Multi-criterial analysis for modelling Matengo/Ngolo pits agro-ecological zones using fuzzy logic in Southern Tanzania

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Abstract. It has known that grain production is declining globally, leading to food insecurity becoming increasingly apparent in tropical countries, particularly in Sub-Saharan Africa. Countries in Sub-Saharan Africa must concentrate on indigenous agricultural methods to mitigate the impact of climate change on grain production while preserving ecological balances and achieving sustainable goals. Matengo/Ngolo pits, practised on steep slopes in the Matengo highlands, southern Tanzania, are indigenous knowledge invented by local communities over the past 300 years. Despite its effectiveness in increasing agricultural productivity, soil moisture retention, and other environmental advantages, Matengo/Ngolo agricultural technique has resulted in severe land cover changes that substantially influence other producing sectors. Understanding the agro-ecological zones is essential for enhancing policy development for the expansion and restrictive of Matengo/Ngolo pits practice that intercepting by decreasing its influence on the shrinkage of other ecological services, achieving sustainable agricultural practice in the Matengo highlands. Therefore, this study employed the multi-criteria parameters under the fuzzy logic algorithm in ArcGIS 10.8 for modelling the Matengo/Ngolo pits agro-ecological zone to realize sustainable land management in Matengo highlands.

1. Introduction

Local knowledge in agriculture production has been a backbone for many indigenous communities worldwide to sustain essential needs such as food production and economic earning. Studies show that local interventions have existed among the indigenous community for decades, and scientists have recognized some to be effective on various scales, such as tackling complex challenges, responding to disasters, and adapting to hazardous environments. In Tanzania, most farmers are known to be small-scale farmers concentrating on producing food and cash crops. The majority of these foods include grain production [1]. Due to climate change and soil infertility in some areas, farmers have been practicing shifting cultivation, most of which are non-intensified farming, while others have been finding the means to intensify farming practices based on local knowledge. Among the local knowledge-based intensified agricultural system is Ngolo or Matengo pits farming system. Ngolo farming has been recognized as intensified agriculture practice by the local Matengo community over the past 100 years. According to estimates, Ngoro was founded between 1700 and 1750 BC and occupies a total area of 18,000 hectares[2]. However, the current situation indicates that Ngolo is fast developing and may exceed that estimate. This meant that it’s one of the earliest evidence of local knowledge and interventions used to boost agricultural production in steep slopes where farmers plant crops in ridges shaped like pits known as "Ngolo or Matengo pits.”[3].

According to studies, Matengo pits/Ngolo farming is the best method for addressing agricultural land scarcity since it allows farmers to cultivate on a very steep sloping slope without triggering soil erosion [4].
Because of its efficiency in soil conservation, water retention, and soil fertility, the Matengo/Ngolo system is believed to be one of the most sustainable local agriculture systems [5]. Simultaneously, Ngolo practices have been shown to increase productivity and so provide a reliable food source for the community. Despite the benefits of the Ngolo system, research shows that it contributes to soil sweeping away during intense rainfall, underlining the need to strengthen the practice in order to realize its full potential [6]. Ngolo, like other agricultural systems, has negative environmental and natural resource implications, including the possibility for landslides if the cultivated area does not fulfil the recommended conditions for cultivating Ngolo ridges. Slope, elevation, soil type, and other factors are among variables. These criteria can be linked utilizing remote sensing and GIS technologies, as well as global remote sensing data, to assist farmers in identifying potential locations suitable for practicing Ngolo. Modeling of agro-ecological zones for Ngolo practices can also help policymakers plan for further intensification of the Ngolo agricultural system and agro-tourism operations, such as those seen in Bali, Indonesia [7]. Geospatial technology is a reliable and robust tool for the planning and management of agricultural practices. It is the ability to link geospatial and temporal data that can model Ngolo farming based on the slope, elevation, existing land uses, soil type and hydrological features (stream orders). The Ngolo agro-ecological zones intend to assist in intensifying the grain production in Matengo highlands since the Ngolo system is meant to cultivate grains such as maize, beans, soya, wheat, and others which farmers in Matengo highlands depend on cash crops and food security.

