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Water spreading weirs altering flood, nutrient distribution and crop productivity in upstream–downstream settings in dry lowlands of Afar, Ethiopia

Research Paper

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Abstract

Afar in Ethiopia is a drought prone area characterized by low rainfall, high temperature and suffering from flash flood emerging from adjacent mountains. We introduced a flood barrier, water spreading weirs (WSWs) in 2015 to convert floods to a productive use and assessed its effect in 2016 and 2017. WSWs resulted in deposition of sediments where sand deposition was higher in the upside of upstream weir whereas silt and clay deposition was prominent at the central location between the two weirs. There was a moisture gradient across farming fields with volumetric water content (VWC) at 20 cm depth varying between 10 and 22% depending on the relative position/distance of fields from the WSWs, consequently, effecting significant difference in yield between fields. There was a positive relationship between VWC made available by WSWs at planting and the yield ($P < 0.001$, $r = 0.76$) and biomass productivity ($P < 0.005$, $r = 0.46$). WSWs created differing farming zone following soil moisture regime, affecting grain and biomass yield. In good potential zones with high moisture content, the WSW-based farming enabled to produce up to 5 and 15 t ha^{-1} yr^{-1} of maize grain and biomass, respectively, while in low potential zones there was a complete crop grain failure. The system enabled pastoralists to produce huge amount of biomass and grain during Belg (short) and Meher (long) growing seasons that was stored and utilized during succeeding dry periods. Furthermore, the practice ensured a visible recovery of degraded rangelands. This was evident from the filling up of the riverbed as well as the two WSW wings with 1 m high and about 450 m length each with fertile sediment from Belg and Meher seasons of 2016 and 2017. Hence, future studies should analyze the sustainability and the potential of flood-based development at large scale.

Introduction

Drought and flood have been affecting livelihoods in the low-lying Great Rift Valley of Africa interchangeably, with millions of people exposed to these extreme events on regular basis. Flash floods occur in lowland areas whereas upstream highlands generate sudden but excessive runoff in the peak rainy months. On the other hand, recurrent drought affects the livelihoods of the pastoral and agropastoral systems, which are forced to adapt mobile ways of life in search for water and feed for most parts of the year and shift in herd composition from grazers to browsers (Belay *et al*., 2005).

The low-lying area in Afar is a drought prone area where rainfall is low, evapotranspiration is high (Fazzini *et al*., 2015) and the capacity to produce food and feed crops is extremely weak (Brown *et al*., 2017). However, the area is hydrologically connected with a series of mountainous terrains of adjacent highlands of Amhara and Tigray regions, which generate a large amount of flood that could be converted to productive use through introducing spate irrigation systems (Steenbergen *et al*., 2011). Diversions of river flow for spate irrigation provide available water resources for increasing local feed and food production and enhancing environmental sustainability (Tesfai and Graaff, 2000; Tesfai and Stroosnijder, 2001; Mehari *et al*., 2005). A detailed review of spate irrigation (Erkossa *et al*., 2013) described the traditional use of floods for supplemental spate irrigation for crop production in different parts of Ethiopia.

While farmers in drought prone areas of Ethiopia, mainly Amhara and Tigray regions benefit from spate irrigation to develop crop–livestock systems (Ham, 2008; Erkossa *et al*., 2013; Hiben and Embaye, 2013), the (agro)pastoral communities in Afar are rarely utilizing these resources. Rather, flood and associated soil erosion have been perceived as top ranking problems by agro-pastoralists in the vicinity of Chifra (Gebreyes *et al*., 2017). The major reasons for low level of spate irrigation could be: (1) limited available labor in pastoral systems because men are mostly in continuous mobility traveling long distances searching forage and water for their livestock; (2) they rarely have experience in farming and in timely agronomic management and (3) there is limited institutional support for pastoralists to learn, adapt and practice flood-based farming in the locality.

Historically, the floods used to be naturally flushed to the low-lying flat lands and rangelands providing opportunity for natural grass to sprout helping (agro)pastoralists for their livestock to browse in rotation on seasonal basis. However, this practice has changed due to increasingly regular extreme events of flood and drought. It has aggravated land degradation and facilitated land use change (Tsegaye, 2010; Seid *et al.*, 2016) by converting the flood channels to deep gullies and undulating landscapes, posing difficulties for the flood to follow its traditional routs.

Moreover, soil erosion and degradation abandoned a large area of rangeland, the productivity of the traditional grazing lands diminished (Gebremeskel, 2006). Overgrazing (Sonneveld *et al.*, 2010), climate change (Meze-Hausken, 2004; Deressa *et al.*, 2008) and expansion of invasive weeds mainly *Prosopis juliflora* (Mehari, 2015) posed additional pressure on the natural grazing land reducing the carrying capacity of the area for livestock grazing. Traditional common property regimes have considerably diminished, and traditional livelihood practices threatened (Schmidt and Pearson, 2016) aggravating conflicts over resources (Hundie, 2010) hence, a slow move from pure pastoralism to agro-pastoralism is evident in Afar (Schmidt and Pearson, 2016). In response to the pressing problems of soil erosion and land degradation, local governments have made effort to implement various soil and water conservation technologies including contour bunds, earthen bunds, stone bunds, gabions/check dams and bench terrace among others in Afar. However, these measures were rarely effective at minimizing the effects of torrential floods, and hence a low to very low adoption rate has been reported (Assen and Ashebo, 2018). One recently tested sustainable flood management intervention in flood–drought prone areas of Ethiopia is water spreading weirs (WSWs) (GIZ, 2012; Nill *et al.*, 2012; Ketter and Amede, 2017), which is stemming from the traditional flood management system.

WSWs are low retention walls designed to dissipate flash flood into rangelands and farms while also reducing runoff and soil erosion. They are made of natural stone and cement and consist of a spillway in the dry riverbed itself, lateral abutments for stabilization and wing walls that span the width of the valley perpendicular to the dry river on both sides of the spillway (GIZ, 2012; Akker *et al.*, 2015). WSWs may alter flood course and the distribution of fertile sediments and nutrients. Sedimentation could improve the physical and chemical properties of soils; builds up soil depth, increases crop production and keeps production costs low as no cost of fertilizer is involved (Tesfai and Stroosnijder, 2001; Tesfai and Sterk, 2002; Mesbah *et al.*, 2016). This would create spatial difference in soil moisture and soil fertility that could determine the area of land to be cultivated and crop productivity and production (Schöning *et al.*, 2012).

