Performance of in situ rainwater conservation tillage techniques on dry spell mitigation and erosion control in the drought-prone North Wello zone of the Ethiopian highlands

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Abstract

Grain production shortfalls in northern Ethiopia are commonly associated with occurrence of intra-seasonal dry spells or droughts and rapid land degradation which adversely impact crop yields. Suitable practices that use available rainwater more efficiently to mitigate impact of dry spells on crops and that protect soil are needed to stabilize and improve grain yields in the predominately rainfed agriculture. During three cropping seasons on-farm experiments tested conservation tillage techniques implemented with oxen-drawn plows on clay loam soil. Tested tillage techniques are subsoiling, open and tied ridges, no till, and conventional tillage with the local \textit{maresha} plow (the control). Effectiveness in improving root zone soil moisture, limiting soil erosion, and improving \textit{Sorghum bicolor} (L.) Moench. and \textit{Cicer arietinum} L.) grain yield were determined. Results demonstrate that performance of the tillage techniques varied with seasonal rainfall distribution and intensity and land slope gradient. Tied and open ridge increased seasonal root zone soil moisture 15–24%. Subsoiling slightly (3%) increased and no till slightly decreased soil moisture but were not statistically different from conventional tillage. Tied ridge and no till significantly reduced seasonal soil loss by up to 11 Mg ha\textsuperscript{–1} during seasons with moderate intensity storms, but during a season with high intensity storms tied ridge on over 9% slope gradient increased soil loss (up to 35 Mg ha\textsuperscript{–1}). The increased soil disturbance of subsoiling led to higher soil loss rates (up to 32 Mg ha\textsuperscript{–1}) than conventional tillage during all seasons. Grain yield decreased and runoff and erosion rates increased rapidly with increasing land slope gradient. During a season with moderate intensity rainfall open and tied ridge increased sorghum yield by 67–73% over the control (730 kg ha\textsuperscript{–1}) while no till decreased yield by 25%. During a season when high intensity rainfall events damaged the ridges, subsoiling had the best sorghum yield with 42% increase over the control (1430 kg ha\textsuperscript{–1}). Poor early season rainfall and fungus attacks resulted in low chickpea yields (200–320 kg ha\textsuperscript{–1}) and statistically insignificant differences between tillage methods. Overall results of the study suggest that on slopes below 8% gradient oxen-drawn ridge tillage and subsoiling, to a lesser degree, can effectively improve conditions that mitigate impact of short dry spells especially during seasons with less intense rainfall events.

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1. Introduction

1.1. The situation

Annual food production shortages in many parts of Ethiopia are commonly linked to unreliable seasonal rainfall meaning dry spells or droughts and environmental degradation. In eastern Africa droughts occur about once to twice every decade often resulting in crop failure while intra-seasonal dry spells of over 2 weeks are an almost seasonal occurrence reducing yields 75% when they occur during flowering or grain-filling crop development stages (Barron et al., 2003; Yilma Seleshi and Zanke, 2004). Widespread rapid cropland degradation in the Ethiopian highlands mostly caused by water erosion and soil nutrient mining practices reduce soil nutrient availability, water holding capacity, and infiltration rate which all exacerbate the effects of meteorological dry spells on crop yields (Kebrom Tekle, 1999; Sonneveld and Keyzer, 2003; Nyssen et al., 2004; Haileslassie et al., 2005).

During non-drought years, there is sufficient rainfall in semiarid and dry sub-humid regions of sub-Saharan Africa including dry drought-prone parts of the Ethiopian highlands to obtain high crop yields even during seasons with short dry spells (Rockström et al., 2002). The main limitation in stabilizing and increasing grain yields in rainfed farming systems of dry-spell prone areas is crop water stress caused by inefficient use of total available seasonal rainfall. Inefficient use of rainfall is often a consequence of poor rainfall partitioning resulting in low root zone soil moisture and/or of poor plant uptake of available soil moisture (Rockström and Falkenmark, 2000). With over 97% of Ethiopian agricultural area rainfed (FAO AQUASTAT, 2002) food production is particularly vulnerable to dry spells. Technologies that use rainwater more efficiently are needed. Conservation tillage and water harvesting technologies offer good prospects for infiltrating and storing more rainfall which is then available for plant uptake during dry periods (Wiyo et al., 2000; Rockström et al., 2002; Motsi et al., 2004). In addition erosion control and soil fertility improvements are needed (Rockström and de Rouw, 1997; Rockström and Falkenmark, 2000; Vancampenhout et al., 2006).

1.2. In situ rainwater conservation tillage techniques

The in situ rainwater conservation tillage techniques tested are open and tied ridging, subsoiling, and no till. Open and tied ridges have demonstrated mixed effectiveness at improving soil moisture in sub-humid and drier parts of sub-Saharan Africa depending on the site soil type, rainfall amount, and land slope gradient (Lal, 1995; Twomlow and Bruneau, 2000; Wiyo et al., 2000; Motsi et al., 2004). The manual formation of ridges as is practiced in some other parts of Africa is not always feasible in the Ethiopian highlands where farmers are used to oxen-drawn tillage with a traditional single tined plow called maresha (Gebregziabher et al., 2006). Temesgen (2000) developed and tested in Ethiopia an oxen-drawn ridger which consists of a relatively inexpensive ridging implement that simply attaches to the conventional maresha plow. He found that the farmers in the study area responded favorably to the ridger. However, farmer adoption and continued use of the ridger after the test period has not been followed up (Temesgen, 2000). Knowledge is limited about the performance (i.e., crop and soil response) of the relatively small ridges, which are 10–20 cm high and 25–50 cm wide, made with the implement.

Subsoil cultivation is a technique that cuts soil deeper than achieved with conventional tillage. Subsoiling improves grain yield by enhancing root growth and infiltrating more rainfall deeper in the soil profile particularly in soils with compacted low permeability sub-layers (Salih et al., 1998; Abu-Hamdeh, 2003; Pikul and Aase, 2003; Xu and Mermoud, 2003; Birkas et al., 2004; Pagliai et al., 2004). Hardpans and soil compaction caused by repeated tillage to the same depth for generations and animal trampling has been reported in Ethiopia (Mwendera and Mohamed Saleem, 1997), but little is known about their prevalence in croplands and the level of impact on agricultural yield. This study tested effectiveness of subsoiling implemented with an oxen-drawn subsoil cultivator recently developed by the Integrated Food Security Program (IFSP) in Debre Tabor, Ethiopia. The tested subsoiler cut the soil at 30–50 cm intervals an additional 6–12 cm below the 6–15 cm tillage depth of conventional tillage with maresha (Nyssen et al., 2000; Gebregziabher et al., 2006).

No till can improve infiltration, reduce erosion, and increase yield as a result of natural processes acting to improve soil quality (Lal, 1995, 1998; Pala et al., 2000; Dominy and Haynes, 2002; Wahl et al., 2004). No till is not commonly practiced in Ethiopia, but Astatke et al. (2003) found some farmers who expressed interest in minimum tillage (permanent broad bed and furrow) because of lower animal draft requirement and the possibility to plant crops earlier because seeds can be sown without waiting for a rain event to soften the soil before tillage, thus providing an early harvest during the
annual period of household food shortage. Although no till sometimes decreases grain yields during the first season of implementation, after several years of cropping with better-adapted management techniques, yield increases have been observed (Lal, 1998; Pala et al., 2000; Astatke et al., 2003). Mulching can improve effectiveness of no till in enhancing soil moisture and reducing soil losses (Lal, 2000). The present study tested no till with 2.5 Mg ha\(^{-1}\) sorghum stalk mulching.