2. Methods

2.1. Study Area

The study takes place in Tanzania's Mbinga District, Ruvuma Region. Mbinga District covers 7921.29 km², in Ruvuma Region southern Tanzania. The rainy season is in full swing from November to May. The average annual rainfall is roughly 1000 mm, while in recent years it has ranged between 1500 and 1700 mm. The Matengo Highlands are the catchment area for Lake Nyasa.

![Figure 1. Study location map](image)

2.2. Methods

This study applied the global free available remote sensing tools data such as DEM (SRTM), FAO soil data and ESRI free LULC map 2020 with 10- resolution. The technics applied include the ranking of parameters values based on the literature revied and fuzzification process, which ended with overlay analysis using fuzzy overlay (Gama algorithm). Figure 2 below illustrate study workflow.
2.3. Data collection

| Data type            | Attribute | Source                        | Uses                               |
|----------------------|-----------|-------------------------------|------------------------------------|
| Sentinel 2 MSI       | 10M       | NASA/GEE                      | Land cover analysis                |
| DEM                  | 30        | SRTM.NASA                     | Topographical analysis             |
| Lithology/Soil type  | 100       | Global Soil/FAO               | Soil analysis                      |
| Precipitation        | Point     | Mbinga District Station data  | Interpolation of rainfall          |
| Social-economic data | Vector    | NBS/Digitization (High-resolution images) | Euclidean analysis |

2.4. Ngolo practice and conditions

It has been revealed that the Ngolo system has been practised in the Matengo highlands for almost a century (Itani 1998). Ngolo's physical characteristics are referred to by his name, which means pit, in which farmers cultivate ridges in the shape of pits beneath steep slopes. Figure 3 (a) and (b) below illustrate the profile and Ngolo ridges respectively. According to research, the Ngolo method is very sustainable because it conserves soil and water while also maturing the soil. The technique can save space in new settlements that have similar natural circumstances, such as mountainous hills and heavy rainfall [6]. It is well recognized that mountainous locations have great agricultural potential, assisted by constant rainfall and moist soil conditions. The rainfall pattern in the Matengo highlands reflects this phenomenon [6]. Rainfall falls in the Matengo highlands from December to May, with the maximum intensity happening between January and February, with considerable rainfall occurring between March and May, but not as firmly as in January and February [6]. The situation of heavy rainfall in high mountainous regions is subjected to draining of soil from the Ngolo ridges, and undoubtedly, heavy rainfall in high mountainous areas is subjected to draining of soil from the Ngolo ridges (Nicol et al. 2015). Previous studies illustrate that it is realized that most of the Ngolo pits are filled with soil eroded as a subsequence of heavy and persistent rains during the rainy season. Furthermore, the Ngolo preparation and cultivation is performed during the dry season, while plantation is performed twice a year, including rain and the dry season or wet season [7]. Therefore, it is essential to consider the rainfall patterns since it the primary drive for soil removal from the mountainous areas cultivated by Ngolo pits. The figure below illustrates the precipitation pattern of the Matengo highlands for the season 2020/2021.
2.5. Elevation analysis
Elevation aspect is among the crucial parameter Ngolo farming [6]. The analysis of the elevation was conducted using the DEM (SRTM) data which provide the helpful in the construction of terraces aiming to avoid erosion. DEM-based topography can be used to identify runoff-contributing areas.

![Figure 3](image)

**Figure 3.** (a) and (b) illustrating Ngolo cultivation profile and Ngolo ridges. Source(Nicol et al. 2015)

2.6. Slope analysis
Matengo pits/Ngolo technique is excellent for usage on steep slopes. Ngolo fields are often cultivated on slopes ranging from 5 to 30 degrees [6]. Therefore, the values below 5 and above 50 degrees, respectively, are unfavourable for Ngolo pits. Understanding this phenom is vital to employ the DEM for slope analysis to identify all the spital locations corresponding with these criteria. The study illustrates that Ngolo pits should be limited to a specific slope level since the risk of loosening soil when overexploited is high. Moreover, the Ngolo practice is not favourable in low slope regions since these areas are highly affected by floods. The water retention in a low land is high, leading to moister bone crop diseases such as lodging disease. The previous study indicates that the Ngolo system has been revealed that Ngolo is more feasible than the Matuta system, which can perform under steep slopes (45%) and help reduce soil erosion(Ellis-Jones and Tengberg 2000). Figure 5 (a) and (b) illustrate the slope (%) and its corresponding ranking respectively.