The governing principle in this approach is that WSWs alter flood velocity, direction and spatial pattern of moisture and sediment deposition modifying spatial distribution of soil moisture, soil physico-chemical characteristics and thereby productivity depending on how effectively water and sediment load from flood events are spread over the command area.

Although WSWs are widely implemented in west Africa (Ackermann *et al.*, 2014), the use of WSWs as an entry point to convert the highly degraded rangeland into a productive land use in extremely dry condition is a new approach for Ethiopia demonstrated in this paper.

Therefore, this study is conducted to quantify the effect of WSW on spatial distribution of soil water, and soil nutrient, and establish the implications of these changes on crop yield of maize in the dryland agropastoral settings.

Materials and methods

Description of the study area

The study is conducted at Shekai Boru site of Chifra district in Afar, located at 11°36′43″N and 40°02′04″ near the base of the eastern escarpment of the Ethiopian highlands (Fig. 1). The site covers 49.3 ha in a drought prone area where annual rainfall ranges from 200 to 500 mm per year, with the rain season extends from July through September (Fig. 2). The area receives floods between March and April, and July and September because the adjacent highlands also receive higher rainfall in both seasons. The mean, minimum and maximum temperatures are: 27.8, 18.3 and 37.6°C, respectively. The soils are variable, ranging from deep alluvial soils in the valley bottoms bordering the highlands to shallow, and mostly gravel-dominated soils in degraded rangelands.

Approaches and conceptual framework

Seasonal floods, emerging from adjacent highlands have been affecting downstream dwellers, washing away and silting fields and rangelands, and degrading grazing areas by creating gullies and eroding farms. On the other hand, the highlands are experiencing runoff, and soil and nutrient erosion (Tamene and Vlek, 2008; Amare *et al.*, 2013) that could be useful for lowlands of Afar. GIZ-Ethiopia has constructed a series of cemented and strong physical structures, 'water spreading weirs', in Shekai Boru landscape following the contour (Nill *et al.*, 2012), which were designed to capture and dissipate flood water to the flat rangelands. ICRISAT Ethiopia has been engaged in developing an approach, creating a new farming system to convert the flood into productive use. The schematic orientation of the weirs and the established farming system is presented in Figure 3. The WSWs were constructed in 2015. For simplicity purpose in this paper, we described the upper WSW in the west side as weir 1, and the lower WSW as weir 2.

Fields were demarcated by tracking the moisture regime made available for effective production of crops resulting from floods regulated by WSWs. In this approach we identified seven locations based on their position relative to the WSWs (Table 1) aiming to represent fields nearby upstream side of the two WSWs (B and D), downstream sides of the two WSWs (C and F), between the WSWs, fields at far upstream of weir 1(A), and far downstream of weir 2(G) (Fig. 3). Each maize field was categorized to the nearest location. Crop, soil and moisture information was analyzed for each location.

Data collection and analysis

Mapping the moisture gradient

The entire area was tracked using GIS systems to characterize soil-water distribution and soil fertility gradients created by WSW, which was modified by sediment emerging from the highlands

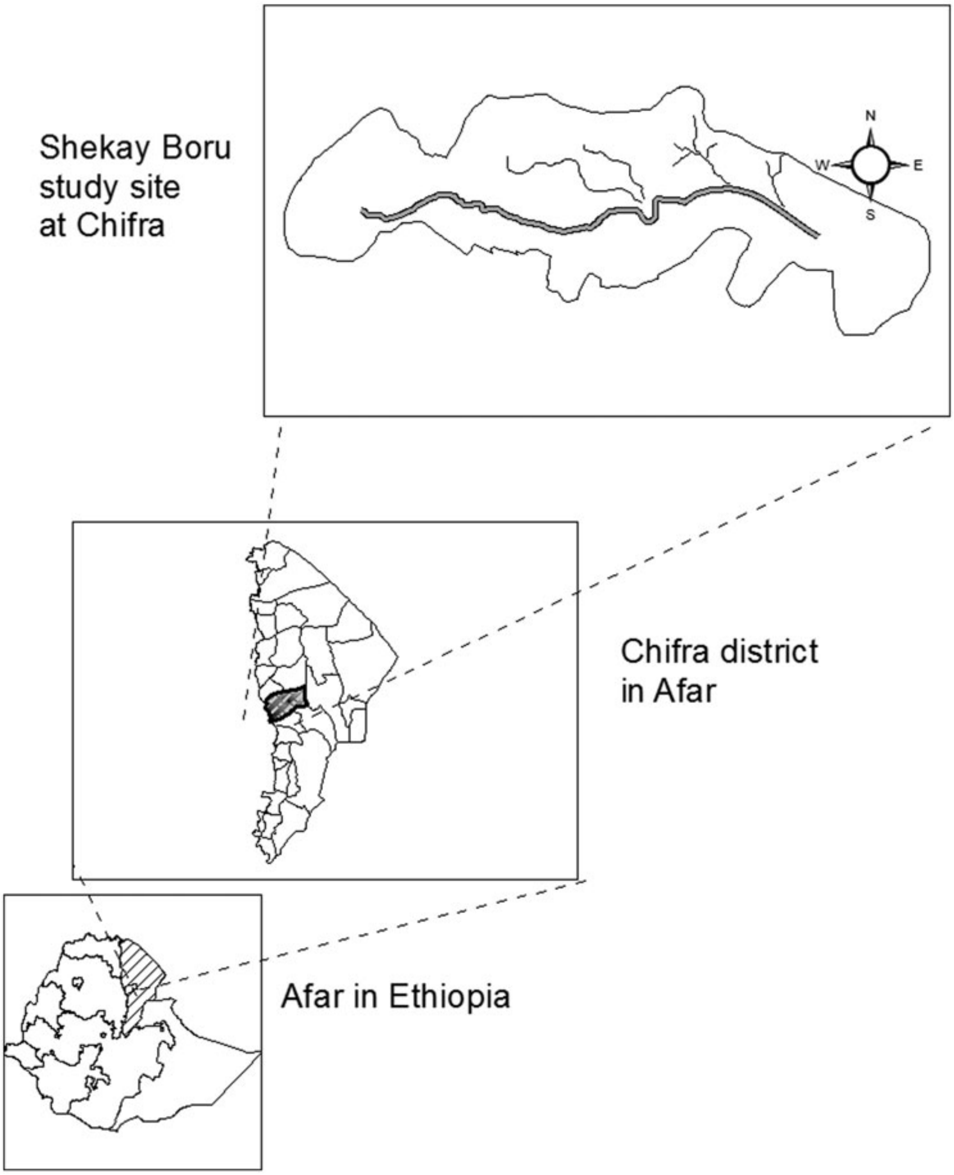

Fig. 1. Location map of the study area in Shekai Boru site at Chifra district of Afar regional state.

