

TransFarm: A Farm-scale Tool Evaluating Trade-offs in Agroecological Transitions

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Abstract

Evidence-based decision-making is crucial to support farmers' incomes during transitions from conventional to agroecological farming. We present the development and piloting of TransFarm, a local, farm-scale trade-off assessment tool designed for use by farmers with facilitation from civil society organisations and extension personnel. TransFarm enables users to explore agroecological transition scenarios involving trade-offs between net farmer income, annual farm water requirement, and carbon stock, using three use cases: crop diversification, livestock integration, and agroforestry-based carbon-stock exploration. The tool combines secondary data on crop and livestock yields, water requirements, and carbon stock parameters with primary data collected from 105 agricultural plots across five agroecological configurations in Chikballapur, Karnataka, India. TransFarm's parameters were iteratively calibrated using field-derived estimates rather than independently validated, achieving a median error of 0% across outcome variables within the calibration dataset. Results indicate that landholding size, plot size, crop diversity, livestock holdings, tree density, and crop residue management significantly influence net income, water requirement, and carbon stock across configurations. Crop diversification and livestock integration can improve farmer income while reducing annual water requirement, although this varies by livestock type and crop combination. In agroforestry scenarios, revenue from carbon-stock monetisation can exceed income lost from forgoing timber, though these estimates are indicative rather than certifiable carbon-credit values. TransFarm offers farmers, CSOs, and extension agencies a lightweight digital platform to iteratively design and compare farm configurations before implementing transitions, though its current parameterisation is specific to the study context, and independent validation across other agro-climatic and market settings remains a priority for future research.

1. Introduction

Farmers the world over are increasingly offered economic incentives and nudges to transition to more environmentally sustainable and agroecological farm regimes. This includes subsidies and buy back guarantees for water-efficient crops, livestock integration to improve manure productivity and reduce inorganic chemical inputs (Brown et al. 2022), and payment for ecosystem services such as biomass carbon on-farm (Foster and Neufeldt 2014), and soil and watershed management (Pokorny et al. 2021). At the farm level, these transitions often involve upfront investments and delayed returns, which may inhibit farmers from undertaking them. Estimating the quantum of co-benefits and the trade-offs involved in realising them can be a complex undertaking, which is often left to non-local actors such as land use planners and policymakers (Kanter et al. 2018). Enabling local actors such as farmers, land users, and civil society organisations (CSOs) to participate in this process is crucial to securing buy-in and achieving social-ecological impact at scale (Bernard et al, 2014). Decision support tools play a pivotal role in enabling farmers to select crops, design farms, and transition to new regimes in response to changing market and policy environments.

A number of agricultural decision support tools exist, with a range of purposes and scaling options (Mottet et al. 2020). Some tools allow farmers to assess the quantitative sustainability of their farms in relation to industry certification standards (Hannus and Sauer 2021), agroecological principles and resilience (Darmaun et al. 2023), or national policy on payments for ecosystem services (Roesch et al. 2023). Some other tools take a more educational and qualitative approach to assessing the social-ecological situation and making recommendations for improvement, especially considering farmer priorities (Ngo et al. 2021). In terms of scale, these tools may use as few as 9 and as many as 118 indicators to evaluate farms and farming practices (Talukder and Blay-Palmer 2017). However, very few of these tools offer farmers support beyond suggesting improvement strategies based on farmer or scheme targets (Coteur et al. 2020). The literature does not document instances of tools that allow farmers to envisage counterfactual or future scenarios and fine-tune them to arrive at desirable configurations at a plot or farm level. This is a gap that our study seeks to fill. The smaller sizes and greater complexity of farms in the Global South (Giller et al. 2021) highlight the need for more nuanced measurements and site-specific tools to enable decision-making at farm scale.

1.1. Overview of agricultural decision support tools

A review of the literature indicates that the scope of agricultural decision support tools ranges from agronomy-based tools like DSSAT and FARMSIM, to wider domains of agri-food systems and social-ecological systems (Table 1). A number of emerging tools and frameworks embed participatory approaches to design, evaluation, and decision-making, and incorporate social, economic, and environmental sustainability components. A subset of decision support tools like MODAM and FarmDESIGN consider agronomic variables in conjunction with ecological variables like atmospheric emissions and soil quality. Our proposed tool, named TransFarm, belongs to this family of tools, using the ecological variables of biomass and soil carbon and farm net water requirements as trade-off parameters against agronomic variables. Among these tools, TransFarm is unique in its simplistic framework and format, and its local focus. It builds on previous agronomic tools like FARMSIM by allowing users to tinker with more than one intervention simultaneously,

and it differs from other agronomic tools like MODAM by not requiring predefined economic and ecological goals. We recognise that agroecological transitions entail larger socioeconomic variables aligned to the elements and principles of agroecology (FAO 2018, HLPE 2019, Table 1), and acknowledge that TransFarm is limited to enabling diversity, efficiency, and recycling. We propose this tool for its ease of use and interpretation across a wide range of end users.

1.2. Conceptual framing

The objective of this paper is to present the development and demonstration of a farm-scale decision support tool, TransFarm, to optimise farm-level outcomes during agroecological transitions like crop diversification, livestock integration and agroforestry. The farm-level outcomes include trade-offs between farmer net income, farm water requirements, and carbon stock. These trade-offs represent both economic and ecological parameters, and frequently come up in agricultural practitioner negotiations in the study area (WELL Labs 2024). Broader research on the trade-offs between economic and ecological parameters in agriculture has identified key performance indicators, including farmer incomes, farm water requirements, and carbon stock as relevant indicators for assessing alternative agricultural configurations. (Olschewski et al, 2010; Kovacs, 2016; Balbi, 2015). Farmer incomes are key drivers of land use patterns at farm and landscape scale. Water requirements of crops and livestock influence cropping and livestock choices at farm-scale, and inform water management decisions at the larger scales. Carbon stock estimation for carbon incentives is generally a landscape-level consideration where land planners, CSOs, and policymakers allocate areas to incentivise or financialise land use regimes (Duchelle et al. 2018; Khorchani et al. 2022). TransFarm attempts to help farmers and CSOs reconcile farm-scale transition decisions with landscape-level transition incentives to optimise outcomes for farmers. To do so, it uses and generates data on the farm-scale impacts of agroecological transitions on farmer income, annual water requirement, and carbon stock, within an agricultural year.

In this paper, we demonstrate three use cases or transition scenarios, namely:

1. Diversifying cropping systems to improve farm income while reducing annual water requirement:: Green revolution-era incentives have locked farmers into unsustainable crop choices with high water requirement in certain regions (Bhogal and Vatta 2021). Water-intensive monoculture paddy or sugarcane can be effectively replaced with diversified millets and intercropping systems (Kayatz et al. 2019) to improve economic water productivity, ie. revenue generated per unit volume of water. TransFarm allows users to compare crop configurations based on locally relevant crop yields, market prices, production costs and water requirements, and to iteratively identify configurations that improve the income–water trade-off.
2. Integrating livestock to augment farmer income and manure supply: Livestock integration is a popular CSO intervention in smallholder agriculture in peninsular India (Chitlapally and Uppalapati 2025). While there can be a significant increase in farmer income with additional livestock, it can also increase resource requirements around fodder, livestock care, and especially water (Reddy et al. 2023). TransFarm enables users to assess the implications of different livestock types and herd sizes for net farmer income, livestock water requirement, fodder availability and manure availability, thereby supporting farm-level livestock configuration decisions. ii. Exploring carbon-stock incentives for agroforestry transitions: Transitioning to agroforestry or biomass conserving farm regimes involves significant upfront costs and delayed returns (Neelakantan and Aryan 2023). Estimating changes in farm carbon stock can nevertheless help users understand the potential biophysical benefits of alternative tree-based configurations and explore whether these changes could support future participation in carbon incentive mechanisms. TransFarm therefore estimates indicative soil and biomass carbon stocks and allows users to explore their potential monetary value under an assumed carbon price; these estimates are not intended to represent certified carbon credits or verified carbon credit revenue. The carbon module is included as an exploratory component to demonstrate how TransFarm can incorporate an additional ecological outcome into farm-level trade-off analysis. Given the assumptions required for estimating soil and biomass carbon in the absence of longitudinal measurements, the carbon outputs are interpreted as indicative scenario estimates rather than validated measurements of carbon sequestration or certifiable carbon credits.

The research question is: To what extent can crop diversification, livestock integration, and agroforestry simultaneously improve net income, water requirement, and carbon stock on a given farm? This question is approached using TransFarm as a trade-off tool interface. Secondary data from government and academic sources are used to generate hypothetical optimal scenarios, and primary data from farm surveys are used to calibrate these scenarios.

Table 1
Comparison of existing agriculture decision support tools and TransFarm by scale, format, and scope

Tool	Purpose	Scale	Format	Geography	Intended users	Reference	Scope
Framework for Assessing the Sustainability of Natural Resource Management Systems or Marco para Evaluación de Sistemas de Manejo de Recursos Naturales Incorporando Indicadores de Sustentabilidad (MESMIS)	Translating general principles of sustainability into operational definitions, indicators, and practices of natural resource management to identify the limits and possibilities of system sustainability given social, economic, and ecological conditions.	Multi-scale systems	Participatory approach using systems mapping and indicators to evaluate system performance	Global, initiated in Mexico	Researchers, institutions, and policymakers	Cândido et al. (2015)	Social-ecological systems
Trade-off Analysis (TOA)	Framework combining foresight analysis and simulation modeling tools in a participatory process to formulate and evaluate strategic decisions.	Multi-scale systems	Participatory approach combining econometric, simulation, and qualitative models to generate scenarios	Global, initiated in the United States	Researchers, institutions, and policymakers	Antle & Valdivia (2021)	Agri-food systems
Farm Sustainability Indicators (IDEA)	Assessing sustainability of agricultural systems using 41 incremental indicators.	Multi-scale systems	Participatory approach using scoring and weighting to identify areas for system performance improvement	Global, initiated in France	Farmers, researchers, institutions, and policymakers	Cândido et al. (2015)	Agri-food systems
Sustainability Assessment of Farming and the Environment (SAFE)	Structured sustainability assessment of production systems, techniques and policies, using principles, criteria, indicators and reference values.	Farm to region	Conceptual hierarchical framework to translate principles to criteria, indicators, and material flows for evaluation	Global, initiated in Belgium	Farmers, researchers, institutions, and policymakers	Van Cauwenbergh et al. (2007)	Agri-food systems
Assessment method for evaluating agroecology effects and the conditions for its development (Memento GTAE)	To characterise socioeconomic conditions enabling agroecology, and to design interventions to promote them.	Multi-scale systems	Participatory approaches to co-develop references, indicators, and enablers of agroecological transitions	Global, initiated in France	Researchers, institutions, and policymakers	Levrard et al. (2019)	Agroecology systems
Tool for Agroecology Performance Evaluation (TAPE)	Assessment of the extent and trajectories of agroecological transitions, and their alignment with agroecological principles and SDGs.	Multi-scale systems	Participatory approach using systems mapping, scoring, and validation to evaluate system performance	Global	Farmers, extension services, researchers, institutions, and policymakers	Mottet et al. (2020)	Agroecology systems