![Figure 4](image)

**Figure 4.** (a) and (b) illustrate the elevation maps
2.7. Dominant soil

Soil types used for agriculture are critical parameters in the planning and processing of the Ngolo agricultural system. Typically, Ngolo farming is carried out in areas with steep slopes, which are specified based on the elevations and slopes, so it is essential to take precautions on the type of soil used to cultivate Ngolo ridges since soil type can influence soil erosion and the potential for landslides. Forest, Ngolo cannot be cultivated in sandy soil, and therefore, sandy soil will be restricted from Ngolo practices since it is not meet the soil suitability criteria. Therefore, the FAO Global Soil Data was employed in this study six soil types were identified in the study area. Figure 6 (a) illustrate the soil type map and 4(b) illustrate the ranking of soil based on its potential in Ngolo farming system.

2.8. Analysis of Land Use Land Cover

The cloud computing has recently assisted scientists in identifying and mapping land cover and change, making precision agricultural modelling and planning more doable. It has long been recognised that land use has a considerable impact on soil erosion and the sediment yield process. Its changes can cause geomorphic responses, which impact the vulnerability of landscapes to erosion [8]. Recently the ESRI has released the global LULC thematic map with a 10m resolution covering the entire global. The LULC classes in the study area were identified namely; water, trees, grass, flooded vegetations, crops, shrubs/scrub, built-up area and barren ground. Based on the nature of the study area and case under...
discuss parameters such as built area, trees, water, scrub/shrubs are given less importance when considering the development of Ngolo farming. While the farm fields under cultivation are highly encouraged for being intensified [9], and therefore are given a high weight. Figure 7(a) and (b) below illustrate the LULC map its corresponding score respectively.

2.9. Stream orders

Streams and stream order are essential for modelling agricultural ecological zones due to their importance in environmental management and degradation. The implications of river streams in the modelling of Matengo pits is revealed its contribution to the increasing Nitrogen amount in the Lake Nyasa waters; hence it is closely associated with increased water weeds due to fertilizers washed during rainfall seasons that path through rivers. Therefore, it is essential to avoid agriculture activities beyond 60m as per EMA 2004.

![Figure 7. (a) and (b) LULC maps](image)

![Figure 8. (a) and (b) stream maps](image)
2.10. Ranking of parameters/criteria

Table 2. Ranking of parameters/criteria

| Parameter          | Minimum | Maximum | Rank |
|--------------------|---------|---------|------|
| Slope              | 0.00    | 6.75    | 1.00 |
|                    | 6.75    | 25.12   | 5.00 |
|                    | 25.12   | 32.55   | 4.00 |
|                    | 32.55   | 41.16   | 3.00 |
|                    | 41.16   | 52.04   | 2.00 |
|                    | 52.04   | 242.63  | 1.00 |
| Elevation          | 467.00  | 851.00  | 1.00 |
|                    | 851.00  | 1104.00 | 2.00 |
|                    | 1104.00 | 1362.00 | 3.00 |
|                    | 1362.00 | 1504.00 | 4.00 |
|                    | 1504.00 | 1700.00 | 5.00 |
|                    | 1700.00 | 2108.00 | 1.00 |
| Soil type          | Lf87-2/3b & I-Bc-c | Lf & I | 1.00 |
|                    | Af42-1/2bc | Af | 2.00 |
|                    | Af43-1/2bc | Af | 3.00 |
|                    | Bc17-2bc | Bc | 4.00 |
|                    | Bc14-2bc | Bc | 5.00 |
| LULC               | Bare Ground/Built Area/Water | - | 1.00 |
|                    | Crops | - | 2.00 |
|                    | Flooded vegetation | - | 3.00 |
|                    | Grass | - | 4.00 |
|                    | Scrub/Shrub/Tree | - | 5.00 |
| Streams            | 0.00    | 60.00   | 1.00 |
|                    | 60.00   | 120.00  | 2.00 |
|                    | 120.00  | 1000.00 | 3.00 |
|                    | 1000.00 | 1500.00 | 4.00 |
|                    | 1500.00 | 3637.43 | 5.00 |

2.11. Fuzzy membership and fuzzy Gamma

The fuzzification technique identifies class imprecision for events with no clearly defined bounds and converts ranked parameters to binary form, with values ranging from 0 to 1, corresponding to the minimum and maximum values [10]. As a result, all five (5) parameters were given fuzzy membership under the linear membership. In addition, the fuzzy Gamma combination approach was employed in this study [11]. Table 3 illustrate the model parameters and corresponding fuzzy membership.