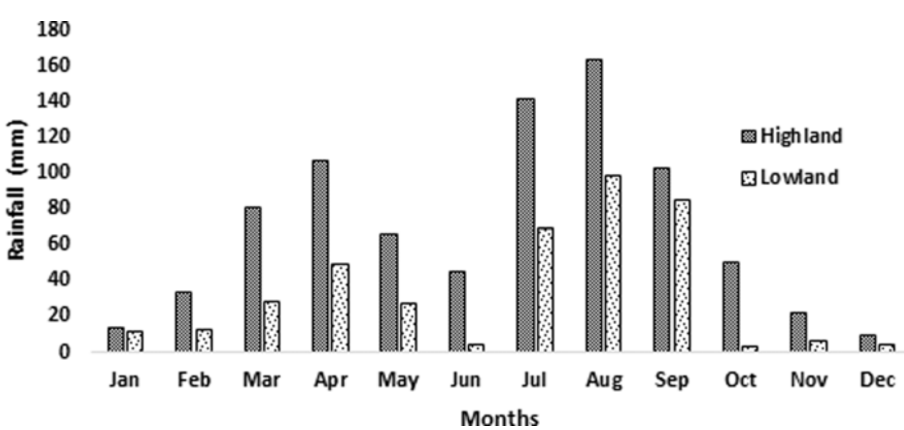

Fig. 2. Average monthly distribution of rainfall (1981–2017) in the lowlands of Chifra and the adjacent highlands based on AgMERRA Climate Forcing Dataset for Agricultural Modeling.

along with the flood, enriching the flat plains. Moisture tracking was conducted by measuring volumetric water content (VWC) at 20 cm depth using TDR 300 instrument (see Spectrum Technologies, Inc., https://www.specmeters.com/soil-and-water/soil-moisture/fieldscout-tdr-meters). The VWC measurement was taken from 188 points with their coordinates covering all fields in the site each of which was averaged from replications of three measurements within 5 m radius. The reading points

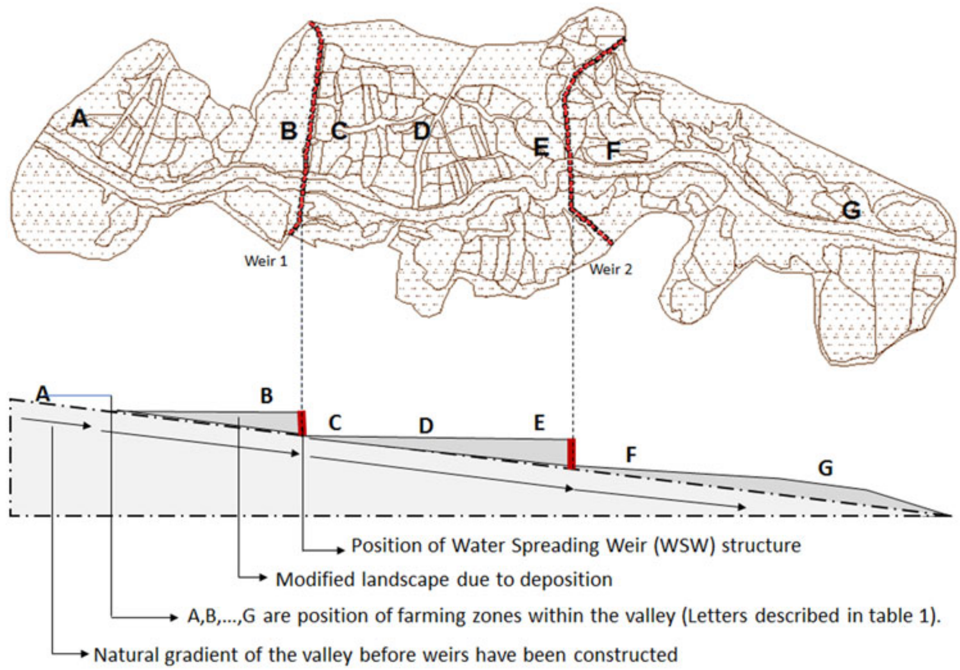

Fig. 3. Schematic representation of the orientation of WSWs and locations (A–G) within the study site.

Table 1. Description of the locations relative to the WSWs in the study site

Locations	Description
Location 'A'	Far upstream of the weir 1 constructed at the end of 2015. It is less impacted by the WSW, hence, it can be considered as control
Location 'B'	Upper side of weir 1. Not cultivated, covered with bushes and shrubs
Location 'C'	Located in the downstream side of weir 1, the excess water that jumps over weir 1 floods into this location
Location 'D'	Farm fields located approximately midway between weir 1 and weir 2 it usually receives the excess water flowing from location 'C' and the flash back of downstream weir 2
Location 'E'	Located at the upper side of and close to weir 2. Fields in this location get moisture from the flash back of weir 2
Location 'F'	Located close to weir 2 the down side. The excess water jumping over weir 2 irrigate this area
Location 'G'	Fields in the eastern extreme end of the site far from weir 2. There is no structure that slows down the flow of flood at or below this location

were georeferenced and values were interpolated for spatial analysis of moisture gradient using the ArcGIS10.4.1 platform. A spatial database on season wide crop information, soil moisture status and other relevant attributes was established.

