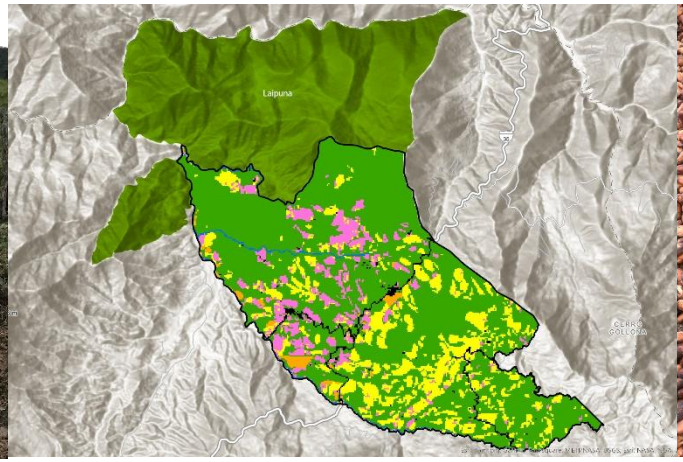
Land-use strategies for dry forest ecosystems: a multicriteria approach for enhanced socioeconomic benefits and ecosystem services under uncertainty

Jonathan Torres-Celi, Thomas Knoke, Luz María Castro

INTRODUCTION






Dry forest of southern Ecuador

- Socioeconomic and environmental importance
- Agricultural inefficiency: degradation, biodiversity loss, migration, and poverty.

Sustainable agricultural production:

better income, life quality, conservation

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Analysis

Optimizing agricultural land-use portfolios with scarce data—
A non-stochastic model

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Robust multi-objective optimization model

Knoke et. al. (2014, 2015, 2016)

Support to decision-making in the land-use planning process

e.g. Castro et al. (2018), Castro & Lechthaler (2022), Gosling et al. (2020, 2021), Reith et al. (2022)

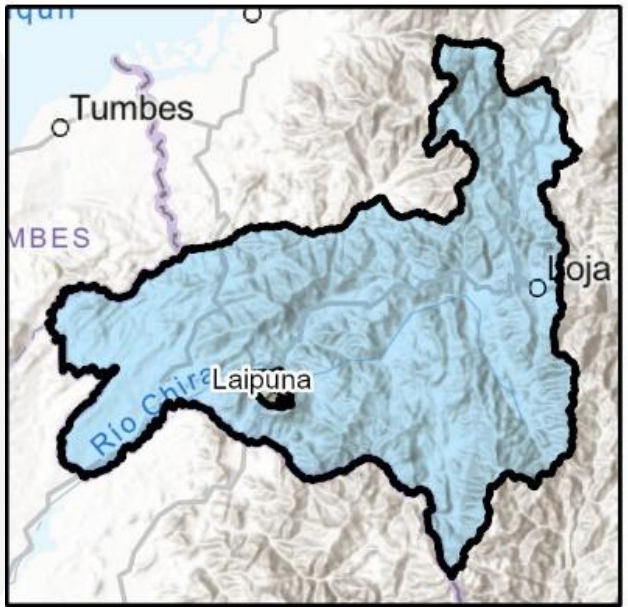
WHAT ARE WE LOOKING FOR?

