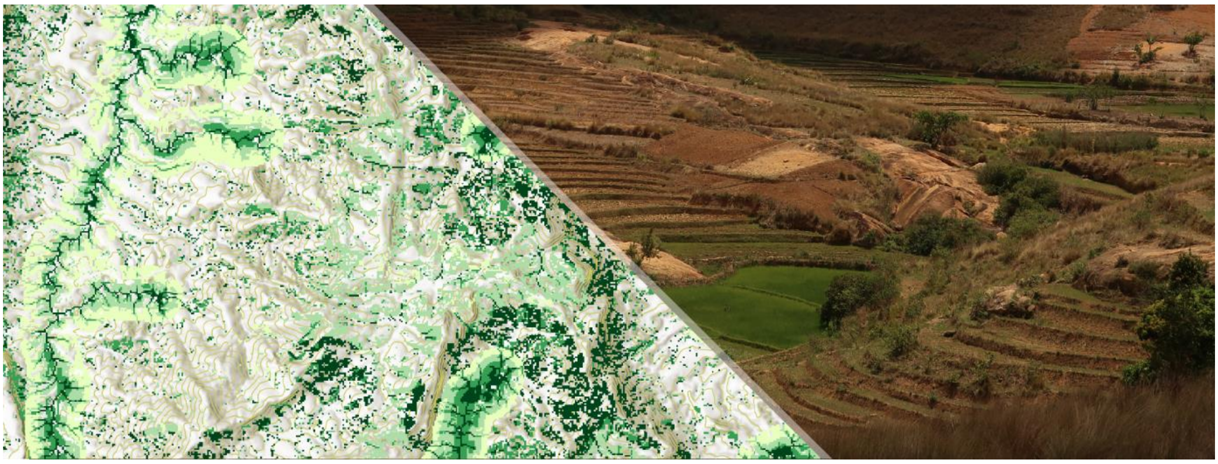
# Land suitability mapping for rice and Artemisia A. outgrower schemes in the Isandra district, Madagascar

## Comparing conventional land suitability approaches and local participatory methods to determine suitable land for the expansion of project TSARA




**MSc thesis by Giudici Ermanno**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**Soil Physics and**

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Land suitability mapping for rice and Artemisia A. outgrower schemes in the Isandra district, Madagascar

Comparing conventional land suitability approaches and local participatory methods to determine suitable land for the expansion of project TSARA.

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# Abstract (En)

This study integrates expert-based and participatory Land Suitability (LS) assessments with logistical constraints, to identify optimal areas for expanding TSARA's outgrower schemes. The TSARA project aims to address several of Madagascar's agricultural challenges by promoting an annual crop rotation, combining rice (*Oryza sativa*) and *Artemisia A.*, targeting smallholder farmers in the Isandra district.

Local technicians were consulted to establish locally adapted suitability criteria, weighed through an Analytical Hierarchy Process consultation, which emphasized the significance of soil fertility requirements and field-level water accumulation. Rural Appraisal was chosen as a participatory qualitative survey methodology, revealing that local farmers correlate soil qualities to specific field types in the landscape, and provided criteria weights through farmer focus-group consultations.

A GIS-based weighted sum analysis produced two 30m-resolution LS maps: one based on remotely sensed expert-defined criteria, and another incorporating farmer-based landform classifications. Results identified three land suitability categories in Isandra: (i) 235 $km^2$ of high agronomic potential that farmers may be overlooking, (ii) 60 $km^2$ where farmers perceive suitability despite lower agronomic potential, and (iii) 222 $km^2$ for optimal implementation where agronomic potential and farmers' perceptions align.

The participatory GIS model successfully identified 48.5% of potential agronomically suitable land. While empirical validation is needed, this study highlights farmer knowledge's potential as a substitute for remotely sensed indicators in environments with limited available field-derived soil data. Conflicting farmers' perceptions regarding crop fertility requirements of local varieties underscored the need to corroborate local knowledge with scientific approaches on crop nutrient management.

Distance from water sources and population centres proved to be strong indicators of current farmers' location. Overall, the integration of remote sensing, participatory farmer knowledge and accessibility constraints in the LS assessment of TSARA's rotation provides a locally adapted, scalable, and practically applicable contribution to the advancements of LS methodologies.

# Résumé (Fr)

Cette étude intègre des évaluations de l'aptitude des terres, tant expertes que participatives, en y associant des contraintes logistiques afin d'identifier les zones optimales pour l'expansion des circuits de production en sous-traitance de TSARA. Le projet TSARA vise à relever plusieurs défis agricoles à Madagascar en promouvant une rotation culturale annuelle associant riz (Oryza sativa) et Artemisia A., à destination des petits exploitants du district d'Isandra.

Des techniciens locaux ont été consultés pour définir des critères d'aptitude adaptés localement, pondérés via une analyse hiérarchique (AHP) mettant en exergue les exigences en matière de fertilité des sols et l'accumulation d'eau au niveau des parcelles. L'évaluation rurale a été retenue comme méthode d'enquête qualitative participative, révélant que les agriculteurs locaux associent les qualités pédologiques à des types de parcelles spécifiques dans le paysage et fournissant ainsi des pondérations de critères lors de consultations en groupe.

Une analyse par somme pondérée basée sur un SIG a permis de générer deux cartes d'aptitude des terres en résolution 30 m : l'une reposant sur des critères définis à partir de données télédétectées et validés par des experts, et l'autre intégrant des classifications morphologiques issues des connaissances des agriculteurs. Les résultats ont permis d'identifier trois catégories d'aptitude à Isandra : (i) 235 km² de parcelles à fort potentiel agronomique potentiellement négligées par les agriculteurs, (ii) 60 km² jugées aptes par les agriculteurs malgré un potentiel agronomique moindre, et (iii) 222 km² d'implantation optimale, où le potentiel agronomique et les perceptions des agriculteurs convergent.

Le modèle SIG participatif a ainsi identifié avec succès 48,5 % des surfaces potentiellement aptes sur le plan agronomique. Bien qu'une validation en conditions réelles soit nécessaire, cette étude met en évidence le potentiel des connaissances des agriculteurs en tant que substitut aux indicateurs télédétectés dans des environnements disposant de peu de données pédologiques issues de relevés sur le terrain. Les perceptions contradictoires des agriculteurs concernant les exigences de fertilité des variétés locales ont souligné l'importance de corroborer les connaissances locales avec des approches scientifiques.

La distance par rapport aux sources d'eau et aux centres de population s'est avérée être un bon indicateur de la localisation actuelle des agriculteurs. Dans l'ensemble, l'intégration de la télédétection, des connaissances participatives des agriculteurs et des contraintes logistiques dans l'évaluation de la rotation de TSARA fournit une contribution holistique, évolutive et applicable dans la pratique aux progrès des méthodologies LS.

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# 1. Introduction

Madagascar is a low-income nation with a population of thirty-two million. Approximately sixty-three percent of the population consists of subsistence farmers, and the island struggles with food security, ranking fourth on the Global Hunger Index (GHI, 2024; WFP, 2024). Madagascar's rainfed agriculture is challenged by climate change, straining the nation's ability to support its rapidly growing population (SDGP 2018 Project Proposal, 2018). Malagasy farmers are highly vulnerable to shocks in their farming systems, and existing risk-coping strategies are insufficient to ensure food security (Harvey et al., 2014).

The urgent need for land management strategies and agricultural innovations has been recognized by the government to address Madagascar's national challenges. The country's strategic plan (2019–2024) prioritizes both immediate food and nutrition security while strengthening agricultural resilience (WFP, 2023). In this context, the TSARA project (*Transformation des Systèmes Agricoles avec du Riz et de l'Artémisia*) aims to tackle these issues by promoting a rotational cropping system combining rice (*Oryza sativa*) and *Artemisia Annua*. This system is introduced to smallholder farmers in the Haute Matsiatra region through outgrower schemes, aiming at improving agricultural sustainability and economic opportunities.

Agricultural development projects, such as TSARA, require robust evaluation of available land to achieve spatially targeted interventions. Land Suitability (LS) assessment is a key method that enables decision-makers to assign optimal uses to specific land areas, and to increase land productivity through crop management (De Marinis et al., 2022). Fundamentally, this technique involves the standardization and overlay of spatial datasets to generate maps that quantify the suitability of a specific land use for a given land unit. LS analysis has been recognized as critical for achieving food security (Moloudi & Mahabadi, 2019; Kumar & Pant, 2022) and for enhancing both the quality and productivity of specific crops (Ozsahin et al., 2022). In Madagascar, the potential of LS methodologies has been explored across various disciplines and at different scales. Rajaonarivelo and Williams (2022) applied LS in forest restoration, Rogers et al. (2010) in biodiversity conservation and Rakotoarison et al. (2020) used multi-criteria evaluation and remote sensing for malaria risk mapping. These previous studies demonstrated the versatility of LS methodologies in addressing environmental and agricultural challenges in the Malagasy context.

A wide range of evaluation approaches can be used to assess land suitability (Moloudi & Mahabadi, 2019). In 1976 FAO introduced its "Framework for land evaluation"**,** which involves evaluating land characteristics and qualities which are most limiting to a certain land use (Mazahreh et al., 2018; Messing & Fagerström, 2001). Although its extensive popularity and application in numerous fields, conventional LS methods have faced criticism for their limited applicability, often being viewed as too static and focused primarily on risks and limitations (Nethononda et al., 2014; Vargas Rojas, 2004). Soil characteristics play a central role in rice LS assessment (DengiZ, 2013). As in other similar development contexts, labour-and cost intensive soil classifications are limited in Madagascar (Brinkmann et al., 2018). The country's soil map has not been updated since the 1960s and previously taken soil samples do not always meet the highest reliability criteria (Nishigaki et al., 2020). Recent efforts for modelling soil organic carbon (SOC) levels highlight the current lack of national soil inventories (Ramifehiarivo et al., 2016). It is thus particularly challenging to base an agricultural LS assessment on either soil type correlations or specific soil parameters in the Malagasy context.

Participatory LS assessments are proposed both to address the FAO framework's limitations and to compensate or complement gaps in conventional data sources with stakeholders' knowledge. This approach not only provides insights into existing management strategies but also contributes to the development of more realistic and locally adapted land use plans (Vargas Rojas, 2004). Mazahreh et al. (2018) have highlighted the potential of stakeholder participation in refining suitability criteria. Fritz-

Vietta et al. (2017) have already harnessed the capabilities of Malagasy farmers, presenting their ability to identifying regulating factors of land and natural resource usage. Participatory LS methods are thus well suited to leverage Malagasy farmers' knowledge in support for land use planning.

The application of Geographical Information Systems (GIS) in LS assessments has gained increasing prominence due to its ability to synthesize large datasets and provide reliable results, making it a preferred tool in regional agricultural studies (Mazahreh et al., 2018; Ozsahin et al., 2022). A multi-criteria evaluation (MCE) is used in the context of LS assessments to determine how the information from several crop experts on distinct land criteria can be combined to form a single metric of evaluation (Al-Hanbali et al., 2021; Ayehu & Besufekad, 2015). Amongst MCEs, the analytical hierarchy process (AHP), as developed by Saaty (1980), has a long-proven history of use in agricultural LS assessments (Kumar & Pant, 2022).

Previous LS studies by De Marinis et al. (2022) have incorporated cost-distance models to assess the accessibility of rural areas. When identifying suitable areas for the expansion of TSARA's outgrower propositions, logistical constraints must be considered to distinguish the practical feasibility of locations identified through both conventional and participatory LS assessments. Given these considerations, the integration of conventional remote sensing techniques, participatory knowledge and logistical constraints offers a promising approach for the LS assessment of TSARA.

## 1.1. Case study: TSARA project

The "*Transformation des systèmes agricoles avec du riz et de l'artimisia"* (TSARA) project, funded by the Netherlands Enterprise Agency (RVO), is active in the Isandra district (1,450 km$^2$) in the central highlands of Madagascar (Figure 1). This diverse landscape corresponds to the southern part of the Betsileo people's country, featuring mountainous terrain and valleys ranging between 800 and 1700 meters of elevation. The region is primarily characterized by ferralitic soils, which are cultivated in lowland areas (called "Basfond") and extensive terrace systems. The high-altitude tropical climate features two distinct seasons: a hot and rainy season from November to April, concentrating 90% of the annual precipitation (1200 mm/y), and a cool-dry season from May to October (INSTAT/Fia, 2017).

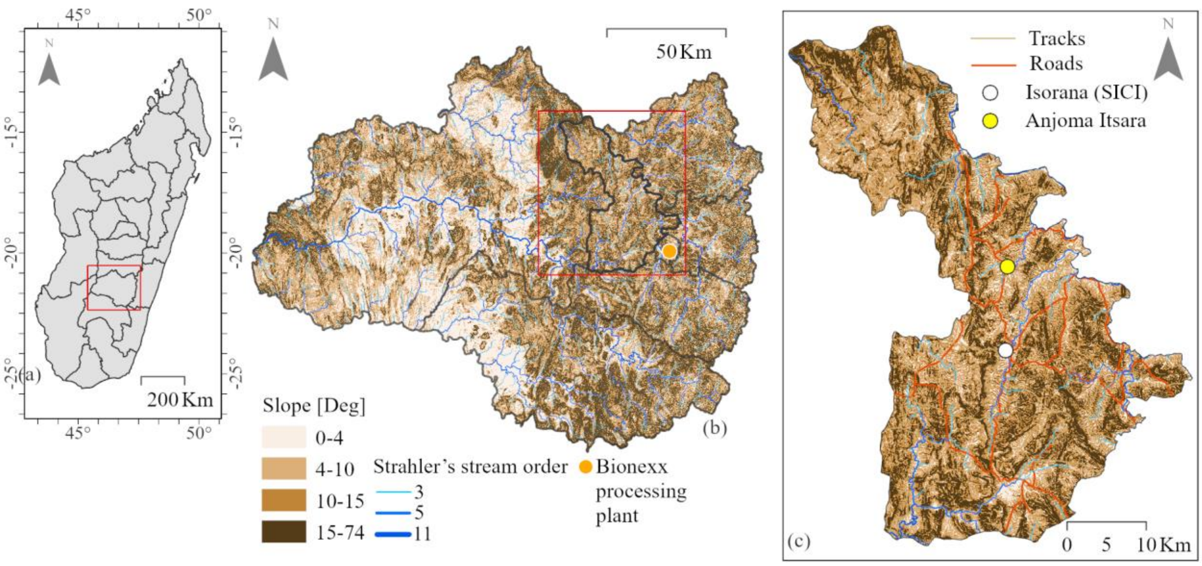


*Figure 1. The Isandra district (c) in the Haute Matsiatra region (b) of Madagascar (a). The sites of the TSARA project are highlighted: Bionexx processing plant in Fianarantsoa and SICI's processing plant in Isorana.*

The project unites a consortium of four parties: two private sector companies - Bionexx, based in Fianarantsoa, and SICI, located in Isorana - the Haute Matsiatra Regional Government, and the

Environmental Sciences Group of Wageningen University. Together, they are developing out-grower schemes proposals that focus on rice and *Artemisia A.* crop rotations. This initiative aims to provide employment and improve income prospects and access to markets for 2,880 smallholder outgrow farmers, with a particular emphasis on empowering women and youth (SDGP 2018 Project Proposal, 2018).