The objective of this study was to test the effectiveness of open and tied ridges, subsoiling, and no till to increase soil moisture and decrease runoff and erosion during three cropping seasons in the highlands of Ethiopia. The research was carried out in the chronically food-insecure drought-prone Lenche Dima watershed in eastern Amhara State, North Wello, Ethiopia.

2. Materials and methods

2.1. Site and environmental conditions

Experiments were conducted during three cropping seasons (2003–04) on a farmer’s field in the Lenche Dima watershed (N 11°50.415′, E 39°43.871′, 1540 m above sea level) located 16 km east of Weldiya town in North Wello, Amhara State, Ethiopia (Fig. 1). Mean annual precipitation in the period from 1975 to 1981 (Ethiopia National Meteorological Services Agency, 1975–1981) and 2003 to 2004 (from the current study) was 849 mm. The rainfall distribution is bimodal with a small rainy season (belg, mean 208 mm) during March–May and main rainy season (kremt, mean 483 mm) during July–October. Mean long-term daily maximum temperature is 33°C in June and the mean daily minimum is 12°C in November. As part of this study daily U.S. Class A pan evaporation, hourly ambient temperature, and 10-min incremental rainfall (tipping bucket raingauge) were monitored in the Lenche Dima watershed for 2003–2004.

The agricultural system at the study area is permanent cultivated fields in a mixed crop livestock complex. The major crops are sorghum, teff, chickpea, and maize. Grain yields vary greatly depending on seasonal rainfall but are generally low with regional averages in Amhara during 2002–2004 of 0.7–1.5 Mg ha\(^{-1}\) sorghum, 0.6–1.0 Mg ha\(^{-1}\) teff, and 0.5–1.1 Mg ha\(^{-1}\) pulses/chickpea (FAO GIEWS, 2002; FAO GIEWS, 2005). The most apparent erosion problem in the watershed is gully erosion in the flat lowland portion of the watershed. Gullies have been actively developing during the last 30 years. Gully rehabilitation was started during 2005 and has been reasonably successful. Very few other non-indigenous conservation practices are in use in this area.

Soil at the farm site is a clay loam with average bulk density of 1.56 Mg m\(^{-3}\) and is classified as vertic luvisol (FAO/ISRIC/ISSS, 1998). According to the farm owner, no nutrients were applied, except for waste from roaming livestock, during continuous cultivation (teff, sorghum, chickpea) of the field for over 10 years prior to the experiments. The baseline soil properties determined at the Duke University Soil Laboratory (Durham, NC/USA) show increasing clay and silt content from 0–30 cm to 30–45 cm depth, low N and fair P nutrient contents, and neutral pH (Table 1).

2.2. Experimental design

The kremt 2003 and belg 2004 experiments were setup as randomized complete block design and the kremt 2004 experiment was split plot (Table 2). Plots were 30 m long and 5–6 m wide and were hydrologically separated by compacted soil bunds 50 cm wide and 30 cm high. Treatments were replicated in three complete blocks. Blocks consisted of contour strips along a toposequence of decreasing slope gradient downhill (concave) on one farmer’s field (~0.75 ha). Plot slopes were 9–11% for the top block 1, 4–8% for the middle block, and 0–3% for the bottom block. Unlike the top and bottom blocks which had similar mean slopes across plots within the same block, in the middle block the treatments were on plots with considerably different slopes (mean slope gradient = M 4%, SS 7%, OR 6%, TR 7%, NT 6%; treatments are
described in the next paragraph). During kremt 2003 a local "early"-maturing (~140 days) red variety (locally called Djigourti) of sorghum (Sorghum bicolor (L.) Moench.) was planted while a local variety of desi-type chickpea (Cicer arietinum L.) was planted during belg 2004. An early maturing (~103 days) striga-resistant improved white variety of sorghum (P-9401 Gobye from Sirinka Agricultural Research Center, Amhara State, Ethiopia) was planted during kremt 2004.

Four land preparation techniques were tested during the first two rainy seasons (kremt 2003 and belg 2004) and a fifth treatment of no till was added during the third season (kremt 2004) of the study. The treatments were conventional tillage with maresha (M) which is the control, subsoiling with an animal-drawn subsoiler (SS), open (OR) and tied ridges (TR) created using an animal-drawn ridger, and no till (NT) with sorghum stalk surface mulching. No nutrients were applied to the plots during the first two seasons of experiments. During the third season (kremt 2004) nutrients were applied to five subplots within each main plot tillage treatment. Subplots were 5–6 m wide (equivalent to main plot width) and 4 m along slope (starting from the top of the plot) and were separated by 1.5 m buffer zones. The nutrient treatments were no nutrient additions (N0); 20.5 kg N ha\(^{-1}\) as urea (N1); 20.5 kg N ha\(^{-1}\) + 46 kg P ha\(^{-1}\) as DAP and urea (N2); 5 Mg ha\(^{-1}\) dry animal manure + 20.5 kg N ha\(^{-1}\) + 46 kg P ha\(^{-1}\) as DAP and urea (N2M1); and 41 kg N ha\(^{-1}\) + 46 kg P ha\(^{-1}\) as DAP and urea (N3). Nutrient treatments were randomly assigned to subplots within each main plot.

### 2.3. Experimental setup and crop management

All plots, except no till, were plowed twice during the off-seasons according to the conventional farm management practice using the conventional oxen-drawn single tine plow called maresha. The first tillage was along the slope contour 2–5 weeks after the previous crop harvest. The second tillage was along the slope after the first rain events of the upcoming cropping season softened the hard dry soil sufficiently for plowing. The final (third) tillage performed the day before sowing (this is slightly different from the traditional production system in which seeds are broadcast in the field before the final tillage, i.e., sowing and final tillage are on the same day) with the appropriate implement for each treatment was along the

### Table 1

Soil characteristics at the experiment site

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Sandb (%)</th>
<th>Siltb (%)</th>
<th>Clayb (%)</th>
<th>Bulk densityc (g cm(^{-3}))</th>
<th>Total Nd (%)</th>
<th>Total Pe (%)</th>
<th>pHf H(_2)O</th>
<th>Organic carbong (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–30(^a)</td>
<td>48 (6)</td>
<td>25 (1)</td>
<td>27 (5)</td>
<td>1.57 (0.18)</td>
<td>0.10 (0.01)</td>
<td>0.14 (0.01)</td>
<td>7.4 (0.2)</td>
<td>1.1 (0.1)</td>
</tr>
<tr>
<td>30–45(^a)</td>
<td>41 (4)</td>
<td>29 (1)</td>
<td>30 (5)</td>
<td>1.56 (0.10)</td>
<td>0.10 (0.01)</td>
<td>0.15 (0.01)</td>
<td>7.4 (0.3)</td>
<td>1.1 (0.1)</td>
</tr>
</tbody>
</table>

- \(^a\) Mean (S.D.).
- \(^c\) Bulk density calculated from sun/air dried weight of 6.3 cm × 5.7 cm soil cores.
- \(^d\) Total N analyzed with CE Instruments Flash 1112 Series NC Analyzer.
- \(^f\) pH in 1:1 soil water mixture measured with digital pH meter.
- \(^g\) Calculated based on formula: organic C = total C – inorganic C, where total C and inorganic C were measured with CE Instruments Flash 1112 Series NC Analyzer using untreated dried soil and soil combusted at 450 °C for 4 h, respectively.

