Supplementary material 3

Table of Contents

1. Objectives for robust optimization: literature review

Table S1 Results of literature review of existing multi-objective, robust optimization studies in forestry, agriculture and agroforestry.

Study	Objective bundle	Objectives	Data collection/sources	Measurement unit	Land use type	Geographical scope
Chreptun et al. (2023)	n/a	Protection from avalanches Carbon storage Recreation Timber production Water quality	Stakeholder perceptions (survey): ability of each forest type to provide each FCP on a scale from 0 to 10 (Germany) or from 0 to 100 (Slovenia), with 10 or 100 being the maximum provision.	score	Forestry	Germany and Slovenia
Gosling et al. (2020)	Socio-economic	Long-term income	Stakeholder perceptions (interviews): ability of each forest type to provide each FCP on a scale from 0 to 10 with 10 being the maximum provision.	score	Agroforestry	Panama
	Socio-economic or short-term	Labor demand				
	Socio-economic, farmer priority, short-term or immediate	Meeting household needs				
	Socio-economic	Financial stability				
	Socio-economic, short-term or immediate	Liquidity				
	Socio-economic or short-term or short-term	Investment costs				
	Socio-economic or short-term	Management complexity				
	Ecological or farmer priority	Protecting water supply				
	Ecological or farmer priority	Protecting soil resources				
	Socio-economic	General preferences	Stakeholder perceptions (interviews): the number of times that land use was ranked as the best or second-best alternative.	score		
Reith et al. (2020)	*Ecological*	Global climate regulation Water regulation Biodiversity Long-term soil fertility Microclimate regulation	Stakeholder perceptions (survey): expert judgement, AHP survey, pairwise comparison	score	Agroforestry	Panama
	Socio-economic	Food security		score		

Study	Objective bundle	Objectives	Data collection/sources	Measurement unit	Land use type	Geographical scope
		Long-term profit Liquidity Stability of economic return Scenic beauty				
Uhde et al. (2017)	*Ecology*	Understory diversity	Primary data: number of aliens, endemics, typical forest species, therophytes, coverage of herb and shrub layer based on vegetation surveys		Forests	Chili
		Soil chemistry	Primary data: pH value, C/N ratio	mol/l		
		Water supply	Annual provision of drinking water; data sources indicated in the publication	mm/year		
		Carbon sequestration	Annual sequestration of carbon by means of above ground biomass; data sources indicated in the publication	Mg CO2eq/ha/year		
	Financial	Net present value (NPV) Payback period (PB)	Modeling, at discount rates of 6, 8 and 10%	US$/ha years		
	n/a	Biodiversity Recreation and tourism Timber production Forest pasture Non-timber forest products Water supply Carbon sequestration	Stakeholder perceptions (survey): expert judgement, AHP survey, pairwise comparison	score		
Jarisch et al. (2022)	Socio-economic	Economic return from timber and fruit	Primary data (Sum of all discounted cash flows occurring during the investment period, NPV) with integrated risks, like fire	US$/ha	Forestry and/or avocado planation	South Africa
		Regain of invested money from timber and fruit	Primary data (Time until the cumulative discounted net revenues cover the up-front costs, PP)	Years		
	Ecological	Carbon sequestration Fertilizer use	Primary data	Mg C/ha kg Nitrogen/ha		
Knoke et al. (2014)	*Carbon relationships*	Biomass production Carbon in plants	Land-use types 'Afforestation': statistical regression models, parameters estimated	Mg/ha/year Mg/ha		Ecuador

Study	Objective bundle	Objectives	Data collection/sources	Measurement unit	Land use type	Geographical scope
		Soil organic carbon	from field data; Land-use types 'Pastures' and 'Abandoned pastures': field data, process-based model for annual below-ground biomass production	Mg/ha	Foresty and/or agriculture	
	Climate regulation	Evapotranspiration	Process-based models, most model parameters estimated from field data	mm		
		Momentum flux		kg/m/s		
	Hydrological regulation	Surface flow	Simulation	mm/year		
		Area-specific discharge				
	Soil quality	pH (delog used for optimization)	Field data	pH		
		Soil organic carbon		%		
		Base saturation		%		
		Carbon in microbial biomass		mg/kg		
		C-mineralization		g Co2-C/kg soil organic carbon		
		N-mineralization		mg N/kg/day		
		PO4-Phosphor		mg/kg		
	Socio-economic benefits	Net present value (NPV)	Evaluation of timber and cattle products with market prices and costs (obtained from household surveys supplemented by data of the Food and Agriculture Organization of the United Nations) at 5% and 8% discount rates	US$/ha		
		Payback period		years		
		Preferences of local populations for each land-use option	Stakeholder perceptions (survey): the number of times that land use was ranked as the best or second-best alternative.	score		
Knoke et al. (2016)	*Carbon relationships*	Biomass production	Land-use types 'Afforestation': statistical regression models, parameters estimated from field data; Land-use types 'Pastures' and 'Abandoned pastures': field data, process-based model for annual below-ground biomass production	Mg/ha/year	Foresty and/or agriculture	Ecuador
		Carbon in plants		Mg/ha		
		Soil organic carbon		Mg/ha		
	Climate regulation	Evapotranspiration	Process-based models, most model parameters estimated from field data	mm		
		Momentum flux		kg/m/s		