The outgrower scheme focus on high-value crops with strong market potential, leveraging the established farmer networks of SICI and Bionexx. The companies provide outgrowers with seeds and technical support and purchase their production at the end of the season. Rice (*Oryza Sativa*) is Madagascar's staple food, yet most paddy cultivation still rely on non-mechanized farming methods with minimal use of external inputs (Moore et al., 2024). In the Haute Matsiatra region, 90% of households practice subsistence rice farming, typically generating only small surpluses for sale during the rainy season, alongside counter-season cropping (SDGP 2018 Project Proposal, 2018). SICI operates a rice milling facility in the village of Isorana and collaborates with nearly 600 farmers in the Isandra district to develop premium rice varieties. *Artemisia Annua* is an annual herb from the *Asteraceae* family. It is cultivated for its leaves, which are dried to extract *Artemisinin*, the key compound for Artemisinin-based combination therapy (ACT) for malaria treatment (Wang et al., 2024). Bionexx has established a national network of 20,000 producers and processes Artemisia at a central facility in Fianarantsoa.

## 1.2 Problem Definition

Both SICI and Bionexx are actively seeking new farmers to expand their operations, as their current processing capacity allows for increased crop acquisition. Their transport logistics require outgrowers to be spatially clustered. The TSARA programme promises to engage 2880 smallholders, yet it lacks clear protocols for selecting suitable areas to initiate outgrower schemes, particularly for the combined production of Artemisia A. and rice. Currently, farmer selection does not consider key agro-environmental factors or local logistical constraints, resulting in strategic planning gaps in the consideration of areas where farmers could benefit from TSARA's propositions. The absence of well-informed suitability assessments increases the risk of suboptimal matching between crop rotation propositions and field characteristics, potentially compromising the success and long-term sustainability of the project.

Despite efforts by national research centres to categorize rice varieties based on regional adaptability (FOFIFA, 2010) and Bionexx's ongoing pursuits in seed amelioration, no LS assessments for either rice or Artemisia A. have been conducted in Madagascar. Therefore, there is no established framework to determine which agronomic criteria are available and best suited for a LS analysis of both crops. Furthermore, any effort of LS assessments in the Haute Matsiatra region must deal with the added challenges and constraints of limited available field-derived soil data.

Beyond these practical challenges, a broader academic research gap exists regarding the comparison and complementation of conventional LS studies with participatory approaches. While numerous studies focus on one method, few directly compare both within a single case study. The effectiveness of participatory LS methods remains therefore understudied. The integration of remote sensing, participatory knowledge and accessibility constraints in the LS assessment of TSARA offers a promising approach to overcome the abovementioned challenges, while considering farmers' needs and experiences to achieve a locally applicable spatial planning of TSARA's propositions.

## 1.3 Research framework

Specific choices have been made within the vast landscape of LS assessments frameworks. This section clarifies the key terminology used in this research:

- *Land suitability* refers to the degree to which a field's agro-environmental characteristics align with a specific crop's requirements, thereby enhancing its likelihood of successful cultivation. Farmers' behaviour affecting the feasibility of outgrower schemes falls outside the scope of this research.
- *Accessibility* refers to logistical constraints on cropping systems, distinguishing theoretical agronomic potential from practical feasibility. This study will consider distance from population centres and access to water in the dry season as accessibility criteria.
- *Expert LS assessment* is based on widely accepted scientific principles and established LS frameworks. It incorporates input from local agronomists, peer-reviewed research, and technical expertise from Bionexx and SICI to develop the crop rotation LS model in GIS.
- *Participatory LS assessment* emphasizes the process of smallholders' engagement. Their empirical knowledge and perceptions of land qualities are integrated with remotely sensed data to shape the crop rotation LS model in GIS.

TSARA is a broad development project with ambitious socio-economic and environmental goals. To define the research boundaries, a more structured version of the TSARA outgrower scheme is considered. The proposed cropping calendar, shown in *Table 1*, serves as a fixed temporal reference for this study. However, it is important to acknowledge that this standardized rotation does not fully capture the inherent flexibility of the rotation system, the variety in famers' individual choices throughout the year or delays in the rainy season's start. The rotation leverages the rainy season's start (November) for growing rice, while Artemisia A. is used as a hand-watered counter crop in the dry months. The rotation will consider a specific rice variety, currently promoted by SICI. Tsipala Fotsy (TSF) is a traditional Malagasy rice variety, with a 130-day cycle, featuring long translucent grains and prized for its taste and higher market value (FOFIFA, 2010). Artemisia A. (AA) is first grown in nurseries and then transplanted to fields in a 4-month cycle.

*Table 1. Simplified version of TSARA rotation crop calendar. TSF: Tsipala Fotsy (traditional rice variety), AA: Artemisia A.*

| *Jan* | *Feb* | *Mar* | *Apr* | *May* | *Jun* |
|---|---|---|---|---|---|
| TSF maturation | | TSF harvest | Field preparation and AA transplanting | AA with manual watering | |
| *Jul* | *Aug* | *Sep* | *Oct* | *Nov* | *Dec* |
| AA maturation | | AA harvest | Field preparation and TSF transplanting | TSF emergence | |

## 1.4 Research objectives & Relevance

This research aims to achieve two main objectives:

*I. Development of suitability maps*: Detailed land suitability maps for a rice and Artemisia A. rotation will be produced at the Isandra district scale. A methodological distinction will be made by utilizing both expert and participatory knowledge. Additionally, practical feasibility will be assessed by integrating farmer accessibility constraints. The goal is to provide TSARA with concrete insights into optimal locations for recruiting new outgrowers.

*II. Methodological evaluation*: The study will assess the qualities of both expert and participatory methodologies by contextualizing their findings within the Isandra district. The goal is to establish a case study approach to contribute to the broader academic discourse on the effectiveness of participatory LS assessments.

The relevance of TSARA is reinforced by its alignment with United Nations Sustainable Development Goals (SDGs). Its key deliverables, enhancing agricultural value chains and building resilience to climate change through improved practices, present promising solutions to some of the challenges faced by Malagasy smallholders. The proposed rotation is based on the country's staple crop (rice). Therefore, the project itself, and the methodologies proposed by this study, offer scalable insights to other agricultural development initiatives seeking to improve Malagasy farmers' incomes and market access through rice rotational cropping systems. Furthermore, the regional government has expressed interest in using lessons learned from Isandra to expand the project to other districts in Haute Matsiatra. While the results will be analysed on the extent of the Isandra district, where current TSARA activities are focused, the GIS-LS assessment will cover the whole Haute Matsiatra region to additionally serve as an experimental tool for prioritizing areas for future expansion.

The comparison between expert-based and participatory LS approaches will offer valuable information to TSARA on the perceived importance of land suitability criteria when considering rice and Artemisia Annua crop rotations. From an academic perspective, this study contributes to the ongoing discourse on LS assessment methodologies, offering a novel comparison between traditional expert-driven and participatory approaches while incorporating accessibility constraints in a specific case study. The case study approach allows for testing how participatory-based proxy criteria could overcome ground-data shortages in rural areas.

The rise in popularity for Artemisia A. cultivation drove research on how environmental factors influence Artemisin content in Madagascar (Suberu et al., 2015). However, no studies have examined the spatial distribution of Artemisia A. in the country. While previous research has assessed the environmental suitability of Artemisia at various scales (Ding et al., 2020; Huang et al., 2010; Jiang et al., 2021; Wang et al., 2024), to the best of the researcher's knowledge, this study is the first to apply LS analysis to Artemisia Annua in Madagascar. Additionally, this research provides an original contribution by incorporating participatory knowledge from Malagasy smallholders into LS assessments.

## 1.5 Research Questions

Following up on the problem definition, the following two main research questions are formulated:

I. *Which areas of the Isandra district, Madagascar, are most suitable for a crop rotation system involving rice and Artemisia annua?*
II. *How does an expert-based approach compare to a participatory-based approach in the development of land suitability maps for TSARA?*

To answer the main research questions, and to guide the research operationalization, specific sub-questions will be answered:

I. What are the most relevant suitability criteria for a rice and Artemisia annua crop rotation in the Haute Matsiatra region, according to experts? And what is their relative importance?
II. Which criteria do local farmers consider when determining land suitability to rice and Artemisia A crop rotation? And what is their relative importance?
III. Which accessibility criteria determine the rotation's practical implementation, and how well do they reflect current farmers' location?
IV. Which municipalities within Isandra are most suited for the rotation?
V. What are the implications of using the expert-based over the participatory-based approach?

# 2. Research methodology

The roadmap in *Figure 2* outlines the stepwise methodology used in this study. A mixed method approach was applied to the Isandra district case study in Madagascar. Two distinct GIS models, expert-based and participatory-based, represent land characteristics which determine the suitability of TSARA's rotation. They are distinguished by the knowledge source these processes are based upon. Both models aim to identify key suitability criteria (chapters *2.1* and *2.2*), assess their relative importance (chapter *2.3*), and locate optimal areas for new TSARA outgrowers (chapters *2.4* and *2.5*). All spatial analysis has been performed on ESRI's ArcGIS Pro 3.1.0.

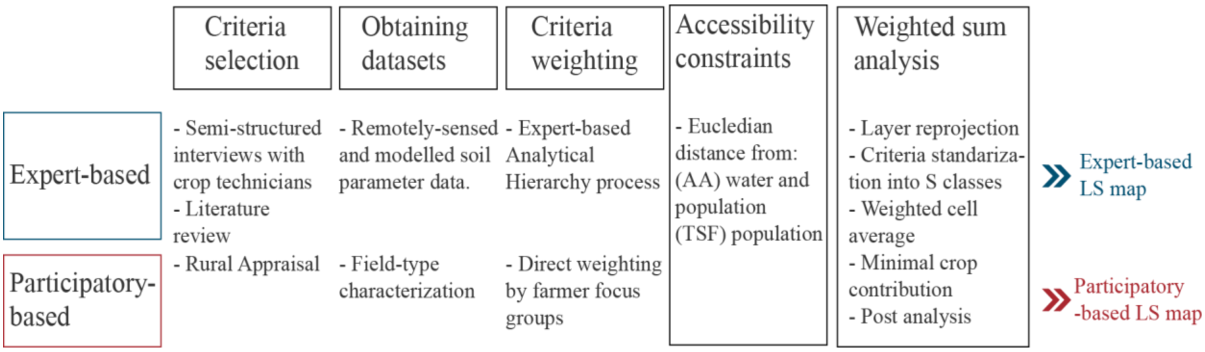


*Figure 2. Methodological roadmap*

## 2.1 Criteria selection

The experts' method criteria were selected through a series of exploratory interviews (n=6) with the field technicians of Bionexx and SICI. The main goal was to understand if criteria used by previous literature on rice and Artemisia A. LS analysis could be translated to the specific environmental and socio-economic conditions of the case study. Consulted studies for the literature review (twelve papers for AA and seven for rice) are listed in *Appendix A.*

A total of six criteria have been selected. Field technicians identified soil fertility as a crucial factor for crop growth. The scarcity of national-level soil data has already been highlighted. *Soil organic carbon (1)* was selected as a proxy to represent broader soil quality indicators for crop success. While this choice helped maintain a manageable number of criteria, it does not fully capture the complexity of soil fertility dynamics. *Soil pH (2)* and *soil depth to bedrock (3)* are selected as criteria to represent soil-crop interactions. *Altitude (4)* and *slope (5)* are considered to locate field qualities on the landscape scale. *Topographic wetness index (6a)* considers the capability of rice fields to accumulate water (TSF specific criteria), while *aspect (6b)* is influential for sun and wind exposure of Artemisia A. leaves (AA specific criteria).

### 2.1.1. Rural Appraisal

Criteria for the participatory method must satisfy the conditions of being mappable, understandable by, and representative, of local farmer opinions. Rural Appraisal (RA)**,** a participatory qualitative survey methodology, encompasses various approaches for assessing rural needs and resources by leveraging local analytical knowledge (Chambers, 1994). In this research, RA was used to rapidly understand how farmers perceive field qualities that influence rice and Artemisia A. cultivation. The first step of the RA method involved ensuring that the translator had a strong understanding of the project. Once she comprehended the research's scope, an interviewing process was co-developed to ensure effective communication with Malagasy farmers. Interviews always started with a clear presentation of the attendees and their roles. Interviews were recorded and written notes were taken. All field visits were grouped between November 14th and December 20th, 2024. At the end of each week, the translator reviewed the newly collected data to clarify any misunderstandings or ambiguities, particularly those related to local terminology. Farmers were selected by the translator around *Isorana* and *Anjoma Itsara*. Those villages, located in the Isandra district (visible in *Figure 1*), have been chosen due to the already existing presence of SICI and Bionexx. Interviewed farmers either cultivated one of the two crops, or both. Farmers that collaborated with either SICI or Bionexx in the past, but not currently, were also eligible.

A mix of semi-structured interviews (n=6), one focus group session (farmer n=7), and field walks (n=3) were conducted. The questions iteratively evolved as the understanding of local conditions and perceptions increased. The first interviews were dedicated to exploring farmers' views on their fields while the two additional focus group sessions, aimed at weighting criteria (n=9), were also used to triangulate farmer-mentioned criteria and to confirm the emerged narratives (frequent topics and statements).

The inducted criteria and their definition, as mentioned by farmers, are listed below:

1. *Slope*. The quality of a field to be naturally flat or to require little slope management (levelling).
2. *Soil fertility*. Fertile soils are perceived as dark, structured, and well-aerated. Fertility can be visually checked by a farmer and is proven when a crop grows vigorously.
3. *Field type*. Farmers expressed a strong belief in the correlation between crop suitability and specific field types. The location of a field in the highland landscape determined its perceived soil qualities. Those qualities are an indicator of crop suitability. According to local denomination, the following field types are distinguished (*Figure 3)*:
    a. *Basfond*: low-lying fields, extensively farmed, high water accumulation capabilities in the wet season (low drainage) and naturally high soil fertility.
    b. *Terracine*: traditional narrow terrace systems of the Betsileo people, extensive terracing until intermediate slopes (estimate 15 degrees), high drainage and low soil fertility.
    c. *Lohasaha*: gently sloping valleys with ample terraces, surrounded on the sides by steeper gradients, they differentiate from low-lying fields as they are located higher up in the landscape, high drainage, and lower soil fertility.
    d. *Tanety*: high-lying field on slopes, considered as marginal land and only suitable for rainfed cultivation, traditionally used for low-yielding rice varieties, high drainage and low soil fertility. They are not considered for either TSF or AA.