Climate data

Rainfall characteristics in adjacent highlands were used as proxy to analyze the potential of flood-based farming in the lowlands. The AgMERRA Climate Forcing Dataset for Agricultural Modeling (Ruane *et al.*, 2015) was used to compare lowland with the adjacent highlands.

The number of wet days (rainfall greater than 1 mm day^{-1}), and number of days that exceed rainfall amounts of 5, 10, 15 and 20 mm day^{-1} were calculated to compare the lowland and the adjacent highland with the assumption that the higher the frequency of high-intensity rains, the higher the potential for flood in the lowland.

Soil data

Soil samples for lab analysis were collected from 15 locations at two depths representing 0–25 cm and 25–50 cm in a grid of five rows running parallel to both sides of the WSWs, by three columns roughly parallel to the river. The first row with three sampling points in location A was upstream far from the effects of WSWs, hence it was used as a control for comparison of soil moisture and yield gradients. The samples were analyzed for various chemical and physical properties in three replications in HORTICUP laboratory at Debrezeit. The Bouyoucos Hydrometer method (Bouyoucos, 1962) was used for texture analysis, the Walkley and Black (1934) method for organic carbon; the Kjeldahl method (Kirk, 1950) for total nitrogen; the steam distillation method (Kister, 1992) for NO_3-N and NH_4-N and the Mehlich-3 method (Schroder *et al.*, 2009) for other elemental determinations (Table 3). The parameters include % clay, % silt, % sand, pH, EC, Ca, Mg, available P and exchangeable K, S, Cu, Zn, B, TN, OC, OM, NO_3-N and NH_4-N. The data were used to characterize and compare the spatial difference in physico-chemical properties of soil resulting from the effects WSWs.

Crop data

Short maturing maize crop was planted following the occurrence of the second flood (mid-April for Belg season and mid-June for Meher season). The first flood improves the workability and increase moisture content of the extreme dry soil that resulted from the preceding dry periods. Land clearing was conducted manually following the first flood by destroying weeds. Tillage was conducted only at the time of planting. No chemical fertilizer was applied at any stage of the cropping seasons, hence it entirely depended on the soil deposit coming from highlands with floods.

Basic crop information including yield and biomass was collected averaged from three quadrats (1 m^2 each) per field. The average field size was 0.26 ha.

Statistical analysis

The VWC, yield and biomass data that were collected from each maize yield were grouped into the nearest of the seven locations (section 'Approaches and conceptual framework'). We used TukeyHSD (Faraway, 2005) to test the significance of differences in yield biomass and VWC between locations using RStudio (https://www.rstudio.com).

VWC in a location is a function of availability of flood water the soil type in the location. The relationship between VWC with yield and biomass was examined using a linear regression model in order to use VWC as proxy indicator for classifying locations into similar farming zones, hereafter referred to as 'homogeneous farming zones' (HFZs). We used the mean values and mean difference between locations from the TukeyHSD test to group the seven locations into three relatively homogeneous and an easy to use recommendation unit for future farm decision and agricultural development by agro-pastoralists. We grouped locations with non-significant difference into similar HFZs represented as high moisture, medium moisture and low moisture zones. The range in VWC from fields within each aggregated HFZ was used as criteria to classify the interpolated VWC map into map of HFZs. We also analyzed the yield, biomass, soil moisture at planting and physico-chemical soil characteristics of the three HFZs.

Results and discussion

Frequency of the high-intensity rainfall

The amount and intensity of rainfall received in the command area and adjacent highlands define the potential for flood-based farming. The effectiveness depends on how often high-intensity rain events happen to generate flood for the lowland. Low and medium intensity rains in the highland also contribute to runoff generation because they improve the antecedent moisture conditions of the soil and increased runoff from successive rains. On average between 1980 and 2010, the lowland around Chifra received 11 days $yr^{-1}$of rainy days with rainfall greater than 10 mm day^{-1} whereas the adjacent highland received 32 days yr^{-1} exceeding 10 mm day^{-1} (Fig. 4). Similarly, the lowland exceeds the 15 and 20 mm day^{-1} intensities for 5 and 2 days yr^{-1}, respectively, whereas the adjacent highland exceeds these amounts for 19 and 12 days yr^{-1}, respectively. The high-intensity rains are more frequent in highlands than in the lowlands. Furthermore, the vast catchment area in the highlands collects and drains huge amount of flood to the lowland.

Effects of WSWs on soil, moisture and productivity gradient in the valley

Soil gradient

The WSWs helped reduce velocity of floods and flash it back to open fields resulting in sediment deposition across fields. The deposition pattern created soil property gradient, which varied depending on the micromorphology of the fields, and the distance of fields from WSWs and the river (Fig. 3).

Location 'A' was dominated by fine texture soils. The location has significantly higher clay content ($P < 0.001$) compared with all other downstream locations. This could be because the location was far upstream of weir 1 (around 400 m) where the soil was the result of localized removals and depositions i.e., the location receives small amount, low velocity localized floods from upstream grazing lands that ends in this location with fine texture suspension materials.

Location 'B' was a high sand deposition area; hence, it was dominated by sand texture soil (Table 2). This was the location where floods get the first encounter with the upper WSW (Fig. 3) and bounce back resulting in velocity reduction that causes accumulation of sand from unloading of heavy suspended materials on the upper side of the weir whereas excess water jumps over the weir to location 'C'. Locations 'C', 'D' and 'E' that are situated between the two WSWs are dominated by silt.

The mean and standard errors of some chemical properties of soils are presented in Table 3. Generally, some of the chemical constituents of the soils of the project site including P, Cu and Fe, are Zn are higher than reported for other parts of the country, for example, in southern rift valley (Alemayehu *et al.*, 2016), Akaki, Alemaya, Ginchi and Sheno (Mamo *et al.*, 2002) and Wolaita (Laekemariam *et al.*, 2016). This could be due to the buildup of alluvial soils through continuous deposition of soils coming from the adjacent highlands dominated by cultivated and grazing land that can export higher sediment and nutrients through runoff (Abegaz *et al.*, 2016; Elledge and Thornton, 2017).

The uncultivated location B was significantly higher in Mo and SI content ($P < 0.05$). This sand-dominated location has significantly lower percentage of total nitrogen and organic matter ($P < 0.05$) compared with other locations.

