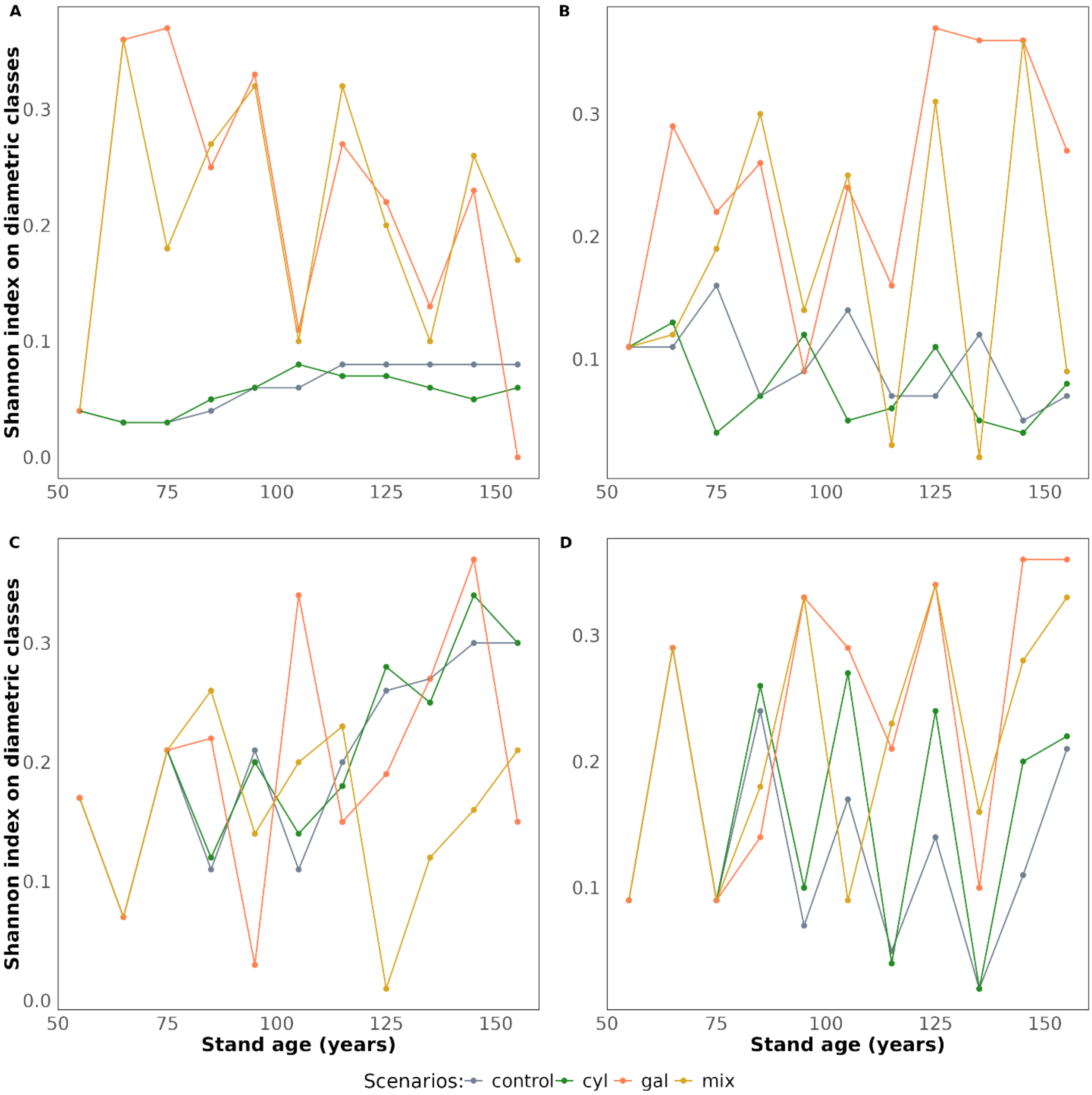

Figure S12. Summary of Shannon-Weaver index evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