Tool	Purpose	Scale	Format	Geography	Intended users	Reference	Scope
Original Agroecological Survey and Indicator System tool (OASIS)	Measuring the extent of operationalisation of agroecological principles and practices on farm using 56 incremental indicators.	Farm to region	Participatory approach using scoring to identify areas for system performance improvement	Global, initiated in Belgium	Farmers, extension services, institutions, researchers	Wezel et al. (2025)	Agroecology systems
Assessment method for the economic-ecological analysis of agroecosystems (Lume)	Recognizing and increasing the visibility of the labour of the different people involved in the management of agroecosystems using qualitative, quantitative, longitudinal, and social methods.	Multi-scale systems	Participatory approach using systems mapping, scoring, and qualitative and economic indicators to evaluate system performance	Global, initiated in Portugal	Researchers, institutions, and policymakers	Petersen et al. (2020)	Agronomy and local economy
Sustainability assessment Adaptive and Low-input Tool (SALT)	Sustainability assessment comparison between different farm regimes.	Farm to region	Conceptual hierarchical framework to translate principles to criteria, indicators, and material flows for evaluation	Global, initiated in Mexico	Farmers, extension services, institutions, researchers	Calleros-Islas (2019)	Agronomy and ecology
Multi-Objective Decision support tool for Agri-ecosystem Management model (MODAM)	Research on production practices and associated economic (e.g. revenues) and environmental (e.g. emissions) targets.	Farm to region	Process-based model combining agronomic and ecological data to estimate economic dimensions of user-defined target scenarios	Global, initiated in Germany	Farmers, extension services, institutions, researchers	MacPherson et al. (2020)	Agronomy and ecology
TransFarm	Estimating trade-offs between farm net income, farm water requirement, and carbon stock .	Farm to region	Excel-based tool combining user-defined agricultural parameters and economic data to generate target scenarios	Local, initiated in India	Farmers, extension services, researchers, institutions, and policymakers	This article, Aryan et al. (2026)	Agronomy and ecology
FarmDESIGN	Optimisation of agronomic and ecological material flows on farm.	Farm to region	Software package optimising user-defined agricultural criteria within a closed system	Global, initiated in the Netherlands	Farmers, researchers	Groot et al. (2012)	Agronomy and ecology
Farm level simulation model (FARMSIM)	Ex-ante and ex-post evaluation of agricultural technologies on farm-level economy and nutrition.	Farm to region	Excel-based tool combining agronomic data to simulate user-defined scenarios	Global, initiated in the United States	Farmers, extension services, institutions, researchers	Bizimana and Richardson (2019)	Agronomy

Tool	Purpose	Scale	Format	Geography	Intended users	Reference	Scope
Agricultural Production Systems sIMulator (APSIM)	Research simulating soil, crop, tree, pasture and livestock biophysical processes to inform agricultural practices.	Crop to farm	Process-based model simulating biophysical interactions in response to user-defined farming practice criteria	Global, initiated in Australia	Researchers	Holzworth et al. (2014)	Agronomy
Global Agro-ecological Zones (GAEZ)	Modelling framework to determine land-crop suitability and potential crop yields based on agroclimatic and biophysical conditions.	Global to sub-national	Geospatial crop suitability model combining spatial ecological and crop science data to generate maps and tables	Global, initiated in Italy	Researchers, institutions, and policymakers	IIASA-FAO (2012)	Agronomy
Decision Support System for Agrotechnology Transfer (DSSAT)	Agronomic decision support tool that simulates crop growth and yield to inform management practices.	Crop to farm	Software package simulating crop growth and yield in response to biophysical conditions	Global, initiated in the United States	Farmers, extension services, institutions, researchers	Gao et al. (2022)	Agronomy

2. Methodology

2.1 Overview of the TransFarm Framework

TransFarm is a spreadsheet-based decision-support tool developed by WELL Labs (Institute for Financial Management and Research, Krea University) in collaboration with the Ashoka Trust for Research in Ecology and the Environment (ATREE), Bengaluru, India. The tool was developed under the Sustainable and Healthy Food Systems (SHEFS) project funded by the Wellcome Trust to support farm-scale planning for agroecological transitions.

The tool is designed primarily for use by farmers with facilitation from civil society organisations, extension personnel or other implementation agencies. A user can enter basic farm characteristics, including landholding size, crop choices, crop-area proportions, tree numbers and livestock numbers, to generate farm-scale estimates of net farmer income, annual water requirement and carbon stock.

The tool enables users to evaluate alternative farm configurations by modifying crop combinations, crop area allocations, livestock holdings and tree densities within an individual farm. It estimates the implications of these changes on three outcome variables: (i) net farmer income, (ii) annual farm water requirement, and (iii) farm-level carbon stock. By comparing multiple farm configurations under specified resource constraints, the tool enables users in identifying scenarios that simultaneously improve farm profitability, water requirement and carbon stock

The workflow of TransFarm consists of five sequential steps: (1) entering farm characteristics, (2) assigning reference parameters from secondary datasets, (3) estimating baseline farm performance, (4) generating alternative farm scenarios by modifying land-use configurations, and (5) comparing scenarios to identify potential win-win outcomes.

2.2 Tool Architecture and Model Formulation

TransFarm consists of three interconnected analytical modules corresponding to the three outcome variables: net farmer income, annual farm water requirement and farm-level carbon stock. Farm-specific information provided by the user is combined with reference values compiled from secondary datasets to estimate the performance of each scenario (Fig. 1, Table 2).

Table 2
Outcome parameters and data requirements used in the TransFarm scenario generation

Parameter	Field-derived estimates from primary data	Tool estimation based on secondary data
Farmer Net Income (FNI)	Net Crop Income (NCI) for a single crop: $NCI_i = (Yield_i * SellingPrice_i + CropResidueSold_i * SellingPrice_i) - (LandPreparationCost_i + SeedCost_i + FertilizerCost_i + PesticidesCost_i + LaborCost_i)$ Here, the subscript "i" represents a specific crop.	- For some crops, Net crop incomes are directly available - In case, net income is not readily available, it is estimated with the formula - Yield*3 year average price - cost of cultivation (A2)
	Net Plot Income (NPI) for a plot with "n" crops: $NPI = \sum NCI_i, \text{ where } i \text{ ranges from } 1 \text{ to } n.$ This equation sums up the Net Crop Incomes for all the crops in the plot.	Net Plot Income (NPI) for a plot with "n" crops: $NPI = \sum NCI_i, \text{ where } i \text{ ranges from } 1 \text{ to } n.$ This equation sums up the Net Crop Incomes for all the crops in the plot.
	Net Livestock Income (NLI) $NLI = (LivestockSold * SellingPrice + EggMilkSold * SellingPrice + ManureSold * SellingPrice) - (CostOfMaintainingLivestock)$	Net income values are readily available in secondary data sources
	Net Farmer Income (NFI): $NFI = NPI + NLI$	Net Farmer Income (NFI): $NFI = NPI + NLI$
Total water requirement for crops and livestock	Farm Water Requirement: This parameter represents the annual supplemental water requirement of the farm beyond effective rainfall for crop production, together with the annual water requirement of livestock. For crop production, it is estimated from crop-specific water requirements, area allocation and effective rainfall, while livestock water requirement is estimated from livestock type and herd size. For a crop-diverse farm, annual supplemental water requirement is estimated from the area-weighted aggregate crop water requirement after accounting for effective rainfall and relevant irrigation-system losses The crop irrigation water required is calculated using the following formulae: In case of borewell or step well, where a motor pump is used: The irrigation water discharge, $Q = \text{Water horsepower} * 3960 / (0.264 * TDH * SG)$ Where, Q is water discharge in Litres per minute Water horsepower is the motor HP TDH is the depth of the borewell in feet And SG is the specific gravity of water, that is 1. The livestock water requirement is self-reported by farmers for the entire herd.	In the tool, annual crop irrigation water requirement is calculated by aggregating crop water requirements and accounting for losses associated with evaporation, percolation, run off, conveyance inefficiencies and irrigation efficiencies. The crop water requirement values for the crops are taken from FAO database and other available literature contextualized to peninsular Indian conditions. The livestock water requirements are readily available in the literature.
Carbon stock	Carbon Stock: Carbon stock represents the estimated quantity of carbon stored in soil organic matter and above- and below-ground biomass within the farm boundary. TransFarm estimates soil organic carbon stock and biomass carbon stock separately and reports their combined value as farm carbon stock.	For scenario comparison, the potential change in soil organic carbon associated with annual manure addition was estimated using the empirical relationship reported by Maillard and Angers (2014). The relationship was applied as a scenario-level approximation to estimate additional SOC associated with manure inputs and was added to the baseline SOC estimate.
Notes on conversion:		
1 acre = 4,046.85 square metres		
1 foot = 0.31 metre		
1 horsepower = 735.50 watts		

Parameter	Field-derived estimates from primary data	Tool estimation based on secondary data
	Soil Organic carbon: $\text{SOC\%} \times \text{bulk density of fine particles} \times \text{thickness of the soil core} \times 0.1$ Biomass carbon: $0.5 \times [(\text{Volume of the above ground biomass} \times \text{Wood density}) \times (1 + \text{Root to shoot ratio})]$	Because the relationship does not explicitly represent variation in soil type, climate, decomposition dynamics, soil depth or time since manure application, the resulting SOC estimates are treated as indicative rather than as temporally resolved measurements of carbon sequestration. Biomass carbon was estimated from tree volume, wood density and an assumed root-to-shoot ratio, using representative girth and height values for mature trees. Because tree age, growth trajectories and site-specific allometric relationships were not measured for all farms, these estimates represent potential biomass carbon stocks under the specified tree configuration rather than measured annual carbon sequestration.
Notes on conversion:		
1 acre = 4,046.85 square metres		
1 foot = 0.31 metre		
1 horsepower = 735.50 watts		

2.3 Data Sources and Parameterisation

The TransFarm database combines farm-specific inputs with reference parameters compiled from government datasets, agricultural universities and published literature.