### Table 2

Summary of experiments during each cropping season

<table>
<thead>
<tr>
<th>Season</th>
<th>Crop</th>
<th>Experiment design</th>
<th>Tillage methods (main plots)</th>
<th>Fertilizer applications(^a) (subplots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kremt 2003</td>
<td>Sorghum</td>
<td>Randomized complete block</td>
<td>Maresha tillage(^b), subsoiling, tied ridges, open ridges</td>
<td>None</td>
</tr>
<tr>
<td>Belg 2004</td>
<td>Chickpea</td>
<td>Randomized complete block</td>
<td>Maresha tillage(^b), subsoiling, tied ridges, open ridges</td>
<td>None</td>
</tr>
<tr>
<td>Kremt 2004</td>
<td>Sorghum</td>
<td>Split plot</td>
<td>Maresha tillage(^b), subsoiling, tied ridges, open ridges</td>
<td>N0: none, N1: 20.5 kg N ha(^{-1}), N2: 20.5 kg N ha(^{-1}) + 46 kg P ha(^{-1}), N2M1: 20.5 kg N ha(^{-1}) + 46 kg P ha(^{-1}) + 5 Mg ha(^{-1}) manure, N3: 41 kg N ha(^{-1}) + 46 kg P ha(^{-1})</td>
</tr>
</tbody>
</table>

- \(^a\) N and P were applied as urea and diammonium phosphate (DAP) and manure was mainly from cattle.
- \(^b\) Maresha tillage is the conventional method and the experimental control.
slope contour. Open and tied ridge plots were constructed with an oxen-drawn ridger implement (Fig. 2a) which is easily attached to the traditional maresha plow (Temesgen, 2000). The ridges were spaced 0.50 m apart. Plowing each row twice resulted in ridge heights of 10–15 cm (due to the hard subsoil conditions at the site) and average width of 0.27 m. Cross ties of 8–12 cm height and at 1–2 m intervals were manually created with traditional hoes for the tied ridge treatment. The conventional tillage and subsoiling plots were plowed along the contour with a traditional maresha (described in Nyssen et al., 2000; Gebregziabher et al., 2006) and a subsoiler, respectively. The animal powered subsoiler named “Tenkara Kend” developed by the Integrated Food Security Program (IFSP) in Debre Tabor, Ethiopia has an adjustable flat blade extension (Fig. 2b) that cuts the soil 6–12 cm below the normal plow depth of conventional maresha tillage (10–13 cm depth in this study). In this study the subsoiler cut the soil at 0.3–0.5 m intervals along the slope contour. On the no till plots no tillage operation had been performed since land preparation with maresha plow for the previous season’s chickpea crop (5.5 months). Narrow lines about 3 cm deep were manually scraped/dug to sow seeds in the no till plots. Regardless of treatment, all plots were manually sown in rows (on top of ridges for tied and open ridging) at 0.5 m spacing. Sowing in rows, which is different from the traditional practice of broadcast sowing, was required for planting on ridges and was implemented on all plots to achieve similar plant spacing between treatments. A surface mulch of dry sorghum stalk 2.5 Mg ha$^{-1}$ stored on another farmer’s field from the previous kremt season was applied 1 day after sowing on the no till plots only. The stalks of the previous year crop on the experiment site were not available anymore since they had been taken by the farm owner for other uses. The stalks were aligned along the slope contour.

During the third season (kremt 2004) of the study nutrients were applied as single dose to subplots (at the rates discussed in the previous section) and incorporated (except for no till which remained surface applied) during the final tillage of land preparation. Locally purchased diammonium phosphate 18-46-0 (DAP) and urea 46-0-0 chemical fertilizers (N–P–K) and dry animal (mainly cattle) manure (1.7% total N, 0.42% total P) collected from local farmers’ stalls were the sources/forms of applied nutrients.

The farmer who owned the land decided when all farm operations (tillage, weeding, harvest, etc.) were to be conducted. About a month after sowing sorghum plots were manually thinned to single plants with an average spacing of 0.25 m between plants and 0.5 m between rows. Weeding was carried out twice manually at 4–5 and 8–10 weeks, respectively, after sowing during each season. The no till plots required an additional weeding 3 weeks after sowing before the other treatment plots were weeded due to excessive weed infestation. No herbicides or pesticides were applied in any of the experiments. The local practice of shilshalo (which is practiced by many farmers in Wello on their sorghum crops, but not chickpea) in which small contour furrows are created with the maresha plow during the second weeding operation was not implemented in any plots because oxen could not plow after planting without disturbing adjacent plots and the soil bunds that separate them.

2.4. Surface runoff measurement

A runoff collection system was setup at the bottom of main plots (5–6 m × 30 m) for conventional maresha tillage, subsoiling, and tied ridge treatments on all experimental blocks while no till plots (kremt 2004) only had runoff collection systems at the top (9–11% slope) and bottom (0–3%) blocks. Each collection
system consisted of a sheet metal collector trough (6 m long × 0.25 m wide × 0.12 m deep) which empties runoff into a series of three storage barrels (0.18 m³ capacity each) interconnected by 10-slot flow divisors (Fig. 3). A plastic sheet was installed from about 10 cm buried below the soil at the bottom edge of the plot and extended over the trough lip into the trough. This effectively prevented runoff from seeping below the trough lip. Around 8 a.m. the following morning after every rainfall event the water level in all barrels was measured. The amount of water collected in the barrels was adjusted for direct and trough collected rainfall and for sediment volume. Daily rainfall amount measured at the farm location and rainfall interception area of trough (Fig. 3) were used to adjust runoff volume for direct rainfall during runoff calculations. The sediment volume measured at the bottom of each barrel and its water content were used to adjust runoff volume for sediment. Runoff volume was calculated using the following equation:

\[
V = \left[ \pi \left( \frac{D_1}{2} \right)^2 H_1 - \left( \pi \left( \frac{D_1}{2} \right)^2 + A_t \right) R - S_1 + W_1 \right] \\
+ 10 \left[ \pi \left( \frac{D_2}{2} \right)^2 H_2 - \pi \left( \frac{D_2}{2} \right)^2 R - S_2 + W_2 \right] \\
+ 100 \left[ \pi \left( \frac{D_3}{2} \right)^2 H_3 - \pi \left( \frac{D_3}{2} \right)^2 R - S_3 + W_3 \right]
\]

(1)

\[ V \text{ is the daily runoff volume from the plot; } H_i \text{ the water height in barrel } i \text{ in the series; } D_i \text{ the diameter of barrel } i; \pi \text{ is } P_i; R \text{ the daily rainfall depth measured at the farm site; } A_t \text{ the rainfall contact area of the runoff collection trough in the plot; } S_i \text{ the total wet sediment volume measured at the bottom of barrel } i; \text{ and } W_i \text{ is the volume of water content in the sediment of } S \text{ calculated based on the loss of water during drying of sediment samples (discussed further below).} \]