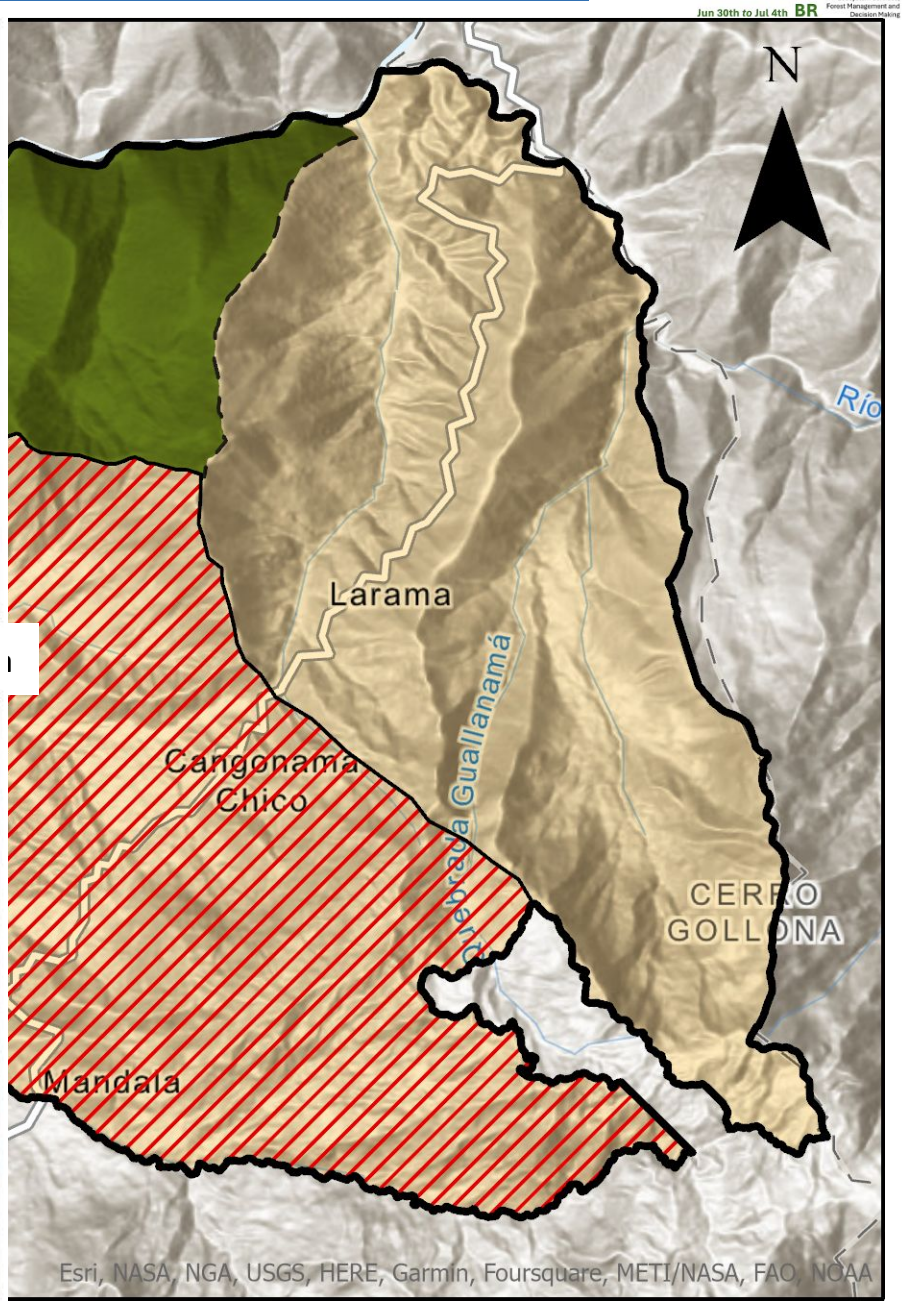
Goal

Set up a robust multi-objective optimization model for land use allocation (at farm level) in the **dry forest of southern Ecuador**

Research questions

- How can we **improve land-use allocation and overall land-use performance**?
- What trade-offs become evident through **Pareto frontier analysis** between socioeconomic and ecological indicators bundles?





RESEARCH APPROACH

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Step 1. Determine the observed land-use compositon

- Map of observed land-use composition GIS Method
- Select productive land-use types
- Definition of productive land-use types

Step 2. Indicators performance

- **Select indicators**
  - Annualized net present value (ANPV)
  - Payback period (PP)
  - Cost - Benefit ratio (CBR)
  - Labor demand (LD)
  - Food production (FP)
  - Biomass production (BP)
  - Carbon storage (C)
  - Water retention capacity (WRC)
- **Calculate performance**

Step 3. Integrate uncertainty

- **Source of variability**
  - Prices and yields
  - Wages
  - Yields
  - Plant growth
  - InVest model assumptions
- **Boopstraping, NORMINV, Monte-Carlo simulation**
- **Mean and standard deviation**

Step 4. Optimal land use modelling

- **Robust multi-objective optimization**
- RStudio package: *optimLanduse*
- **Optimal land-use allocation**
- Guaranteed performance
- **Compare optimal vs. Observed land-use**

Step 5. Trade-off analysis

- GP optimal vs observed land-use
- **Robust Pareto frontiers**
- Pareto optimal land-use allocation