Crop parameters for approximately 56 commonly cultivated crops including yield, market price, straw yield, residue production and crop water requirement were compiled from the Agritech Portal of Tamil Nadu Agricultural University, Directorate of Economics and Statistics (Government of India), University of Agricultural Sciences Bengaluru, Department of Agriculture Karnataka and crop-specific technical publications (Annexures). Where multiple estimates were available, preference was given to the most recent peer-reviewed or government-published values, and a single reference value was adopted for each parameter.

Livestock parameters including milk yield, egg production, feed requirement, water requirement and manure production were obtained from published reports and extension manuals covering cattle, goats and poultry systems.

Carbon stock estimation parameters were derived from publicly available GIS datasets and published methodologies for soil organic carbon and biomass carbon stock estimation. Historical carbon price information was included only to provide indicative estimates of potential carbon value and was not treated as a guaranteed income source.

The tool therefore combines user-defined farm characteristics with standardised reference parameters to generate comparable estimates across alternative farm configurations.

2.4 Study Area

The study was conducted in Chintamani Taluk of Chikkaballapur District in Karnataka, India (Fig. 2). The district lies within the Eastern Dry Agro-climatic Zone and receives approximately 680–890 mm of annual rainfall. Red soils dominate the landscape, together with lateritic and alluvial soils.

Approximately 24% of the district's net sown area is irrigated, while the remaining agriculture is predominantly rainfed. Major crops include finger millet, maize, pulses, oilseeds, vegetables and horticultural crops such as mango, grapes, pomegranate and sapota. The proximity of Chikkaballapur to Bengaluru provides farmers with access to diversified agricultural markets, resulting in a wide range of existing cropping systems. This diversity made the study area suitable for evaluating the applicability of TransFarm across contrasting agroecological configurations.

2.5 Sampling Design and Field Measurements

Field surveys were conducted during the agricultural year from June 2022 to May 2023.

Five agroecological configurations representing increasing levels of crop diversification and tree integration were identified (Table 3): monoculture field crops, intercropped field crops, fruit tree plantations, integrated field crops with fruit trees, and systems incorporating timber trees.

Table 3
Codes and descriptions of plot configurations based on crop diversity

Category Code (No. of plots)	Category Name	Summary
A (24)	Monoculture Field Crops	Conventional monocropping practices, where a single crop is grown in an agricultural plot
B (22)	Intercropping(Field Crops)	Multiple crop species are cultivated simultaneously in the same field, promoting biodiversity and potentially improving soil health
C (20)	Fruit tree plantations	One or more fruit trees in a single plot
D (20)	Field crops + Fruit Trees	Combines fruit trees and crops in an integrated system, aiming to maximize ecological and economic benefits.
E (19)	Field crops and /or Fruit Trees + Timber Trees	In addition to fruit trees and/or field crops, timber trees are also incorporated for benefits in the long term

A total of 105 agricultural plots were surveyed, with 19–24 plots representing each configuration. Because diversified farming systems are relatively uncommon within the study region, snowball sampling was adopted with support from Janapada Foundation, a local civil society organisation working on sustainable agriculture.

The agricultural plot was considered the unit of analysis irrespective of farm size. Detailed household surveys recorded landholding characteristics, crop combinations, livestock holdings, management practices, production costs, yields, irrigation practices, residue management and tree characteristics. These measurements enabled independent estimation of farmer income, annual water requirement and carbon stock from primary field observations.

2.6 Scenario Design Protocol

To demonstrate the application of TransFarm, one representative farm from each of the five agroecological configurations was randomly selected for scenario analysis. Such a random selection prevented potential bias in selecting farms that could demonstrate maximum change from baseline through scenario generation.

For each selected farm, existing farm characteristics were first entered into TransFarm to generate a baseline scenario representing current farm performance. Subsequently, crop combinations, area allocation, livestock numbers and tree densities were systematically modified while maintaining fixed land area, rainfall and irrigation availability.

Each scenario was evaluated against resource constraints incorporated within the tool, including land availability, biomass availability and water availability. Multiple iterations were generated until configurations were identified that simultaneously increased farmer income while reducing annual farm water requirement. These scenarios formed the basis for evaluating the three intended use cases of TransFarm.

Scenario generation was conducted by researchers from WELL Labs in consultation with practitioners from Janapara Foundation, who had contextual knowledge of the farming systems represented in the study. The exercise demonstrated the operational use of the spreadsheet in generating and comparing alternative farm configurations; however, it was not designed as a formal user evaluation.

2.7 Parameter Calibration and Error Assessment

TransFarm was not subjected to independent validation or statistical calibration using optimisation algorithms. Instead, the model parameters and assumptions were iteratively reviewed using field-derived estimates from the 105 surveyed plots. Where systematic

discrepancies were identified between tool-generated estimates and field-derived estimates, relevant parameter assumptions were revised to improve contextual fit for the study area. This process is treated as calibration rather than independent validation.

Following calibration, the remaining discrepancies between TransFarm estimates and field-derived estimates were assessed using percentage error.

Error was calculated as

$$\text{Error \%} = [(\text{Tool Estimate} - \text{Field-derived estimate}) / \text{Field-derived estimate}] * 100$$

The distribution of errors across farm categories and livestock systems was examined using boxplots to identify systematic patterns in model deviation.

2.8 Statistical Analysis

Because primary data were not normally distributed, non-parametric statistical methods were adopted.

Kruskal–Wallis tests were used to compare farmer income and additional water requirement across agroecological configurations, crop residue management practices and livestock systems. Spearman rank correlation analysis was used to examine relationships among continuous variables (Annexure 4).

The statistical analyses served two purposes: (i) to evaluate differences among farming system configurations represented in the primary dataset and (ii) to assess whether relationships observed in field measurements were adequately reflected in TransFarm outputs.

3. Results

3.1. Tool generated farm-scenarios

In the subsequent sections, each use case objective is demonstrated by a hypothetical scenario in which TransFarm can help farmers to plan an agroecological transition to the optimal scenario. The following subsections demonstrate three use cases of TransFarm using hypothetical farm-scale scenarios. The subsequent error-estimation analysis examines discrepancies between tool-generated estimates and field-derived estimates from the 105 surveyed plots. This is followed by the calibration of the tool with the primary data.

3.1.1. Crop diversification: income–water requirement trade-offs Diversifying cropping systems to improve water productivity

Figure 3 presents the average position of the crop categories analysed based on the crop income-irrigation water requirement trade-off analysis performed with primary data. None of the crop diversification categories are well within the high income-low water requirement quadrant (although category D comes closest). These visualisations can highlight to users that the crop combinations under the umbrella terms of ‘intercropping’ (with field crops, category B) or ‘agroforestry’ (with field crops and fruit trees, category D) cannot be generalised as ‘optimal’ scenarios.

For example, in Fig. 4, a hypothetical scenario generated by TransFarm is illustrated in the form of a trade-off matrix for the corresponding design parameters represented in plot illustrations. The position in the win-win quadrant was achieved by iteratively changing the design parameters in TransFarm, including the crop choices, crop area percentage or tree densities. Crop area percentage can equal more than 100% in case of crop rotation (e.g. category A in Fig. 4).

3.1.2. Livestock integration: income–water requirement trade-offs

Based on the income-water trade-off analysis performed with primary data (Fig. 5), the average per unit values for any of the livestock species were not in the high income-low water requirement quadrant. On average, the surveyed farmers had 4 cows/buffalo, 19 goats/sheep and 40 chickens. As concerns per unit income/water ratio, the cow/buffalo falls in a high income - high water requirement quadrant, whereas goat/sheep and poultry fall under a low income-low water requirement quadrant (Fig. 6). A larger number of small ruminants and poultry with a lesser number of cows/buffaloes could lead to the win-win quadrant of high income-low water. The correlation of livestock income and annual water requirement with the type and herd size are further established by statistical analysis in Table 4 and Annexure 4.

TransFarm can enable users to build appropriate livestock herd sizes so that the weighted average of the income and water requirement with herd size falls within the high income - low water requirement quadrant. For example, a farmer having 1 cow/buffalo, 4 goat/sheep and 40 chickens is represented by the weighted average scenario and is in the high-income, low-water requirement quadrant in Fig. 6. But it also comes with practical challenges of its own, including maintaining the large herd size and market linkages compared to established dairy procurement systems connected to the cows/Bufaloes.

In case of a transition combining crop diversification and livestock integration, design parameters and input variables are apportioned at plot level proportional to the plot size (Fig. 7). This scenario considers that crop diversification and livestock integration co-occur in an attempt to generate fodder to feed the livestock. In a departure from monoculture (especially paddy in this study area), this can have a significant reduction in farm water requirement. Within this landscape, a combination of field crops and trees is likely to have up to thrice as much income increase when integrating livestock as compared to a field crop only configuration.

3.1.3. Agroforestry: income–carbon stock trade-offs:

The average trade-offs between income and carbon stock based on primary data is in Fig. 8. In this average scenario, the fall in average net income is around INR 104407 (USD 1253 as of 2023)per acre on an average, while the indicative monetary value associated with the estimated additional carbon stock is around INR 81130 (USD 974)per acre, considering an assumed conservative market price of USD 10 per tCO₂. This monetary estimate represents a scenario-based valuation of estimated carbon stock and should not be interpreted as expected carbon-credit revenue, since eligibility, additionality, permanence, leakage, monitoring, reporting and verification, transaction costs and crediting-period requirements were not assessed in this study. A hypothetical scenario generated by TransFarm is presented in Fig. 9 with the design parameters represented in the table beside. In this scenario, the fall in net income is around INR 24216 (USD 291)on an average and average increase in revenue from carbon stock monetisation is around INR 106837 (USD 1282), considering a conservative market price of USD 10 per tCO₂. In this case, the TransFarm output guides the user to explore potential credit commitment with the specified design parameters (Assumptions and calculations in Annexure 3).

For modelling the optimal scenario, the user needs to iteratively change the design parameters that have significant correlation with the outcome variables, which are farmer income and biomass carbon stock in this case. Based on statistical tests documented in Table 5 and Annexure 4, significant correlations were able to be established between outcome variables and design parameters including plot size and tree density. Biomass carbon stock has a negative correlation with the number of crops per plot (crop diversity in Annexure 4) which could be due to reduction in tree density with increase in number of crops per plot.

3.2. Calibration and error assessment The tool error estimation process assesses three key parameters: incomes, annual water requirement, and carbon stock, with the aim of improving accuracy through error analysis. Crop income error estimation revealed initial discrepancies, especially due to varied crop prices, prompting a shift from average to a range-based income calculation, resulting in a significant reduction in errors. Similarly, error estimation of annual crop water requirement identified over-irrigation and data accuracy issues, leading to corrective measures such as correcting the primary data and considering category-wise error distribution, ultimately achieving a median error of 0%.

