Evaluation of soil fertility gradients under different soil and water conservation technologies in Majulai watershed, West Usambara Mountains, Tanzania

S.B. Mwango¹, B.M. Msanya¹, P.W. Mtabwa¹, D.N. Kimaro², J. Deckers⁴, J. Poesen⁴, J.L. Meliyo³, L.S. Mulungu³ and N.I. Kihupi²

¹Dept of Soil Sci., Sokoine Univ. of Agric., P.O. Box 3008 Chuo Kikuu, Morogoro, Tanzania
²Dept of Agric. Eng. and Land Planning, Sokoine Univers. of Agric., P.O. Box 3003 Chuo Kikuu, Morogoro, Tanzania
³Pest Management Centre, Sokoine Univ. of Agric., P. O. Box 3110 Chuo Kikuu, Morogoro, Tanzania
⁴Dept of Earth and Environ. Sci., Katholieke Universiteit Leuven, Celestijnenlaan 200 E, B-3001 Heverlee, Belgium

Abstract

Indigenous soil and water conservation technologies such as miraba and micro-ridges have been widely practised in Usambara Mountains, Tanzania. However, their potential and constraints have not been fully investigated. This study aimed to determine and compare soil fertility status with respect to gradients under bench terraces, micro-ridges and miraba in order to explore their strengths and weaknesses for improvement. A free survey was carried out in Majulai watershed on Acrisols where 108 composite soil samples were collected at 0-30 cm depth in upper, middle and lower parts within bench terraces, micro-ridges and miraba as well as at the upper, mid and lower slope categories of the terrain. Soil fertility status under bench terraces was higher (P ≤ 0.05) in pH, total nitrogen, phosphorus and K than under micro ridges, miraba while the control was the least. The mean soil nutrients under bench terraces were 5.5 pH, 0.14 % total nitrogen, 21.5 mg kg⁻¹ phosphorus and 0.4 Cmol kg⁻¹ K⁺; 5.0. The respective values were pH, 0.16% total nitrogen, 11.6 mg kg⁻¹ phosphorus and 0.4 Cmol kg⁻¹ K⁺ under micro ridges. Under miraba the mean soil nutrients were 5.0 pH, 0.12 % total N, 3.6 mg kg⁻¹ P and 0.4 Cmol kg⁻¹ K⁺ while mean nutrients in the control treatment were 4.8 pH, 0.15 % total nitrogen, 3.5 mg kg⁻¹ phosphorus and 0.3 Cmol kg⁻¹ K⁺. In all the soil and water conservation technologies, soil fertility was not significantly (P ≤ 0.05) affected by slope positions for most soil nutrients except Mg²⁺ and pH, the mean values were higher (P ≤ 0.05) in upper slopes 2.9 Cmol kg⁻¹ Mg²⁺ and 5.5 pH than the mid slopes 1.9 Cmol kg⁻¹ Mg²⁺ and 4.8 pH and lower slopes 2.1 Cmol kg⁻¹ Mg²⁺ and 4.8 pH under miraba, while under bench terraces pH was significantly higher in lower slopes 6.1 than the mid slopes 5.2 and upper slopes 5.3. There were clear trends of soil fertility gradients indicating that lower parts under bench terraces, miraba and micro ridges had relatively higher soil fertility status than the middle and upper parts. Control had relatively equal soil fertility status within its parts. These observations alert for management strategies and technological adjustments that could improve the pattern and magnitude of spatial variations of soil nutrients for sustained crop productivity in Usambara Mountains.

Key words: soil fertility status, soil fertility gradients, bench terraces, micro ridges, miraba

Introduction

Majulai village in the western Usambara Mountains is among those most affected by different forms of soil erosion (Vigiak et al., 2005) and is therefore, experiencing decline in soil fertility, deterioration of soil quality and reduced soil productivity (Wickama and Mwihomeke, 2006). This has adverse impacts on economic and social development (Tenge, 2005).

Farmers have locally developed soil and water conservation (SWC) measures such as miraba, micro-ridges and stone bunds as an integral part of their farming systems, while introduced measures have often been rejected or minimally adopted because the widely practised indigenous SWC technologies were not integrated for improvements (Msita et al., 2010). According to Msita (2013), miraba are
rectangular grass strip bounds that do not necessarily follow contours; these are mostly preferred and widely practiced and unique in the Usambara Mountains.