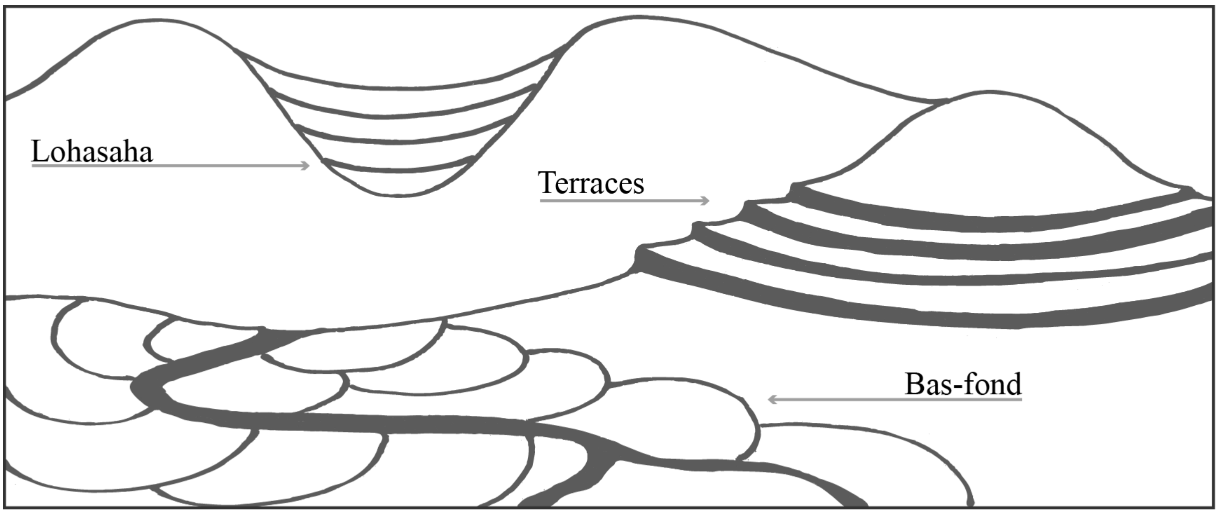


*Figure 3. Farmer identified field types: Lohasaha, Terraces and Bas-fond.*

## 2.2 Obtaining datasets

The effectiveness of GIS LS mapping depends heavily on accessing accurate and comprehensive data that faithfully mirrors real-world conditions across different layers (Mazahreh et al., 2018). The quality and availability of data directly influence the outcomes of analyses, underscoring the importance of consistent and thorough reviews of GIS datasets (Al-Hanbali et al., 2021).

Field-derived soil data is scarce in the Malagasy context. The last attempt to classify the island's soils dates to the efforts of Delenne and Pelletier (1980) and has not been improved since. Alternative data sources have been explored: this research builds upon ISRIC soil datasets, modelled with machine learning using global compilation of soil ground observations (Hengl et al., 2017), and open-access remote sensing elevation data (Copernicus).

### 2.2.1 Datasets for expert-based analysis

Datasets for the expert-based analysis are summarized in *Table 2.*

*Table 2. Datasets characteristics and source for the expert-based analysis.*

| Criteria | TSF | AA | Datasets characteristics | Source |
|---|---|---|---|---|
| Soil organic carbon | *v* | v | Soil organic carbon content [g/kg], weighted average till root depth (30cm), 250m resolution. Chosen as a proxy indicator for soil fertility. | ISRIC SoilGrids 2017 |
| Soil pH | v | v | Soil pH x 10 [KCl], weighted average till root depth (30cm), 250m resolution. | ISRIC SoilGrids 2017 |
| Soil depth to bedrock | v | v | Absolute depth to bedrock [cm], 250m resolution. | ISRIC SoilGrids 2017 |
| Altitude | v | v | Global DEM [m], 30m resolution. Proxy for climatic variability in the landscape. | Copernicus DEM 2019 |
| Slope | v | v | Slope function [Deg], based on DEM (30m). | Computed |
| Topographic Wetness Index | v | | Based on DEM (30m). Proxy indicator for the capability of a rice field to accumulate water from neighbouring cells. | Computed |
| Aspect | | v | Based on DEM (30m). Proxy indicator for solar radiation intensity and damaging effect of dominant eastern winds on AA aerial parts. | Computed |

### 2.2.2 Datasets for participatory-based analysis: field-type characterization

The identification of landscape features is required to leverage the farmer-mentioned correlation between crop suitability and specific field type. To the best of available knowledge, no previous studies have been conducted on field type identification in the Haute Matsiatra region. A landform classification analysis was performed using topographic attributes, as numerous physical and biological processes shaping landscapes are closely correlated with topographic position. The Topographic Position Index (TPI) is defined as the difference between the elevation of a given cell and the mean elevation within a predetermined neighbourhood (De Reu et al., 2012). It gives a measure of the relative position of a cell in the surrounding landscape, influenced by the scale of the analysis. Combining different neighbourhoods' radiuses allows for the identification of nested landform features (*Figure 4*).

*Basfond & Lohasaha.* All field types, as recognized by farmers, are characterized as flat. A threshold value for flat fields was established at 4 degrees to account for the high propension of Betsileo farmers to level unsuitable slopes, therefore greatly increasing agricultural land availability. A classification approach combining nested TPI values (broader landscape features with a radius of 1Km and finer-scale analysis with a 90 m radius to reflect average plot sizes) and slope analysis was used to distinguish low valley bottoms from higher grounds.

*Terraces*. Terraces do not conform to the previous classification method, as their narrow width often falls below the 30-meter resolution of the DEM. Given the widespread terrace use in Betsileo agricultural traditions, a distinct methodology is developed to identify this key landscape feature. Terraces construction's feasibility is constrained by a maximum slope threshold, which is not absolute and depends on soil stability, structural integrity of retaining walls and hydrological management. Considering empirical evidence and traditional terrace engineering, an upper slope value of 15 degrees is considered. The lower threshold aligns with the previous classification of flat fields at 4 degrees. Potential terrace areas are defined as zones falling within the appropriate slope range (4–15°) and possessing sufficient water availability to sustain irrigated agriculture. The criteria underlying water availability assumptions are further elaborated in section 2.4.

The remaining participatory datasets (slope and soil fertility) are common to the expert methodology. As farmers defined soil fertility though dark colour and soil aggregation, SOC is taken as a proxy indicator.

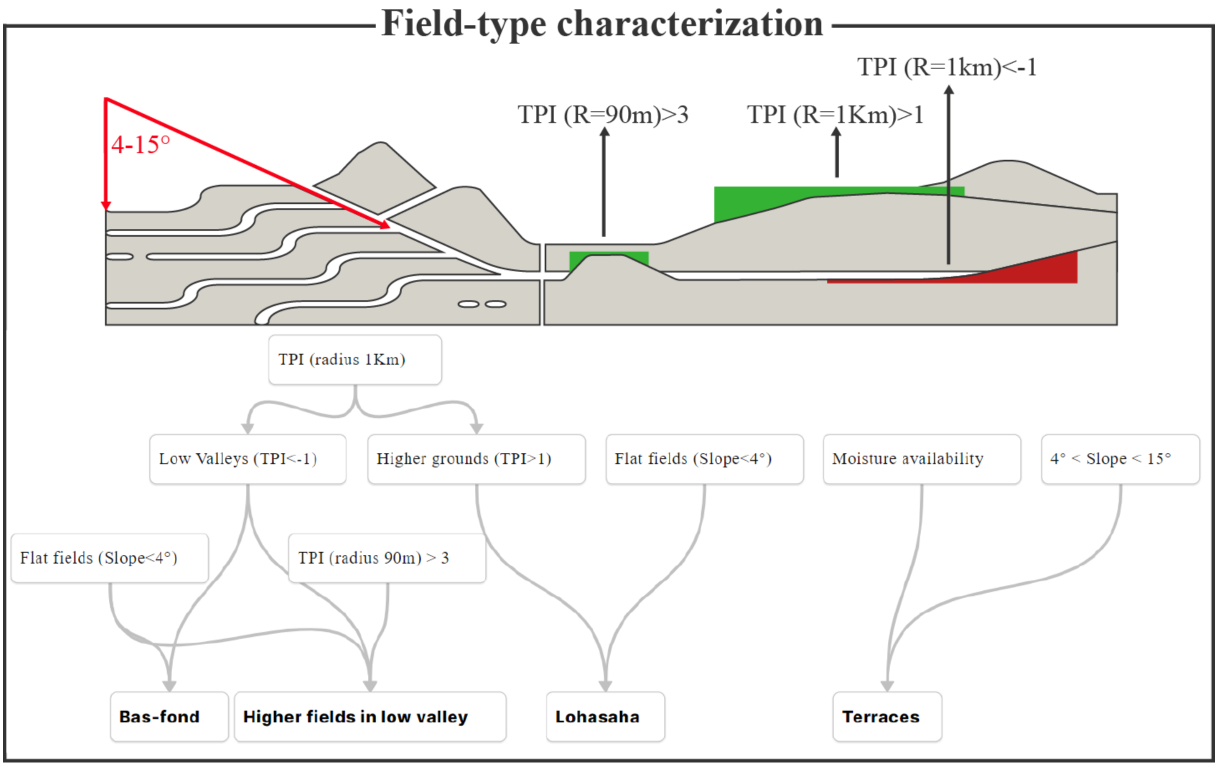


*Figure 4. Schematic illustration and flowchart synthesizing the logic behind the landform characterization. Nested TPI values have been used to define higher grounds, lower valleys, and higher fields in low valleys. Agricultural fields are flat (Slope<4°), while plausible terraces span slope ranges up to 15°, where moisture is available.*

## 2.3 Criteria weighting

Multi-criteria analysis techniques are widely used decision-support tools which support complex decision making. Given the fundamental differences in knowledge sources between the expert-based and participatory approaches, two distinct criteria-weighting techniques were applied.

### 2.3.1 Expert-based Analytical Hierarchy Process (AHP)

To assign the relative importance of LS criteria, the *Analytical Hierarchy Process* (AHP) was applied. This method leverages the human intrinsic ability to compare the intensity of importance between different criteria (Forman & Peniwati, 1998). Criteria were evaluated by experts through a pairwise comparison matrix using Saaty's rating scale (*Table 3).*

*Table 3. Saaty's continuous rating scale for pairwise comparison of criteria. The ratings are exemplified as follows: "Criteria A has a 'moderate' importance over Criteria B." Intermediate values (2,4,6,8) are also eligible.*

| *Equal* | *Moderate* | *Strong* | *Very strong* | *Absolute* |
|---|---|---|---|---|
| 1 | 3 | 5 | 7 | 9 |

The research boundaries require a strong focus on the local applications of both crops within the Isandra district case study. It is therefore inherently challenging to perform AHP with a large number of candidates. It is generally assumed that the significance of expert competence increases as the group size decreases. In a weekly structured domain, examination can often only be conducted in small groups (Tsyganok et al., 2012). Therefore, a small number of technicians (n=3) delivering extension services for each of the two crops were selected.

Additional measures were implemented to increase the validity of the AHP procedure, thereby reducing the number of experts needed. They build upon a bias in human psychology: the tendency to overestimate values of smaller measures. Following Andriichuk et al. (2020), AHP reliability was improved by proposing a specific order for the pairwise comparisons. The final sequence is built upon an initial, non-strict structuring of importance. The methods' details are elucidated in *Appendix B.*

*Aggregation of individual judgments.*

Numerous techniques exist for the aggregation of the expert's individual judgements (Ossadnik et al., 2015), with differences among methods largely dependent on the characteristics of the expert group. Both AHP workshops (comprising SICI and Bionexx's technicians) involved a synergistic unit of experts that satisfy the following conditions: (1) experts had equivalent roles and shared the same objectives, and (2) they were willing to collaborate as a cohesive group.

Given that these conditions for a homogeneous group were met, the aggregation of individual judgments (AIJ), using geometric mean, method was applied. This approach enables the achievement of high group judgement consistency (Ossadnik et al., 2015). Initially, experts answered to each criteria comparison on an individual matrix, then the geometric mean for each entry is taken to create a joint matrix. The individual entries allow to spot inconsistencies, which are investigated by further questioning.

The relative weight of each criterion and the consistency ratio (CR)'s value was calculated following the directives of Saaty's method. The results are shown in *Figure 5.* Both AA's consistency ratio (CR=0.05) and TSF (CR=0.03) are below the reference CR of 0.10, indicating high consistency levels.

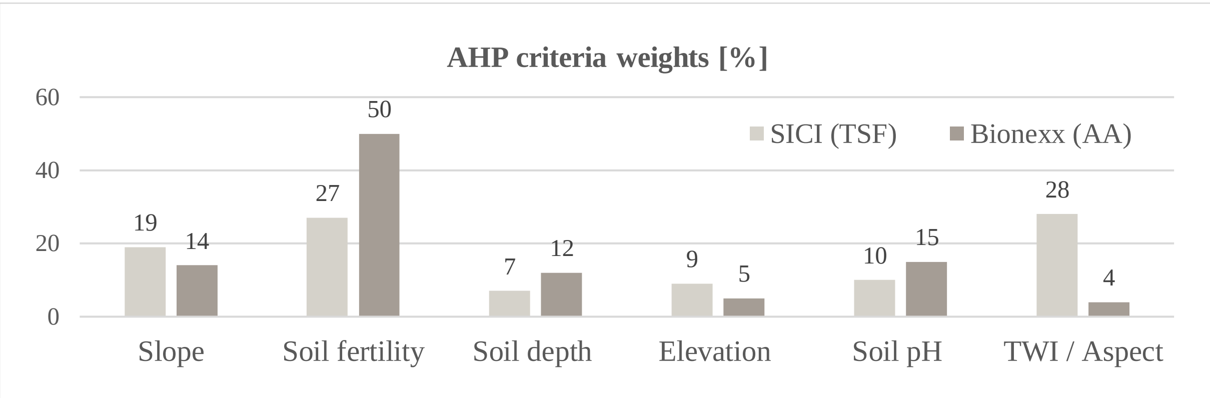


*Figure 5 Artemisia A. and Tsipala Fotsy criteria weights, as determined by Bionexx and SICI's technicians through AHP.*

### 2.3.2 Direct weighting by farmer focus groups

A replicable and easily understandable method was designed to weigh the participatory LS criteria. Two villages, *Isorana* and *Anjoma Itsara*, were selected based on the availability of farmers already engaged in both TSF and AA outgrower schemes. Two focus group sessions reunited a total of ten farmers (five per village). Small groups were intentionally preferred over large ones to minimize anchoring bias and bandwagon effect, ensuring that individual farmers could freely express their perspectives on the previously selected criteria. All participants confirmed that the criteria were representative and validated the previous statements on fertility requirements and field type characteristics that underly construction of the participatory model. The validated statements are listed in *Appendix C*. The three criteria (slope, soil fertility and field type) were visually represented through drawings and thoughtfully explained by the translator. Farmers were asked to distribute 10 pebbles among the three criteria (choosing among high and low fields) according to their perceived relative importance. An average of the gathered responses is shown in *Table 4.*

*Table 4. Participatory criteria weights [%] for AA and TS.*

| **Tsipala Fotsy** | **Average** | **Isorana** | **Anjoma I.** |
|---|---|---|---|
| Slope | 17 | 18 | 16 |
| Soil Fertility | 32 | 38 | 26 |
| Field type | 51 | 44 | 58 |
| **Artemisia A.** | **Average** | **Isorana** | **Anjoma I.** |
| Slope | 13 | 16 | 10 |
| Soil fertility | 46 | 40 | 52 |
| Field type | 41 | 44 | 38 |

## 2.4 Accessibility analysis

The previously analysed criteria primarily include environmental and pedometric factors, which focus on soil formation and its suitability for agriculture. In this research, accessibility is defined by two additional conditions essential for the success of a crop.

First, suitable fields must be within practical reach for farmers to cultivate. During the Rural Appraisal phase, farmers were asked to indicate the distance they typically travel to reach their fields. Hypothetical maximum walking distances were also discussed, while factual distances were measured and recorded during field walks. The findings converge on an approximate upper limit of 4 kilometres, or a one-hour walk carrying tools. The Euclidean distance tool (ArcGIS) was applied to a pre-census World Bank dataset (2018) of house locations in the Haute Matsiatra region (*Figure 6a*).