Carbon stock estimation, based on the Maillard and Angers formula, encountered challenges such as baseline soil organic carbon stock estimation inaccuracies and the formula's limited significance. Corrections included using a range of baseline soil organic carbon values and considering variations in carbon content of organic matter.

Following contextual calibration, the median error was 0% for the three outcome variables across the assessed categories. These results indicate improved agreement between tool estimates and field-derived estimates within the calibration dataset, but should not be interpreted as independent validation of predictive accuracy

Refer to Annexure 3 for detailed analysis of error distribution and error correction.

3.3. Relationship between farm design parameters and outcomes The average farmer land holding in the surveyed sample was 5.89 acres, and the average plot size was 1.95 acres (Table 4, Table 5, and Annexure 4). The study area had a good diversity in crop selection, with 52 different crops observed across the 105 plots. =Mango (fruit trees), Ragi (millets, grain crops), Red gram (pulses), *Milia dubia* (fodder trees), Silver oak (timber trees), Jowar (sorghum, fodder crops), Tomato (horticulture field crops) etc. are the dominant crop choices across different crop types. Regarding the irrigation sources, nearly 70% of the surveyed farmers don't have access to irrigation sources like groundwater and largely depend upon the rainfall; in the remaining plots, groundwater is being used in addition to the rainwater for irrigation. Around two-thirds of the borewell-irrigated plots were category A (monoculture field crops). In other words, all the

monoculture category (A) plots needed an additional source of irrigation like borewell. Also, 90% of the plots were owned by farmers with livestock, and on an average one farmer owned 4 cows/buffalo, 19 goats/sheep and 40 chickens.

Landholding and plot size, crop diversity, livestock herd size, tree density, varied significantly across all five categories. Similarly, estimated per acre values of income, water requirement, and biomass carbon stock varied significantly across the five categories. Water requirement and income also varied across the nine types of crops, three residue management strategies, and sources of irrigation. Herd size, income, and water requirement varied significantly depending on the type of livestock. Annexure 4 tabulates the results of the correlation analysis performed between outcome variables and potential design parameters; a higher correlation is attributed for the criticality of the design parameters in deciding the outcome. For example, net income had low positive correlations with plot size, crop area percentage, and fruit tree density (Annexure 4). Biomass carbon stock had a low positive correlation with plot size, and a high positive correlation with fruit tree density. Water requirement had a moderate positive correlation with crop area percentage, and livestock income. Thus, plot size, crop area percentage, and tree density emerge as important design parameters in tool development.

Table 4
Sample profile

Sample Profile		
Land area	Average Landholding size (acres)	5.58
	Average plot size (acres)	1.95
Livestock	Farmers with Livestock (%)	90.6
	Farmers without livestock (%)	9.4
Crop distribution (%) [This is based on the number of instances in which a particular crop type was cultivated in any plot for any season as the main crop or intercrop.]	Fodder trees (%)	1.4
	Cereals (%)	7.2
	Milletts (%)	13
	Pulses (%)	26.3
	Fodder crops (%)	1
	Horticulture field (%)	17.4
	Timber tree (%)	8.9
	Fruit tree (%)	24.6
Irrigation water source	Borewell (%)	30.2
	Rainfed (%)	69.8
Average Herd Size	Cow/Buffalo	4
	Goat/ Sheep	19
	Poultry	40
Note on conversion: 1 acre = 4,046.85 square metres		

Table 5
Descriptive statistics and Kruskal-Wallis statistics for primary data collected from farms across plot configuration categories

Categorical Variable	Continuous Variable	Median	Mean	sd	KWA chi	p
Crop configuration (df = 4)	Landholding Size (Acres)	4.25	5.89	4.45	26.396	2.633e-05
	Plot Size (Acres)	1.5	1.95	1.35	19.924	0.0005168
	Crop Diversity (n)	2	3	1.71	54.753	3.661e-11
	Livestock Holdings (n)	1.5	1.945	1.347	19.154	0.000733
	Net Annual Income (Rupees)	71226	148770	322721.1	12.683	0.01293
	Total Water Requirement (Cubic meters)	0	1644	4789	43.145	9.657e-09
	Total Biomass Carbon Stock (tCO ₂)	15	15.6	196.0281	87.136	< 2.2e-16
	Fruit Tree Density (n/acre)	18	28	33	79.739	< 2.2e-16
	Timber Tree Density (n/acre)	0	14	58	90.911	< 2.2e-16
Crop type (df = 8)	Crop Water Requirement	NA	NA	NA	204.03	< 2.2e-16
	Crop Income	NA	NA	NA	46.441	1.96E-07
Crop residue management (df = 2)	Crop Income	NA	NA	NA	16.156	0.002816
	Crop Water Requirement	NA	NA	NA	57.977	7.72E-12
Livestock type (df = 2)	Livestock Income	18336	60364	129686.5	27.576	1.03E-06
	Livestock Annual Water Requirement	12471	912922	4358225	38.083	5.38E-09
	Herd Size	7	19.48	67.52	34.444	3.32E-08
Source of irrigation (df = 2)	Crop Income	NA	NA	NA	7.6753	0.02154
	Crop Water Requirement	NA	NA	NA	244.47	< 2.2e-16
KWA: Kruskal Wallis Anova; 1 acre = 4,046.85 square metres						

4. Discussion

4.1. The utility of TransFarm in enabling agroecology transitions

The literature on agroecological transitions calls for systemic transformations across scales and over time, including issues of market linkages, governance, and territories (Duru et al. 2015, Wezel et al. 2016). The use of TransFarm can facilitate these transformations by scaling them at plot and farm level, from a farmer's point of view. In comparison to other tools in the agronomy and ecology category (Table 1), TransFarm takes a simplistic and inductive approach to demonstrating trade-offs. Agroecological practices and agronomic outputs are factored in by the user, rather than being modeled as processes and outcomes as done by other tools. This allows for user-designed outcomes balancing ecological and economic interests, rather than outcomes based on guidelines, frameworks, and principles (e.g. SALT, MODAM). This simplified input interface does allow farmers to incorporate intercropping, crop rotation, crop coverage, and crop loss, and crop use (on-farm), as part of agronomic calculations, but does not model these processes (e.g. APSIM), allowing instead for iterative adjustments by the user themselves. We posit that this iterative and dynamic process allows users to explore the potential and constraints of their plots, farms, or regions without externally administered benchmarks for practices and indicators. Often, this level of granularity can unlock a range of transition options for farmers that may not be on offer at scale through conventional agricultural extension or CSO programmes (Wezel et al. 2020).

In the Indian context, the small scale of farms and the critical role of CSOs and implementation agencies in driving collective decision-making suggest that this tool is more likely to be used by intermediaries than by farmers directly. While the decision-making may still rest with the farmer, the user of the tool is typically a CSO facilitator or implementing agency working with farmer collectives. This was also the case in our study, where the tool was piloted through a CSO that had already enabled agroecological transitions in the area. A key feature of the study is that TransFarm was tested ex-post using farm configurations representing transitions that had already occurred.

This allowed us to examine whether the tool could reproduce and compare the diversity of farm configurations observed in the study area. The resulting demonstration suggests potential for ex-ante scenario exploration, although such prospective use requires further independent validation.

Participatory approaches (e.g. IDEA, MESMIS, TAPE) tend to apply general principles of social and environmental sustainability to derive local indicators to guide transitions (Mottet et al. 2020). However, these approaches are often methodologically intensive, and may prove more responsive to the needs of researchers and agricultural support institutions rather than farmers themselves (Darmaun et al. 2023). TransFarm takes a land-based approach (e.g. Hernández-Ochoa et al. 2022) to quantify the economic and biophysical variables associated with different farm regimes, and estimate the costs and benefits associated with them. In doing so, the tool leaves out the livelihood aspect of agricultural production, such as off-farm incomes, and non-farming activities such as food processing. We believe that several tools (e.g. Lume, GTAE) already exist to address this aspect of the agricultural economy, and can be used in conjunction with the simpler TransFarm, to account for the livelihood impacts of agroecological transitions. We envision that reconciling participatory methods with simpler quantitative tools like TransFarm will provide a rich understanding of the realities of achieving agroecological transitions. For example, TransFarm elicits the principles of diversity, circular economy, and knowledge sharing at farm scale in its user interface (Wezel et al. 2020). The outputs could be used to inform better governance at regional scale (See Section 4.2). This paper demonstrates use cases for farmer income trade-offs when diversifying land under different types of crop and livestock. However, given the presence of appropriate data, the tool can also be used to calculate the value of carbon and water ecosystem services provided by agroecological infrastructures (such as hedges, embankments, forest edges, etc.).

4.2. Implications for multi-stakeholder landscape planning

Agroecology, rooted in sustainable land management principles, offers an alternative to industrial agriculture, but is faced with challenges to uptake due to perceived long-term sacrifices (FAO 2018). Current adoption rates of sustainable practices are low, attributed to factors like lack of knowledge, economic incentives, and market differentiation (Gupta et al. 2021). Hastily implemented transitions without considering local conditions can lead to short-term economic trade-offs and deeper social-ecological impacts. Advocating for agroecological transitions requires transparent translation and communication of benefits, including intangible improvements such as process optimisation and ecosystem services (Hannus and Sauer 2021). This study demonstrated the usefulness of a decision-making tool in assessing co-benefits and trade-offs in three scenarios: crop diversification, integrating livestock on-farm, and carbon financing for agroforestry.

The results from primary data analysis indicate that landholding and plot size, crop diversity, livestock holdings, tree density and crop residue use significantly influence farm configurations (crop choice) and outcomes (income, water requirement, and carbon stock). Spatiotemporal crop diversity (Fig. 5) tends to nudge farm outcomes towards improving farm income while reducing annual water requirement. Similarly, diversified livestock holdings also improve livestock income while reducing annual water requirement. While these links have been empirically established over large landscapes (Chabert and Sarthou 2020), TransFarm provides fine-scale data on plot design and herd sizes that are feasible at farm level. The tool also highlights the farm configurations in which such diversification is most and least feasible, helping users prioritise interventions or target specific types of farmers in the given region. This modality is especially important in contexts like India, where small landholdings prevail (Giller et al. 2021) and where land use transitions are increasingly incentivised through mechanisms such as carbon credit schemes (e.g. Green Credit Programme 2023). Temporal variations in crop cycles play a significant role in the carbon storage capacity of a landscape (Indrajaya et al. 2024, Khorchani et al. 2022). TransFarm can enable users to plan and apportion farms in a way that does not compromise their income. The ability to diversify crops, livestock, and income sources (including through carbon schemes) is likely to help farmers and CSOs build farm- and landscape-level resilience by incorporating dynamic adaptation strategies in case of short-term shocks, without falling short on long-term commitments to ecosystem integrity (e.g. carbon sinks, water flows, biodiversity). Such adaptation has been identified as a crucial need in carbon credit schemes (Hajjar et al. 2021).