2.5. Soil loss measurement

Water samples were taken from each barrel of the runoff collection system described above after vigorously stirring for about 30 s. The water samples were analyzed at Sirinka Agricultural Research Center (SARC) laboratory in Sirinka, Ethiopia for suspended sediment concentration using the filtration technique. This method involves filtering 100 ml of water sample to capture sediment particles larger than 1.2 μm and then oven drying this sediment at 105 °C for 24 h before weighing. After emptying water from the barrels the volume of sediment left at the bottom was measured by counting the number of 1-liter cups, and fractions thereof, required to empty the barrel. A 400 ml sample of sediment was sun/air dried for 1–3 weeks (depending on the weather) and weighed to determine the dry weight. This same procedure of measuring the volume of sediment and drying a 400 ml sample was used to determine amount of sediment that deposited in the collector trough after each storm. All sediment is reported on a dry weight basis. Total sediment is the sum of suspended, barrel, and trough deposited sediment. Total sediment was calculated using the following equation:

\[
S_d = [S_1 F_1 + 10S_2 F_2 + 100S_3 F_3] + [C_1 V_1 + 10C_2 V_2 + 100C_3 V_3] + T_s C_i
\]

(2)

\[ S_d \] is the total dry mass of sediment from a runoff event; \( S_i \) the total wet sediment volume measured at the bottom of barrel \( i \); \( F_i \) the fractional dry weight of sediment in the sediment volume \( S_i \) based on the dried weight of a 400 ml sample from barrel \( i \); \( V_i \) the volume of runoff water measured in barrel \( i \); \( C_i \) the concentration of suspended sediment in a 100 ml sample of runoff from barrel \( i \); \( T_s \) the total wet sediment volume measured in the runoff collection trough; and \( C_i \) is the fractional dry weight of sediment in the sediment volume \( T_s \) based on the dried weight of a 400 ml sample.

2.6. Soil moisture measurements

Soil moisture was measured regularly (at 1–2 week intervals) with TDR soil moisture probes (Hydrosense 620, Campbell Scientific Inc.) and gravimetric field technique. Five to ten TDR measurements were taken with 12-cm long probes within three depth ranges (0–15, 15–30, and 30–45 cm) in random locations at the top
half of each plot (in buffer zones between nutrient treatments during kremt 2004). Measurements at 15–30 cm and 30–45 cm were taken by first digging small holes to 15 and 30 cm depths, respectively, before inserting the TDR probes directly into the undisturbed soil below. Readings from the probes were recalibrated for high clay soil type using results from gravimetric measurements taken concurrently at the same location. Linear regression was used to calibrate for each soil depth separately (0–15 cm, $r^2 = 0.70, P < 0.001$; 15–30 cm, $r^2 = 0.50, P < 0.001$; 30–45 cm, $r^2 = 0.41, P < 0.001$) due to increasing interference of higher clay content with depth (Table 1) on TDR measurements. Gravimetric measurements were taken regularly with 6.3 cm diameter × 5.7 cm height soil cores for each depth. Moist soil weight was measured immediately in the field. Samples were sun/air-dried for 1–3 weeks depending on climatic conditions before determining dry weight.

2.7. Grain yield and plant measurements

Grain yield was measured on two 2 m × 2 m quadrats for each kremt 2003 sorghum plot and two 3 m × 3 m quadrats for each belg 2004 chickpea plot. The kremt 2004 sorghum grain yield was measured on 2 m × 2 m quadrats in each subplot (total of 20 m² per main plot). All grain yields are for cleaned (ready for human consumption) grain adjusted to 12% moisture content.

For the kremt 2003 sorghum and belg 2004 chickpea experiments above-ground plant biomass and root mass were measured on six randomly selected plants distributed throughout each plot. During kremt 2004 above-ground biomass and root mass were measured for three randomly selected sorghum plants on each subplot giving a total of 15 plants per main plot. All plant and root samples were sun/air dried for at least 3 weeks before determining dry weight. During kremt 2004 maximum root depth was measured on three randomly selected plants per plot from no till (NT), subsoiled (SS), and conventional maresha tilled (M) plots by digging 60 cm deep trenches adjacent to plants and measuring the depth of the plant’s deepest principal root end (i.e., not including possible root hairs).

2.8. Statistical analysis

Analysis of variance (ANOVA) to determine the statistical significance of treatment effects was calculated using the General Linear Model (GLM) and $F$-test in MINITAB software (Minitab Inc., 2005). Treatment effects are considered to be statistically significant at $P < 0.05$ and $< 0.10$. Tukey’s honestly significant difference (HSD) for multiple comparisons was calculated in MINITAB to determine individual treatment differences ($P < 0.05$ and $< 0.10$).

3. Results and discussion

3.1. Agro-climate

Rainfall amount and quality during the study period varied greatly between cropping seasons. Fig. 4 shows on-site measured rainfall, mean temperature, and pan evaporation. Rainfall for each crop growth period from sowing to harvest totalled 422 mm for kremt 2003, 232 mm for belg 2004, and 418 mm for kremt 2004.

Fig. 4. Monthly rainfall, pan evaporation, and mean temperature at the experiment site during July 2003 to October 2004.
Although the kremt 2003 and kremt 2004 seasons had similar rainfall totals their quality for crop production in terms of temporal distribution was remarkably different. During the kremt 2003 season 65% (273 mm) of the total seasonal rainfall depth came during a 3-week period from the last day of July until the third week of August. The month of September 2003, which is a critical water requirement period for initiation of sorghum reproductive growth, only received 52 mm of rain and had an 11-day dry spell with no significant rainfall event (over 2 mm). The month of October 2003 during sorghum early grain-filling there was no rainfall while the period of November until sorghum harvest at the beginning of December received negligible rainfall. The poor temporal distribution of rainfall during kremt 2003 with periods of intense rainfall followed by lengthy dry spells contrasts with the kremt 2004 season which had similar total rainfall but no significant dry spell. As seen in Fig. 4, during kremt 2004 the months of July, August, and September received better-distributed proportions of the seasonal total rainfall compared with 2003 and in 2004 rainfall even extended into October (49 mm) providing critical water during the sorghum grain-filling stage. Rainfall events during kremt 2003 were generally stormy with short duration and high intensity while the kremt 2004 events were generally medium intensity long duration. Kremt 2003 had eight events with $I_{30}$ (30-min maximum rainfall intensity) over 25 mm h$^{-1}$ all occurring after sowing and with a maximum $I_{30}$ of 93 mm h$^{-1}$ compared with kremt 2004 which only had three events with $I_{30}$ over 25 mm h$^{-1}$ all occurring before sowing and with maximum $I_{30}$ of 31 mm h$^{-1}$.

During belg 2004 rainfall was especially poorly distributed with essentially all precipitation coming during the period of mid-March until the end of April. There was a 37-day dry spell with no rain after sowing chickpea on 11 February and negligible (one event of 2 mm) rainfall during the 36 day period from the last week of April until the end of May which corresponded with the late grain-filling and maturity periods for the chickpea crop. Belg rainfall events were dominated by highly intense storms including four events with $I_{30}$ (30-min maximum rainfall intensity) over 25 mm h$^{-1}$ all occurring over a month after sowing and with a maximum $I_{30}$ of 75 mm h$^{-1}$.

Mean daily temperature varied between 20 and 28 °C during the 1.5-year period with maximum mean temperatures occurring during June and minimum mean during December (Fig. 4). Temperature and pan evaporation followed similar trends during the year. For all months, except August 2003, monthly pan evaporation exceeded precipitation. Pan evaporation rates are quite high with monthly means of 4–9 mm per day due to generally dry windy conditions, relatively hot temperatures, and many clear sunny days. The highest evaporation rates occurred during months/periods with no (or little) precipitation and dry land-surface conditions in the landscape surrounding the pan which probably resulted in pan evaporation greatly overestimating potential evaporation during those dry periods. Brutsaert and Parlange (1998) determined that the pan factor can be as much as 2 when the surrounding land is dry.