These SWC technologies are considered to play a vital role in soil conservation and agricultural productivity (Tenge, 2005). However, the extent of their contribution to conservation agriculture (“a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment”) (FAO, 2007) have not been fully exploited. There is still a gap between the recognition of indigenous SWC practices and an effective use of such practices in sustainable conservation agriculture developments (Vigiak et al., 2005). Moreover, some of these technologies in other countries have been criticised for development of soil fertility gradients which cause spatial and temporal variability of crop response to applied fertilisers (Vanlauwe et al., 2007). This study aimed at evaluating chemical soil fertility status under bench terraces, micro-ridges and miraba with respect to soil fertility gradients in order to explore their strengths and weaknesses for improvement under smallholder farming conditions in Majulai village, West Usambara Mountains, Lushoto, Tanzania.

The specific objectives were to

- determine and compare soil fertility status under the studied SWC technologies
- determine and compare the influence of slope positions of the terrain on soil fertility status under the studied SWC technologies
- determine and compare the magnitude of soil fertility gradients within the studied SWC technologies

Materials and methods

Description of the study sites
This study was conducted in the Majulai village (about 360 ha) (4°36′ 9″, 4° 38′ 4″; 38°19′ 46″, 38°20′40″) in western Usambara Mountains, Lushoto District, Tanzania (Fig. 1). The altitude range is 1360-1800 m. The area is warm and dry with an average daily temperature of 16-21°C. The annual rainfall is 500-1700 mm. Annual reference evapo-transpiration (ETo) as estimated by local climate estimator software (New_LocClim) (FAO, 2006) ranges from 100 to 135 mm (Fig. 2).

Fig. 1. Location map of the Majulai Village, Lushoto District, Tanzania

Transforming rural livelihoods in Africa: How can land and water management contribute to enhanced food security and address climate change adaptation and mitigation?

Fig. 2. Mean (± SD) monthly rainfall and estimated reference evapo-transpiration (ETo) (± SD) based on New_LocClim estimator (FAO, 2006). Source: rainfall data from Mlola Meteorological station (n = 37 years 1975-2011)

Study design and soil sampling techniques
A free survey was conducted in Majulai watershed after a base map prepared at a scale of 1:50,000 using Arc View 3.2 GIS software, soil profiles were excavated and described using guidelines for soil profile description (FAO, 2006). Soils were classified according to the World Reference Base for Soil Resources (FAO, 2007). One hundred and eight composite topsoil samples at a depth 30 cm were collected systematically using an auger based on three factors, i.e. SWC technologies, slope positions of the terrain and parts within SWC technologies. Soil and water conservation technologies included bench terraces, miraba, micro-ridges and a control (non-SWC technologies); slope positions were upper, mid and lower slopes and parts within SWC technologies were lower, middle and upper parts, all replicated three times.

Soil analysis
Soil analysis was done following Moberg (2001) laboratory manual. Organic carbon (OC) was measured using the dichromate oxidation method, total nitrogen (TN) by Kjeldahl method, available phosphorus (Bray-I), exchangeable bases (Ca^{2+} and Mg^{2+}) by atomic absorption spectrophotometer, exchangeable Na^+ and K^+ by flame photometer and pH in water by normal laboratory pH meter.

Statistical analysis
All data collected were subjected to Analysis of Variance (ANOVA). GenStat statistical analysis software (GenStat, 2011) was used for the analysis and Least Significant Difference (LSD_{0.05}) was used to detect mean differences between SWC technologies.

Results and discussion
Soils and topographic settings
Soils of the ridge summits are mainly Haplic Acrisols (Profondic), those of upper and mid slopes are Cutanic Acrisols (Profondic, Chromic), while on the lower slopes the soils are Cutanic Acrisols (Profondic, Clayic, Chromic). Stagnic Acrisols (Hyperdystric, Profondic) and Haplic and Gleyic Fluvisols (Humic, Eutric) occupy respectively the toe slopes and the valley bottoms (Fig. 4).
Transforming rural livelihoods in Africa: How can land and water management contribute to enhanced food security and address climate change adaptation and mitigation?