The design of TransFarm was influenced by consultations with CSO practitioners and farmer groups, particularly those involved in land and water governance. Many typical users, especially older male farmers, tend to have a short-term outlook focused on financial viability, driven by chronic agrarian distress and widespread youth migration to non-farm sectors (Srinivasan et al. 2021). As a result, TransFarm places emphasis on monetary outcomes as an entry point for dialogue and decision-making. However, the tool's focus on land and water as framing variables was equally shaped by CSOs involved in natural resource management, who were looking for ways to incentivise sustainable practices in commons governance, such as watershed development, agroforestry, or community grazing lands (WELL Labs 2024). This convergence of farmer needs (income) and CSO objectives (sustainability) shaped the simplified yet purposeful structure of the tool. During piloting, farmers and advisors found the visual and modular structure of the tool intuitive, especially when used in facilitated settings. They appreciated the ability to estimate trade-offs between farm choices and income. However, some users noted the

absence of off-farm income, gendered labor roles, or food self-provisioning from the analysis (e.g. Varsha et al. 2025). While this simplicity may limit the tool's use as a full livelihood model, it was seen as helpful in clarifying decisions within the scope of farm-level land use. In this way, TransFarm acts less as a prescriptive tool and more as a deliberative platform — enabling facilitated decision-making by CSO actors with farmers.

The database generated by farmers and CSOs can provide valuable landscape-level insights on land use and the feasibility of different interventions. Information on farm configurations and the related water requirement, carbon stock, and agrobiodiversity can help prioritise ecosystem services such as through catchment management, high value nature farming, selective silviculture, etc. For example, data from the first use case objective of increasing water productivity could be shared with a government department like the water resource department or irrigation command area authorities. A government agency or local functionaries in charge of releasing the water through irrigation canal structures would be able to use TransFarm to estimate the water demands and monitor water productivity based on aggregating farm-scale scenarios at distributary scale or at a command area scale. The government departments with the mandate of increasing water productivity could recommend the water user associations to use TransFarm for crop planning exercises and local functionaries could hold negotiations around water release based on data and evidence. The farm-scale results from TransFarm, if aggregated at distributary and canal command area level, have the potential to get integrated with the ongoing automation of canal infrastructure (Charkha, Karva and Loliyana, 2019). However, the utility of TransFarm for such local landscape planning is contingent on improved agronomic data consolidation and accessibility. The Directorate of Economics and Statistics (<https://desagri.gov.in/>) under the Ministry of Agriculture and Farmers Welfare could play a pivotal role in making such up-to-date information available to the public.

Philanthropic and donor organisations would be able to take informed funding decisions based on the estimated impact numbers for crop diversification interventions, or carbon credit scheme enrolment. For example, in high biodiversity areas, selective silviculture may be a more attractive option delivering benefits from both timber production and carbon credits, while simultaneously reducing the impact on biodiversity (Wurz et al. 2022, Latterini et al. 2023). On the other hand, crop diversification may yield positive outcomes when infrastructure (e.g. seed banks, silos, mills) and market linkages are well-developed (Bandula et al. 2023). TransFarm enables users to aggregate the net income derived from such diversification before investing in an intervention. Government and philanthropic agencies implementing a livestock promotion scheme and distributing a particular breed or type of livestock could also be informed of the economic and ecological impacts of the selected livestock in the given environment. Whereas existing tools necessarily seek to optimise farm outcomes towards pre-specified targets (e.g. certification, yields), TransFarm enables users to tweak inputs on continuous scales to arrive at desired outcomes. At landscape level, it also allows for a diversity of farm configurations. Research has found that diverse mosaic landscapes often tend to sustain multiple ecosystem services and healthy ecosystem functioning (e.g. Maskell et al. 2019, Tscharncke et al. 2021). Therefore, TransFarm is likely to contribute to improved land use planning.

4.3. Limitations and future validation

Agricultural systems are inherently complex, influenced by a multitude of interconnected factors beyond the scope of TransFarm. While the tool provides valuable insights, it may not fully capture the intricacies of real-world farming dynamics, including social, economic, and environmental dimensions. Following are some of the limitations of the study and TransFarm:

While the tool proposed in this research paper offers insights into farm configurations and outcomes, factors such as institutional capacity, policy support, farmer engagement, labour considerations, and intangible economic incentives are crucial for maximising farm scale impact but are beyond the tool's ambit.

The TransFarm interface is a simple excel sheet with formula embedded in it which would require further refinement for improving error margins and accuracy, situational model assumptions, and user experience. We acknowledge the limited local scope of the tool, and recommend that future research in other parts of Indian and similar Global South contexts can contribute to more detailed evaluations of parametrisation, validation, and portability. The GAEZ database (IIASA 2018) can provide district-level input data on agronomy, but primary local data collection will be essential to validate local utility.

The present study does not provide an independent validation of TransFarm. The same primary dataset was used to inform parameter refinement and to assess discrepancies between tool-generated and field-derived estimates. The resulting error assessment therefore indicates the degree of agreement after contextual calibration rather than predictive performance on an independent dataset. Independent validation using data from farms not involved in calibration, across different agro-climatic and market contexts, is required before the tool can be considered transferable beyond the study context.

The tool is as good as the back end data available

TransFarm's effectiveness is intrinsically tied to the accuracy, relevance, and timeliness of the data it relies upon. Agricultural practices, market conditions, and environmental factors can vary significantly from one region to another, necessitating localised data and analysis. While TransFarm may provide relative comparisons of crop choices and farm configurations that remain constant over time, changes in policy frameworks, market conditions, technological advancements, and environmental factors can all impact the validity and relevance of the tool's outputs.

The carbon module is exploratory and subject to greater uncertainty than the income and water components. SOC estimates associated with manure addition rely on an empirical relationship that does not explicitly represent variation in soil properties, climate, decomposition dynamics and time horizons. Biomass carbon estimates similarly rely on assumed mature-tree dimensions and generic biomass conversion parameters. These assumptions limit the precision of the estimated carbon stock. Accordingly, the carbon outputs should be interpreted as indicative scenario-level estimates rather than measurements of annual carbon sequestration

The associated monetary values should likewise not be interpreted as expected carbon-credit revenue. The analysis does not assess project additionality, permanence, leakage, monitoring, reporting and verification, buffer requirements, transaction costs, eligibility or crediting periods. The carbon component is therefore best understood as an exploratory mechanism for examining the potential economic implications of alternative carbon-stock configurations

The study did not undertake a formal usability or user evaluation. Scenario generation was conducted by researchers and practitioners familiar with the study context, but no structured assessment of task completion, comprehension, usability, trust or perceived usefulness was undertaken. The study therefore demonstrates operational use of the tool rather than establishing direct farmer usability. Future work should evaluate the tool with intended users, particularly facilitators from civil society and extension organisations, and assess whether the interface and outputs support real-world farm planning

The present study does not include a formal uncertainty or sensitivity analysis. TransFarm's outputs depend on a number of uncertain and locally variable inputs, including crop prices, crop water requirements, the manure-to-SOC transfer coefficient, and assumed tree allometry, and the error assessment reported in Section 3.2 characterises agreement with field-derived estimates rather than the sensitivity of model outputs to variation in these inputs. Future work should include a formal uncertainty and sensitivity analysis to characterise how variation in key input parameters propagates through to farm-scale income, water requirement, and carbon stock estimates.

5. Conclusion

This study demonstrates the potential of TransFarm as a farm-scale decision-support tool for exploring trade-offs between farmer income and ecological outcomes under alternative agricultural configurations. By combining farm-specific information with agronomic, economic and biophysical reference data, TransFarm enables users to iteratively modify crop combinations, crop-area allocation, livestock holdings and tree density and examine their implications for net farmer income, annual farm water requirement and carbon stock.

The scenario analysis demonstrates how the tool can make otherwise complex trade-offs explicit at the farm level. Crop diversification scenarios illustrate opportunities to improve farmer income while reducing annual water requirements, while livestock integration scenarios demonstrate how livestock can contribute to farm income while introducing additional demands on water and other farm resources. The agroforestry scenarios further demonstrate how changes in tree density can influence the relationship between farm income and carbon stock. Together, these applications illustrate the value of considering economic and ecological outcomes simultaneously rather than assessing individual interventions in isolation.

An important feature of TransFarm is its iterative and user-driven approach. Rather than prescribing a fixed pathway for agricultural transition, the tool allows users to explore alternative combinations of farm enterprises within the constraints of land, water and biomass availability. This makes it particularly relevant for organisations working with farmers to design context-specific interventions, where farmer income, resource availability and ecological objectives need to be considered together.

The study also shows how farm-level scenario analysis can provide a basis for connecting individual farm decisions with broader agricultural planning and investment priorities. Civil society organisations, extension agencies and other implementation actors can use such tools to explore intervention options, identify potential trade-offs and better align farmer interests with wider objectives such as water conservation and ecological improvement.

TransFarm is therefore best understood not as a tool for identifying a single optimal farm system, but as a framework for making the consequences of alternative farm configurations visible and comparable. Its continued application across farming systems and agro-climatic contexts, together with further refinement of its parameters and assessment through independent datasets and user engagement, can strengthen its usefulness as a practical tool for supporting agricultural transition.

Declarations

Ethics approval and consent to participate

The study was ethically reviewed and approved by the Humanities and Social Sciences Research Ethics Committee of the University of KwaZulu-Natal (Ref. No. HSS0287/018). All participants in the study were informed of the purpose of the study, and their informed verbal consent was taken prior to the collection of data.

Consent for publication

All authors have read and consent to the publication of this study in its present form.

Data Availability Statement

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Conflict of Interest

The authors declare no conflict of interest.