ROBUST MULTI-OBJECTIVE OPTIMIZATION

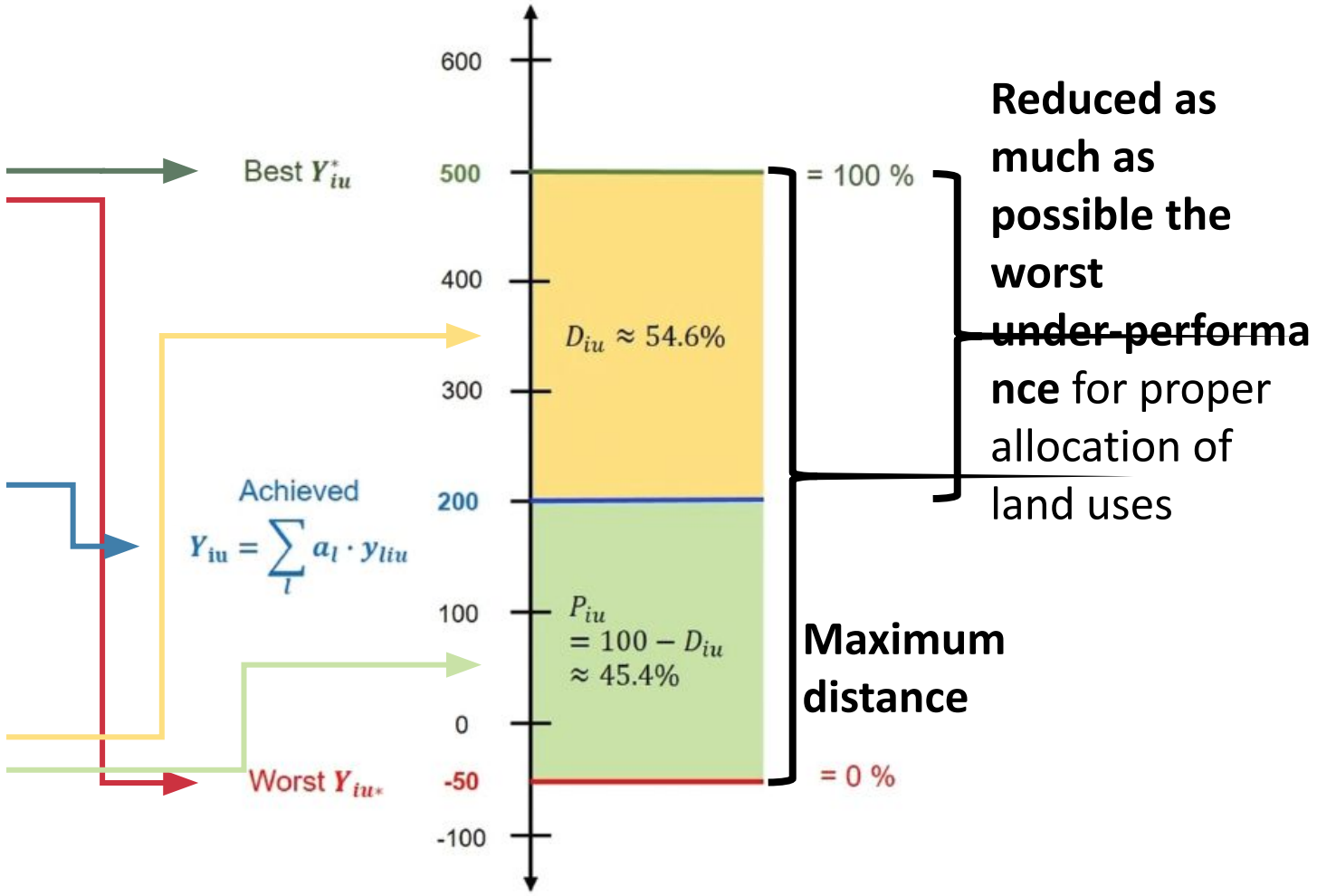
- Mean values ($\hat{y}_{i,l}$)
- Standard Deviation ($SD_{i,l}$)

- Uncertainty-adjusted values ($y_{i,l,u}$): best- and worst-case scenario

- Guaranteed performance per uncertainty scenario (normalized min - max)

- Performance analysis ($D_{i,u}$ and $P_{i,u}$) and land uses allocation

- The **guaranteed performance index** quantifies the percentage of minimum achievable performance across all indicator bundles



Knoke et. al. (2014, 2015, 2016, 2020, 2022)

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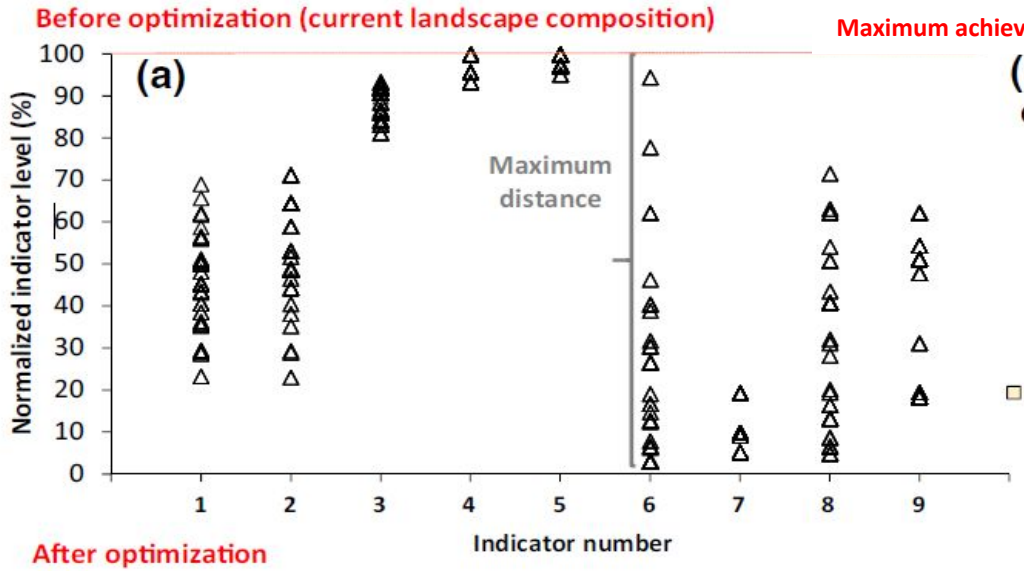

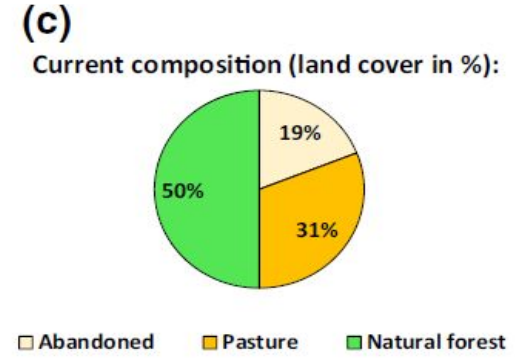

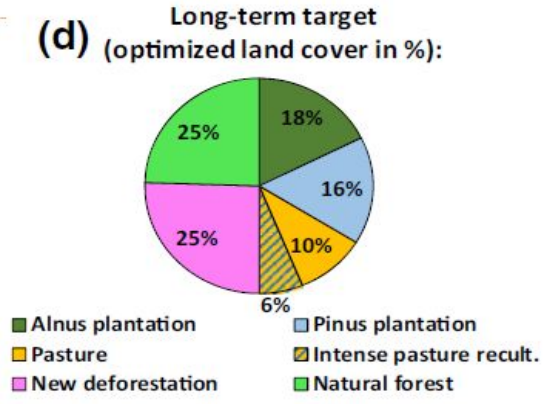

Knoke et. al. (2014, 2015, 2016, 2020, 2022)