Study	Objective bundle	Objectives	Data collection/sources	Measurement unit	Land use type	Geographical scope
	Hydrological regulation	Surface flow	Simulation	mm/year		
		Area-specific discharge				
	Soil quality	pH (delog used for optimization)	Field data	pH		
		Soil organic carbon		%		
		Base saturation		%		
		Carbon in microbial biomass		mg/kg		
		C-mineralization		g Co2-C/kg soil organic carbon		
		N-mineralization		mg N/kg/day		
		PO4-Phosphor		mg/kg		
	Net present value (NPV)	At 5% discount rate At 8% discount rate	Evaluation of timber and cattle products with market prices and costs (obtained from household surveys supplemented by data of the Food and Agriculture Organization of the United Nations) at 5% and 8% discount rates	US$/ha		
	Payback period	At 5% discount rate At 8% discount rate		years		
	Preferences of local populations for each land-use option	With subsidy Without subsidy	Stakeholder perceptions (survey): the number of times that land use was ranked as the best or second-best alternative.	score		
Knoke et al. (2020)	n/a	Soil expectation value	Primary data; discounted	Euros/ha	Forests	Mountainous areas in Central Europe
		Amount of timber harvested	Primary data; adjusted by hazard rate	m3/ha		
		Sum of cash flows (long-term income, 0% discount rate)	Primary data; establishment costs, net revenues from salvaged timber and net revenues from scheduled timber harvests into this criterion	Euros/ha		
		Average amount of carbon stored in aboveground forest biomass	Primary data; averages around the lifespan of the tree species; did not account for the carbon stored post harvesting in timber products or for substituting material or energy with timber	Mg/ha		
Friedrich et al. (2021)	n/a	Financial services: Financial return (Annuity)	Data sources indicated in the publication	Euros/ha/yr	Forestry	Germany (Southeast)
		Climate protection: Carbon storage		tC/ha/yr		
		Ecosystem stability: Survival rate S		Probability (0 < S < 1)		

2. Optimization model input data: formulae

$$\hat{p}_{f,i} = \frac{1}{K}\sum_{k=1}^{K} p_{f,i,k} \quad for\ i = 1, 2, 3, \ldots, 6, 8, 9 \tag{1}$$

$$SEM_{f,i} = \frac{SD_{f,i}}{\sqrt{K}} \quad for\ i = 1, 2, 3, \ldots, 6, 8, 9 \tag{2}$$

$$\hat{p}_{f,7} = (\#best + \#second\ best)_f \tag{3}$$

$$r_f = \frac{\hat{p}_{f,7}}{\sum_f^F \hat{p}_{f,7}} = \frac{p_{f,7}}{n}$$

$$SEM_{f,7} = n \times \sqrt{\frac{r_f \times (1 - r_f)}{n}} \quad , \tag{4}$$

where n = the minimal sample size for the objective across all forest types (Table 4)

3. Uncertainty scenarios: exemplar illustration

Uncertainty scenario (u)	Coniferous	Deciduous	Mixed deciduous-coniferous	Forests without intervention
1	+	+	+	+
2	+	+	+	-
3	+	+	-	+
4	+	+	-	-
5	+	-	+	+
6	+	-	+	-
7	+	-	-	+
8	+	-	-	-
9	-	+	+	+
10	-	+	+	-
11	-	+	-	+
12	-	+	-	-
13	-	-	+	+
14	-	-	+	-
15	-	-	-	+
16	-	-	-	-

+	Optimistic estimate $p_{i,f}^{+}$
-	Pessimistic estimate $p_{i,f,m}^{-}$

Fig. S1 An example of uncertainty scenarios for an optimization with one objective and four forest stand types, resulting in 16 scenarios per objective. Each uncertainty scenario consists of a unique combination of optimistic (green boxes) and pessimistic (red boxes) estimates of the forest stand type performance scores for each objective.