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Author Contribution

All authors have read and consented to publication of this manuscript. Conceptualisation: Abi Tamim Vanak, Veena Srinivasan, Mallika Sardeshpande, Syamkrishnan Aryan; Investigation, Methodology: Syamkrishnan Aryan, Mallika Sardeshpande; Data Curation, Visualisation: Syamkrishnan Aryan, Manjunatha G; Formal Analysis, Writing – original: Syamkrishnan Aryan, Mallika Sardeshpande; Writing – review and editing: Mallika Sardeshpande; Funding Acquisition, Supervision: Abi Tamim Vanak, Veena Srinivasan

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Figures

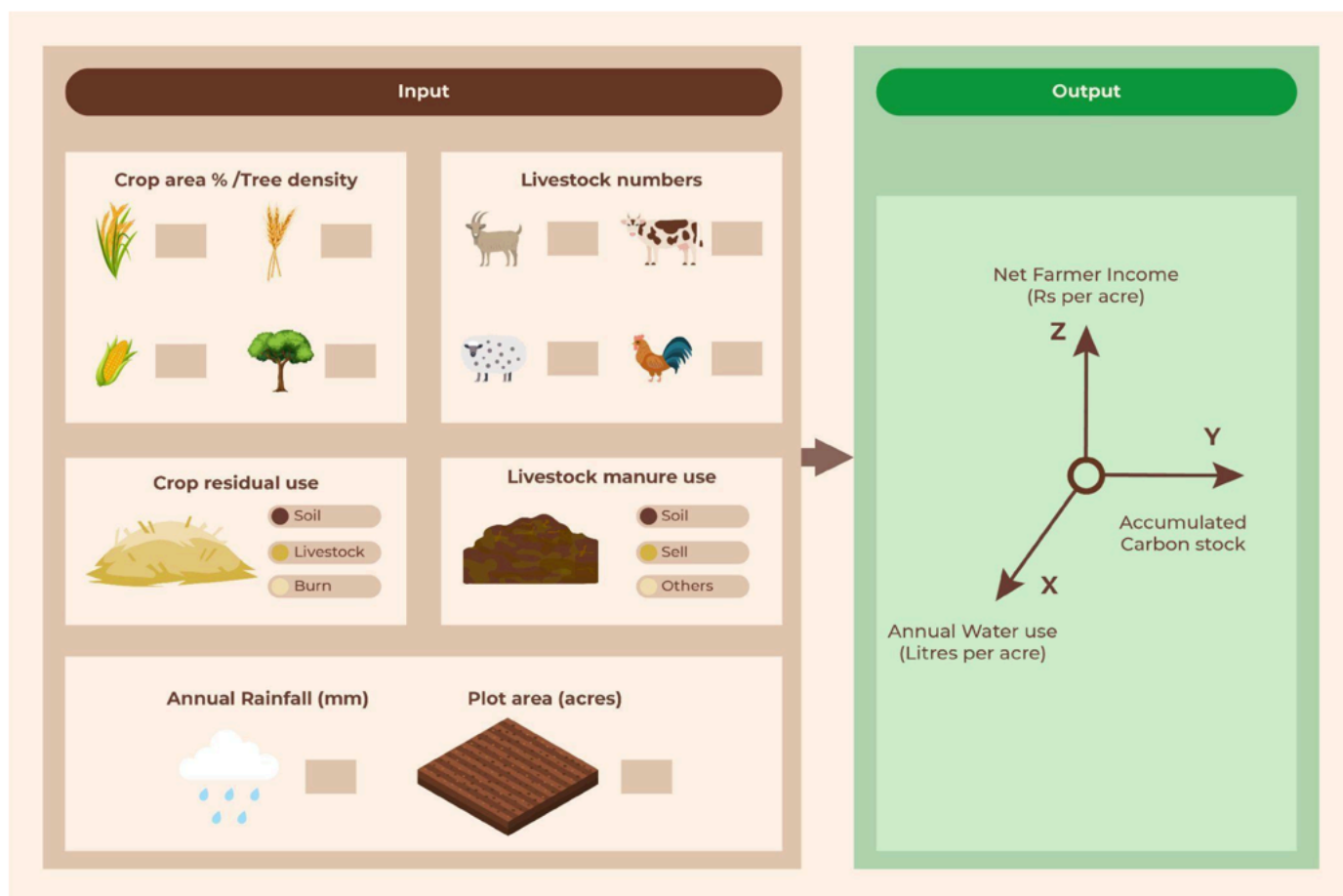


Figure 1

Illustration representing excel based tool interface of the TransFarm

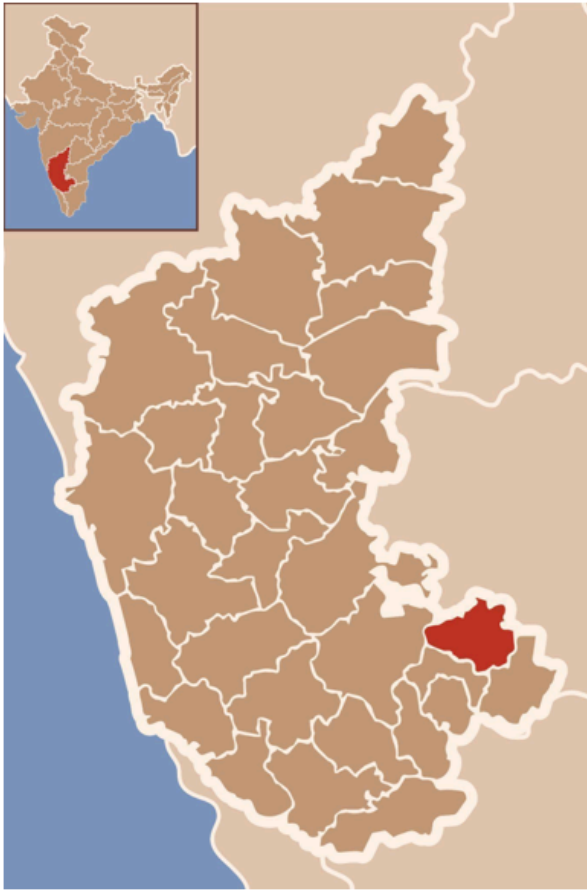


Figure 2

Study area - Chikkaballapur in Karnataka

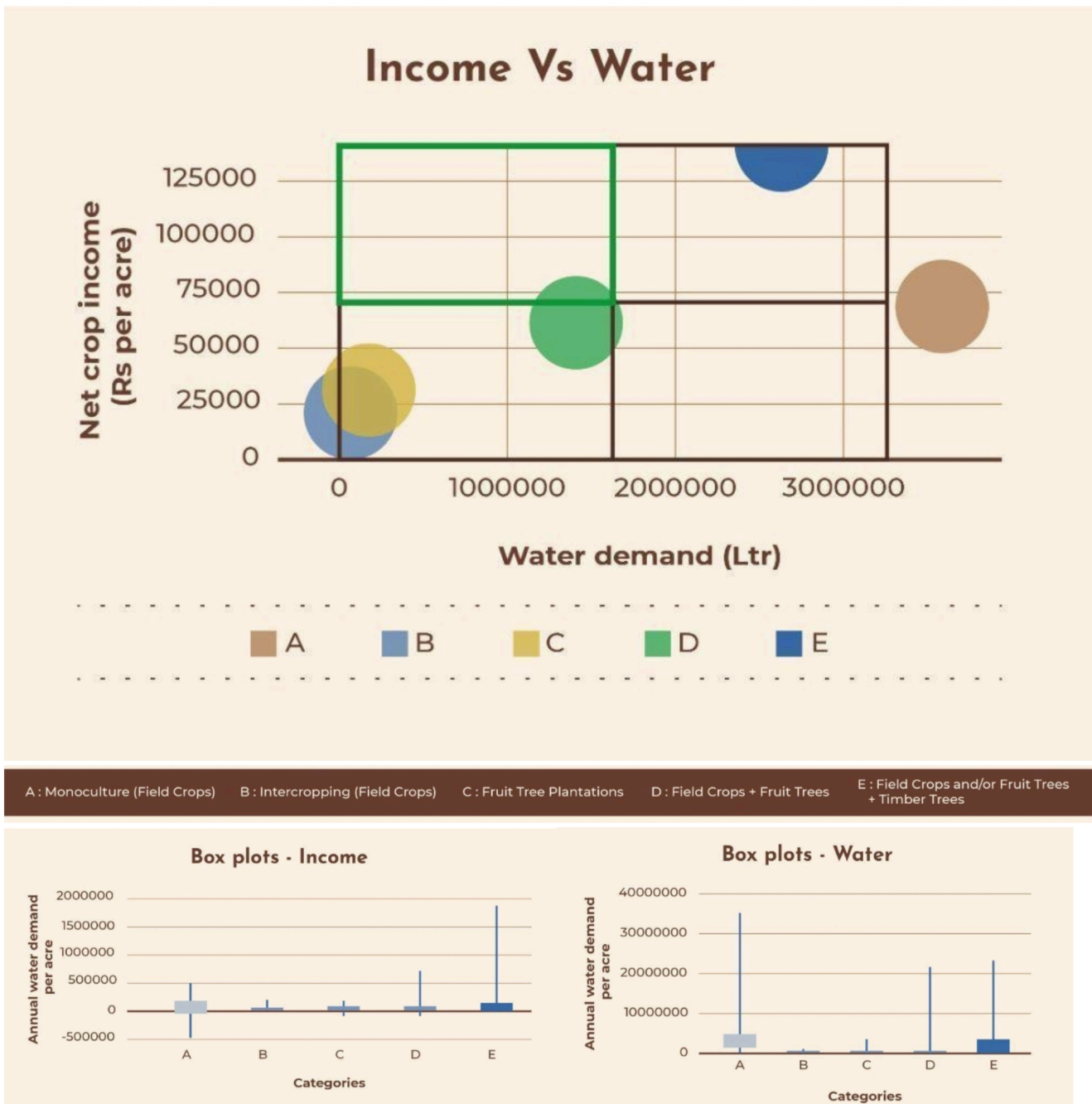


Figure 3

Trade-off matrices with category averages (primary) and Variations within the categories (box plots)