Moreover, there was no significance difference in most physico-chemical properties of soils between the two layers at 0–25 and 25–50 cm depths. This could be because these depths are results of short time of deposition (2016–2017) from several random floods that could be assumed to carry similar composition of suspended loads.

WSW-based production provided enormous advantages in rehabilitating degraded rangeland. This was evident from the quick filling up of gullies in the degraded grazing lands that was converted into a green valley after implementation of WSW-based forage and food crop production (data not presented). Variation in the soil's physical and hydrological properties, as reflected by spatial differences in soil moisture, may be advantageous in minimizing widespread runoff and erosion, by creating spatial isolation of runoff producing areas and by promoting discontinuity in hydrological pathway (Fitzjohn *et al.*, 1998). Weir 1 and weir 2 that were constructed at 1-m high have been completely filled with fertile sediments throughout the wings just in 2 years. The deep river bed was filled up to

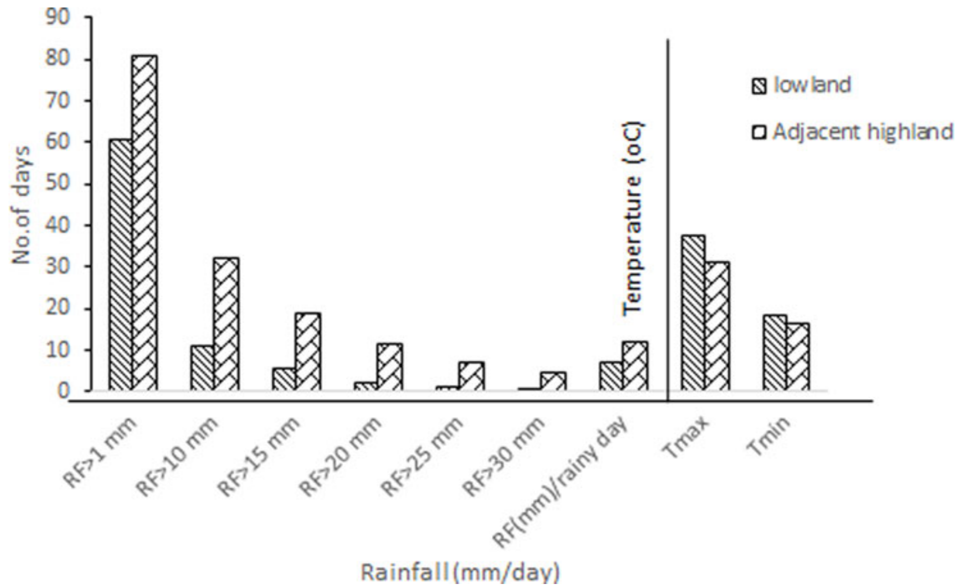

Fig. 4. Average rainfall characteristics (1981–2017) used as a proxy indicator to compare the flood potentials the lowlands around Chifra and the adjacent highlands.

Table 2. Mean values for physical properties of soils (0–25 cm depth) in the various production locations at the Shekai Boru site, Chifra district of Afar

	Location A	Location B	Location C	Location D	Location E
	Mean (s.e.)	Mean (s.e.)	Mean (s.e.)	Mean (s.e.)	Mean (s.e.)
% Sand	21.9 (2.1)	42.8 (7.4)	33.8 (5.1)	27.1 (7.6)	20.4 (3.3)
% Silt	43.4 (2.0)	32.6 (5.7)	37.8 (4.8)	45.8 (6.2)	50.2 (3)
% Clay	34.7 (1.7)	24.7 (1.9)	27.3 (0.8)	27.1 (1.6)	29.3 (0.5)
pH (H_2O)	8.2 (0.02)	8.3 (0.02)	8.30 (0.02)	8.3 (0.04)	8.1 (0.03)

s.e. in bracket is the standard error of means.

Table 3. Summary statistics for chemical properties of soils in the various locations at the Shekai Boru site, Chifra district of Afar

	Location A	Location B	Location C	Location D	Location E
	Mean (s.e.)	Mean (s.e.)	Mean (s.e.)	Mean (s.e.)	Mean (s.e.)
EC (Ms cm^{-1})	0.15 (0.01)	0.14 (0.00)	0.13 (0.00)	0.12 (0.00)	0.15 (0.01)
Mg (Mg kg^{-1})	614.9 (52.2)	653.8 (51.4)	611.6 (14.2)	503.9 (13.7)	710.1 (8.5)
K (Mg kg^{-1})	387.3 (20.7)	281 (30.3)	311.4 (25.2)	443.5 (52.5)	474.8 (33.5)
P (Mg kg^{-1})	22.5 (1.2)	17.1 (0.4)	20 (1.4)	27.4 (4.2)	22.9 (1.1)
S (Mg kg^{-1})	38.8 (1.1)	35.1 (2.2)	33.8 (0.7)	32.8 (1)	36.9 (0.6)
Zn (Mg kg^{-1})	0.96 (0.09)	1.01 (0.1)	0.89 (0.06)	0.98 (0.11)	1.17 (0.02)
B (Mg kg^{-1})	1.35 (0.1)	0.94 (0.13)	1.02 (0.08)	1.29 (0.1)	1.37 (0.01)
Mo (Mg kg^{-1})	0.13 (0)	0.19 (0.02)	0.16 (0.01)	0.16 (0.01)	0.16 (0.02)
SI (Mg kg^{-1})	730.8 (17.2)	575.1 (28)	630.6 (21.1)	684.1 (20.8)	696.9 (5)
Al (Mg kg^{-1})	617.4 (17)	454.3 (29)	502.3 (27.5)	578.2 (35.9)	571.4 (8)
TN (Mg kg^{-1})	0.08 (0)	0.04 (0.01)	0.06 (0.01)	0.07 (0.01)	0.09 (0.0)
OC (Mg kg^{-1})	0.90 (0.02)	0.53 (0.09)	0.55 (0.1)	0.69 (0.09)	0.94 (0.03)
OM (Mg kg^{-1})	1.56 (0.03)	0.91 (0.15)	0.95 (0.11)	1.2 (0.16)	1.62 (0.15)
C·N (Mg kg^{-1})	11.9 (0.5)	12.1 (0.3)	10.4 (0.7)	10.9 (0.4)	10.7 (0.2)
NO_3-N (Mg kg^{-1})	2.5 (0.4)	2.1 (0.5)	2.1 (0.3)	1.6 (0.2)	3.6 (0.7)
NH_4-H (Mg kg^{-1})	21 (2)	22.8 (1.2)	20.2 (1.8)	20.7 (0.6)	21.8 (2.1)

flat level (data not presented) such that it has created a safe livestock and human crossing area, which is not possible in sections outside of this intervention area. Several governmental and non-governmental projects deal with erosion control but a preference for techniques that function in the Ethiopian Highlands, including hillside terracing and gabion construction, couldn't adequately address problems forged in the lowlands (Schmidt and Pearson, 2016).