4. Supplementary results

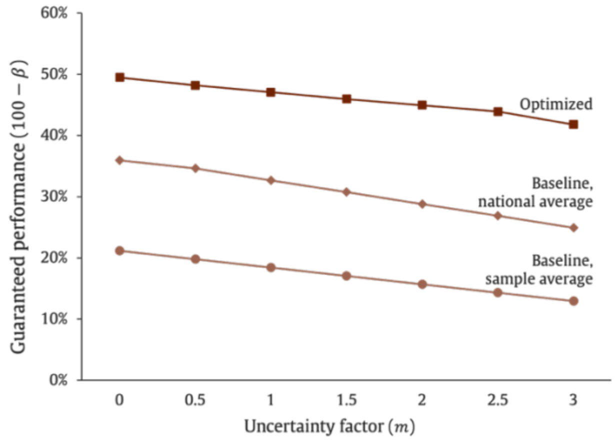

Fig. S2 Guaranteed performance ($100 - \beta$, where 100% is the target level) of the baseline forest compositions (sample and national average) compared to the forest composition, optimized for all nine objectives.

Table S2 Top 20 objective groups that produce optimized forest compositions best fitting to the sample average baseline forest composition, with the uncertainty level $m = 3$.

N	Objective group
1	Liquidity, Ecological functions of the forest, **Management complexity**, Management costs
2	Liquidity, **Management complexity**, Management costs
3	Liquidity, **Management complexity**
4	Long-term income, Liquidity, Carbon storage and sequestration, Natural hazards protection, **Management complexity**, General preferences
5	Long-term income, Liquidity, Carbon storage and sequestration, **Management complexity**, General preferences
6	**Management complexity**, General preferences
7	Long-term income, Natural hazards protection, **Management complexity**, General preferences
8	Liquidity, Carbon storage and sequestration, **Management complexity**, General preferences
9	Liquidity, Natural hazards protection, **Management complexity**, General preferences
10	Long-term income, Liquidity, Natural hazards protection, **Management complexity**, General preferences
11	Long-term income, Liquidity, **Management complexity**, General preferences
12	Long-term income, Liquidity, Ecological functions of the forest, **Management complexity**, General preferences
13	Long-term income, **Management complexity**, General preferences
14	Liquidity, **Management complexity**, General preferences
15	Ecological functions of the forest, **Management complexity**, General preferences
16	Natural hazards protection, Ecological functions of the forest, **Management complexity**, General preferences
17	Long-term income, Ecological functions of the forest, **Management complexity**, General preferences
18	Liquidity, Ecological functions of the forest, **Management complexity**, General preferences
19	Carbon storage and sequestration, **Management complexity**, General preferences
20	Long-term income, Natural hazards protection, Ecological functions of the forest, **Management complexity**, General preferences

Table S3 Top 20 objective groups that produce optimized forest compositions best fitting to the national average baseline forest composition, with the uncertainty level $m = 3$.

N	Objective group
1	Liquidity, **Management complexity**, Management costs
2	Liquidity, Ecological functions of the forest, **Management complexity**, Management costs
3	Ecological functions of the forest, **Management complexity**, General preferences
4	Natural hazards protection, Ecological functions of the forest, **Management complexity**, General preferences
5	Long-term income, Ecological functions of the forest, **Management complexity**, General preferences
6	Liquidity, Ecological functions of the forest, **Management complexity**, General preferences
7	Long-term income, Natural hazards protection, Ecological functions of the forest, **Management complexity**, General preferences
8	Liquidity, Natural hazards protection, Ecological functions of the forest, **Management complexity**, General preferences
9	Long-term income, Liquidity, Natural hazards protection, Ecological functions of the forest, **Management complexity**, General preferences
10	Carbon storage and sequestration, **Management complexity**, General preferences
11	Long-term income, Carbon storage and sequestration, **Management complexity**, General preferences
12	Long-term income, Carbon storage and sequestration, Natural hazards protection, **Management complexity**, General preferences
13	Carbon storage and sequestration, Natural hazards protection, Ecological functions of the forest, **Management complexity**, General preferences
14	Long-term income, Carbon storage and sequestration, Natural hazards protection, Ecological functions of the forest, **Management complexity**, General preferences
15	Liquidity, Carbon storage and sequestration, Natural hazards protection, Ecological functions of the forest, **Management complexity**, General preferences
16	Long-term income, Liquidity, Carbon storage and sequestration, Natural hazards protection, Ecological functions of the forest, **Management complexity**, General preferences
17	Carbon storage and sequestration, Natural hazards protection, **Management complexity**, General preferences
18	Long-term income, Carbon storage and sequestration, Ecological functions of the forest, **Management complexity**, General preferences
19	Liquidity, Carbon storage and sequestration, Natural hazards protection, **Management complexity**, General preferences
20	Liquidity, Carbon storage and sequestration, Ecological functions of the forest, **Management complexity**, General preferences