The same questions and considerations were repeated to understand the maximum conceivable distance from a water source in dry season. This measure is essential to sustain manual watering of AA during the first two months from transplanting. Considering the heavy weight of water buckets, and the repeated trips needed to water an entire plot daily, a maximum Euclidean distance of 500 meters was defined. During the Rural Appraisal, farmers indicated two common water sources, visible in *Figure 6b*:

1. *Perennial rivers*. Strahler's stream order system was applied to identify flow accumulation patterns and classify streams based on their hierarchy. The smallest stream order that still supported most settlements in its immediate vicinity was selected as the threshold for defining perennial rivers. Those rivers are assumed to be perennial or at least provide access to stagnant water for irrigation.
2. *Spring wells*. The highlands are scattered with wells that remain functional in the dry season. Due to the impossibility of directly identifying wells, Normalized Difference Vegetation Index (NDVI) is used as a proxy indicator under the following reasoning: cells with higher dry season NDVI are indicative of fields with enough moisture to support vegetation and thus are more likely to be located near a well or on its stream course. A global, open-source Copernicus NDVI dataset (Copernicus, n.d.) with a 300m resolution was utilized, capturing two key moments in the agricultural cycle: the start of the dry season's AA cycle (April), and during the mature stage of the crop in June. To reduce computational requirements, and due to the high annual variability of local rain patterns under climate change, only data for 2024 was considered. The dataset was processed by merging and averaging

NDVI values after cloud masking. The resulting dataset was classified to find cells that are indicative for healthy crop vegetation. Values falling within the $60^{th}$ and $80^{th}$ percentile (calibrated for the Isandra district) were considered, as lower NDVI values indicate arid soils, and higher values correspond to dense forests.

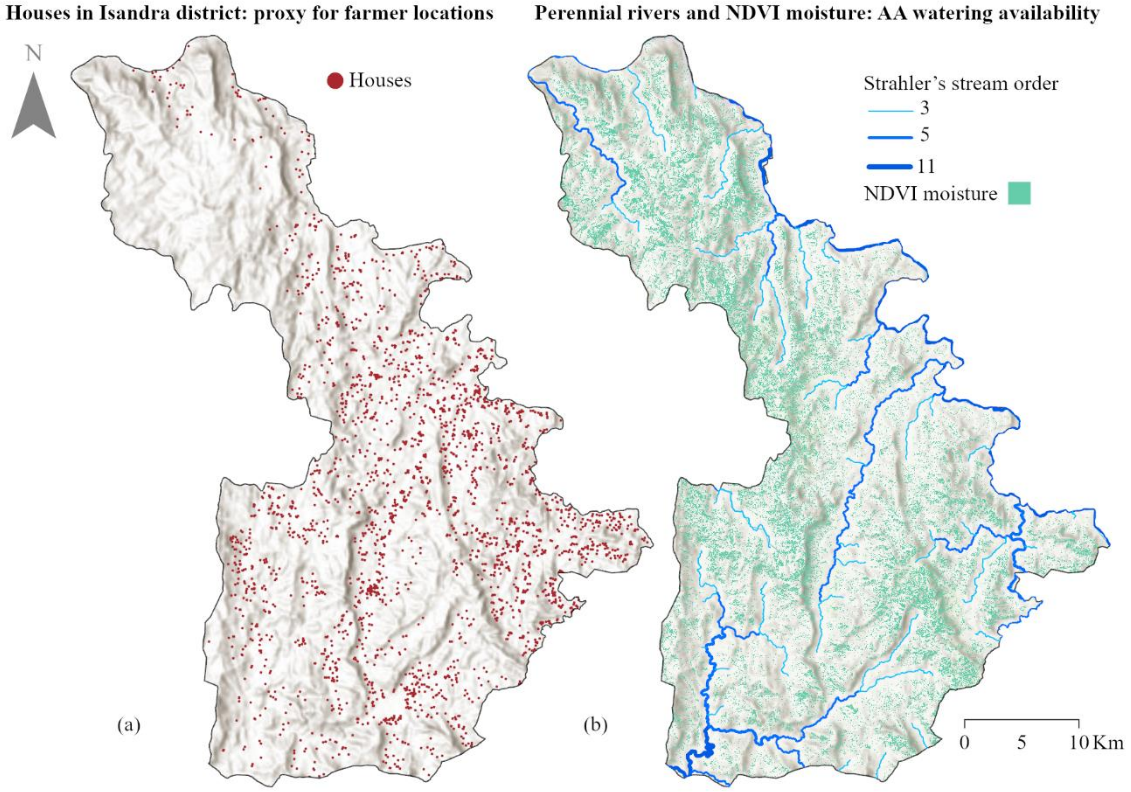


*Figure 6 The two crop-specific accessibility constraints: AA must comply with both distance from farmer locations (a) and distance from water sources (b). TSF's accessibility constraints are limited to proximity to farmer locations (settlements).*

## 2.5 Weighted sum analysis

Weighted sum analysis is conducted to combine all data sources into the TSARA rotation LS maps. All criteria rasters are first projected to a common geographic coordinate system (WGS 1984), then resampled to a uniform resolution of 30m and snapped to the base DEM layer to ensure cell alignment. Individual LS models are constructed using the Suitability Modeler tool in ArcGIS.

### 2.5.1 Criteria Normalization

Criteria layers are standardized into four continuous suitability (S) classes (0<S<100), adapted from the FAO framework for land evaluation: "Not suitable" (S=25), "Marginally suitable" (S=50), "Moderately suitable" (S=75) and "Highly suitable" (S=100). Criteria suitability thresholds were established based on a combination of previous literature, field observations and insights gathered from the Rural Appraisal and expert consultation phases.

Accessibility rasters are also standardized to ensure consistency of units. The accessibility suitability raster for AA (*Table 5*) assigns double the importance on distance from available water in comparison with distance to population to account for the high propension of farmers to cover distances to reach suitable fields.

*Table 5. Criteria normalization for the accessibility suitability raster (Artemisia A.)*

| **Criteria** | **Weight [%]** | **Normalized classes** | **Explanation** |
|---|---|---|---|
| Distance from available water [m] | 66.5 | 0-124: S=100<br>124-249: S=75<br>249-374: S=50<br>374-500: S=25 | Distance from rivers and high-moisture spots. Four equal distance classes. |
| Distance to population [m] | 33.5 | 0-1000: S=100<br>1000-4000: S=75 | Full suitability score in a 1km range, high suitability for all distances to 4km because of high farmer availability to walk to fields. |

TSF fields accumulate water in the rainy season through precipitation, canals, and overflow from neighbouring fields. These water management modalities all depend on rainfall, which is assumed to be uniform on the extend of the Isandra district. Water availability is therefore not considered in the TSF accessibility analysis (*Table 6*).

*Table 6. Criteria normalization for the accessibility suitability raster (*Tsipala Fotsy*)*

| **Criteria** | **Weight [%]** | **Normalized classes** | **Explanation** |
|---|---|---|---|
| Distance to population [m] | 100 | 0-1000: S=100<br>1000-4000: S=75 | Full suitability score in a 1km range, high suitability for all distances to 4km because of high farmer availability to walk to fields. |

Table 7 shows the criteria normalization procedure for the agronomic suitability rasters. Classes were either manually defined or created by fitting the dataset with one of the Suitability Modeler tool's functions. Criteria weights deriving from the participatory consultation and AHP procedures are applied to compute the weighted average for each cell.

*Table 7. Criteria normalization for the agronomic suitability rasters. Both participatory and expert models are considered for Artemisia A. and Tsipala Fotsy.*

| **Suitability model** | **Criteria** | **Weight [%]** | **Normalized classes** | **Explanation** |
|---|---|---|---|---|
| Participatory Tsipala Fotsy | Slope [Deg] | 17 | 0-4: S=100<br>4-7: S= 75<br>7-15: S=50<br>>15: S= 25 | Slope intervals, adjusted to Isandra case study. |
| | SOC [g/kg] | 32 | Arc GIS function: Logistic decay. Lower threshold (20th percentile = 8.16) | High and sustained farmer preference for low SOC values (lower threshold accounts for unfertile soils that do not support agriculture), quickly decays with high SOC values. |

| | | | | |
|---|---|---|---|---|
| | Field type [Lohasaha and terraces] | 51 | Lohasaha and terraces: S=100<br>100m buffer: S=75<br>Else: S=25 | Full suitability for identified fields, 100 m buffer to account for modelling imprecisions. |
| Participatory Artemisia A. | Slope [Deg] | 17 | 0-4: S=100<br>4-7: S= 75<br>7-15: S=50<br>>15: S= 25 | Slope intervals, adjusted to Isandra case study. |
| | SOC [g/kg] | 32 | ArcGIS function: Logarithmic curve | Rapid increase of suitability with increasing SOC. Suitability flattens at higher SOC values because of saturation and microbial competition. |
| | Field type [Basfond] | 51 | Basfond: S=100<br>100m buffer: S=75<br>Else: S=25 | Full suitability for identified fields, 100 m buffer to account for modelling imprecisions. |
| Expert Tsipala Fotsy | Elevation [m] | 9 | ArcGIS function: symmetric linear | S=100 at 1250m of altitude. The functions scores high in the 1000-1500m optimal elevation interval and linearly lower approaching the extremities. Source: datasheet FAO |
| | Slope [Deg] | 19 | 0-4: S=100<br>4-7: S= 75<br>7-15: S=50<br>>15: S= 25 | Slope intervals, adjusted to Isandra case study. |
| | SOC [g/Kg] | 27 | ArcGIS function: Logarithmic curve | Rapid increase of suitability with increasing SOC. Suitability flattens at higher SOC values because of saturation and microbial competition. |
| | Soil pH | 10 | <4.5: S=25<br>4.5-5.0: S=50<br>5.0-5.5: S=75<br>5.5-6.0: S=100<br>>6.0: S=75 | Source: datasheet FAO Adjusted to Isandra local conditions. |
| | Soil depth [m] | 7 | ArcGIS function: symmetric linear | Preference to intermediate soil depths. Deep soils are not suited for TSF and not realistic in the Isandra district (dataset incongruencies), very shallow soils inhibit root growth. |
| | TWI | 28 | ArcGIS function: MS large | Good water accumulation capacity has high preference. |

| | | | | |
|---|---|---|---|---|
| Expert Artemisia A. | Elevation [m] | 5 | ArcGIS function: symmetric linear | S=100 at 1250m of altitude. The functions scores high in the 1000-1500m optimal elevation interval and linearly lower approaching the extremities. Source: datasheet FAO |
| | Slope [Deg] | 14 | 0-4: S=100<br>4-7: S= 75<br>7-15: S=50<br>>15: S= 25 | Slope intervals, adjusted to Isandra case study. |
| | SOC [g/Kg] | 50 | ArcGIS function: Logarithmic curve | Rapid increase of suitability with increasing SOC. Suitability flattens at higher SOC values because of saturation and microbial competition. |
| | Soil pH | 15 | <4.5: S=25<br>4.5-5.0: S=50<br>5.0-5.5: S=75<br>5.5-6.0: S=100<br>>6.0: S=75 | Source: datasheet FAO Adjusted to Isandra local conditions. |
| | Soil depth [m] | 12 | ArcGIS function: logistic growth | Rapid suitability increases with deepening soils, the added effect of deeper soils flattens. |
| | Aspect | 4 | North-West: S= 100<br>North: S= 75<br>West: S= 75<br>Else: S= 0.50 | Accounts for damaging effect of dominant easter winds and for the desired intense solar radiation on North-facing slopes. |

### 2.5.2 Sub model integration

*Figure* 7 provides a schematic representation of the integration process, illustrating how individual LS models were combined to produce the final expert and participatory LS maps for TSARA's rotation.

TSF and AA were assigned equal weight within the rotation, while agronomic suitability was given twice the weighting of accessibility criteria. This approach highlights the agronomic focus of the LS assessment and mitigates potential inflation of suitability scores due to accessibility factors.

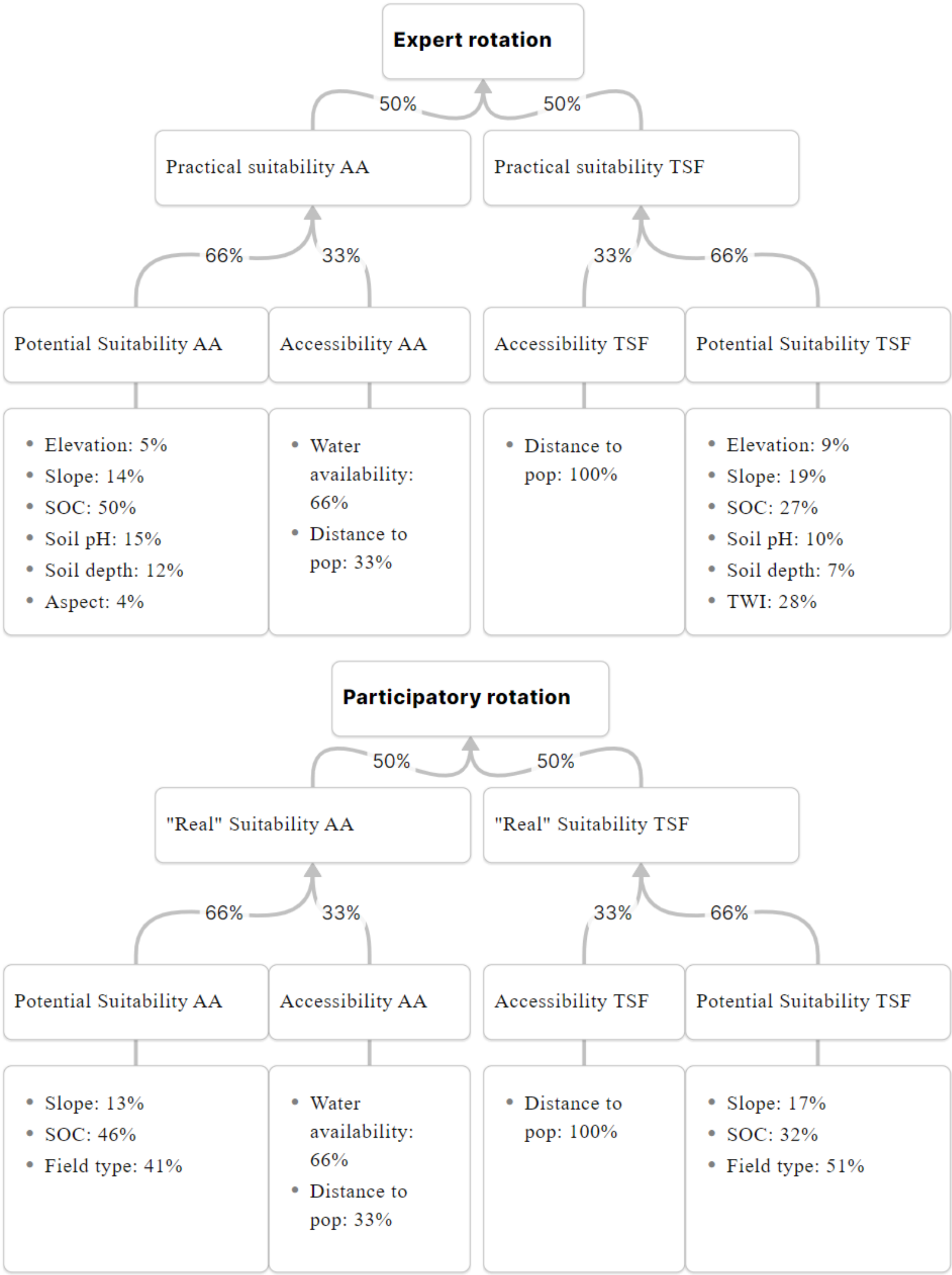


*Figure 7. Integration of individual LS models into expert and participatory LS assessment of TSARA's crop rotation*

### 2.5.3 Post-analysis

Equal crop suitability contribution to the rotation is ensured by masking cells that do not meet minimum suitability requirements (S=40) for either TSF or AA. The goal is to avoid overcompensation of accessibility scores, and to ensure that selected cells guarantee a minimum suitability for every component of the rotation. The chosen accessibility criteria are then evaluated through a comparison with existing AA outgrowers. Furthermore, the LS maps are overlayed with a land use map to investigate correlation with existing agricultural fields and, finally, suitable cells are categorized by municipality.