LAND USE PERFORMANCE INTEGRATING UNCERTAINTY

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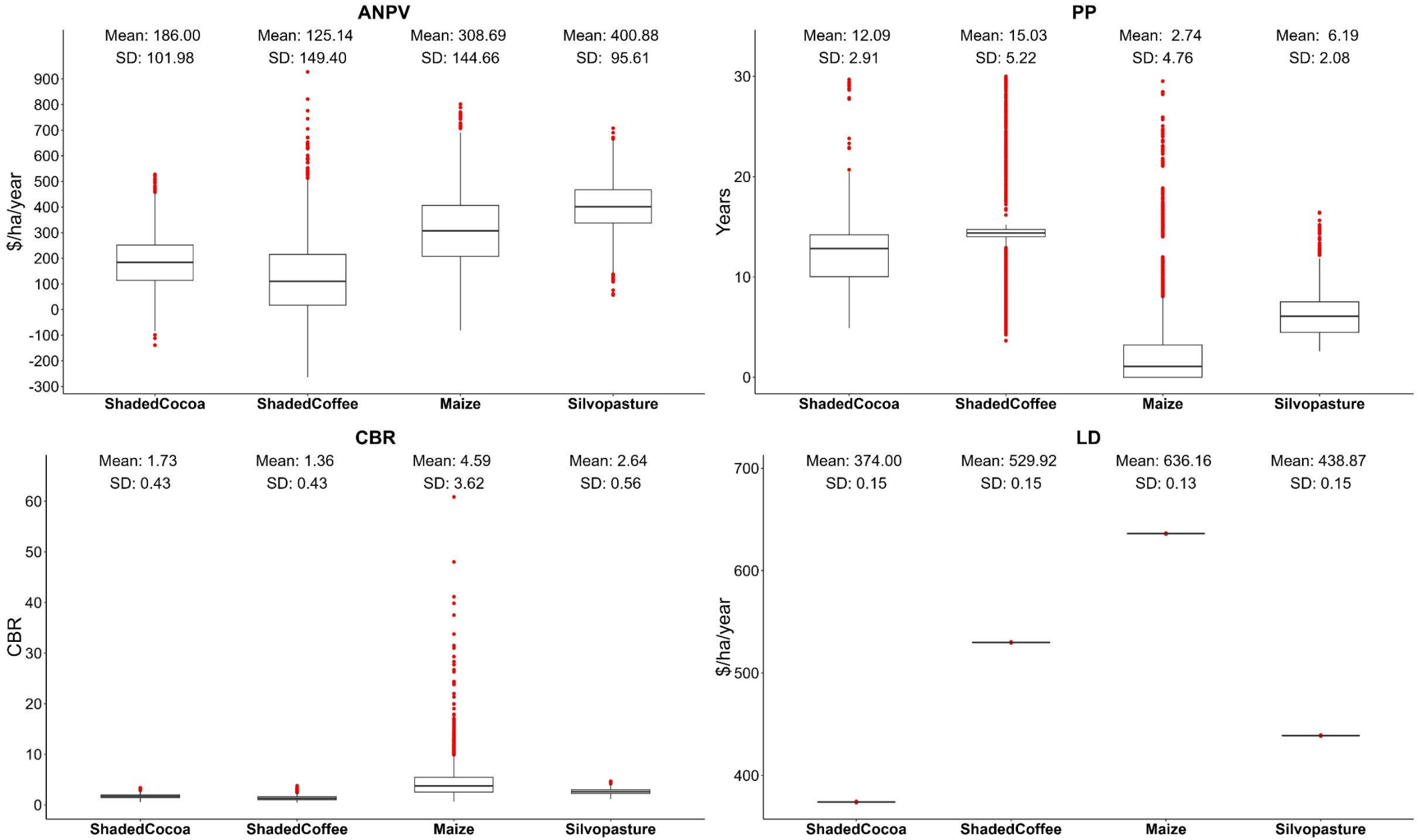
Mean values $\hat{y}_{i,l}$ for each land use *i* and indicator *l*

Uncertainty measure ($SD_{l,i}$)