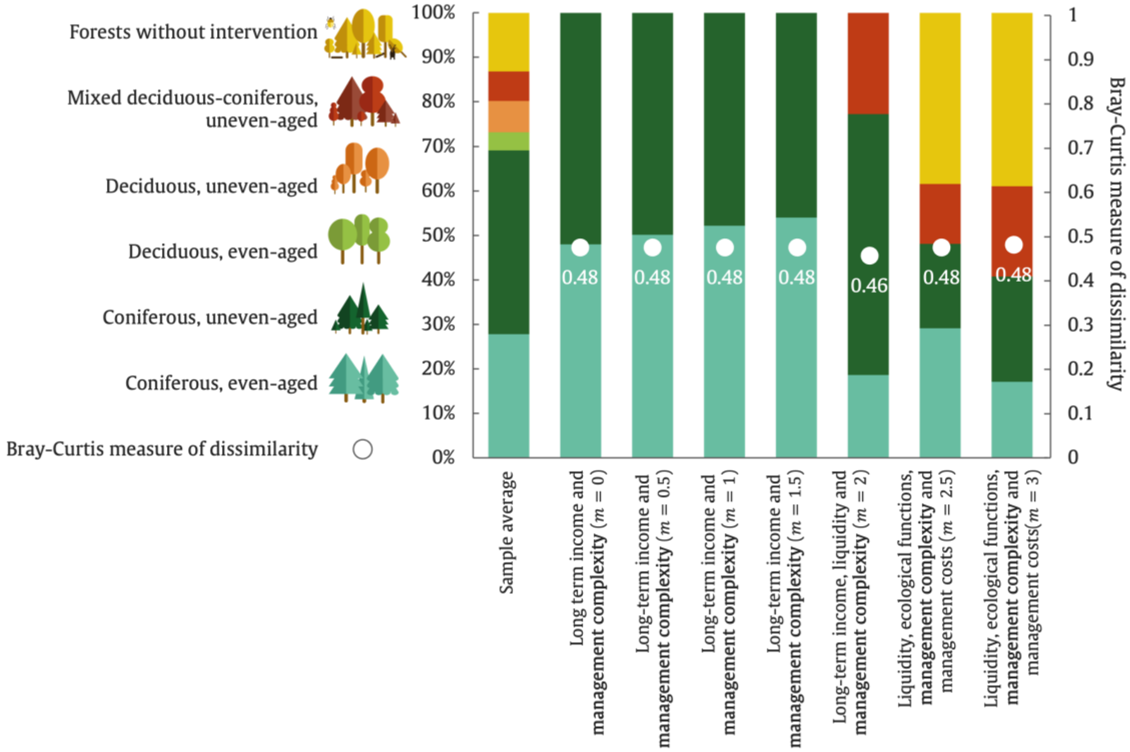

Fig. S3 Ideal forest landscape compositions (shares of land attributed to each forest stand type, left axis), optimized for the best fitting combinations of objectives for the sample average forest composition baseline across increasing levels of uncertainty (specified in parentheses on the x-axis). Points signify the Bray-Curtis measure of dissimilarity between the ideal and baseline forest landscape compositions for each objective group (right axis).