**Soil fertility status under the studied SWC technologies**

The mean and range (in brackets) under bench terraces for the studied soil nutrients were pH 5.5 (4.3-6.6), total N 0.14 (0.10-0.21) %, OC 1.6 (1.2-2.5) %, P 21.5 (0.9-127.5) Mg kg⁻¹, Ca²⁺ 8.2 (5.6-12.3) Cmol kg⁻¹, Mg²⁺ 2.9 (2.1-3.9) Cmol kg⁻¹, K⁺ 0.4 (0.2-0.6) Cmol kg⁻¹, Na⁺ 0.5 (0.3-0.5) Cmol kg⁻¹. Under micro-ridges the mean soil nutrients status and range were pH 5.0 (3.8-6.0), total N 0.16 (0.06-0.26) %, OC 2.0 (1.0-3.5) %, P 11.6 (1.0-38.1) Mg kg⁻¹, Ca²⁺ 7.5 (5.3-12.4) Cmol kg⁻¹, Mg²⁺ 2.3 (1.1-4.1) Cmol kg⁻¹, K⁺ 0.4 (0.2-0.9) Cmol kg⁻¹, Na⁺ 0.4 (0.3-0.6) Cmol kg⁻¹, whereas under *miraba* the soil nutrients status were pH 5.0 (4.2-6.2), total N 0.12 (0.06-0.18) %, OC 1.7 (0.8-3.0) %, P 3.6 (0.2-12.3) Mg kg⁻¹, Ca²⁺ 6.6 (5.1-8.9) Cmol kg⁻¹, Mg²⁺ 2.3 (1.3-4.0) Cmol kg⁻¹, K⁺ 0.3 (0.1-0.8) Cmol kg⁻¹, Na⁺ 0.4 (0.3-0.6) Cmol kg⁻¹ and pH 4.8 (4.0-5.6), total N 0.15 (0.1-0.2) %, OC 1.7 (0.7-2.6) %, P 3.5 (1.5-6.0) Mg kg⁻¹, Ca²⁺ 6.4 (4.0-8.9) Cmol kg⁻¹, Mg²⁺ 2.1 (1.1-4.3) Cmol kg⁻¹, K⁺ 0.3 (0.1-0.6) Cmol kg⁻¹, Na⁺ 0.4 (0.3-0.6) Cmol kg⁻¹ under control. The soil fertility status were different between the studied SWC technologies, where the following attributes were significantly different: pH at (F35, 72 = 5.93, *P* < .001); OC at (F35, 72 = 3.25, *P* = .05); total N at (F35, 72 = 3.25, *P* = .03); P at (F35, 72 = 6.35, *P* < .001); Ca²⁺ at (F35, 72 = 10.56, *P* < .001); Mg²⁺ at (F35, 72 = 7.47, *P* < .001); K at (F35, 72 = 3.36, *P* = .02); and Na⁺ at (F35, 72 = 3.89, *P* = .012) (Table 1). The SWC technologies depicted higher pH under bench terraces than *miraba*, micro ridges and control; OC contents were higher under micro ridges than bench terraces and control; total N contents were higher under micro ridges and control than under *miraba*; K⁺ contents were higher under bench terraces and micro ridges than control; P, Ca²⁺ and Na⁺ were higher under bench terraces than micro ridges, *miraba* and control; Mg²⁺ contents were higher under bench terraces than micro ridges, *miraba* and control. In general, bench terraces had higher fertility as compared to micro ridges, *miraba* and control. Similar observation was reported by Kyaruzi (2013) where bench terraces and *miraba* influenced soil chemical properties such as pH, total N, OC, CEC, Ca²⁺ and Mg²⁺when compared to the control. This is probably because bench terraces (Fig. 4) are nearly level surfaces supported by grass barrier bunds that allow retention of plant nutrients.

**Table 1.** The impact of the studied SWC technologies on soil fertility status in Majulai Village, Lushoto, Tanzania

<table>
<thead>
<tr>
<th>SWC technologies</th>
<th>Total count</th>
<th>pH</th>
<th>%TN</th>
<th>%OC</th>
<th>P (mg kg⁻¹)</th>
<th>Ca²⁺ (Cmol kg⁻¹)</th>
<th>Mg²⁺ (Cmol kg⁻¹)</th>
<th>K⁺ (Cmol kg⁻¹)</th>
<th>Na⁺ (Cmol kg⁻¹)</th>
<th>LSD (P ≤ .05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bench terraces</td>
<td>27</td>
<td>5.5</td>
<td>0.14</td>
<td>1.61</td>
<td>21.45</td>
<td>8.18</td>
<td>2.89</td>
<td>0.42</td>
<td>0.48</td>
<td>0.04</td>
</tr>
<tr>
<td>Micro ridges</td>
<td>27</td>
<td>5.0</td>
<td>0.16</td>
<td>2.02</td>
<td>11.61</td>
<td>7.46</td>
<td>2.27</td>
<td>0.40</td>
<td>0.43</td>
<td>0.02</td>
</tr>
<tr>
<td><em>Miraba</em></td>
<td>27</td>
<td>5.0</td>
<td>0.12</td>
<td>1.73</td>
<td>3.60</td>
<td>6.60</td>
<td>2.29</td>
<td>0.31</td>
<td>0.41</td>
<td>0.01</td>
</tr>
<tr>
<td>Control</td>
<td>27</td>
<td>4.8</td>
<td>0.15</td>
<td>1.69</td>
<td>3.50</td>
<td>6.43</td>
<td>2.05</td>
<td>0.27</td>
<td>0.40</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**Fig. 4.** Bench terraces at the upper slopes of Majulai village, Lushoto, Tanzania.
Micro-ridges are spaced closely together, and are too small to resist heavy runoff (Fig. 5). However, the canals associated with the ridges act as reservoirs which allow retention of plant nutrients, whereas *miraba* (Fig. 6) are broader and wider and the surfaces are not levelled as in the case of bench terraces.