LAND USE PERFORMANCE INTEGRATING UNCERTAINTY

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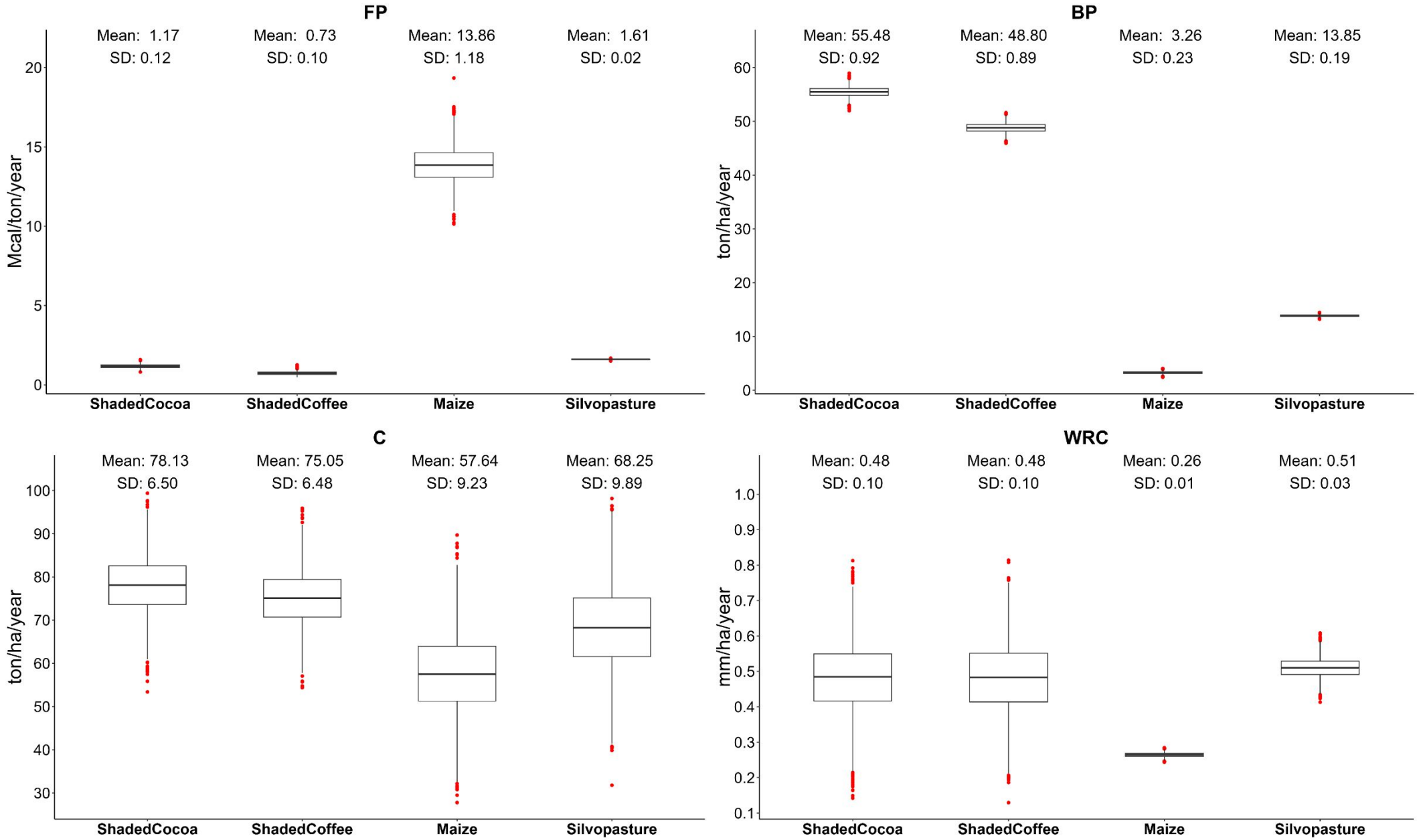
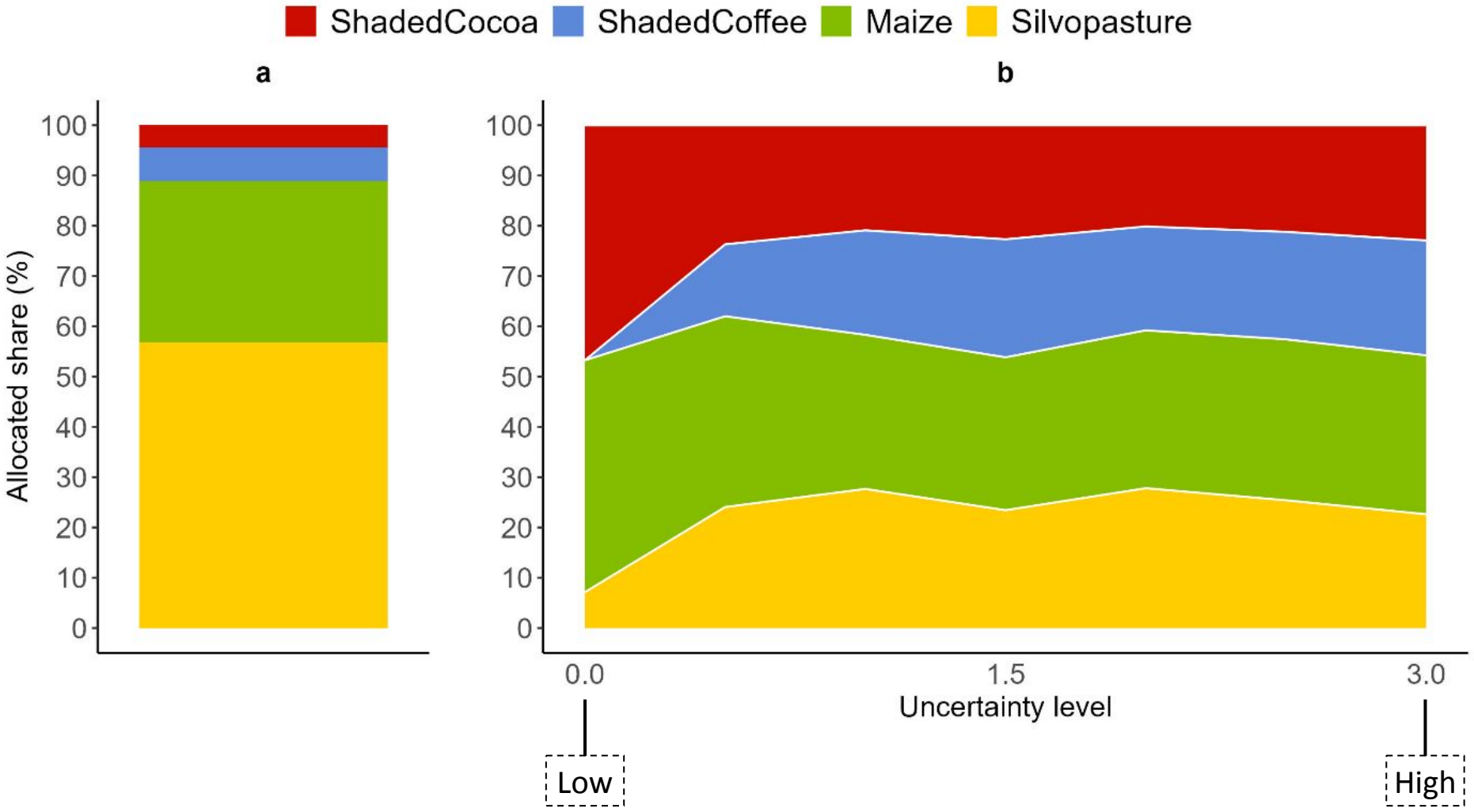