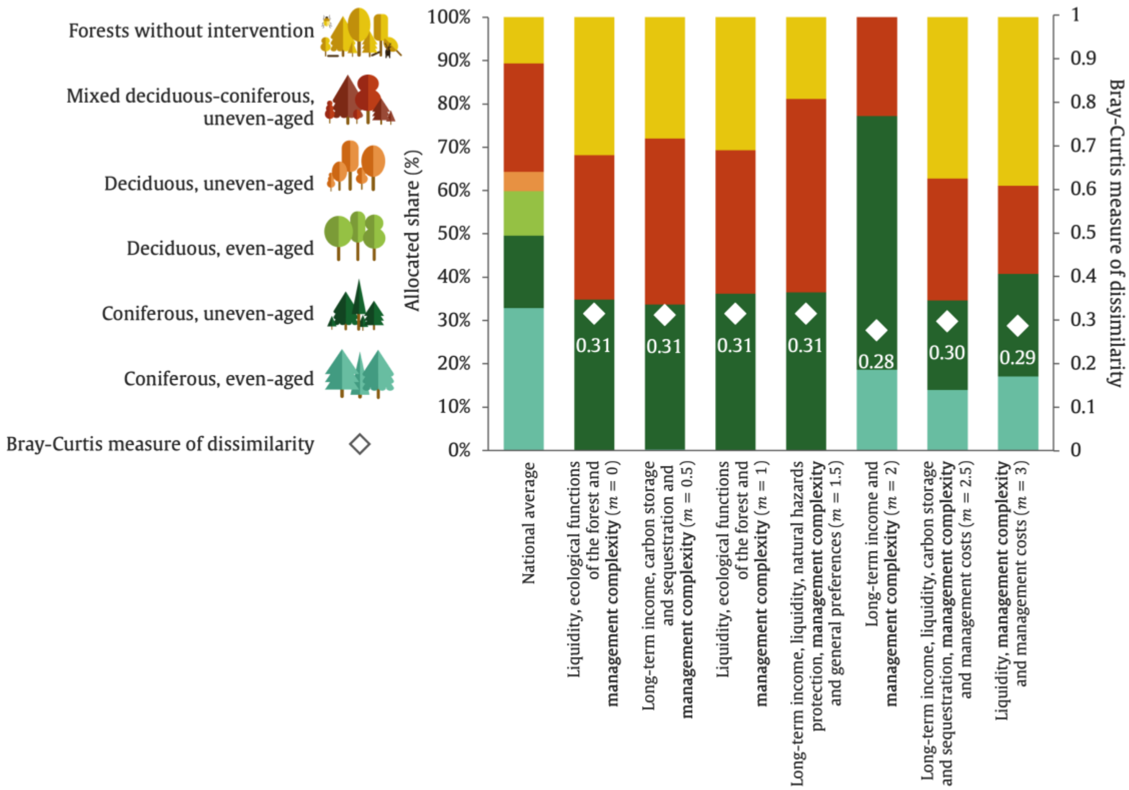

Fig S4 Ideal forest landscape compositions (shares of land attributed to each forest stand type, left axis), optimized for the best fitting combinations of objectives for the national average forest composition baseline across increasing levels of uncertainty (specified in parentheses on the x-axis). Points signify the Bray-Curtis measure of dissimilarity between the ideal and baseline forest landscape compositions for each objective group (right axis).