**Fig. 5.** Micro-ridges at the lower slopes of Majulai watershed, Lushoto, Tanzania

**Fig. 6.** *Miraba* at the lower slopes of Majulai watershed, Lushoto, Tanzania

**Effects of slope positions on soil fertility status under the studied SWC technologies**

Slope positions of the terrain had no influence on soil fertility status under the studied SWC technologies for most of the soil nutrients except for Mg$^{2+}$ which was significantly different at ($F_{35, 72} = 2.30, P = .04$) and pH at ($F_{35, 72} = 2.18, P = .05$) (Table 2). The mean values were higher in upper slopes 2.9 Cmol kg$^{-1}$ Mg$^{2+}$ and 5.5 pH than the mid slopes 1.9 Cmol kg$^{-1}$ Mg$^{2+}$ and 4.8 pH and lower slopes 2.1 Cmol kg$^{-1}$ Mg$^{2+}$ and 4.8 pH under *miraba*, while under bench terraces pH was higher in lower slopes 6.1 than the mid slopes 5.2 and upper slopes 5.3.

There were clear trends under bench terraces such that soil nutrients were relatively higher in lower than in the mid and upper slopes except K$^+$ and Na$^{2+}$ which were relatively higher in upper than in the mid and lower slopes (Table 2). Similar observation was reported by Reza *et al.* (2011), where slope positions were controlled the translocation of soil nutrients in a hill slope and contribute to the spatial variation of soil nutrients.
Transforming rural livelihoods in Africa: How can land and water management contribute to enhanced food security and address climate change adaptation and mitigation?
Micro-ridges, miraba and control showed similar trend with relatively higher concentrations of most of the nutrients except Ca$^{2+}$ and K$^+$; Ca$^{2+}$ and Mg$^{2+}$ and Ca$^{2+}$ and Na$^+$, respectively, were higher at the upper than the mid and lower slopes (Table 2). This situation can be caused by the in-born soil properties whereby subsurface horizons were relatively richer in Ca$^{2+}$, Mg$^{2+}$, K$^+$ and Na$^+$, the subsurface soils had been exposed out in upper slopes due to settlements which are mainly concentrated in this slope category, and furthermore people dig and use deeper soil layers for painting their houses. A similar observation was reported by Berset (2009) in Sri Lanka where the carbon content in the upper soil layers of the steep slope category was higher than in the flat slope category. These observations pointed out that anthropogenic accelerated erosion may sometimes outweigh the effect of natural erosion, which was expected to be highest in upper steep slopes.

**Effects of different parts within SWC technologies on soil fertility gradients**

The lower, middle and upper parts within bench terraces, micro-ridges and miraba had no influences to soil fertility gradients (Table 3). A similar trend was reported by Damene et al. (2011) where fertility gradients under terracing were similar. However, this study reveals a clear (though non-significant) trend of soil fertility gradients existence in all the studied SWC technologies (Table 3).

Generally, lower parts of plots under bench terraces, miraba and micro-ridges had relatively highest soil fertility status followed by the middle parts, with the upper parts being the least fertile. However, control revealed equal status within its parts (Table 3). This trend is probably because bench terraces are constructed by cutting the upper soil and filling at the lower parts thus exposing the infertile subsoil at the upper part, whereas micro-ridges and the grass strip bunds in miraba act as reservoirs which allow retention of soil nutrients in place. Stak et al. (1999) reported a similar trend under terraces formed from natural vegetation strips where the upper parts revealed depleted plant nutrient levels and attributed this to the redistribution of sediments from upper to lower terrace zones that lead to the development of soil fertility gradients. Reza et al. (2011) also reported the depletion of soil nutrients at the upper parts to be associated with the movement of nutrients down the slope. Lee et al. (2003) reported the efficiency of grass strip for retaining 80% of total N and 78% of total P, by capturing sediments from runoff.
Table 3. Influence of different parts of the studied SWC technologies on fertility gradients in Majulai Village, Lushoto, Tanzania