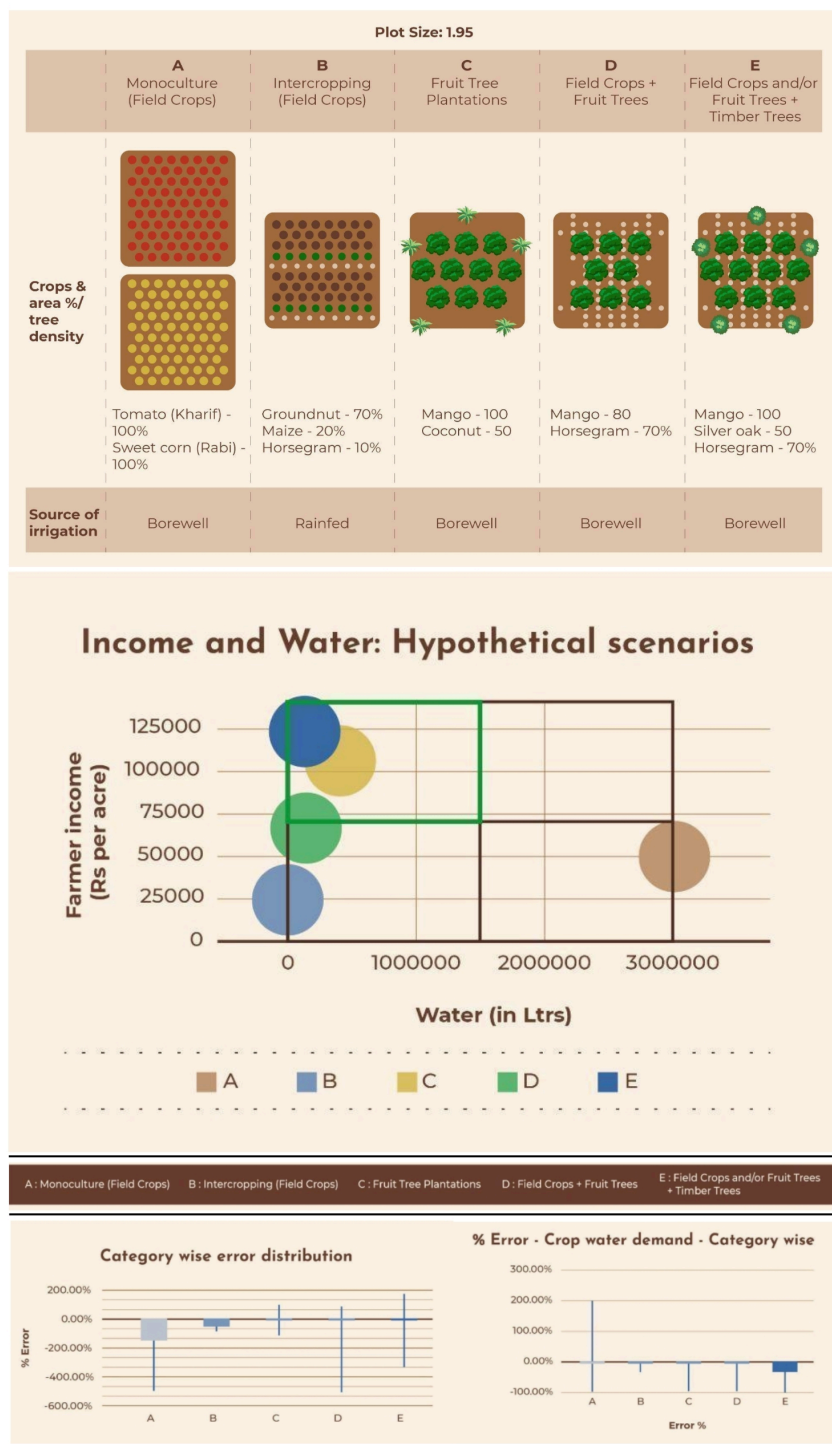


Figure 4

Income - Water trade-offs for hypothetical scenarios generated by the tool with the given design parameters

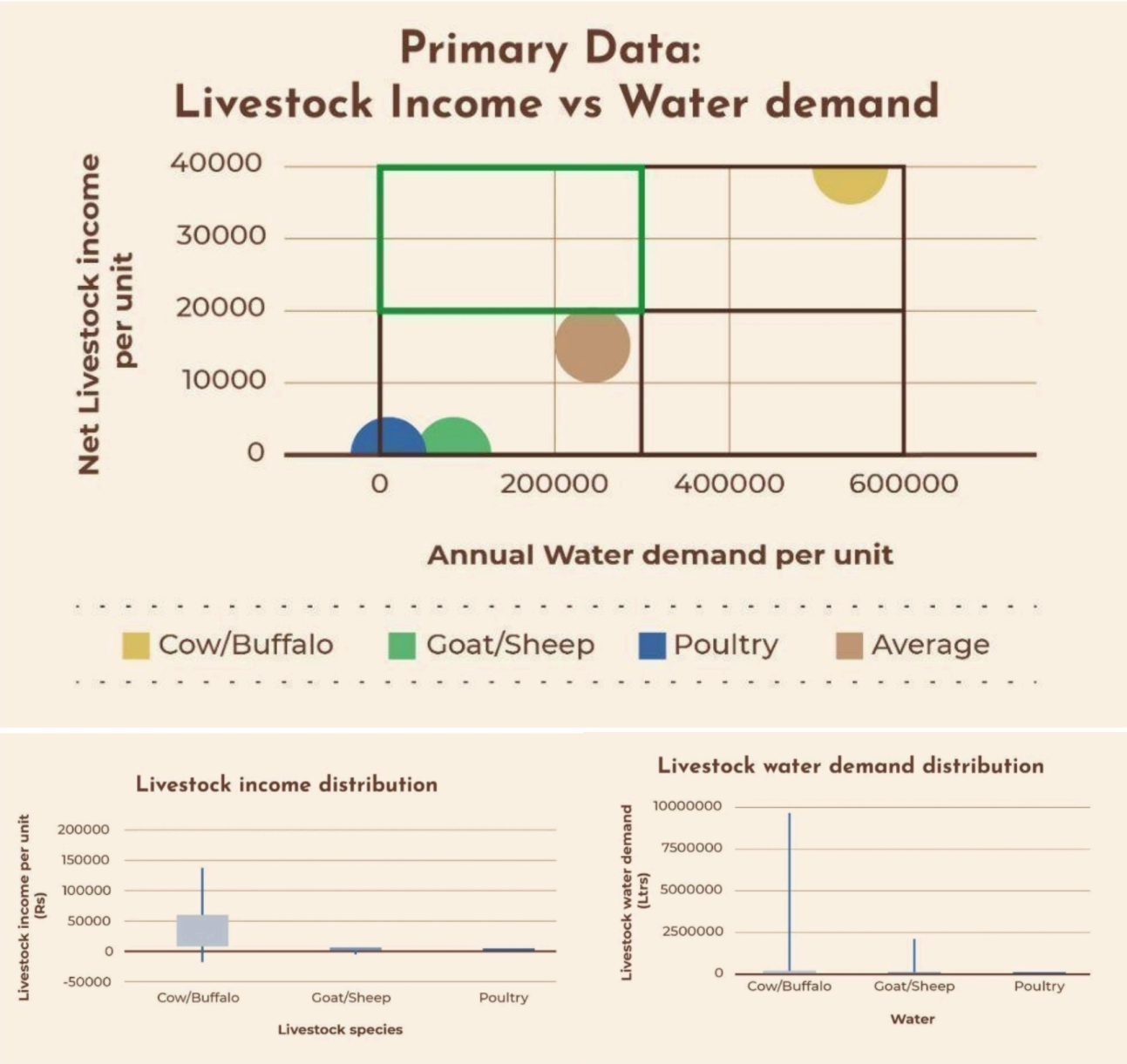
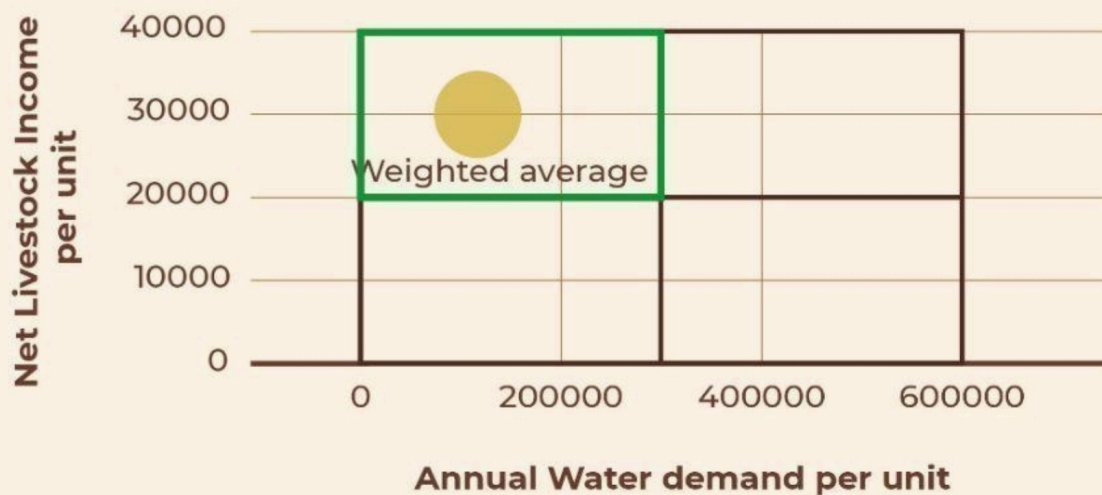


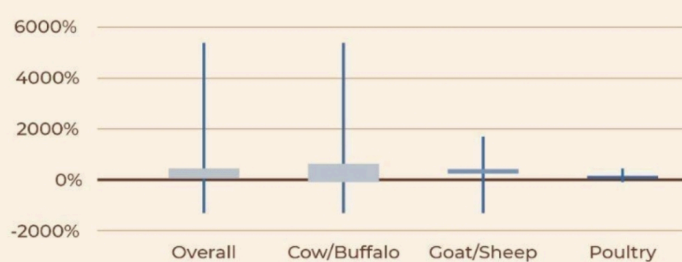
Figure 5

Income - Water trade-offs for additional livestock

Hypothetical scenario: Livestock Income vs Water demand



Livestock income: Error distribution



Livestock water demand: Error distribution

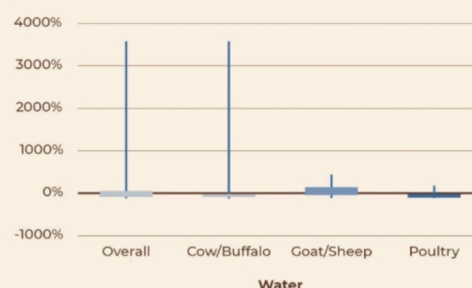
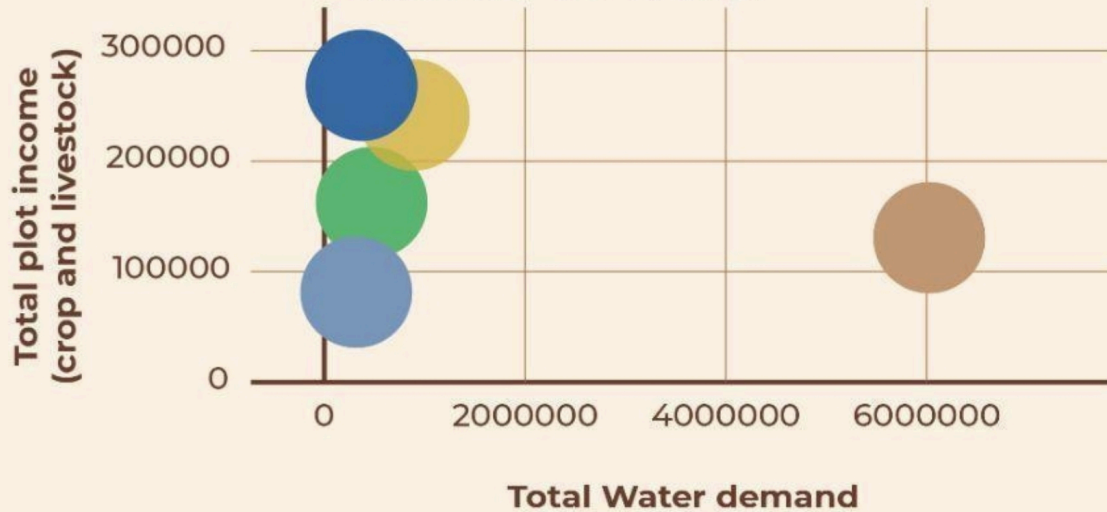