### 3.2. Surface runoff

Surface runoff from plots was significantly affected by tillage method, slope, and seasonal rainfall characteristics. Table 3 presents runoff during belg and kremt 2004 (the kremt 2003 runoff is not presented due to missing/poor quality data during several major storms early in the season which destabilized the collection system divisors). The block with the steepest slope gradient of 9–11% had significantly ($P < 0.05$) more runoff across tillage treatments with over 20% of total seasonal rainfall lost (from field-scale perspective) to surface runoff compared with the 0–3% and 4–8% slope gradient generating less than 15% rainfall runoff.

Among tillage treatments conventional tillage with maresha produced the most surface runoff volume followed by subsoiling, no till with stalk mulch, and tied ridge in that order. Subsoiling produced less (12% less belg 2004 and 8% less kremt 2004), but statistically similar runoff depth compared to conventional tillage with maresha. The effect of subsoiling on runoff was more significant on the 0–3% slope gradient during both seasons (Table 3). At steeper slopes rainwater might not have enough residence time on the plot to take advantage of the deeper soil cutting which is the main feature of subsoil tillage.

During kremt 2004 tied ridge and no till with mulch produced less than half the runoff depth of conventional maresha tillage. Tied ridge and no till were particularly effective at capturing rainwater on the 0–3% slope gradient with over 98% of seasonal rainwater captured in-field. In the case of the 4–8% slope, tied ridge performed well (75% less runoff than conventional tillage) during the less intense better temporally distributed rains of kremt 2004 season while during belg 2004 it performed similarly to conventional tillage due to numerous ridge breaks caused by intense rain storms and also because the tied ridge plot had a steeper slope gradient (7%) compared with the conventional...
During all seasons most ridges on the 9–11% slope gradient broke while on the 0–3% slope gradient there were no breaks for the tied ridges. All ridges wore down as the rainy season progressed resulting in progressively less efficient capture and storage of rainwater. During the 2003 kremt season final measured ridge height was on average 1.5 cm, belg 2004 season was 4 cm, and kremt 2004 season was 2.5 cm. The longer rainy period of the kremt rainy seasons (57 rainy days kremt 2003 and 48 rainy days kremt 2004 compared with 20 rainy days during belg 2004) with almost twice as much total seasonal rainfall and differences in the planted crops (kremt sorghum, belg chickpea) are possible reasons for greater ridge flattening during the kremt seasons.

3.3. Soil loss

Differences in seasonal rainfall characteristics greatly affected erosion rates (Table 4). The kremt 2003 season which had many high intensity storms at the beginning of August before crop establishment produced over twice the mean soil loss rate of any other season. The highly intense nature of belg 2004 rains resulted in similar seasonal soil loss as the kremt 2004 season which had less intense but almost twice as much total rainfall.

Slope gradient significantly influenced erosion rates and even more than it affected runoff rates. The 9–11% slope gradient had a 17–89-fold increase in soil loss over the 0–3% slope gradient but a less than fivefold increase in surface runoff (Tables 3 and 4). During the rainy seasons we observed that on the 0–3% slope gradient no rills were apparent while at the steeper slopes and especially the 9–11% slope gradient all plots had at least one rill before the end of the cropping season. This suggests that the primary erosion mechanism at the 0–3% slope gradient was interill erosion while at the steeper slopes rill erosion combined with interill erosion to significantly increase soil loss rate. The incidence of ridge failures was also high on the steep slope gradient. After breaking, the concentrated flow of captured rainwater through the ridge gaps led to rill formation. Qualitative assessments of rills during the study period noted deep narrow rills on the open ridge plots, numerous microrills on the tied ridge plots, deep wide rills on conventional and subsoil plots, and shallow wide rills on the no till plots. The formation of rills on 9–11% slope gradient regardless of tillage technique suggests the distance between stone bunds (or other soil conservation structures) should be less than the standard research plot length of 30 m, used in soil conservation studies in Ethiopia (SCRP, 2000), and particularly for slopes steeper than 9% gradient in the Wello region on this type of soil.

Table 3
Surface runoff during belg and kremt 2004a cropping seasons

<table>
<thead>
<tr>
<th>Treatment slope</th>
<th>Surface runoff (mm)</th>
<th>Seasonal runoff coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–3%</td>
<td>4–8%b</td>
</tr>
<tr>
<td>Chickpea belg 2004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maresha</td>
<td>35</td>
<td>32</td>
</tr>
<tr>
<td>Subsoiling</td>
<td>23</td>
<td>29</td>
</tr>
<tr>
<td>Tied ridge</td>
<td>6</td>
<td>33</td>
</tr>
<tr>
<td>Mean for slope class**</td>
<td>20 A</td>
<td>31 A</td>
</tr>
<tr>
<td>Sorghum kremt 2004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maresha</td>
<td>41</td>
<td>57</td>
</tr>
<tr>
<td>Subsoiling</td>
<td>25</td>
<td>63</td>
</tr>
<tr>
<td>Tied ridge</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>No tillc</td>
<td>6</td>
<td>–</td>
</tr>
<tr>
<td>Mean for slope class**</td>
<td>18 A</td>
<td>45 B</td>
</tr>
</tbody>
</table>

Different letters are significantly different (Tukey’s test). **P < 0.05.

a Kremt 2003 not presented because missing and poor quality data for several major storms that occurred early in the season.
b Note conventional maresha tillage on 4% slope gradient while subsoiling and tied ridge are on 7% slope gradient.
c NT not measured during the season’s first month (18–31 July 2004) which comprised about 5% of total kremt 2004 runoff depth on the other treatment plots.
intense rainfall storms (kremt 2004), but drastically increased erosion (compared to conventional tillage) up to 35 Mg ha\(^{-1}\) during the season with many high intensity storms (kremt 2003) particularly on the steeper slopes (Table 4). The high runoff rates combined with increased soil disturbance of conventional and subsoil tillage resulted in high seasonal soil loss rates (up to 32 Mg ha\(^{-1}\)) on the steeper slopes (>9\%). On the gentle slope gradient (0–3\%) both subsoiling and conventional tillage had similar low levels of soil loss (<2 Mg ha\(^{-1}\)). Slope gradient and tillage technique affected both suspended sediment and total sediment losses (Table 4) suggesting impacts on erosion and transport of both fine and heavier soil particles.

The sustainable maximum soil loss rate for the Ethiopian highlands ranges between 6 and 10 Mg ha\(^{-1}\) (these rates do not account for colluviation which may occur in some areas). The lower 6 Mg ha\(^{-1}\) is based on the annual soil formation rate for the climatic zone (semi-arid to dry subhumid or called dry woina dega agroecological zone in Ethiopia) cited by Nyssen et al. (2004). The higher soil loss tolerance limit of 10 Mg ha\(^{-1}\) was applied by Mwendera and Mohamed Saleem (1997) in their study of effect of cattle grazing pressure on soil loss. Given a sustainable maximum in situ soil loss rate as 6–10 Mg ha\(^{-1}\) and the soil loss rates measured in this study, cropping on the steepest (9–11\%) slope gradient is not sustainable (assuming there is no colluviation in the area because the plots were hydrologically separated) with any of the tested tillage methods (except possibly no till which was only tested for one season). Conversely, soil loss rates on 0–3\% slope gradient were low (<2M gh a\(^{-1}\)) for all tillage methods during all seasons. Taking into account that for the 4–8\% slope gradient tied ridge was on a plot with 7\% slope gradient like subsoiling but resulted in lower soil loss rates suggests that tied ridge could be sustainable up to a steeper slope gradient limit than subsoiling on our soil type (Table 4). The results of this study underscore the importance of implementing soil conservation structures such as stone bunds, fanya juu, etc. (Herweg and Ludi, 1999; SCRP, 2000; Gebremichael et al., 2005; Vancampenhout et al., 2006) in combination with the improved tillage practices especially on slopes greater than 9\%.