Soil moisture gradient

The soil moisture condition varies spatially depending on the position of the fields relative to the WSWs, the amount of flood received that varies from time to time and season to season, and the frequency of floods that could affect the anticipated moisture condition.

Generally, there was significant difference in VWC across most locations whereas relative homogeneity is observed between locations A and G, C and E and D and F (Fig. 5). The farm fields that are situated below the downstream weir showed a significantly lower VWC compared with fields between the weirs ($P < 0.001$). This is because the water that flows over weir 2 runs faster as there is no structure that slows down the flow (locations A and G).

One of the advantages of WSWs was the ability to safely distribute flood water to the open flat lands so that flood could be converted into productive use for biomass and grain production. The moisture made available as a result of WSWs was spatially variable and influences the performance of grain and biomass productivity. Generally, VWC at the time of planting in 2017 main season ranged between 10 and 22%. The range depends on the relative distance of the fields from the WSWs and the river as well as the microtopography of fields. However, heavy floods have the tendency to create concentrated overflow at the tails of WSWs, therefore, cultivators need to prepare safe drainage to avoid the potential danger of land degradation and its impact on food security.

Productivity gradient across locations

Maize fields are used as proxy to analyze productivity gradient because of the high demand of maize for water and nutrients compared with other cereals (FAO, 1991). Generally, maize yield was low in the upper most location A and lower-positioned locations F and G compared with locations in the middle (Table 4). Biomass productivity was also low in the lower locations F and G. Both yield and biomass productivities have similar trends with VWC at planting. However, the relationship was stronger between VWC and yield.

Generally, there was a significant difference in yield ($P < 0.005$) and biomass ($P < 0.005$) productivity among the different locations (Fig. 6). Locations A and G showed significantly lower grain yield compared with locations C, D, E and F ($P < 0.05$).

Locations F and G show lower biomass productivity compared with locations A, C and D ($P < 0.001$). Biomass from location E was lower than that of location C ($P < 0.005$). However, there was no difference in biomass productivity between locations F and G.

There was a positive relationship between VWC and yield ($P < 0.001$, $r = 0.76$), as well as VWC and biomass ($P < 0.005$, $r = 0.46$) (Figs. 7a and b). Hence, the influence of soil moisture on productivity is evident; therefore, moisture can be a good indicator for making agricultural decisions.

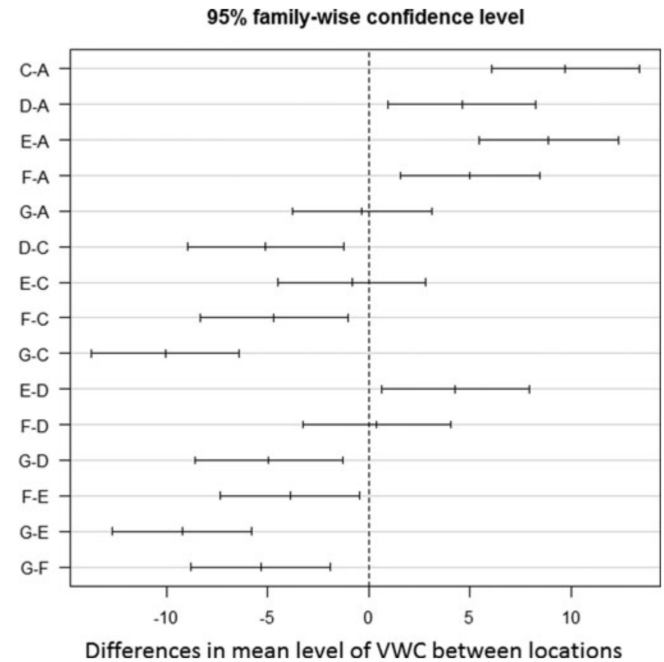

Fig. 5. Difference in mean levels of VWC between locations in Shekai Boru site at Chifra.

Homogeneous farming zone

Through their experience in flood management in the Belg and main seasons of 2016 and 2017, agropastoralists have learned to visually characterize their fields as poor, medium or good potential depending on the moisture content. Our approach of statistics and GIS-based clustering and mapping of locations into HFZs would simplify agro-pastoralists' farming decision (Fig. 8).

One of the new elements of this approach we introduced in this study compared with other studies of spate irrigation in Ethiopia is the use of moisture tracing approach to guide decision on seasonal crop allocation and management. This helped to compare productivity difference created due to the influence of moisture gradient. Consequently, maize yield was found to be higher ($P < 0.001$) in the high moisture zone than both in medium and low moisture zones. However, the difference in mean biomass was significant only between the fields with high and low moisture condition ($P < 0.05$).

Farming zone with poor potential (FZ-P)

FZ-P constitutes locations 'A' and 'G'. The lower productivity in the FZ-P was strongly associated with the low soil moisture condition due to: (i) the absence of WSW below location 'G' where flood runs without any structural barrier to dissipate the flow velocity causing soil erosion. (ii) The long distance of location 'A' from the nearest WSW that makes it difficult to supply water particularly from low intensity/amount floods. Agro-pastoralists in this zone may consider planting short maturing dryland crops like mung bean or biomass may be the primary focus of production although considerable yield could be attained.