<table>
<thead>
<tr>
<th>SWC technologies</th>
<th>Total count</th>
<th>Parts within SWC technologies</th>
<th>Mean pH</th>
<th>% TN</th>
<th>% OC</th>
<th>P mg kg⁻¹</th>
<th>Ca²⁺ Cmol kg⁻¹</th>
<th>Mg²⁺ Cmol kg⁻¹</th>
<th>K⁺ Cmol kg⁻¹</th>
<th>Na⁺ Cmol kg⁻¹</th>
<th>LSD (P ≤ .05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bench terraces</td>
<td>9</td>
<td>Upper part</td>
<td>5.5</td>
<td>0.14</td>
<td>1.53</td>
<td>17.38</td>
<td>7.51</td>
<td>2.67</td>
<td>0.38</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Middle part</td>
<td>5.6</td>
<td>0.14</td>
<td>1.62</td>
<td>20.80</td>
<td>8.24</td>
<td>2.96</td>
<td>0.42</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Lower part</td>
<td>5.5</td>
<td>0.15</td>
<td>1.66</td>
<td>26.16</td>
<td>8.82</td>
<td>3.03</td>
<td>0.46</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>Miraba</td>
<td>9</td>
<td>Upper part</td>
<td>5.0</td>
<td>0.14</td>
<td>1.82</td>
<td>10.00</td>
<td>7.43</td>
<td>2.23</td>
<td>0.35</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Middle part</td>
<td>4.9</td>
<td>0.16</td>
<td>2.10</td>
<td>10.24</td>
<td>6.85</td>
<td>2.19</td>
<td>0.39</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>Micro-ridges</td>
<td>9</td>
<td>Upper part</td>
<td>4.9</td>
<td>0.16</td>
<td>2.14</td>
<td>14.73</td>
<td>8.10</td>
<td>2.39</td>
<td>0.46</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Middle part</td>
<td>5.1</td>
<td>0.12</td>
<td>1.51</td>
<td>2.87</td>
<td>5.88</td>
<td>2.17</td>
<td>0.27</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Lower part</td>
<td>5.0</td>
<td>0.12</td>
<td>1.77</td>
<td>3.31</td>
<td>6.93</td>
<td>2.32</td>
<td>0.31</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>9</td>
<td>Upper part</td>
<td>4.8</td>
<td>0.14</td>
<td>1.67</td>
<td>3.20</td>
<td>6.34</td>
<td>2.12</td>
<td>0.22</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Middle part</td>
<td>4.8</td>
<td>0.15</td>
<td>1.64</td>
<td>3.30</td>
<td>6.46</td>
<td>2.10</td>
<td>0.26</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Lower part</td>
<td>4.8</td>
<td>0.15</td>
<td>1.75</td>
<td>3.92</td>
<td>6.48</td>
<td>1.94</td>
<td>0.33</td>
<td>0.36</td>
<td></td>
</tr>
</tbody>
</table>

Conclusions and recommendations

Bench terraces and micro-ridges performed significantly better in fertility retention than miraba and the control. Slope positions of the terrain influenced translocation of most soil nutrients under all the studied SWC technologies where lower slopes had higher soil nutrients than the mid and upper slopes. Clear trends of soil fertility gradients were observed whereby bench terraces, miraba and micro-ridges had higher fertility status at the lower parts than the middle and upper parts; whereas the control had relatively equal fertility status within its parts.

Further studies are necessary to test crop performance for soil fertility gradients under different parts within the studied SWC technologies for improvement. Supportive SWC measures such as mulching should be tested and accompanied under miraba and micro ridges for their improved efficiencies. For improved effectiveness of bench terraces, stabilising grass bunds at the edges of bench terraces should be cut to about 30 cm height and not at the ground as usually practiced in Usambara Mountains.

Acknowledgement

The authors are grateful to the VLIR-UOS supported RIP-DSS SUA Project on “Enhancing Indigenous Knowledge on Conservation Agriculture for Poverty Alleviation and Sustainable Livelihood, Usambara Mountains, Lushoto, Tanzania”, and the Tanzania Commission for Science and Technology (COSTECH) for providing financial and logistical assistance to the research.

References


Transforming rural livelihoods in Africa: How can land and water management contribute to enhanced food security and address climate change adaptation and mitigation?