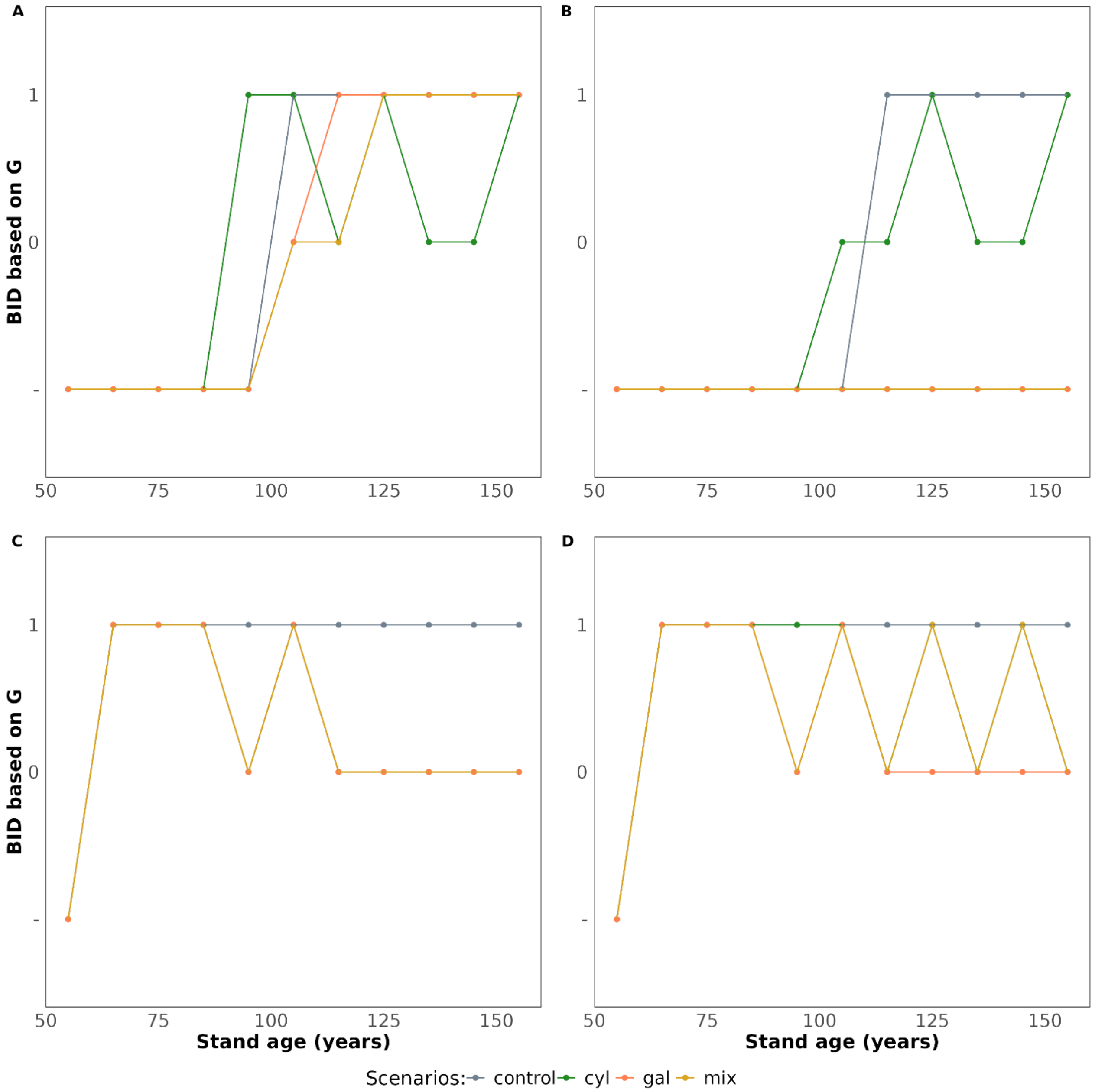

Figure S13. Summary of stand BID index based on basal area evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.