MULTI-OBJECTIVE OPTIMIZATION AT THE FARM LEVEL

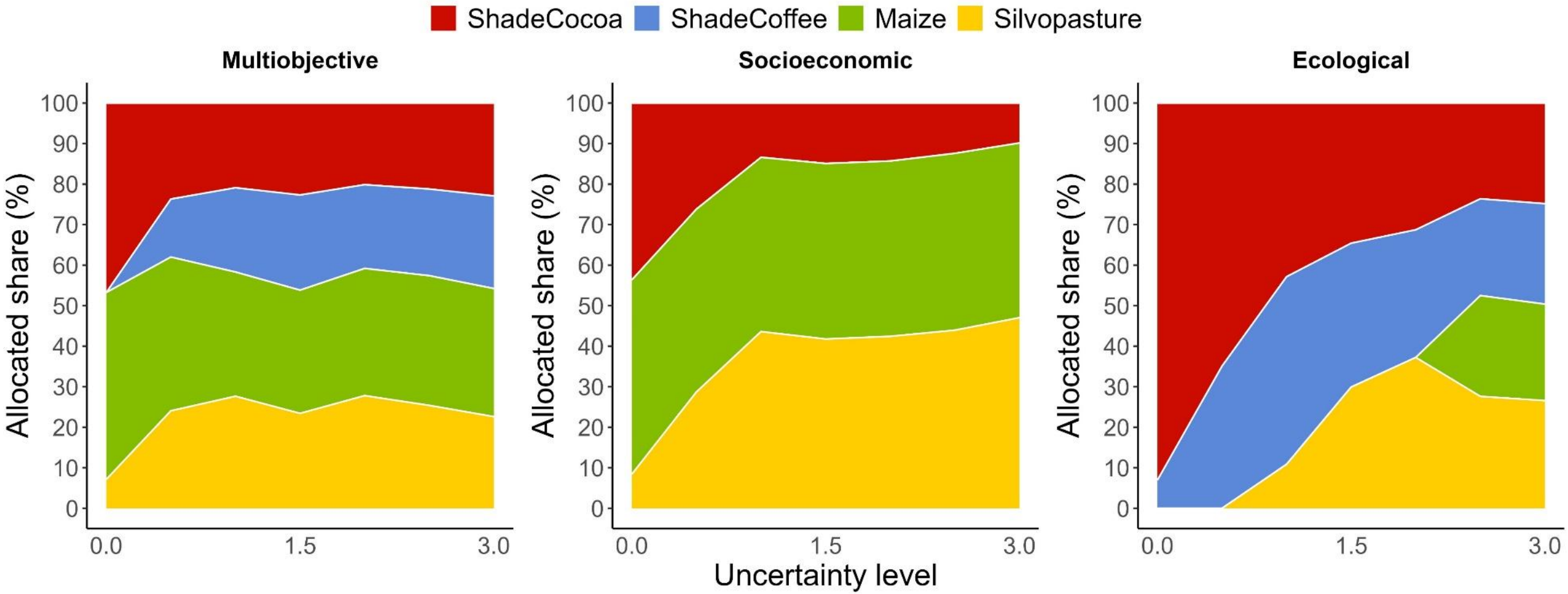


- **Multi-objective composition** (without taking into account any specific farmer preference for both indicator bundles) **differs** from the **observed composition**