### 3.4. Soil moisture for dry spell mitigation

The amount of rainwater stored in the soil profile during the cropping season is important for plant growth (in rainfed agriculture) given the unreliable temporal distribution of rainfall observed at the study site. Effective tillage techniques capture rainwater and store sufficient moisture in the soil during rainy periods for

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**Table 4**

Soil loss during each cropping season

<table>
<thead>
<tr>
<th>Treatment slope</th>
<th>Total sediment (Mg ha(^{-1}))</th>
<th>Suspended sediment (Mg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–3%</td>
<td>4–8%</td>
</tr>
<tr>
<td>Sorghum kremt 2003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maresha(^{b})</td>
<td>1.6</td>
<td>9.9</td>
</tr>
<tr>
<td>Subsoiling(^{b})</td>
<td>1.8</td>
<td>23.3</td>
</tr>
<tr>
<td>Tied ridge(^{b})</td>
<td>1.7</td>
<td>12.4</td>
</tr>
<tr>
<td>Mean for slope class**</td>
<td>1.7 A</td>
<td>15.2 B</td>
</tr>
<tr>
<td>Chickpea belg 2004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maresha</td>
<td>0.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Subsoiling</td>
<td>0.7</td>
<td>6.2</td>
</tr>
<tr>
<td>Tied ridge</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Mean for slope class**</td>
<td>0.5 A</td>
<td>2.8 B</td>
</tr>
<tr>
<td>Sorghum kremt 2004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maresha</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Subsoiling</td>
<td>0.2</td>
<td>5.5</td>
</tr>
<tr>
<td>Tied ridge</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>No till(^{c})</td>
<td>&lt;0.1</td>
<td>–</td>
</tr>
<tr>
<td>Mean for slope class**</td>
<td>0.1 A</td>
<td>2.1 B</td>
</tr>
</tbody>
</table>

Different letters significantly different (Tukey’s test), \(*P < 0.10, **P < 0.05.

\(^{a}\) Note conventional maresha tillage is on 4\% slope gradient while subsoiling and tied ridge are on 7\% slope gradient.

\(^{b}\) Data missing for the season’s first two major erosion events 31 July 2003 and 1 August 2003 which received 59 and 37 mm rainfall, respectively.

\(^{c}\) NT not measured during the season’s first month (18–31 July 2004) which comprises about 7\% of total kremt 2004 soil loss on other treatment plots.
continuing plant uptake during dry periods. Fig. 5 presents soil moisture at 0–15 and 30–45 cm depths for each crop season. Overall trends show that the tied ridge plots had the best soil moisture within and across cropping seasons and at all depths (however, the effect of tillage method on seasonal soil moisture was only statistically significant during kremt 2004 at 30–45 cm depth, $\alpha = 8\%$). Tied ridge volumetric soil moisture was on average 24% higher at 0–15 cm depth and 9% higher at 30–45 cm depth compared to conventional tillage. However, effectiveness of ridges at capturing rainfall declined with steeper land slope gradient and more intense seasonal rainfall events which broke many ridges reducing their efficiency to store rainwater.

Open ridges performed second best with higher seasonal soil moisture than subsoiling, no till, and conventional tillage. Open ridge soil water content averaged 15% higher at 0–15 cm depth and 3% higher at 30–45 cm depth than conventional tillage (Fig. 5). An advantage of open ridge is that it required less labor to construct and was as effective as tied ridge at capturing rainwater. As in the case of tied ridges, many open ridges broke on the plots with steeper slopes. However, ridge breaks for open ridges affected entire crop rows (in terms of rainwater storage) while breaks in tied ridges only affected the row interval between ties. Once breaks occurred in open ridges rainwater captured between ridges produced localized runoff through the break opening which then caused more ridge breaks downslope. Ridge breaks caused by intense storms is the reason for relatively less effectiveness of open ridge on soil moisture during kremt 2003 (Fig. 5a and b) and belg 2004 (Fig. 5c and d) compared with kremt 2004 (Fig. 5e and f). An observed shortcoming of planting on ridges was their dryness at the beginning of the season which delayed seed germination and retarded early plant growth (discussed in next section). Fig. 6 shows how ridge moisture was significantly ($\alpha = 5\%$) and consistently lower (51% less on average) than in the furrow/flat bed.

Subsoiling slightly increased (3% overall) soil moisture compared with conventional tillage but not consistently for all seasons and soil depths. Any additional moisture during dry periods is important for plant growth especially during reproductive growth and grain-filling. During kremt 2003 and belg 2004 subsoiling and conventional maresha tillage had similar 0–15 cm surface soil moisture, but subsoiling had better soil moisture at 30–45 cm depth (Fig. 5a–d) which is important for longer-term water storage. Rainfall distribution during kremt 2004 resulted in better (compared to kremt 2003 and belg 2004) soil moisture for all tillage methods (Fig. 5e and f). In all cases after a prolonged dry period the differences in moisture content between treatments became smaller as the plants used all the remaining moisture in the soil.

No till with stalk mulching was only tested during the kremt 2004 cropping season. Fig. 5e and f shows that soil moisture for no till was similar to that of conventional maresha tillage. Additional tests during cropping seasons with more intense rainfall and with longer no till periods (i.e. to permit natural processes of soil quality/structure improvement to occur) are needed to better determine effect of no till on soil moisture in the northern Ethiopian highlands dryland cropping systems.

### 3.5. Grain yield and plant growth

Sorghum grain yield responded significantly to land preparation tillage method during both 2003 and 2004 kremt seasons, but for the chickpea crop of belg 2004 tillage treatments did not produce statistically significant yield differences (Table 5). Among the tested land preparation methods subsoiling, tied ridges, and open ridges increased sorghum grain yield while no till reduced yield.

Subsoiling significantly increased grain yield by 42% during kremt 2003 and 33% during kremt 2004 compared to conventional tillage with maresha. In the

<table>
<thead>
<tr>
<th>Treatment season</th>
<th>Grain yield (kg ha⁻¹)</th>
<th>Plant density (pl m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sorghum* kremt '03</td>
<td>Chickpea belg '04</td>
</tr>
<tr>
<td>Maresha</td>
<td>1430 A</td>
<td>730 A</td>
</tr>
<tr>
<td>Subsoiling</td>
<td>2030 B</td>
<td>970 B</td>
</tr>
<tr>
<td>Open ridges</td>
<td>1470 A</td>
<td>1220 B</td>
</tr>
<tr>
<td>Tied ridges</td>
<td>1530 AB</td>
<td>1260 B</td>
</tr>
<tr>
<td>No till</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Different letters are significantly different (Tukey’s test), *$P < 0.10$, **$P < 0.05$. 