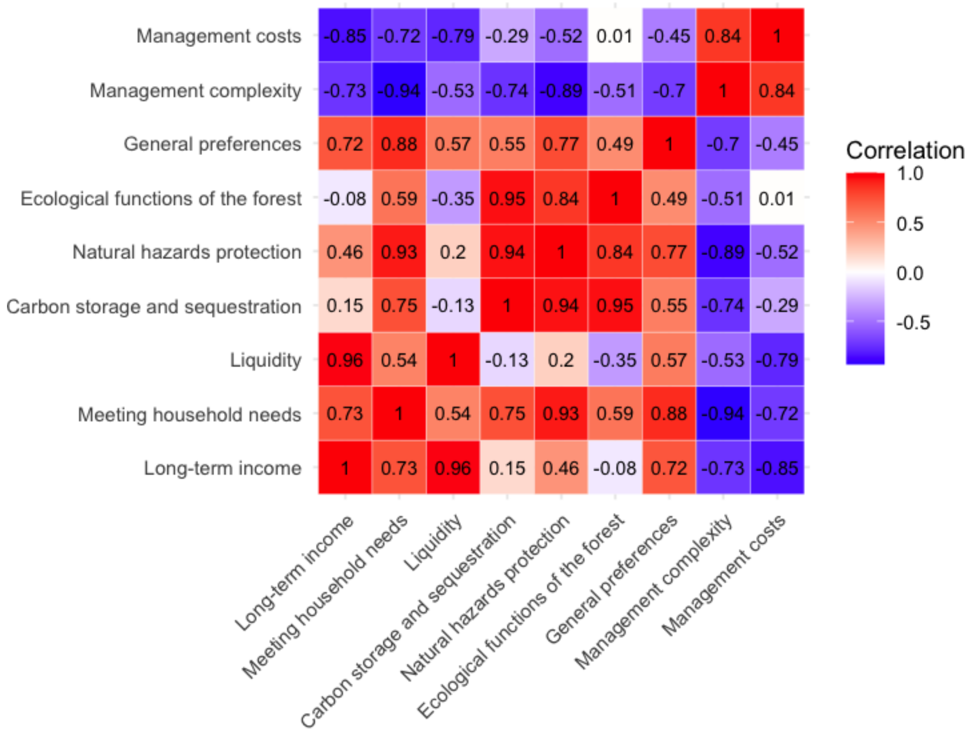

Fig. S5 Pearson correlation matrix of the management objectives based on the expectations (i.e., average performance scores) for each forest type.

References

Chreptun, C., Ficko, A., Gosling, E., & Knoke, T. (2023). Optimizing forest landscape composition for multiple ecosystem services based on uncertain stakeholder preferences. *Science of The Total Environment*, *857*, 159393. https://doi.org/10.1016/j.scitotenv.2022.159393

Friedrich, S., Hilmers, T., Chreptun, C., Gosling, E., Jarisch, I., Pretzsch, H., & Knoke, T. (2021). The cost of risk management and multifunctionality in forestry: A simulation approach for a case study area in Southeast Germany. *European Journal of Forest Research*, *140*(5), 1127–1146. https://doi.org/10.1007/s10342-021-01391-y

Gosling, E., Reith, E., Knoke, T., & Paul, C. (2020). A goal programming approach to evaluate agroforestry systems in Eastern Panama. *Journal of Environmental Management*, *261*, 110248. https://doi.org/10.1016/j.jenvman.2020.110248

Jarisch, I., Bödeker, K., Bingham, L. R., Friedrich, S., Kindu, M., & Knoke, T. (2022). The influence of discounting ecosystem services in robust multi-objective optimization – An application to a forestry-avocado land-use portfolio. *Forest Policy and Economics*, *141*, 102761. https://doi.org/10.1016/j.forpol.2022.102761

Knoke, T., Bendix, J., Pohle, P., Hamer, U., Hildebrandt, P., Roos, K., Gerique, A., Sandoval, M. L., Breuer, L., Tischer, A., Silva, B., Calvas, B., Aguirre, N., Castro, L. M., Windhorst, D., Weber, M., Stimm, B., Günter, S., Palomeque, X., … Beck, E. (2014). Afforestation or intense pasturing improve the ecological and economic value of abandoned tropical farmlands. *Nature Communications*, *5*(1), 5612. https://doi.org/10.1038/ncomms6612

Knoke, T., Kindu, M., Jarisch, I., Gosling, E., Friedrich, S., Bödeker, K., & Paul, C. (2020). How considering multiple criteria, uncertainty scenarios and biological interactions may influence the optimal silvicultural strategy for a mixed forest. *Forest Policy and Economics*, *118*, 102239. https://doi.org/10.1016/j.forpol.2020.102239

Knoke, T., Paul, C., Hildebrandt, P., Calvas, B., Castro, L. M., Härtl, F., Döllerer, M., Hamer, U., Windhorst, D., Wiersma, Y. F., Curatola Fernández, G. F., Obermeier, W. A., Adams, J., Breuer, L., Mosandl, R., Beck, E., Weber, M., Stimm, B., Haber, W., … Bendix, J. (2016). Compositional diversity of rehabilitated tropical lands supports multiple ecosystem services and buffers uncertainties. *Nature Communications*, *7*(1), 11877. https://doi.org/10.1038/ncomms11877

Reith, E., Gosling, E., Knoke, T., & Paul, C. (2020). How Much Agroforestry Is Needed to Achieve Multifunctional Landscapes at the Forest Frontier?—Coupling Expert Opinion with Robust Goal Programming. *Sustainability*, *12*(15), 6077. https://doi.org/10.3390/su12156077

Uhde, B., Heinrichs, S., Stiehl, C. R., Ammer, C., Müller-Using, B., & Knoke, T. (2017). Bringing ecosystem services into forest planning – Can we optimize the composition of Chilean forests based on expert knowledge? *Forest Ecology and Management*, *404*, 126–140. https://doi.org/10.1016/j.foreco.2017.08.021