- **Remarkable diversification and balance in land use distribution**, from the moderate level of uncertainty (possible yield fluctuations of different land use types)

Observed (a) and multi-objective (b) land-use composition at the farm-level

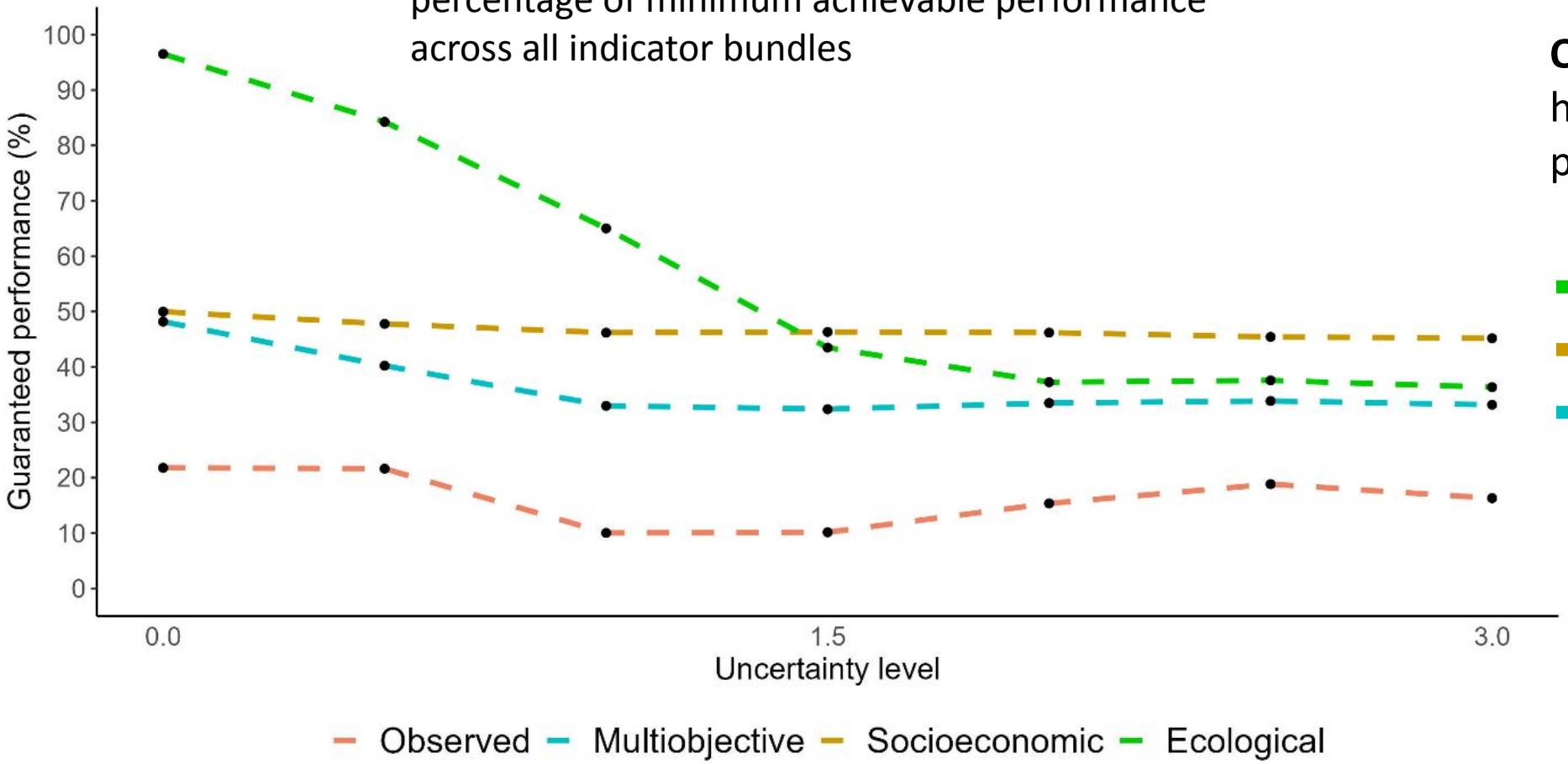
MULTI-OBJECTIVE OPTIMIZATION AT THE FARM LEVEL



- The **multi-objective model** presents a **better distribution of land use** options at all levels of uncertainty, resulting in a **balanced composition even at the highest** uncertainty

MULTI-OBJECTIVE OPTIMIZATION AT THE FARM LEVEL

- The **guaranteed performance index** quantifies the percentage of minimum achievable performance across all indicator bundles



Optimized portfolios showed higher guaranteed performance:

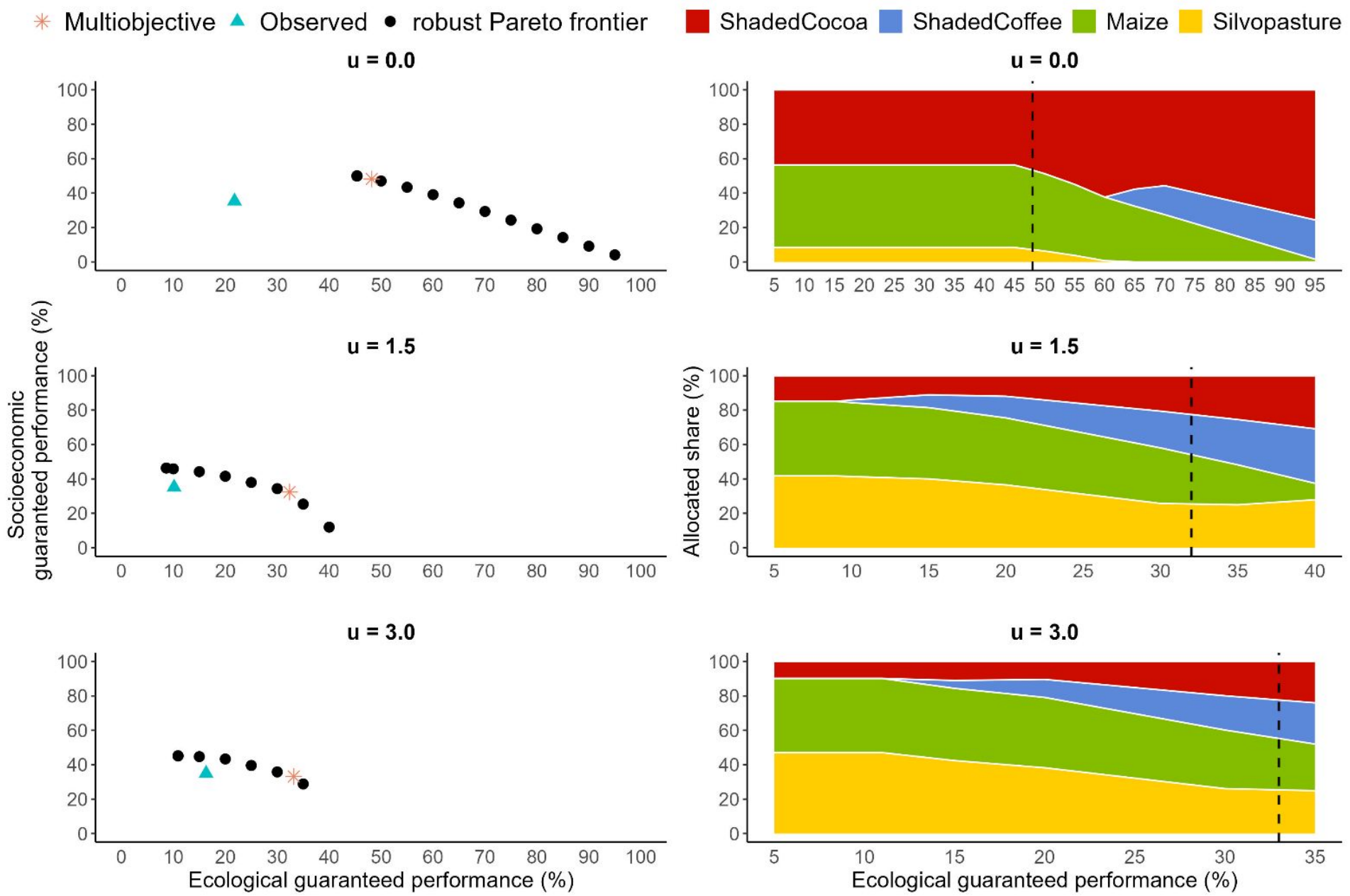
- **Ecological** (97% to 36%)
- **Socioeconomic** (50% to 45%)
- **Multi-objective** (48% to 33%)

- The **observed farmland portfolio achieved lower GP than optimized portfolios**, ranging from 22% to 16% across uncertainty levels

PARETO FRONTIERS: TRADE – OFFS ANALYSIS

- **The Pareto frontier analysis reveals clear trade-offs** between socioeconomic and ecological objectives in land-use planning

- Under low uncertainty, the trade-off is almost linear: socioeconomic performance **begins at 50% and drops to 4% as ecological benefits rise from 45% to 95%**



OPTIMIZED LAND-USE STRATEGIES

Increase Shaded Cocoa

Shaded cocoa emerges as a key component in optimized portfolios, offering strong ecological benefits while maintaining economic viability

Expand Shaded Coffee

Shaded coffee cultivation provides long-term ecological and socioeconomic benefits, particularly valuable under high uncertainty scenarios

Maintain Maize

Despite low ecological performance, maintaining a stable share of maize provides seasonal returns and short-term income security during

Reduce Silvopasture

While currently dominant, reducing silvopasture allocation improves overall farm performance, though its regular income from dairy and cattle remains

CONCLUSIONS

Robust Multi-objective Optimization Value

The model is a helpful tool for sustainable land-use planning in dryland ecosystems, especially in data-scarce regions

Farmer Decision-Making

They already diversify intuitively as a risk-coping strategy, but tend to prioritize short-term, income-driven choices over ecological performance

Agroforestry Potential

Transitioning toward agroforestry systems with shade cocoa and coffee, while reducing silvopasture and retaining some maize, offers a promising strategy for balancing objectives and benefits

Policy Support Needed

Supportive policies including payments for ecosystem services, access to specialized credit, and technical assistance are crucial to facilitate transitions to more sustainable land uses

Thank you!

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