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Fig. 5. Soil moisture (lines) and daily rainfall (hanging bars) during kremt 2003 at (a) 0–15 cm depth and (b) 30–45 cm depth; during belg 2004 at (c) 0–15 cm depth and (d) 30–45 cm depth; and during kremt 2004 at (e) 0–15 cm depth and (f) 30–45 cm depth. The bars shown in all the figures represent the minimal difference [5% honestly significant difference (HSD)] for statistical significance by Tukey's test at $\alpha = 5\%$. The effect of tillage method on soil moisture was only statistically significant during kremt 2004 at 30–45 cm depth.
Fig. 5. (Continued).

(d) 30

Volumetric Moisture (%)

Rainfall (mm)

1-Jan-04 1-Feb-04 1-Mar-04 1-Apr-04 1-May-04 1-Jun-04

- Maresha - Subsoiling - Open ridge - Tied ridge

=5% HSD

(e) 50

Volumetric Moisture (%)

Rainfall (mm)


- Maresha - Subsoiling - Open ridge - Tied ridge - No till

=5% HSD

(f) 30

Volumetric Moisture (%)

Rainfall (mm)


- Maresha - Subsoiling - Open ridge - Tied ridge - NO till

=5% HSD
cases of kremt 2003 and belg 2004, subsoiling produced the best grain yield among the tested tillage methods while tied and open ridge performed better during kremt 2004 (Table 5). The improved grain yield of subsoiling is probably due to combined effects of slightly improved soil moisture and better root growth than conventional tillage. Table 6 presents plant root mass and total above-ground biomass. Root mass for subsoiling was higher than for conventional tillage during kremt 2003 and belg 2004 and lower during kremt 2004. Measurement of maximum principal roots depth during kremt 2004 found a mean depth of 27.3 (±1.2S.D.) cm for subsoiling, 22.1 (±6.1) cm for conventional tillage with maresha, and 20.0 (±1.0) cm for no till \((P = 0.15)\). This suggests that although root mass for kremt 2004 was lower in subsoiled plots the root depth was longer improving access to water and nutrients from a deeper soil volume which resulted in better yield and biomass than conventional tillage and no till.

The potential benefit of ridging to improve grain yield (open ridges 67% increase, tied ridge 73% increase) was very apparent during the sorghum 2004 season. The seasonal difference in ridge performance (Table 5) in the case of kremt 2003 and kremt 2004 is probably due to difference in rainfall intensity while poor performance during belg 2004 was associated with both the high intensity of storms and the long dry spell early in the growing season. Highly intense storms during kremt 2003 broke unprotected (i.e. little crop cover) unconsolidated ridges resulting in washing away of seeds, exposure/uncovering of young plant roots on ridges, and loss of plants at the ridge break gaps. The many sorghum plants that survived had retarded early growth due to lodging and difficulties with root and plant establishment. In terms of plants lost, tied ridge was more impacted due to numerous ridge breaks between ties compared with open ridge which generally had only one or two breaks in the entire row. As seen in Table 5, this resulted in 21% less plant density for tied

Fig. 6. Soil moisture at 0–15 cm depth on top of ridges (open symbols) and in the adjacent furrows (closed symbols) and daily rainfall (hanging bars) during all cropping seasons (2003–2004). The bar shown in the figure represents the minimal difference [5% honestly significant difference (HSD)] for statistical significance by Tukey’s test at \(\alpha = 5\%\).
ridges compared with open ridges and 13% less than on plots with conventional tillage (2003). Seed and young plant losses were partially compensated for by plant number adjustments made on all plots during plant thinning which is a common local practice. During kremt 2003 significantly lower soil moisture in ridges compared to flatbeds (Fig. 6) retarded early sorghum plant growth (27-days after sowing mean plant biomass was 3.9 g m\(^{-2}\) tied ridges, 4.9 g m\(^{-2}\) open ridges, 6.7 g m\(^{-2}\) conventional tillage, 7.1 g m\(^{-2}\) subsoiling; \(P < 0.05\)), but as the season progressed and plant roots advanced deeper into the soil the ridge dryness effect became inconsequential resulting in higher plant biomass at harvest on ridge tillage plots (Table 6).

During belg 2004 a major reason for poor performance of all and especially open and tied ridge treatments was the long dry spell early in the growing season. The increased working (displacement and turning over) of surface soil associated with ridging during land preparation resulted in increased evaporation losses of pre-tillage residual soil moisture. As seen in Fig. 6, ridges (where chickpea seed was sown) were excessively dry during the first month after sowing which resulted in poor germination rates.

No till with stalk mulching produced the least grain of all tillage treatments (Table 5). The hard soil in no till plots resulted in poor root growth (Table 6) and plant establishment (i.e., lodging) which, in addition to the increased weed infestation, explain the poor grain and biomass production. It is of interest to mention that no till plots had the first and best germination rate (about 2 days earlier) of all treatments possibly due to the initially better surface moisture than the tilled plots which inverted dry surface soil and exposed subsoil to drying by the sun and wind.

Sorghum responded well to nitrogen additions. Table 7 presents grain yield for the nutrient subtreatments during the 2004 sorghum experiment. Addition of 20.5 kg ha\(^{-1}\) nitrogen as urea significantly increased grain yield by 62%. However, addition of 46 kg ha\(^{-1}\) phosphorus as DAP together with 20.5 kg ha\(^{-1}\) nitrogen resulting in less yield increase than only the urea (N) application and did not produce a statistically significant difference in yield compared with no nutrient addition. The addition of 5 Mg ha\(^{-1}\) animal manure in addition to 46 kg ha\(^{-1}\) phosphorus and 20.5 kg ha\(^{-1}\) nitrogen as chemical fertilizer resulted in a slight (7%), but statistically significant (\(P < 0.05\)), increase in yield compared with similar fertilizer application rate without manure (Table 7). The best grain yield increase of 109% was obtained with 41 kg ha\(^{-1}\) nitrogen and 46 kg ha\(^{-1}\) phosphorus. This gain is likely more due to the high N application rather than the P component given the statistically insignificant yield increase (compared with no nutrient addition) obtained with the same P application but at lower N rate (20.5 kg ha\(^{-1}\)). Grain yield responses to nutrient additions overall suggest that N is the most limiting nutrient and that grain yield can easily double with application of the current local Sirinka Agricultural Research Center recommended dose of 41 kg ha\(^{-1}\) nitrogen and 46 kg ha\(^{-1}\) phosphorus for North Wello and the particular variety of improved sorghum used here. Further nutrient studies are needed to determine optimum doses of N and P fertilizer application and the longer term soil health benefits of manure application.

Although there was no statistically significant interaction between land preparation method and nutrient addition on grain yield the best mean yield of 1.75 Mg ha\(^{-1}\), which is a four-fold increase over the 0.43 Mg ha\(^{-1}\) obtained from conventional maresha tillage with no nutrient addition, was produced by combining tied ridge and fertilizer application (Table 7). No till demonstrated the least response to the surface applied fertilizer nutrient additions compared to other treatments which incorporated the nutrient applications during tillage. Sorghum yield could have been higher during kremt 2004 for all

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**Table 7**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No nutrient additions</th>
<th>Urea (N(_{20,5}))</th>
<th>DAP + urea (N(<em>{20,5}) P(</em>{46}))</th>
<th>DAP + urea (N(<em>{20,5}) P(</em>{46})) + manure (5 Mg ha(^{-1}))</th>
<th>DAP + urea (N(<em>{4,1}) P(</em>{46}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maresha</td>
<td>430</td>
<td>670</td>
<td>520</td>
<td>670</td>
<td>920</td>
</tr>
<tr>
<td>Subsoiling</td>
<td>710</td>
<td>880</td>
<td>900</td>
<td>1000</td>
<td>1380</td>
</tr>
<tr>
<td>Open ridges</td>
<td>570</td>
<td>1290</td>
<td>1280</td>
<td>960</td>
<td>1240</td>
</tr>
<tr>
<td>Tied ridges</td>
<td>820</td>
<td>1310</td>
<td>1000</td>
<td>1210</td>
<td>1750</td>
</tr>
<tr>
<td>No till</td>
<td>220</td>
<td>270</td>
<td>460</td>
<td>660</td>
<td>460</td>
</tr>
<tr>
<td>Overall mean</td>
<td>550 A</td>
<td>890 B*</td>
<td>840 A</td>
<td>900 B**</td>
<td>1150 B**</td>
</tr>
</tbody>
</table>

Different letters are significantly different (Tukey’s test), *\(P < 0.10\), **\(P < 0.05\).