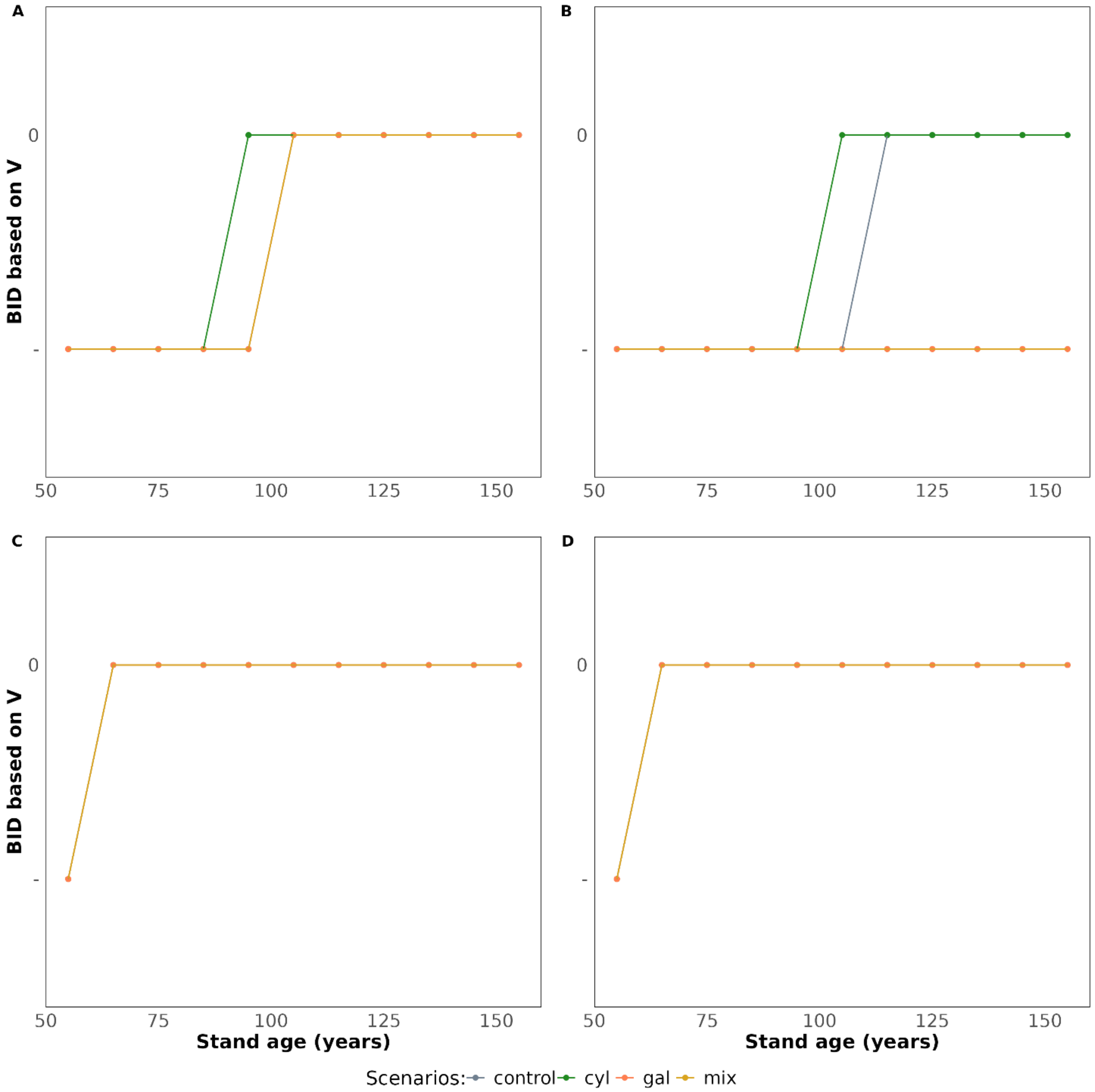

Figure S14. Summary of stand BID index based on volume evolution over the 100-year simulation. Labels refer to (A) SG02 plot and (B) SO02 plot for stand structure transformation, and (C) SG02* plot and (D) SO02* plot for irregular stand management.