Table 3. The parameters and corresponding fuzzy membership

| S/N | Parameter                        | Membership |
|-----|----------------------------------|------------|
| 1   | Elevation                        | Linear     |
| 2   | Slope                            | Linear     |
| 3   | Euclidean distance to streams    | Linear     |
| 4   | Land cover type                  | Linear     |
| 5   | Soil type                        | Linear     |
3. Results and Discussion

According to the analysis results, there are five agro-ecological zones that are classified based on their potentials, namely, zone of very high potential, high potential, medium, low, and very low potential. The most favorable zone with very high for cultivation of Ngolo agriculture accounts for approximately 0.24% of the entire Matengo highlands. Previous study revealed that the total area occupied by Ngolo cultivation was 18,000 hectares (180 km$^2$) [2], while the potential area for Ngolo cultivation was estimated to cover 19.3239 km$^2$ among the entire 7921.29 km$^2$. The implication is that farmers adaptation of Ngolo system is exceeding the environmental carrying capacity based on the parameters provided in which the study indicates that zone with high potential has covered 1743.633 km$^2$ which is equivalent to 22.06% of the total area. Therefore, this implies that, the zone of very high and high potential shows that they are underutilized whereby 10.210% were cultivated until 2013. However, land use attention needs to consider the role aimed at boosting farming on farms currently being cultivated rather than focusing on establishing new farms especially in the agricultural zone that does not allow Ngolo farming as outlined in this study. It has been revealed by previous studies that the in order to increase production agricultural intensification is recommended, which comprises of the new hybrid of seeds and industrial agrochemicals [1], however based on the results of this study Mbinga district have the potential for production of cereals or grain crops through the application Ngolo system which is more effective studies shows that yield high results even without application of agrochemicals [2]. According to the results, zone of medium, low and very low should not applied for Ngolo expansions since there are risks associated with poor site locations for Ngolo cultivations [5]; these risks include soil erosion, landslides, and soil fertility loss. The Matengo highlands, which are part of the Lake Nyasa basin, have long been recognised to have been subjected to undue strain, particularly in the form of catastrophic deforestation caused by vast and uncontrolled agricultural operations [12]. The results are resembling the previous study that increasing agriculture productivity through intensifying the farm fields under cultivation is required and restricting further expansions by optimizing geo-spatial locations( Agro-ecological zones for Ngolo cultivation) in order to avoid further loss of natural habitat and biodiversity [9].

![Ngolo Agro-ecological zones distribution](image)

Figure 9. (a) and (b) Ngoro-agroecological zones
Table 4. Size distribution of suitable zones for Ngolo farming in Mbinga district

| SUITABILITY | ZONE  | AREA     | %  |
|-------------|-------|----------|----|
| Very low    | ZONE E| 3744.237 | 47.36 |
| Low         | ZONE D| 2094.496 | 26.49 |
| Medium      | ZONE C| 303.903  | 3.84 |
| High        | ZONE B| 1743.633 | 22.06 |
| Very high   | ZONE A| 19.3239  | 0.24 |

4. Conclusion
The study concludes that only 10.210% of the Ngolo intensification has been utilized the rest has been known to be underutilized. Based on the output of this results there are need for coordinating the expansion of Ngolo farming in order to intensify cereal production in order to ensure food security in Matengo highlands and sub-Saharan Africa. Furthermore, Ngolo farming as a traditional farming need to be modernized by utilizing its benefits and eliminating challenges such as washing of soil from ridges during rainy season and linkage of fertilizers and pesticides to water sources. The use of biochar has the potential to intensify Ngolo farming in future. Therefore, the area identifies as the medium, low and very zone for Ngolo cultivation should be protected to avoid the risk of landslides and soil infertility. The study also suggests that Ngolo farming should be integrated with the agroforest system to avoid soil washout during the rainy season, especially in areas with steep slopes. Furthermore, the farmlands located near water sources can be treated with biochar to retain the Ammonium fertilizer that could be carried by rainwater.

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