Farming zone with medium potential (FZ-M)

FZ-M comprises of locations 'D' and 'F' with medium soil moisture condition. Both locations have better access to flash flood from both WSWs compared with FZ-P. However, low intensity/

Table 4. Maize yield and biomass obtained across locations in 2017 Meher season at the Shekai Boru site, Chifra district of Afar

Locations	Yield	Biomass	HI	VWC
	Mean (s.e.)	Mean (s.e.)	Mean (s.e.)	Mean (s.e.)
A	3.32 (0.44)	17.51 (0.85)	0.15 (0.02)	17.51 (0.66)
B	Not cultivated	Not cultivated	Not cultivated	Not cultivated
C	5.16 (0.25)	19.8 (1.17)	0.22 (0.02)	19.30 (0.68)
D	4.72 (0.28)	17.8 (2.18)	0.23 (0.03)	19.18 (1.17)
E	5.13 (0.55)	12.21 (1.15)	0.35 (0.04)	18.01 (0.33)
F	4.17 (0.28)	9.19 (0.94)	0.37 (0.01)	13.04 (1.13)
G	2.65 (0.12)	7.17 (0.37)	0.30 (0.01)	13.82 (0.58)

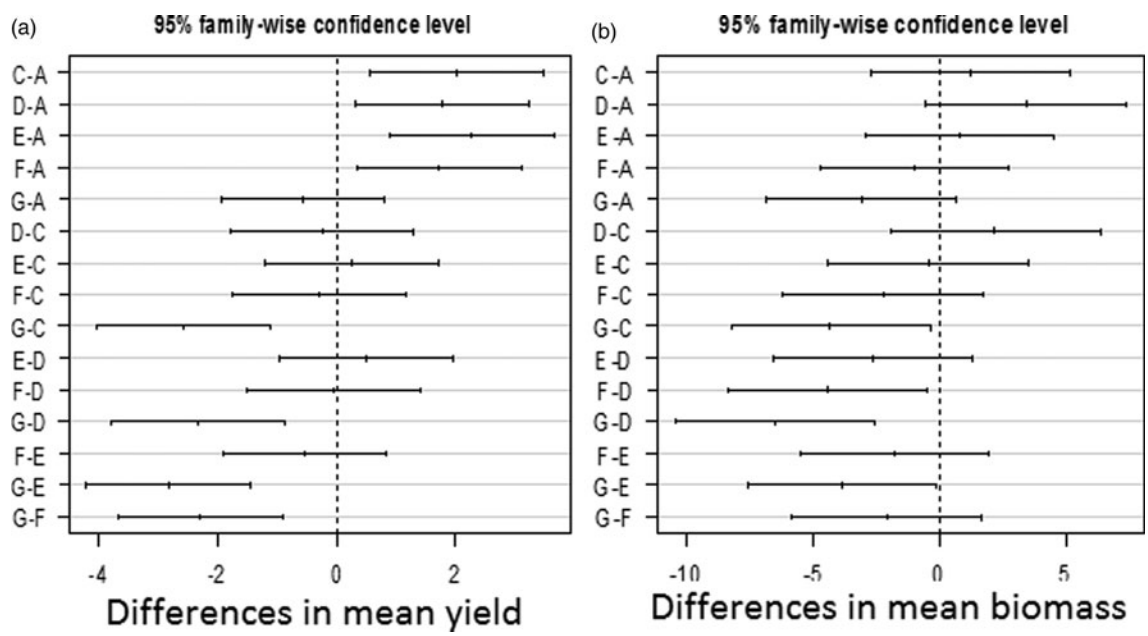

Fig. 6. Difference in mean levels of maize yield (a) and biomass (b) across between locations in Shekai Boru site at Chifra.

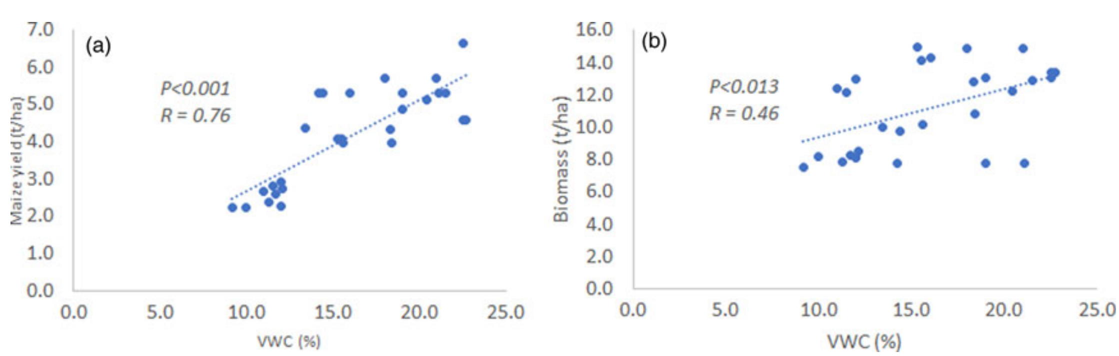

Fig. 7. (a) Relationship between VWC at planting and maize grain yield. (b) Relationship between VWC at planting and maize biomass.

amount floods either from the excess of location 'C' or flash back of weir 2 have difficulty to reach the zone. Similarly, low intensity floods usually have little to jump over weir 2 and flood part of FZ-M. Agro-pastoralists who have fields in this region could attain an optimal yield level and good biomass productivity.

Farming zone with good potential (FZ-G)

FZ-G usually receives the high amount of moisture. Locations B, C and E make up FZ-G. This zone covers fields located immediately upstream of WSWs, and fields immediately downstream of WSW with condition that there is another WSW below to slow