Figure 6

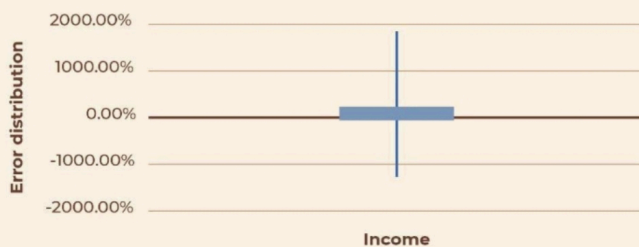
Income - Water trade-offs for hypothetical scenario

Crop diversification and livestock integration: Income vs Water



- A (Monoculture (Field Crops))
 ■ B (Intercropping (Field Crops))
 ■ C (Fruit Tree Plantations)
- D (Field Crops + Fruit Trees)
 ■ E (Field Crops and/or Fruit Trees + Timber Trees)

Error distribution- Total Income



Error distribution- Total Water demand

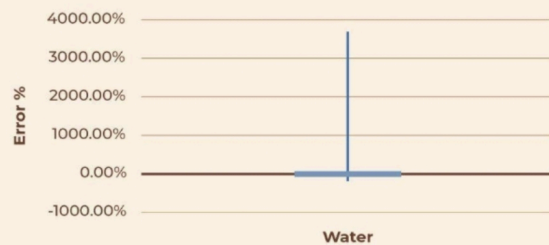


Figure 7

Income - Water trade-offs

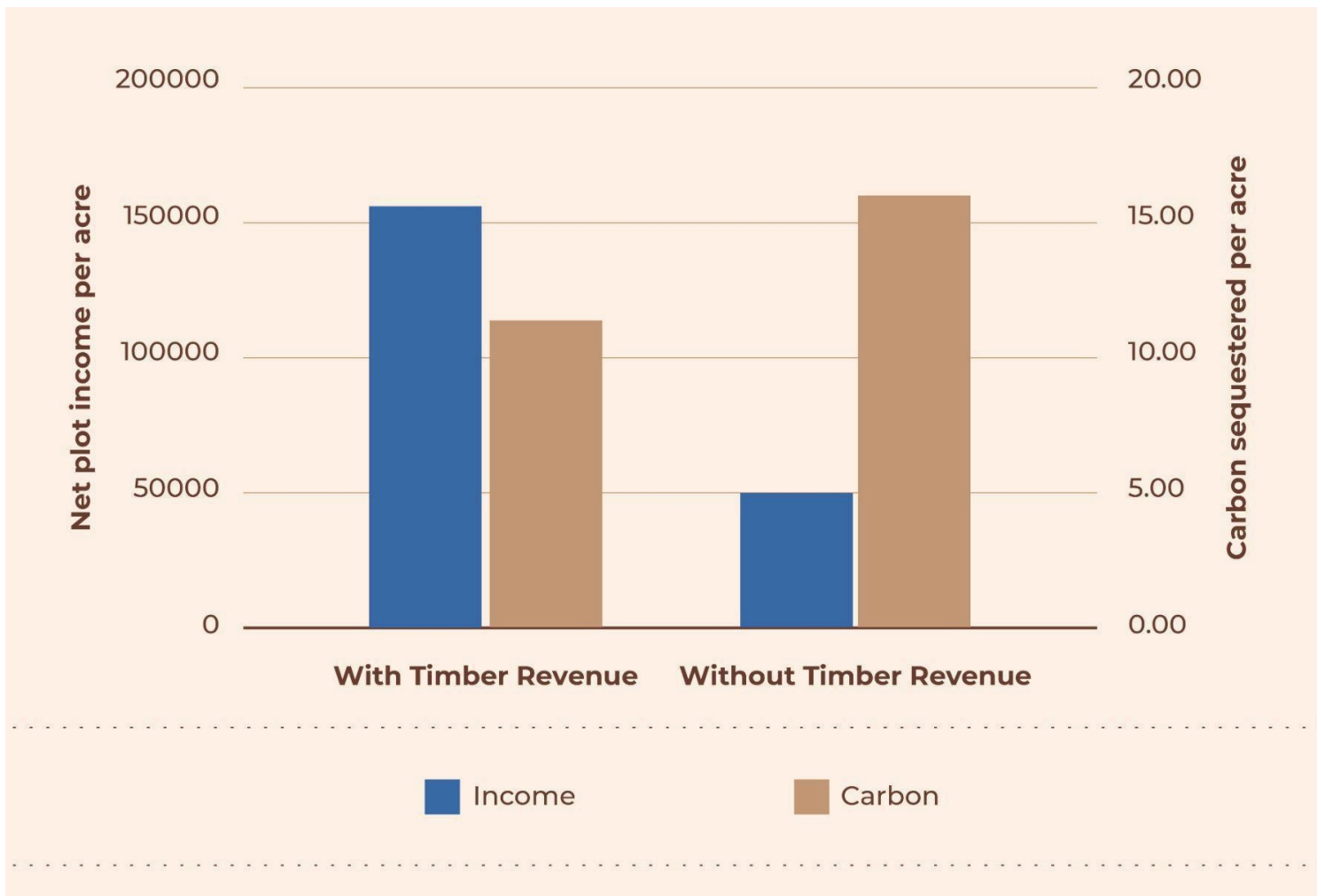


Figure 8
Income - Carbon stock trade-offs for timber based agroforestry

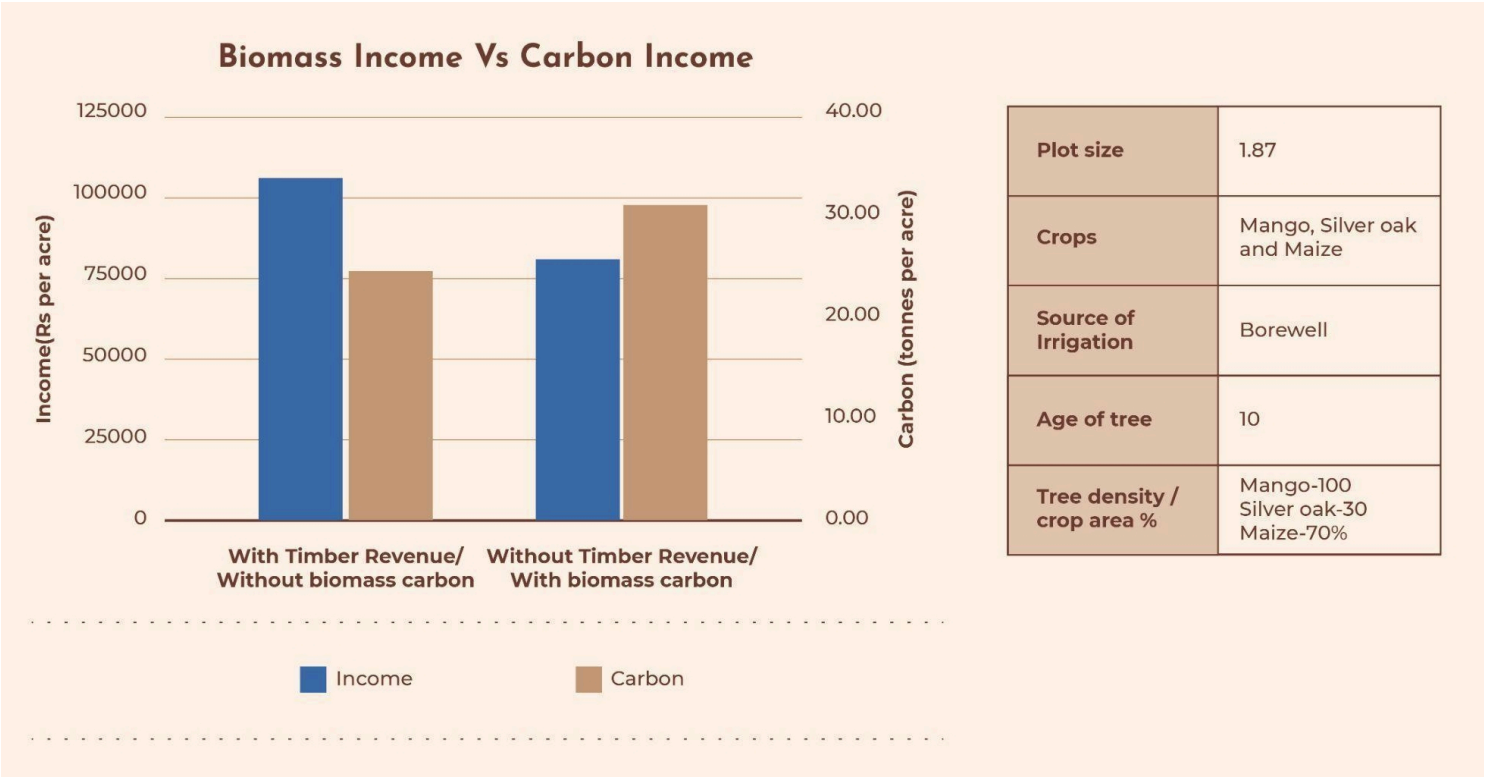


Figure 9

Timber Income - Carbon stock - Income trade-offs for timber-based agroforestry - Tool generated hypothetical scenarios

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [TransFarmAnnexures.docx](#)