# 3. Results

## 3.1 Land suitability maps

The results of both the participatory and expert-based methods are presented as two land suitability rasters, each with a 30-meter resolution, covering the Haute Matsiatra region. These rasters indicate suitability scores on a continuous scale from 0 to 100, representing the feasibility of implementing the TSARA rotation under given accessibility conditions. *Figure 8* provides a detailed comparison of both suitability maps at the Isandra scale. A clear pattern emerges, with most continuous high-suitability areas concentrated along perennial rivers. Moist areas on high grounds, as identified by the NDVI analysis, are a minority and rarely group into contiguous land units.

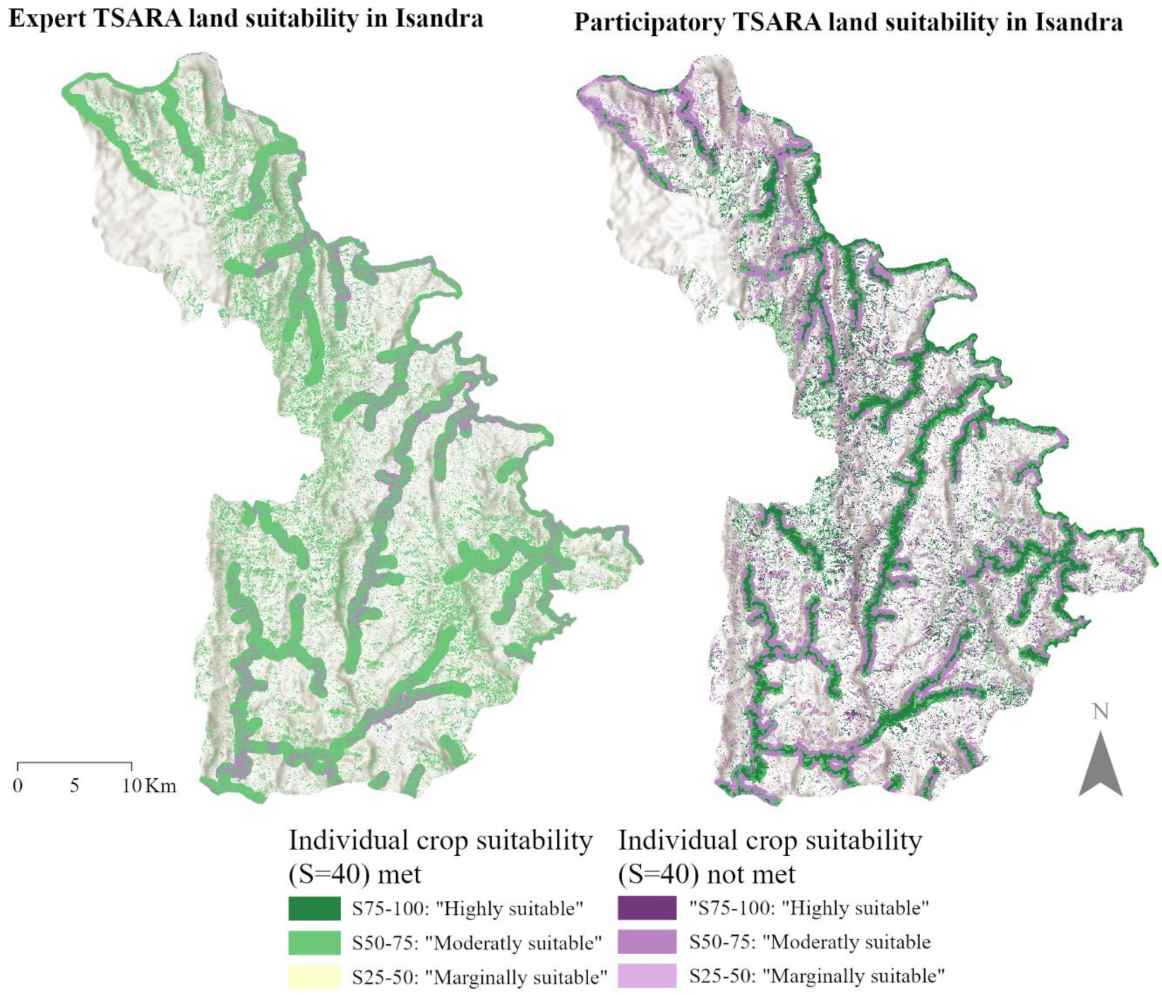


*Figure 8. Participatory and expert land suitability maps for TSARA's rotation in the Isandra district. In purple, suitable cells that do not meet the individual crop minimum suitability standard (S-40).*

Both expert and participatory-based suitability rasters have been converted into datasets containing each cell's suitability score. The total extent of suitable land is summarized in *Table 8.* At both regional and district scales, the expert model identified a larger extent of suitable land. The difference is particularly pronounced in the Isandra district, where the expert model estimated up to 62% more suitable land. At the Haute Matsiatra scale, both methods yield similar estimates of suitable land.

*Table 8. Extent of suitable areas.*

| | Area (km$^2$) | | % of total surface | |
|---|---|---|---|---|
| *Scale* | *Exp* | *Part* | *Exp* | *Part* |
| Isandra district | 457 | 282 | 33.5 | 20.7 |
| Haute Matsiatra | 4541 | 3914 | 21.5 | 18.5 |

The histograms in *Figure 9* provide a visual representation of the distribution of suitability values. 99.7% (456 km2) of expert suitable land and 31% (89 km2) of participatory suitable land are classified as “moderately suitable”, 69% (193 km$^2$) of participatory suitable land lies in the “highly suitable” category. The overall viability of TSARA’s rotation is high, the higher suitable cell count of the expert method and the higher overall S score of the participatory method are discussed in *Section 4.2*.

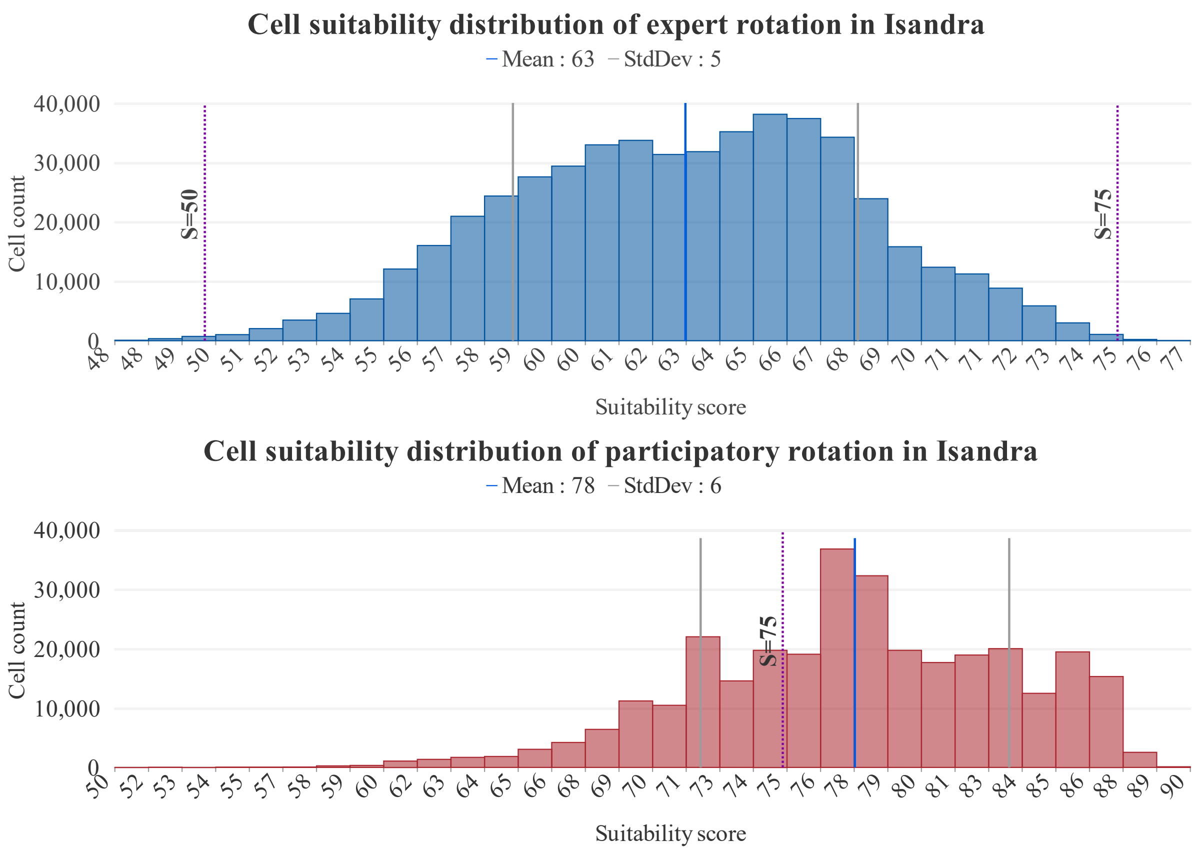


*Figure 9. Cell count of suitable land according to the expert and participatory methodology.*

## 3.2 Validation of accessibility conditions.

Bionexx maintains a geolocated dataset of farmers participating in AA outgrower schemes, enabling the evaluation of the accessibility model's accuracy. Known farmer locations were compared against the combined agronomic and accessibility-based AA suitability rasters. This study assumes that AA is primarily cultivated during the dry season, as outlined in the simplified framework (*Section 1.3*). While the dataset may include farmers following alternative cropping cycles, the validation remains relevant, given that the majority of Bionexx outgrowers cultivate AA in the dry season. Results indicate that AA's suitability and accessibility conditions (proximity to population centres and water sources) successfully identified 676 out of 1,060 AA farmers in the Isandra district (~60%). Considering only AA accessibility constraints identifies 64% of farmers (*Figure 10*). However, a certain degree of imprecision exists in both the LS maps (due to resampling and projection steps) and the farmer dataset (as field coordinates are recorded inconsistently, field sizes vary, and mobile GIS locators used by Bionexx technicians introduce spatial inaccuracies). To account for these sources of error, a 30m buffer (equivalent to one raster cell) was applied, increasing the accuracy to 80%. These findings demonstrate that the chosen accessibility conditions are strong predictors of actual AA farmer locations, highlighting the importance of accessibility conditions in distinguishing applicable land suitability from agronomic potential.

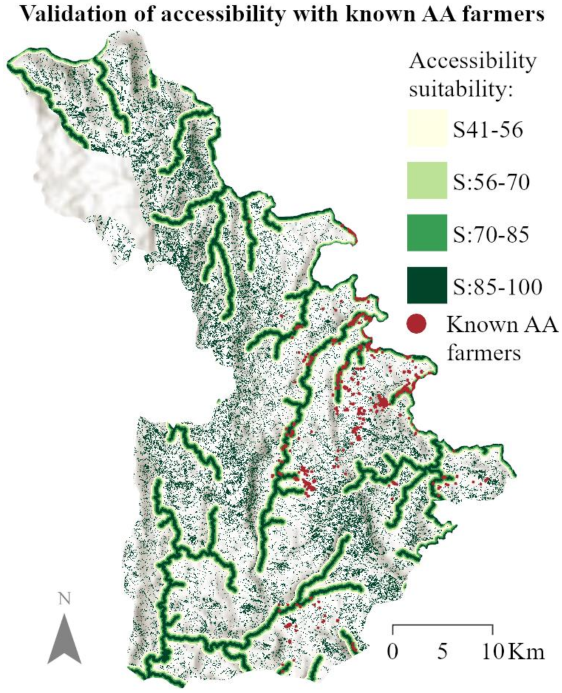


*Figure 10. Known AA farmers and accessibility suitability (with equal width classes).*

## 3.3 Land use analysis

Suitable land was categorized based on current land use (from Buchhorn et al., 2024) to better understand the local applicability of the LS assessment, as land already under agricultural use would be easier to integrate into the TSARA rotation. Non-agricultural land, on the other hand, would require conversion efforts such as land levelling, nutrient management, and new agreements on land ownership. The results (*Figure 11*) demonstrate strong consistency across methods (expert and participatory) and scales (Isandra and Haute Matsiatra). Around 40% of the land currently classified as agricultural is also suitable (considering minimum suitability requirements, S=40, for both TSF and AA) for the TSARA rotation, suggesting significant potential for integrating the new rotation within existing agricultural fields. On the other hand, a lower share (30.4% of expert model and 26.9% of participatory model) of all the identified suitable cells already correspond to agricultural fields, suggesting potential to convert other land uses to the new rotation.

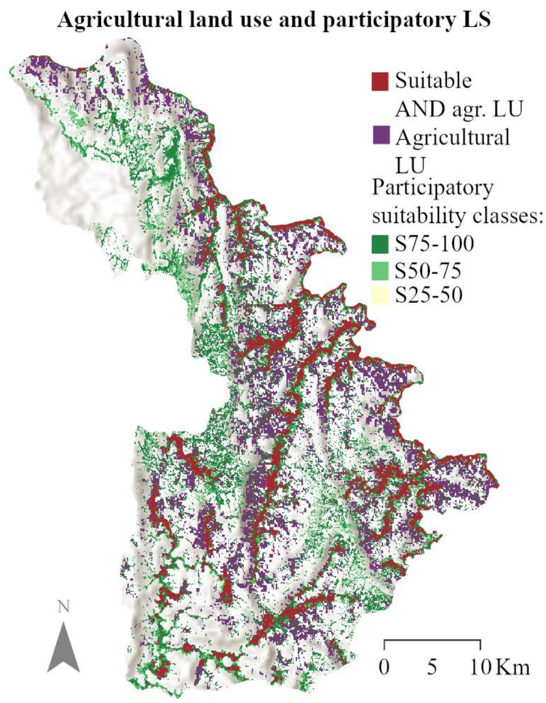


*Figure 11. Participatory suitability classes and current agricultural land use. Areas in red satisfy both criteria.*

## 3.4 Suitability cells count per municipality

Suitable cells were grouped by municipality for both the expert and participatory models (*Figure 12*). The objective is to assess the spatial distribution of suitability within the Isandra district, as both SICI and Bionexx require farmers to be spatially clustered for logistical reasons. The findings reveal distinct patterns in suitability distribution and potential areas for expansion (*Table 9*). (1) *Fanjakana*: Largest absolute area of suitable land but does not score highly in terms of suitability density. (2) *Ambalamidera II* and *Ankarinarivo Manirisoa*: High suitability density in both models. These municipalities are small, contain a high proportion of suitable land, and do not currently host Bionexx or SICI farmers. They offer a combined 41.7 km² (expert) or 30.3 km² (participatory) of new potential land for TSARA rotation. Their suitability is further enhanced by their proximity to SICI's processing plant in Isorana. (3) SICI is operating in *Isorana* and *Anjoma Itsara*. Both municipalities have comparable suitable areas in both models. *Isorana* scores better on total availability of suitable land while *Anjoma Itsara* promises a higher density of suitable land. (4) *Soatana* also hosts SICI farmers. The municipality has the lowest extension of suitable areas but could be considered by Bionexx for the rotation. (5) Bionexx farmers are mainly located in two of the district's municipalities. *Andoharanomaitso*, in the South, also scores well on absolute suitable area for the rotation. This municipality could therefore offer a potential expansion opportunity for SICI to introduce Tsipala Fotsy rotation to AA farmers. (6) *Ambondrona* (where SICI is also already present) yields similar promising results, with the additional benefit of being closer to the processing plant in Isorana.