\(^a\) N and P additions are expressed in kg ha\(^{-1}\).
treatments, but conditions of long duration light rains resulted in high yield losses by pests (especially stalk borer) and disease.

Slope gradient had a significant effect on grain yield across all tillage methods and for all seasons (Table 8). Grain yield decreased as plot slope gradient increased for both sorghum seasons while chickpea yield increased with slope gradient. The decreased sorghum yield with steeper slopes is in part explained by less soil moisture associated with increased runoff and poorer performance of conservation tillage for steeper slopes and the high erosion rates (with consequent soil quality differences). The reason for low chickpea yield on the 0–3% slope gradient was fungus attack during the second half of the growing season only affecting that block. This resulted in plant losses, pods with few and smaller seeds, and decreased plant density especially for the subsoiled plot (Table 5). A possible reason for fungus attack on only the 0–3% block could be that the generally better soil moisture status measured there created more favorable conditions for fungus growth (Bhatti and Kraft, 1992; Pande et al., 2005). There were no statistically significant grain yield response interactions between slope gradient and tillage method or between slope gradient and nutrient additions.

4. Local farmer insights

Comments and insights of 12 other local farmers who tested the conservation tillage treatments on their own fields (these were separate trials by other farmers and were not part of the controlled experiment presented above) and 28 others who visited the experiment site were sought and recorded to determine prospects and issues for wider-scale adoption and adaptation of conservation tillage methods. All the farmers were interested in testing the subsoiling while none were interested in testing the ridge tillage or no till. Discussions with farmers revealed their disinterest/unwillingness to test ridge tillage was the much higher labor requirements of an additional tillage for ridge formation, manual planting along ridges, and, in the case of tied ridges, manual construction of cross ties. Conventionally sorghum and chickpea seed are sown by broadcasting before final tillage with the maresha plow during land preparation. This requires little labor compared with manual planting along rows as for ridges. In the case of subsoiling (flatbed), the conventional practice of broadcast sowing can just as easily be applied. The farmers expressed concern for the weight of the subsoiler putting extra strain on the plow operator and the oxen (new lighter models are under development). Subsoiling is more demanding on oxen resulting in approximately 1/4 to 1/3 less area plowed per day (as observed in our experiments and by farmers) and the need of healthy strong oxen. For the case of no till, farmers were very skeptical that better grain yields can be obtained without tillage and were concerned about the manual labor for the more frequent weeding required without use of expensive/unavailable herbicide. The extra labor to bury seeds in shallow strips to prevent washing away was also of concern. The prospects for applying mulch is complex within the current farming system that has open field livestock foraging during the off-seasons and competing demands of crop residues for firewood, construction materials, and livestock feed.

Additional studies are required to compare the local farmer practice of shilshalo in which small furrows are created with the maresha plow during the second weeding operation to the tested ridging practice in which small ridges are constructed at the beginning of the season before sowing. An advantage of shilshalo will likely be less early season moisture stress and less plant loss and damage than were observed with the ridging/planting practice in the present study. Brhane et al. (2006) found in Tigray region of Northern Ethiopia that shilshalo produced slightly higher grain yield and soil moisture than flat bed, but tied-ridging before planting produced the best grain yield and soil moisture. We did not implement shilshalo in the present

Table 8
Slope gradient effect on grain yield (kg ha$^{-1}$)

<table>
<thead>
<tr>
<th>Treatment slope</th>
<th>Sorghum kremt '03**</th>
<th>Chickpea belg '04*</th>
<th>Sorghum kremt '04**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–3% 4–8% 9–11%</td>
<td>0–3% 4–8% 9–11%</td>
<td>0–3% 4–8% 9–11%</td>
</tr>
<tr>
<td>Maresha</td>
<td>1410 1540 1350</td>
<td>140 210 310</td>
<td>830 830 430</td>
</tr>
<tr>
<td>Subsoiling</td>
<td>2400 1990 1700</td>
<td>290 310 380</td>
<td>1100 940 810</td>
</tr>
<tr>
<td>Open ridges</td>
<td>1600 1830 990</td>
<td>80 260 390</td>
<td>1900 890 680</td>
</tr>
<tr>
<td>Tied ridges</td>
<td>1960 1470 1150</td>
<td>210 400 220</td>
<td>1510 1160 1020</td>
</tr>
<tr>
<td>No till</td>
<td>– – – –</td>
<td>– – –</td>
<td>– – –</td>
</tr>
<tr>
<td>Overall mean</td>
<td>1840 B 1710 A 1300 A</td>
<td>190 A 300 B 320 B</td>
<td>1240 C 880 B 620 A</td>
</tr>
</tbody>
</table>

Different letters are significantly different (Tukey’s test), *P < 0.10, **P < 0.05.
study because oxen could not plow after planting without disturbing adjacent plots.

5. Conclusion

Results of on-farm experiments during three cropping seasons demonstrate that conservation tillage can be beneficial for improving soil moisture, raising grain yields, and reducing runoff and soil loss in the northern Ethiopian highlands. However, performance varied greatly depending on seasonal rainfall intensity and temporal distribution and land slope gradient. Overall, tied ridge tillage was the most effective at improving rainfall partitioning (i.e. less runoff loss from fields) and root zone soil moisture for dry spell mitigation and at reducing soil loss. However, the relatively small ridges created using the oxen-drawn ridger worked better for slopes less than 8% limiting their applicability to mainly footslopes, valley bottoms, and plains. Open and tied ridge on steeper slopes resulted in significant soil loss, rill formation, plant damage with ridge breaks, and reduced rainwater capture and storage efficiency. Also, planting on the ridge resulted in decreased chickpea yield due excessive ridge dryness during a belg 2004 early season dry spell.

Subsoiling was moderately effective for improving sorghum yield, improving soil moisture, and reducing runoff. However, our results suggest that increased soil disturbance associated with subsoiling can result in severe erosion rates on steep slopes. Subsoiling performed best on slopes less than 8% under the soil conditions in this study and performed better in terms of grain yield than ridges when early season rainfall was very intense (ridge damaging). The potential benefits of subsoiling in other areas of Ethiopia might differ depending on the presence and extent of a plow pan. No till with stalk mulching reduced soil loss, but also decreased grain yield substantially over one season.

Application of fertilizers, especially nitrogen, in combination with conservation tillage (tied and open ridges and subsoiling) resulted in an over three-fold increase in grain yield compared with conventional practice of mesha tillage and no nutrient addition. This finding underscores the importance of applying an integrated rainwater management and soil nutrient improvement program to address poor rainfed grain yields in northern Ethiopia.

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