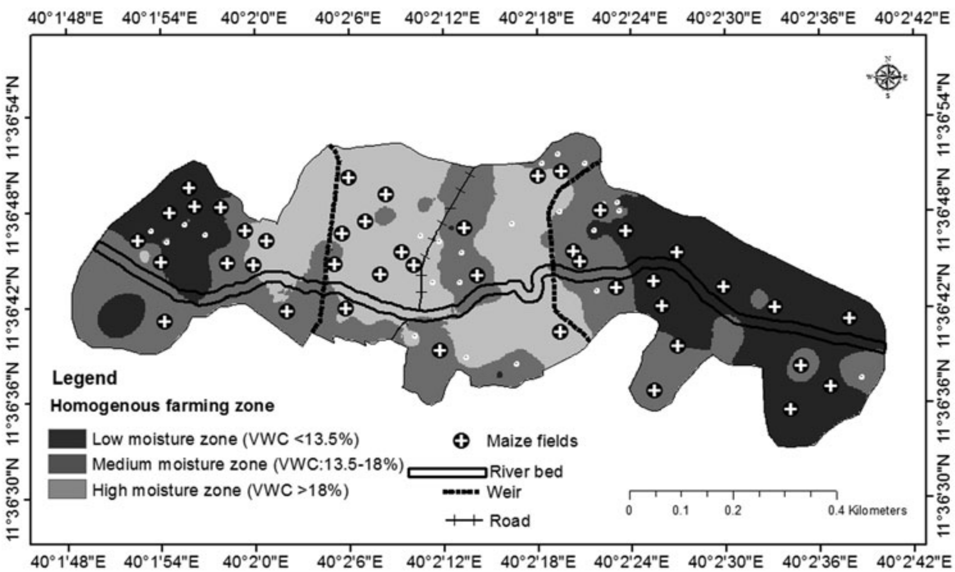

Fig. 8. Map of homogeneous farming zones based on soil moisture gradient at the start of the Meher season of 2017 at Shekai Boru site of Chifra in Afar.

down and flash back the excess flood. This zone also receives maximum deposition. The 1-m high WSW has been completely filled with fertile deposition across the length of the wings from floods in 2016 and 2017. This justifies the need to continue construct cascade of WSW upstream and downstream of the existing scheme.

In general, yield and biomass were higher for Meher seasons than for Belg. Only fields with good and medium moisture status provided grain yield during the 2016 Meher and 2017 Belg seasons. This could be partly explained by the terminal drought due to short flood seasons and changing planting dates. However, biomass productivity was good for all seasons.

The implementation of WSW-based production in one of the degraded rangelands of Afar enabled to attain biomass productivity of 17–28 t ha^{-1} yr^{-1} from Belg and Meher seasons (Table 5).

This productivity level was attained without the application of any chemical fertilizer. The high yield could be the associated with continual movement of nutrients from upstream across seasons of 2016 and 2017. This result was in line with other studies where well managed floods increased crop production, and reduces cost of production (Tesfai and Sterk, 2002). In Afar, the use of nitrogen, phosphorous and potassium inputs from inorganic and organic sources was nil whereas the input from sedimentation that is originating from irrigation water and sedimentation of eroded soil materials was the highest of all the regions in Ethiopia (Haileslassie *et al.*, 2005).

The productivity differs from location to location depending on the spatial variability of moisture as influenced by WSWs.

Gebremeskel (2006) has made a quantitative assessment of the biomass productivity of rangelands in Afar where he estimated average dry matter productivity (of 2 years) of 0.75 t ha^{-1} yr^{-1} in severely degraded rangelands, and 1.35 and −2.15 t ha^{-1} yr^{-1} on moderately and slightly degraded rangelands, respectively.

Therefore, our result demonstrated that (i) WSW-based production provided tremendous productivity advantage compared with the natural regeneration of grazing lands and (ii) can close a huge biomass gap in the (agro)pastoral community and provide additional gain from grain production contributing toward food security of the community. Unlike in the open grazing system, the biomass produced using this system can be stored for dry periods that help to build resilient (agro)pastoral community. This was practically demonstrated in 2016/2017 and 2017/2018 when beneficiaries could pile huge amount of biomass on top of acacia trees and inside fenced plots and used it for livestock feeding in times when feeding livestock from the natural grazing was hardly possible. Gumma *et al.* (2019) estimated that a minimum of 720,000 and 550,000 ha of land could be used for planning flood-based development in Afar using the *Meher* and *Belg* seasons, respectively. This depicts a huge potential for scaling up of WSW-based production of such high productivity level. This is particularly important because the carrying capacity of

Table 5. Grain and biomass productivity in the three seasons at Shekai Boru site at Chifra

Season	Moisture condition[a]	Maize yields		Biomass	
		Average	S.E.	Average	S.E.
Meher 2016	Good	2.56	0.39	16.98	2.54
Meher 2016	Medium			12.58	2.25
Meher 2016	Poor			6.76	3.08
Belg 2017	Good	2.10		10.70	
Belg 2017	Medium			14.30	
Belg 2017	Poor			6.10	
Meher 2017	Good	5.39	0.17	17.23	1.43
Meher 2017	Medium	4.19	0.07	13.75	1.59
Meher 2017	Poor	2.76	0.15	10.70	1.76

See Figure 8 for spatial distribution of these moisture classes.

the natural range land is under high pressure from invasive weeds (Haregeweyn *et al*., 2013; Mehari, 2015; Rogers *et al*., 2017), and rangeland degradation (Tilahun *et al*., 2016) whereas the use of crop residue as livestock feed has a positive impact on food security (Beyene, 2015). Furthermore, WSWs have the capacity to facilitate artificial recharge of ground water (Raes *et al*., 2008; Mesbah *et al*., 2016).

For sustainability, community participation as well as operation and maintenance strategy is important (Amede *et al*., 2007; Castelli *et al*., 2018) as increasing the height of WSWs after the weir height is filled with sediment is required. Therefore, reconstruction of head work periodically could be challenging (Komakech *et al*., 2011) because it involves additional labor and cost.

Conclusion

The two water-spreading weirs constructed in the study area have positively affected the distribution of the soil and moisture. The WSW-based farming has transformed the degraded grazing land in such a dry environment into a highly productive green valley. The flood that is spread across the farm lands by the WSWs enabled to produce huge biomass and additional grains on the degraded grazing lands which is far greater than the biomass productivity of the natural grazing land. The WSWs affected the moisture gradient across the farming zones, hence, biomass and grain yield productivity are influenced by the VWC that was made available by the WSWs across fields. Furthermore, the implementation of WSW-based farming ensures quick filling up of the degraded lands, gullies in the farm lands within the WSWs, and the deep channel of the main river bed with fertile sediment. We conclude that this development model has a huge potential for scaling up to the vast areas of Afar, other regions and countries with similar situation and resource bases. However, scaling up needs to be preceded by detailed analysis of the potential of flood-based development in the region of interest (Gumma *et al*., 2019).

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