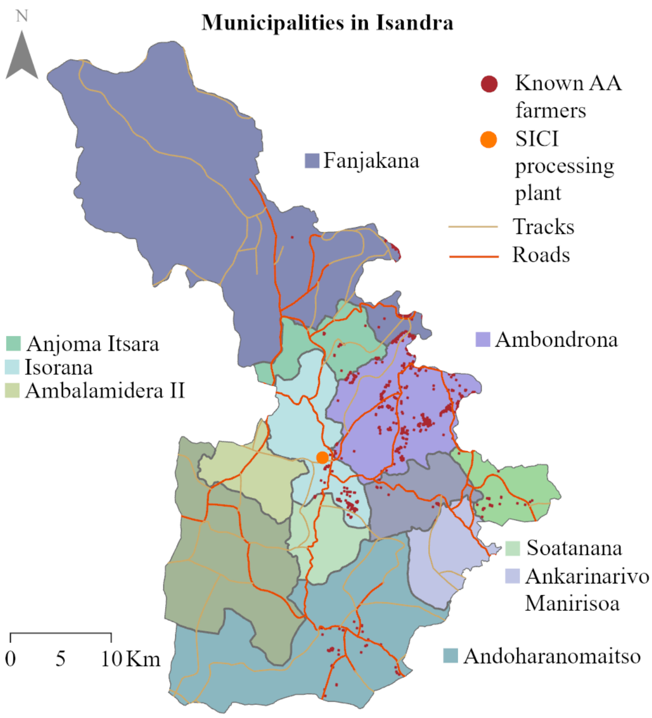


*Figure 12. Municipalities in Isandra and known AA farmer locations.*

*Table 9. Total and relative share of suitable land for all municipalities in Isandra. All suitable cells have a minimum value of S=50 ("Moderately suitable"), a distinction is made between the expert and the participatory-based methodologies.*

| | | **Expert-based methodology** | | | | **Participatory-based methodology** | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Municipality* | *Surface [km²]* | *Suitable area [km²]* | *Rank* | *Suitability [%]* | *Rank* | *Suitable area [km²]* | *Rank* | *Suitability [%]* | *Rank* |
| Isorana | 82 | 22.5 | 6. | 27.3 | 11 | 16.4 | 5.0 | 19.9 | 9 |
| Anjoma Itsara | 50 | 18.1 | 9 | 36.5 | 4 | 13.5 | 9.0 | 27.2 | 5 |
| Andoharanomaitso | 228 | 78.1 | 2 | 34.3 | 7 | 46.7 | 2.0 | 20.5 | 8 |
| Ambondrona | 122 | 33.9 | 4 | 27.7 | 10 | 28.5 | 3.0 | 23.4 | 6 |
| Ambalamidera II | 48 | 19.4 | 8 | 40.2 | 3 | 14.9 | 7.0 | 30.8 | 1 |
| Ankarinarivo M. | 55 | 22.3 | 7 | 40.8 | 2 | 15.4 | 6.0 | 28.2 | 2 |
| Soatanana | 43 | 15.7 | 11 | 36.2 | 5 | 9.3 | 11.0 | 21.6 | 7 |
| Nasandratrony | 53 | 25.5 | 5 | 47.6 | 1 | 14.7 | 8.0 | 27.4 | 4 |
| Mahazoarivo | 167 | 52.3 | 3 | 31.4 | 9 | 26.2 | 4.0 | 15.7 | 11 |
| Fanjakana | 471 | 153.4 | 1 | 32.6 | 8 | 84.0 | 1.0 | 17.8 | 10 |
| Iavonomby V. | 44 | 15.8 | 10 | 35.9 | 6 | 12.4 | 10.0 | 28.1 | 3 |

# 4. Discussion

The following chapter will discuss the results by considering a methodological comparison (4.1), an evaluation of the participatory results (4.2), limitations and assumptions of this research (4.3), an attempt at contextualization and a description of the emerging farmer narratives (4.4), and a confrontation with the current academic discourse (4.5).

## 4.1 Method comparison

Considering the results of one method over the other does carries distinct implications. The expert-based methodology identifies the *agronomic potential of the TSARA rotation* at field level, while the participatory approach provides a *measure of the farmers' perceived correlation between soil qualities and field type*.

The two models roughly coincide in their suitability score (|Exp-Part|<10) only on 21.7% (48.20 km$^2$) of shared suitable cells. The two models diverge in their assigned suitability values: the participatory one scores significantly higher (Part-Exp>10) in 78% of shared suitable cells.

Overlaying the two methods' suitability maps provides new insight into their level of agreement and their distinct contributions to LS assessment. *Figure 13* illustrates the new map; cells are distinguished by three different colour scales:

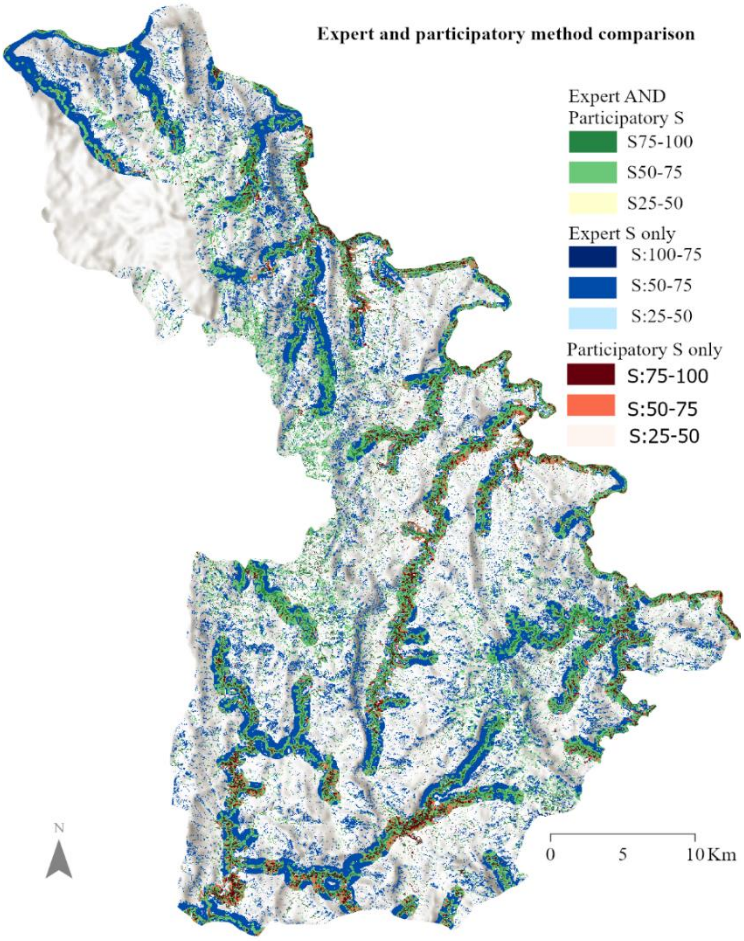


*Figure 13. Expert and participatory method comparison in three distinct colour scales.*

- When a suitable cell is only identified by the expert method, it indicates fields where *farmers overlook high agronomic potential* (symbolized by a scale of blues, total area in Isandra of 235 km$^2$).
- When a suitable cell is only identified by the participatory method, it indicates fields where *farmers recognize suitability despite lower agronomic potential* (symbolized by a scale of red, total area in Isandra of 60 km$^2$).
- When a suitable cell is identified by both methods, it indicates fields for *optimal implementation* (symbolized by a scale of greens, total area in Isandra of 222 km$^2$), where farmer perception aligns with agronomic potential.

## 4.2 Evaluation of participatory results

Given that TSARA's joint outgrower schemes are still limited in adoption across the district, a direct empirical evaluation of the expert- and participatory-driven models is currently not feasible. However, meaningful insights can still be drawn from a comparative analysis of the two approaches. Assuming that the expert model serves as an indicator of potential suitable land in the Isandra district, the participatory method successfully identifies 48.5% of this land (222km²). In other words, farmers recognize the agronomic potential of half of the land deemed suitable by the expert model. Additionally, the participatory approach identifies 60 km² of land not classified as suitable in the expert model, meaning that 21.3% of the participatory model's suitable areas fall outside expert-defined potential land (*Figure 14*). This discrepancy suggests that there is potential for expansion into suboptimal areas that are nevertheless preferred by farmers. However, the relatively small size of this subset supports the reliability of the participatory method in identifying agronomically suitable land for the rotation. At the same time, farmers do not recognize a substantial portion of expert-defined potential land (235 km²) as suitable, highlighting opportunities to expand the TSARA rotation into these areas. However, this would require greater efforts from extension services to bridge the gap between expert assessments and farmers' perceptions.

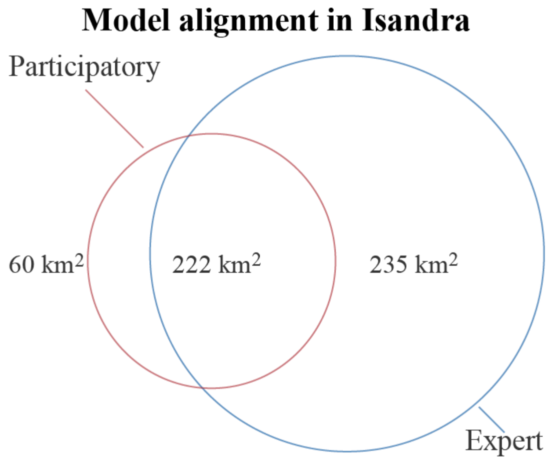

*Figure 14 Suitable cell alignment between expert and participatory-based models in the Isandra district.*

*Considerations on slope*

When TSARA's rotation suitability was assessed, prior to considering the minimum suitability requirements (S=40) for individual crops, both the participatory and expert methods covered the entire accessibility layer. *Figure 8* shows that most land classified as suitable by the expert model, but not identified by the participatory method, is located on higher slopes, further from riverine valley bottoms. The participatory method places significant emphasis on slope, both as an absolute criterion and as a key factor in determining field types, whereas the expert method both incorporates a broader range of criteria and considers suboptimal slopes. As a result, the participatory approach is more strictly confined to flat fields. Both models consider current slopes as derived from digital elevation models. While larger slope suitability intervals were included to account for farmers' ability to flatten fields, the participatory model remains particularly sensitive as it may underrepresent farmers' perspective on the potential for converting steeper slopes into suitable agricultural land. This also explains why, in cases where both methods identify flat land as suitable, the participatory method assigns higher suitability scores in 78% of cases. Additionally, the expert method's less stringent slope criteria account for the broader extent of areas it identifies as suitable (235 km$^2$) compared to the participatory method.

## 4.3 Limitations and assumptions

The objectivity and reliability of this study's outcomes are shaped by every methodological decision made throughout the research process. As the author, it is essential to acknowledge the worldview that influenced these choices. I am a technically oriented student from Western Europe, and my perspective on TSARA has been shaped by my own constructs of what constitutes a successful development project, and by my close collaboration with the driving actors Bionexx and SICI. My research approach aligns with a pragmatic worldview, emphasizing intended consequences. As a result, multiple methods for data collection and analysis were combined, with the goal of producing suitability maps. In this process, farmers' statements that aligned with my developing understanding of the case study were prioritized for further triangulation, while information that did not fit within the dominant narrative of the TSARA rotation was underrepresented.

A major language barrier separated me from the interviewees. Translation bias arose as meaning was potentially lost or altered in the process of conceptualizing questions in English, translating them into French, and then interpreting responses from Malagasy. Moreover, the translator, being aware of the research scope, may have inadvertently influenced responses. Differences in agricultural conceptualization also played a role: my own framework led me to categorize farmers' perceptions of field qualities into a finite set of criteria. Although all observations that inform the GIS models were corroborated by farmers during the criteria weighting sessions, certain nuances and perspectives may have been lost in the process.

Both the participatory and expert-based TSARA rotation maps represent simplified versions of reality. The following section will elucidate on the consequences of the models' assumptions and limitations:

1. The participatory model assumes a rigid dichotomy, where AA is suitable for low-lying fields, and TSF is suited to higher elevations. While this assumption builds on the correlation between field location and soil type, it does not account for farmers' ability to manage soil nutrients (e.g., through compost or manure application). As a result, the model may underrepresent AA's suitability on higher ground.
2. The case study is based on a static vision of the plausible TSARA rotation. The NDVI analysis, which specified the location of terraces and wells, was performed in April and June. Therefore, limiting AA's watering availability considerations to the dry season. In truth, farmers are more flexible in their crop and field choice: TSF can also be cultivated in the dry season, and some farmers plant AA in the wet season. The proposed NDVI approach overshoots well availability in more humid environments.
3. The GIS models were conceptualized and calibrated on observations that were made in southern Isandra between November 2024 and January 2025. While the model can be considered representative of other highland areas in the Haute Matsiatra region, its accuracy decreases as landscapes, biomes, and water availability diverge from the study area. The results are therefore highly case sensitive. Moreover, some of the utilized modelled datasets (most notably ISRIC's "soil depth to bedrock" raster) poorly reflect actual conditions.
4. The final suitability rasters do not include low suitability values. Merging the agronomic model with accessibility conditions results in the omission of least-suitable areas, as fields closer to water sources and population centres tend to score higher in both accessibility and agronomic criteria. While this artificially inflates suitability, it reflects a real-world process in which farmers are more likely to cultivate easily accessible fields, even if their conditions are suboptimal.
5. The weighted sum approach was used to score the suitability of a single field for both crops in a rotation. However, farmers suggest that fertility requirements between crops may make this approach impractical or impossible. Nevertheless, the classification of result by municipal share of suitable land successfully identified macro-areas with a high average suitability for both crops. As a result, the model remains effective in locating potential areas of adjacent fields.
6. Although the criteria were co-developed, no iterative feedback loops were established to refine the models based on input from either farmers or experts after the initial assessment. To enhance model validation and ensure its practical applicability, field-level validation and farmer engagement in Isandra and Anjoma Itsara are recommended.
7. TSF's low fertility requirements, as identified through the Rural Appraisal, were incorporated into the participatory GIS LS assessment by assigning higher suitability to lower SOC ranges. Consequently, the findings of this method are specific to rice varieties with similar fertility requirements to TSF.

## 4.4 Result contextualization and emerging narratives

The study's limitations are not confined to the quantitative methodology on GIS. Both models rely on knowledge provided by individual respondents, introducing subjectivity into the analysis. During the rural appraisal data collection phase, diverse and sometimes contrasting narratives emerged. The following section will elucidate on the extent of (dis)agreement regarding the concepts that underpin the GIS-based approach. Additionally, an effort is made to contextualize the otherwise purely agronomic rotation within the farmers' perceptions and behaviour. Statements are based on twenty-four coded farmers interviews (reported in Appendix C) as conducted in the various stages of Rural Appraisal.

### 4.4.1 Rural Appraisal

The Rural Appraisal methods offer an instrument to investigate the nuances that were lost in the categorization of farmers' interviews into a set of finite criteria.

Farmers strongly agreed on TSF's requirement for low soil fertility, as excessive soil fertility is thought to cause stem overgrowth at the expense of grain production. On the other hand, there is consensus on the correlation between high soil fertility and higher AA yields. As a result, the proposed TSARA rotation is often perceived as non-compatible within the same field. However, some farmers manage to grow both crops in a rotation, on varying field types. When consulted, they confirm the two contrasting requirements but specify that both crops can still be cultivated on suboptimal soils. Nutrient management emerges as the key variable: fields are fertilized before planting AA, leading to excess fertility that negatively affects the subsequent TSF cycle. Similarly, other counter crops that enhance soil qualities, such as vegetables and legumes, have a perceived negative effect on TSF yields. No scientific evidence currently supports the claim that excessive nutrients reduce TSF productivity. While this remains a contested issue, the current sample size of farmers is too small to draw definitive conclusions, highlighting the need for further research. These contrasting narratives are reflected in the GIS modelling approaches. In the expert-based methodology, high fertility (approximated with soil organic carbon) is considered a desirable criterion, whereas in the participatory approach, low fertility is preferred. This distinction results in two different map interpretations: one highlighting areas with strong agronomic potential for the crop rotation, and the other reflecting where farmers more readily recognize suitability based on their field knowledge.

Both crops in the TSARA rotation are positively regarded by most farmers. TSF and AA both fetch higher prices compared to the alternatives, typically sold at weekly local markets, because of their value and SICI and Bionexx's premium prices. Farmers perceive AA as better adapted to dry conditions and less water-intensive than other options. Additionally, AA has a longer growth cycle compared to other counter-season crops. While this delayed income may pose challenges for farmers seeking a more consistent cash flow, it also enables them to plan for future investments and cover significant expenses. The most often mentioned barrier to adoption is the perceived incompatibility of crop fertility requirements. Some farmers suggest integrating traditional rice varieties, which are better suited to fertile soils, into the AA rotation. Additionally, potential adopters mention a lack of knowledge regarding the cultivation of new crops. This knowledge gap is addressed through visits from SICI and Bionexx field technicians, who provide technical support.

### 4.4.2 Considerations on weighting methods

*AHP*

An analysis of the spread of AHP results confirms the previous observations on the relative low importance of slope in both TSF (19%) and AA (14%) field suitability. Four out of the six criteria have an absolute weight difference of less than 7%. The outliers are soil fertility, which scores extremely high in AA AHP (50% vs 27% for TSF), and the crop specific criteria: TWI (TSF) scores 28% while aspect

(AA) scores only 4%. The latter suggests that aspect might be less relevant in the Isandra case study when compared to global AA assessments.

In *AHP*, the type of aggregation technique impacts how experts' judgements are grouped. This research assumed the consulted experts to be a synergistic unit with equivalent group members and therefore performed an Aggregation of Individual Judgements (AIJ). To assess the validity of this assumption, the Aggregation of Individual Priorities was performed, as if the group members did not behave consistently. The mean absolute deviation between AIJ and AIP criteria weights was minimal (0.93%), concluding that the criteria weights were not sensitive to the aggregation technique. An analysis of the individual experts' Consistency Ratios supports Ossandnik et al. (2015)'s claim: AIJ improves collective consistency levels (0.07 CR reduction for TSF and 0.08 CR reduction for AA).

*Participatory criteria weighting*

The spread of individual criteria weights was less evident in the participatory analysis. Criteria weights rank order shows the high perceived importance of soil fertility for AA cultivation (46%), and the relative higher importance of adequate field type in the case of TSF (51%).

Farmers in Isorana and Anjoma Itsara were asked about their crop-specific preferences for low- and high-lying fields. This helped triangulate the previously induced correlation between field type and soil characteristics, namely that high-lying fields are generally less fertile than low-lying ones. The results were consistent between the two villages regarding TSF suitability, with 80% of respondents selecting high-lying fields (Lohasaha). However, preferences for AA varied between villages. In Isorana, farmers favoured low-lying fields (Bas-fond), whereas in Anjoma Itsara, they preferred high-lying Lohasaha, citing greater water availability despite sub-optimal soil characteristics. These findings suggest that during the dry season, water availability can take precedence over field location in determining AA suitability. High village variability on soil characterization and perception was also noticed in previous studies by Brinkmann et al. (2018) in Southwest Madagascar.

Both expert AHP and participatory criteria weighting show a systematic underrepresentation of slope as a suitability criterion. This discrepancy may originate from different perspectives of scale when assessing suitability. LS analysis evaluates criteria on a broader landscape level, where topographic differences are more pronounced, and agricultural fields are clearly distinguished on flat slopes. Farmers and field technicians evaluate criteria on a field level. Agricultural fields are collectively perceived as flat land units. As a result, slope is regarded more as an inherent characteristic than an active criterion for field selection.

## 4.5 Confrontation with academic discourse

Land suitability (LS) assessments published in English remain limited in the Malagasy context. Rajaonarivelo and Williams (2022) and Rakotoarison et al. (2020) have employed similar methodologies: GIS, AHP and weighted sum analysis. The latter study, in particular, highlighted the challenges posed by data scarcity and the necessity of using remotely sensed proxy criteria, which significantly shaped the methodological choices in this research. Despite these contributions, spatial planning of agricultural development projects in Madagascar remains understudied.

This research approached the lack of ground-sourced (soil) data by leveraging farmer knowledge, particularly their perceptions of soil quality and its correlation with field types. Vergas Rojas (2004) similarly identified that farmers use soil-landscape relationships to determine land use decisions. Previous ethnopedological studies in Madagascar support the reliability of farmer knowledge in land assessments that informs this research's participatory methods. Brinkmann et al. (2018) demonstrated that local farmers' soil classifications were effective predictors of crop yields, while Fritz-Vietta et al. (2017) confirmed farmers' ability to interpret landscapes for sustainable land management. In the current study, the Rural Appraisal conducted in Isandra validated farmers' ability to assess soil fertility based on topsoil colour and texture. While these findings underscore the potential of using farmers knowledge as a substitute for remotely sensed proxy indicators, the Isandra case study also revealed conflicting narratives regarding crop fertility requirements, highlighting the importance of corroborating local knowledge with a scientific approach to nutrient management.

This research builds upon the critiques by Nethononda et al. (2014) and Vargas Rojas (2004) regarding the FAO LS framework. Instead of focusing on the most limiting criteria, the chosen methodology focuses on a weighted sum of standardized criteria. As a shortcoming, this method can overcompensate the suitability of a cell with non-limiting criteria. This study partially mitigates that risk by structuring the weight distribution to reflect the most significant factors identified through AHP and participatory multi-criteria evaluation. The methodology ensures that critical criteria retain a higher share of influence in the final suitability assessment. Consequently, when key criteria score low, they are rarely overcompensated by less important criteria. This approach remains particularly advantageous in the present study, as all included criteria represent the direct input of experts and farmers and should be carefully considered in land-use planning. Nevertheless, limiting factors should still be explicitly reviewed by SICI and Bionexx technicians when evaluating new areas based on the generated suitability maps.

Moloudi and Mahabadi (2019) cautioned against the arbitrary selection of cutoff points in LS criteria standardization. This paper addresses that concern by providing informed thresholds when stakeholders specified criteria boundaries, and by applying function-based standardization to align datasets with physical phenomena in case of discrepancies between data availability and case-study conditions. The chosen criteria also diverge from previous literature on rice and Artemisia A. LS assessments (*Appendix A*) in the omitted use of climate variables. This decision was based on the limited climate variability across the case study area.

## 4.6 Participatory and expert-driven method evaluation

This research provides a novel contribution by synthesizing a variety of existing methodologies within a single case study. The expert-driven assessment offers an easy replicable and efficient form of land evaluation, as it relies on low-cost methods and does not necessitate field visits. However, its accuracy is inherently dependent on the quality of the available datasets, and the selected criteria may lack local adaptability. The participatory analysis was able to overcome these shortcomings by providing farmer-refined and weighted suitability criteria, resulting in more realistic and locally adapted land use plans. This aligns with previous findings by Vargas Rojas (2004) and Mazahreh et al. (2018). The participatory methodology applied in this study was primarily defined by the origin of knowledge, with farmer inputs being interpreted through a GIS model and subject to the researcher’s perspective. Future research could build upon this approach by exploring direct land evaluation through participatory mapping activities, thereby reducing the influence of external interpretation.

The inability to empirically validate the results of both methodologies, given the limited current adoption of the TSARA rotation, restricts the capacity to determine the relative effectiveness of one approach over the other. Furthermore, this constraint limits the assessment of whether farmer knowledge (specifically, soil-field type correlations) can compensate for the scarcity of ground-truth data. Nevertheless, the findings underscore how the combined implementation of expert and participatory-driven methodologies enhances conventional LS assessments, by enabling spatial planners to differentiate between agronomic potential and farmers’ perception of planned interventions.

# 5. Conclusions and recommendations

This research had the objective of locating new areas of suitable land for the expansion of TSARA's ougrower schemes propositions of rice (Tsipala Fotsy variety) and Artemisia A. rotations in the Isandra district. Rural Appraisal was chosen as a participatory qualitative survey methodology, yielding the observation that local farmers correlate soil qualities to specific field types in the landscape. Crop experts were consulted during Analytical Hierarchy Process sessions. Soil fertility scored the highest relative weight amongst *Artemisia A*. criteria (50%), while criteria for rice suitability underscore the combined importance of field water accumulation capabilities (28%) and soil fertility (27%). Cell suitability was determined with a weighted sum analysis on standardized criteria. The resulting land suitability maps (30m resolution) were overlayed distinguishing three types of suitable lands in Isandra: (1) 235 $km^2$ of suitable fields where farmers possibly overlook the rotations agronomic potential, (2) 60 $km^2$ of fields where farmers recognize suitability despite lower agronomic potential and (3) 222 $km^2$ of fields for optimal implementation (alignment of agronomic potential and farmers' perception). Validation with current Artemisia A. outgrowers demonstrates that the chosen accessibility conditions (distance from water sources and population centres) are strong predictors of actual field locations. Around 40% of the land currently classified as agricultural is either moderately or highly suitable for the TSARA rotation, suggesting significant potential for integrating the new rotation within existing agricultural fields.

This studied contributed to a gap in the current academic discourse on LS methodologies by synthesizing both a conventional, expert-based, and participatory land suitability assessment to a single case study. The participatory GIS model successfully identified 48.5% of agronomically suitable land. The remaining share of agronomically suitable land, which is not recognized by the participatory method, underscores the importance of extension services in bridging the gap between farmers' field perceptions and the suitability of crop rotations. The participatory analysis was able to overcome shortcomings of the FAO's "Framework for land evaluation" by providing farmer-refined and weighted suitability criteria, resulting in more realistic and locally adapted land use plans. The current limited adoption of TSARA rotation prevents empirical validation of both methodologies, restricting comparison of their effectiveness. This also hinders evaluating whether farmer knowledge (soil-field correlations) compensates for scarce ground-truth data. Nevertheless, the findings highlight how integrating expert and participatory methodologies enhances LS assessments, helping spatial planners distinguish agronomic potential from farmers' perceptions of interventions.

These findings underscore the potential of using farmers' knowledge as a substitute for remotely sensed proxy indicators, however, the approach introduces a significant limitation: the approach is highly case-sensitive, restricting its generalizability to other landscapes where soil–field type perceptions may differ. Additionally, the Isandra case study revealed conflicting narratives regarding crop fertility requirements, emphasizing the need to corroborate local knowledge with scientific approaches on crop nutrient management.

Overall, the integration of remote sensing, participatory farmer knowledge and accessibility constraints in the LS assessment of TSARA's rotation provides a locally adapted, scalable, and practically applicable contribution to the advancements of LS methodologies.

## 5.1 Case-study Recommendations

TSARA's key stakeholders, SICI and Bionexx, are invited to consult the constructed LS maps when considering new macro-areas for the introduction of new outgrower schemes propositions. The municipality-based reclassification of suitable areas has highlighted the potential of *Ambalamidera II* and *Ankarinarivo Manirisoa* for the expansion of TSARA propositions. They offer a combined 41.7 $km^2$ (agronomic potential) or 30.3 $km^2$ (farmers' perception) of new moderately to highly suitable land. Their suitability is further reinforced by their proximity to SICI's processing plant in Isorana. *Anjoma Itsara*, *Isorana* and *Ambondrona*, where both SICI and Bionexx are present, are confirmed in their high suitability ranges. *Soatana* offers Bionexx the opportunity to leverage existing SICI farmers into the combined rotation.

Contrasting fertility requirements between Artemisia A. and Tsipala Fotsy were frequently mentioned by farmers as the strongest barriers to adoption. Exploring the potential of a new rice variety into the TSARA rotation was proposed as a viable alternative. Lack of knowledge on cultivation techniques also inhibited new farmers to partaking in the rotation, reinforcing the central role of the extension services during recruitment campaigns for new outgrowers.

## 5.2 Further research

The *TSARA* project, in collaboration with *Wageningen University and Research*, presents an opportunity for continued research on the Isandra case study in coming years. Local knowledge institutes, like the ISST of Fianarantsoa, could be leveraged for further collaboration.

The diverging narratives regarding crop fertility requirements call for better understanding of individual crops' effects within the rotation. In particular, the supposed fertilizing effect of Artemisia A. counter cropping, and Tsipala Fotsy's preference for nutrient-poor soils should be further investigated. Future studies should carefully distinguish and compare farmers' perceptions (with larger sample sizes) with agronomic crop requirements (evaluated under both controlled experiments and field conditions).

The Isandra case study additionally exemplified the need to determine detailed baseline assessments for Madagascar's soils. This study provided an attempt to address the lack of soil type or soil parameters databases by utilizing remotely sensed data and landform characterization as proxies. While this approach holds promises to other data-scarce environments, it requires further evaluation through empirical data which was not available in the Isandra case study. Specifically, future research should seek to corroborate LS map results with real-world suitability observations and assess the assumptions underlying the participatory GIS model with a larger number of farmers in the district.

This research could be continued by further categorizing suitable cells by slope class, to test the hypothesis that slope is responsible for the differences in suitability extent and intensity between the participatory and expert methods. The role of other criteria could be further investigated by performing sensitivity analysis. As discussed in Section *4.6* future research could explore direct land evaluation through participatory mapping activities, as a mean to assess the efficacy of utilizing farmer knowledge to compensate for lacking ground-data.

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# On the use of Artificial Intelligence

To the best of my intentions, Artificial Intelligence (AI) has been used as a tool to complement research activities in accordance with the guidelines of *Wageningen University and Research*.

My French level is conversational. *DeepL* has thus been utilized for translation purposes from English to French when preparing for interviews with both experts and translator, the programme has also translated the French version of the abstract.

*Semantic Scholar*, *Consensus* and *Elicit* were all used to complement the use of *Google Scholar* in finding relevant papers for the bibliography.

The use of generative AI (*ChatGPT*) has been used to enhance brainstorming capabilities while constructing the methodology. It was used to investigate useful tools in ArcGIS and solve errors, complementing ESRI documentation. *ChatGPT* was also prompted to provide criticism on the text's readability.

Spelling and grammar checks were performed by *Microsoft Word*.

# Appendix A. Literature review crop criteria

The following literature has been consulted for the identification of suitability criteria for both Artemisia Annua and rice.

*Artemisia Annua*:

- Ding et al. (2020)
- FAO, ( n.d.)
- Ferreira et al. (2005)
- Gingade et al. (2014)
- Huang et al. (2010)
- Mofokeng et al. (2024)
- Nadali et al. (2014)
- D. Wang et al. (2022)
- J. Wang et al. (2024)
- WHO (2006)
- Zhang et al. (2011)
- Zhang et al. (2017)

*Rice*:

- Al-Hanbali et al. (2021b)
- Ayehu et al. (2015)
- Maddahi et al. (2016)
- Ozhain et al. (2022)
- Ayoade (2016)
- Biswal et al. (2013)
- DengiZ (2013)

# Appendix B. Reducing the number of experts pair-wise comparisons

High comparison numbers in an AHP matrix can reduce efficiency. To address this issue and ensure sufficient discussion time for each comparison, a maximum of six criteria were selected. The resulting 15 individual comparisons are considered acceptable in the time frame of the experts' AHP sessions.

To increase the validity of the methodology, the sequence of pair-wise comparisons is considered. Building on Andriichuk et al. (2020)'s approach, criteria must first be roughly ranked based on a review of relevant literature. This research considers nine papers discussing the hierarchy of environmental factors for Artemisia A. and rice (as mentioned in *Appendix A*).

The most frequently mentioned criteria, ranked in order of importance, include precipitation, temperature, sun, slope and elevation. However, these findings present a challenge, as they do not fully align with the specific conditions of Haute Matsiatra. Most articles perform LS assessments on a global scale. Criteria like temperature and precipitation are thus over-represented, while they offer no-or little variation in the case study of Haute Matsiatra. A new rough ranking of alternatives is proposed in *Table X*, integrating insights of previous literature with an assessment of local needs.

*Table 2. Provisional criteria rank for rice and Artemisia A.*

| **Criteria rank** | **Rice** | **Artemisia A.** |
|---|---|---|
| $a_1$ | Soil fertility | Soil fertility |
| $a_2$ | Slope | Slope |
| $a_3$ | TWI | Soil depth |
| $a_4$ | Soil depth | Elevation |
| $a_5$ | Elevation | Soil depth |
| $a_6$ | Soil pH | Soil pH |

The following questioning order for pairwise comparisons was followed:

1st turn: ($a_1$, an)

2$^{nd}$ turn: ($a_1$, $a_n$-1) and ($a_2$, $a_n$)

...

n-1 turn: ($a_1$, $a_2$) and ($a_{n-1}$, $a_n$)

# Appendix C. Interview classification

*Table X* lists all statements and observations from the rural appraisal and direct weighting methodologies during the field visits in Anjoma Itsara and Isorana. The following codes were used: accessibility, context, criteria, fertility and slope.

*Table 3. Coded statements and observations from field visits.*

| **Person** | **Gender** | **Location** | **Rural appraisal method** | **Crop** | **Statements and observations** | **Code** |
|---|---|---|---|---|---|---|
| Farmer 1 | F | Anjoma Itsara | Interview | AA | Some farmers will walk up to one hour to go to their fields, that is 3-4 km. | Accessibility |
| | | | | | There are fields with constant water throughout the year, when watering AA they do not have to walk more than 200-400m. | Accessibility |
| Farmer 2 | F | Isandra | Interview | AA, TSF | Artemisia is more labour intensive; they had to stop due to difficulties. | Context |
| | | | | | The choice to cultivate AA is dictated by the good price they get for it (creates income for pork, school expenses, buying other food). | Context |
| | | | | | AA is cultivated in the same fields as TSF. They are low fields on aerated soils | |
| | | | | | AA: They water every day for the first 2 weeks, then once every two days for the whole cultivation period. 10l for 15 plants. | |
| | | | | | They mention that they must walk 2h with 6 people to get their AA to the collection point | Accessibility |
| | | | | | The ideal TSF field has not too much water, not too many nutrients. Flat fields are problematic with hurricanes. | Criteria |
| | | | | | The ideal AA field is flat as it makes it easier to irrigate. | Criteria |
| Farmer 3 | M | Isandra | Interview, field visit | AA, TSF | AA fertilizes the field, no need to add compost after AA. | Fertility |
| | | | | | A good AA field is on a riziere, close to a water canal, has a good position and workable soil. Slope and soil are not important. | Criteria |

| | | | | | | |
|---|---|---|---|---|---|---|
| Farmer 4 | M | Isandra | Interview, landscape walk | TSF, traditional rice | TSF is productive on low fertility, the stem will fall with high soil fertility. | Fertility |
| | | | | | He has never done AA as he misses the knowledge of how to cultivate it. | |
| | | | | | TSF needs to be on a riziere, not on a Tanety (pluvial rice). | Slope |
| Farmer 5 | M | Isandra | Interview | TSF, traditional rice | He does not consider AA for economic reasons (income is delayed to later in the growing season when compared to other crops) and lack of knowledge (technicians have not done awareness campaigns in their village). | Context |
| | | | | | Artemisia grows well in the "rizières" (Basfond). | Criteria |
| | | | | | TSF on soils with low fertility, X265 on high fertility. | Fertility |
| | | | | | Fertility is recognized by a darker colour (and clumps of organic matter). | Fertility |
| | | | | | TSF does not work after a counter season with other crops. | Fertility |
| | | | | | TSF must be on terrace, but AA can be on a slope. | Slope |
| | | | | | Traditional rice (no SRI) is more adapted to climate change. | |
| | | | | | TSF is done on fields that are further to water sources, where it would be difficult to water a counter season (field is resting). Other varieties are rotated with veggies closer to water. | Criteria |
| | | | | | He can sell products at SICI (30m walk and heavy weights but he is used to it). | Accessibility |
| Farmer 6 | M | Isandra | Interview | TSF, traditional rice | Stopped SRI because of climate change. | |
| | | | | | TSF: Nov->Apr (So to sell to Le Relais in July) | |
| | | | | | He does a double rice rotation, that is why he needs to compost twice a year (Zebu manure). | |
| | | | | | A counter season with vegetables would be bad for TSF. | Fertility |
| | | | | | Field characteristics are not important to choose a rice variety (management and climate are more important). | |
| Farmer 7 | M | Isandra | Group session I | AA, traditional rice | Watering AA 3 times a week for 2 months by using the canals on the border of the field. | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Farmer 8 | M | Isandra | Group session I | AA | | |
| Farmer 9 | F | Isandra | Group session I | AA | Some rizieres are more fertile because water with nutrients will flow in from other fields. | Fertility |
| Farmer 10 | F | Isandra | Group session I | TSF, traditional rice | TSF grows better on less fertile soil and without a counter season. | Fertility |
| | | | | | She prefers a paddy field with no inflowing water from other neighbours. | |
| Farmer 11 | F | Isandra | Group session I | TSF | TSF grows better on less fertile soil and without a counter season. | Fertility |
| | | | | | The fertility of the soil is defined by the counter season. | Fertility |
| Farmer 12 | F | Isandra | Group session I | TSF | TSF grows better on less fertile soil and without a counter season. | Fertility |
| Farmer 13 | M | Isandra | Group session I | TSF, AA | Do many farmers experience the problem of delayed incomes with AA?<br>- AA has a 5-month cycle, other veggies just 2. AA is seen as a longer-term investment for other projects (like buying a zebu). Some farmers might need money before. | |
| | | | Group session I | | It is better to have flat fields for AA, but also it will also grow on a slope. The key is having abundant water. | Slope |
| | | | | | The characteristics of fields suitable for Tsipala Fotsy are:<br>- The soil should have good water retention capacity, preferably clay soil.<br>- The location can be in low-lying areas if water management is good, ensuring that water from other rice fields does not flow into these fields. Water from other fields may carry manure, making the fields too fertile. Fields located in higher areas are also an option if there is a good water source.<br>- The soil quality can be moderately fertile.<br>- The field should be close to the house, around 5 to 10 minutes on foot, to allow regular monitoring of the crops. | Criteria |

| | | |
|---|---|---|
| | The characteristics of fields unsuitable for Tsipala Fotsy are:<br>- Highly fertile soil is unsuitable for Tsipala Fotsy because the plants may only produce leaves and stems, affecting yield and causing the plants to topple due to weight and wind.<br>- A depth of more than 30 cm is not suitable, as Tsipala Fotsy does not grow well in such conditions based on the farmers' experience. (Farmers mention that a good depth is until only the feet would sink in the mud).<br>- The field should be flat to distribute water evenly, avoiding areas that are overly flooded or excessively dry. | Criteria |
| | According to the farmers, Artemisia adapts well to drought conditions, whereas other off-season crops require a lot of water. Given the effects of climate change, they have opted for Artemisia. Additionally, Artemisia fetches a higher price compared to other crops. | Criteria |
| | What are the most important qualities/characteristics of a field for Artemisia?<br>- The soil should be fertile, located at the foot of a hill or mountain, or in a rice field that can be dried.<br>- Proximity to a water source, such as a river, stream, or lake, is essential.<br>- Artemisia can be grown on sloped land if contour lines are created to prevent erosion.<br>- For sloped fields, a north-facing orientation is preferred, as this provides good soil exposure and sunlight, which is beneficial for Artemisia.<br>- The location of the field far from the farmer's house is not an issue, as Artemisia has little risk to be stolen. | Criteria |
| | What qualities/characteristics of a field are unsuitable for Artemisia?<br>- Poorly drained and compacted soils are unsuitable for Artemisia. Such soils are difficult to work with, retain water, and have poor aeration. | Criteria |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | Are there differences between a good field for Artemisia and one for Tsipala Fotsy?<br>Yes, there are differences. The most significant distinction lies in soil preference: Artemisia prefers dry soil with controlled irrigation, making it suitable for the off-season, whereas Tsipala Fotsy prefers moist soil. There is also a difference in soil fertility requirements, with each crop having specific needs. | Criteria |
| Farmer 14 | M | Anjoma Itsara | Interview | AA, traditional rice | He rotates AA with his traditional rice variety, and it works very well as AA increases the fertility. It would not work with TSF. | Fertility |
| | | | | | TSF needs higher grounds (more drainage and less inflowing nutrients from other fields). | Fertility |
| | | | | | Confirms: AA does not get stolen, AA gives good price, AA requires fertile fields. | |
| | | | | | A fertile soil is darker in colour. Soils are fertile when AA grows nice and tall | Fertility |
| | | | | | AA is possible on a slight slope if soil and water requirements are satisfied. | Slope |
| | | | | | AA goes bad if there is too much standing water on the fields. | |
| | | | | | Recollection is in Anjoma Itsara (1:15h walking with 35Kg ... "not very heavy"). | Accessibility |
| Farmer 15 | M | Anjoma Itsara | Interview, transect walk | AA, traditional rice | AA grows well on Baiboho and Lohasaha, AA needs fertile soils. | Fertility |
| | | | | | AA and TSF are not cultivated in the same fields because of the fertility issue. Farmers will either own more than one field or rent one out. | |
| | | | | | AA improves soil quality. | |
| | | | | | TSF prefers a mix of clay and sand soil, good drainage to keep little water (max 3 cm) also in case of rain. | |
| | | | | | Confirms TSF: No TSF after veggie counter season, good water management needed, Low soil fertility required, better to have shallow soils (20cm). | |
| | | | | | Confirms AA: AA is possible on a slight slope if soil and water requirements are satisfied. | Slope |
| | | | | | He walks 40 min to the collection point of Bionexx and 15 min to SICI. | Accessibility |

| | | | | | | |
|---|---|---|---|---|---|---|
| Translator | F | Isorana | Confirming statements | / | AA:<br>- Can be further from house<br>- Requires medium to fertile soils (could require fumie)<br>- Makes the soil more fertile for the next cultivation<br>- A fertile soil is darker (some field locations are more fertile)<br>- Could grow on a slight slope, but no one does it<br>- Lots of sun, wind protection<br>- Watering every day and then twice a week, last 2 month nothing<br>- Causes delayed income | Criteria |
| | | | | | TSF:<br>- Does not work after veggie counter season<br>- Does not work after AA<br>- Clay-sandy soils, good drainage<br>- Smaller soil depth | Criteria |
| Farmer 16 | M | Isorana | Group session II (weights) | TSF, AA | | |
| Farmer 17 | M | Isorana | Group session II (weights) | TSF, AA | | |
| Farmer 18 | M | Isorana | Group session II (weights) | TSF, AA | | |
| Farmer 19 | M | Isorana | Group session II (weights) | TSF, AA | | |
| Farmer 13 | M | Isandra | Group session II (weights) | TSF, AA | | |
| | | | Group session II (weights) | | TSF requires low soil fertility. | Criteria |
| | | | | | TSF requires good soil drainage. | Criteria |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | Lohasaha and terraces have mostly lower soil fertility and good drainage. | Criteria |
| | | | | | Lower fields like Baiboho and Basfond are more fertile. Less suitable for TSF but you can still make it work. | Criteria |
| | | | | | AA needs good soil quality ("Lonaka"). | Criteria |
| | | | | | All farmers add compost before AA. | Criteria |
| | | | | | It is difficult to manage TSF low fertility requirements, other farmers that were doing the TSF AA rotation had to stop because of it. | Fertility |
| Farmer 20 | F | Anjoma Itsara | Group session III (weights) | TSF, AA | AA on Tanety, TSF on Lohasaha. | |
| Farmer 21 | F | Anjoma Itsara | Group session III (weights) | TSF, AA | AA on Baiboho, TSF on Lohasaha. | |
| | | | Group session III (weights) | | Had to stop doing the rotation exactly because of the fertility compatibility problem. X265, on the other hand, works well. TSF requests a lot of attention, especially right water management. | Fertility |
| Farmer 22 | M | Anjoma Itsara | Group session III (weights) | TSF, AA | On two different Lohasaha. | |
| Farmer 23 | F | Anjoma Itsara | Group session III (weights) | TSF, AA | AA on Tanety, TSF on Lohasaha. | |
| Farmer 24 | F | Anjoma Itsara | Group session III (weights) | TSF, AA | Rotation on same Baiboho field (but it has an intermediate position in the landscape, and less fertility than usual). | |
| | | | Group session III (weights) | | TSF requires low soil fertility. | Criteria |
| | | | | | TSF requires good soil drainage. | Criteria |
| | | | | | Lohasaha and terraces have mostly lower soil fertility and good drainage. | Criteria |
| | | | | | Lower fields like Baiboho and Basfond are more fertile. Less suitable for TSF as they make for 'light grains'. | Criteria |
| | | | | | All fields receive extra fertilizers before AA | Fertility |

| | | |
|---|---|---|
| | The fumie for AA are increasing the fertility, the rotation does therefore not work ... either TSF or AA will have the wrong nutrient amount. They would like SICI to change rice variety, it would solve the fertility issue. | Fertility |