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ORIGINAL PAPER

Contribution of land drainage innovation to maize (*Zea mays*) yield improvement in waterlogged farmers' field, Northern Ethiopia

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Abstract: Irrigation is a primary engine for economic growth in drylands. However, it suffers from waterlogging due to seepage, such as in the Tigray region of Ethiopia. The objective of this study was to evaluate the effect of a stone-trench drainage innovation on the yield and growth components of maize (*Zea mays* L.). A completely randomized experimental design with three replications was adopted. The study combined three soil amendments: T1 (dam silt application at a rate of 34.32 ton ha^{-1}), T2 (without dam silt and manure application of farmers' practice), and T3 (manure application at a rate of 12.00 ton ha^{-1}) in combination with drainage and without drainage. Yield and growth components were recorded and analysed using analysis of variance. Financial analysis of the innovation, as well as field day demonstrations and evaluations, were carried out. The results indicated that crop growth in non-drained condition was delayed on average by 4.2 days to 50% germination, 22.8 days to the start of flowering, 7.8 days to the start of silking, and 27.9 days to 50% silking. Moreover, the plots with drainage resulted in an average of 5-fold higher grain yield than non-drained condition. Subsequently, a highly significant statistical difference ($p \leq 0.01$) in grain yield was observed between the two conditions. The financial analysis indicated a positive net benefit after three years since installation of the innovation. Moreover, the plots within the drainage condition were preferred most by up to 90% of the field day participants'. Stone-trench drainage innovation can, thus, be promoted in waterlogged irrigation fields.

Keywords: *Zea mays* L., land, drainage, maize, yield.

Introduction

Livelihoods in sub-Saharan Africa highly depend on agriculture. For instance, in Ethiopia, it contributes about 50% to the GDP and 80% to export earnings (Zerssa et al., 2021). However, most cultivated lands in Ethiopia are under a rain-fed system, which directly affects the country's economy (Abdisa et al., 2022; Temesgen, 2023). Therefore, many areas of the country depend on rainfall to ensure agricultural production, resulting in poor yields due to the effects of climate change.

According to Yihun et al. (2013), the drylands in Ethiopia account for over 70% of the total landmass and 40% of the arable

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land. Land degradation and frequent periods of drought have led to crop yield losses in the northern Ethiopian region of Tigray (Wassie, 2020). Irrigated agriculture is thus considered a primary engine of economic growth, prompting the construction of numerous micro-dams in the 1990s (Amede, 2015). However, these irrigation schemes have faced challenges due to inappropriate technologies and poor irrigation water management, often leading to crop failure (Gebul, 2021).

Most parts of irrigation canals are unlined, with irregular cross-sections and improper alignment. These limitations have led to waterlogging problems in irrigated soils and intensified the process of salinization due to the absence of drainage n etworks (Shitu et al., 2022). According to Yohannes et al. (2017), a conveyance loss of more than 45% has been detected in some irrigation schemes in the Tigray region of Ethiopia, contributing to waterlogging. Besides, farmers often practice poor irrigation scheduling and inappropriate irrigation methods characterized by over-irrigation and a rising groundwater table, followed by field saturation (Habtu et al., 2018).

The presence of excessive moisture in the soil fills the pore spaces and ultimately suffocates the root environment by prohibiting proper aeration. Under such conditions, the water and nutrient uptake capacity of plants are reduced, and their growth becomes prolonged and stunted. Waterlogged irrigated lands require drainage to remove excess water from the surface and subsurface. Adequate drainage can keep the soil moisture at about the field capacity range while improving physical soil structure, nutrient supply, and controlling soil salinity problems (ICAR, 2013).

In areas with water tables at or near the land surface following heavy rainfall, canal seepage, or excess irrigation application, the productivity of agricultural soils is limited, demanding artificial drainage to make the soils fertile and convenient for tillage equipment. The practice of artificial drainage to relieve saturated agricultural lands is centuries old, aiming to improve soil productivity by removing and disposing of excess water from the rooting zone (Haszler, 1989) and to improve the workability of the soil by drying (Stephan, 1997). The productivity of saturated soils can thus be improved by minimizing or controlling their moisture levels.

Based on a preliminary field survey and discussions with the farmers in the Hayba irrigation project in the Tigray region of northern Ethiopia, the irrigated lands were initially cultivated for rain-fed crops such as teff (*Eragrostis tef*) with a yield of 2000 kg ha^{-1}, chickpea (*Cicer arietinum*) with a yield of 1200 kg ha^{-1}, vetch (*Lathyrus aphaca*) with a yield of 1600 kg ha^{-1}, barley (*Hordeum vulgare*) with a yield of 2400 kg ha^{-1}, and wheat (*Triticum aestivum*) with a yield of 2800 kg ha^{-1}. After the introduction of irrigation in the study area in 1998, other crops began to be cultivated. These included maize (*Zea mays* L.) with a yield of 4800 kg ha^{-1} and onion (*Allium cepa*) with a yield of 30000 kg ha^{-1}. Since 2000, however, the yield in the study area started to decline as the areas became waterlogged and unproductive.

Promoting surface and subsurface drainage technologies in this area may improve the situation. However, there have been no previous studies addressing the drainage problems and solutions in the area. Yet, the drainage problem may worsen in the near future and contribute to land degradation. Therefore, the objective of this research was to compare and analyse crop yields under drained and non-drained conditions.

Materials and Methods

Study site description and physical soil characteristics

The experiment was conducted in the Hayba irrigation project, located about 41 km southwest of Mekelle city, the capital of the Tigray region in Ethiopia (Figure 1), at

13°17’3” N and 39°15’23” E, with an elevation of about 2208 m above sea level.

Based on 35 years of data analysis, the average annual rainfall at Dengolat station (approximately 5 km away from the experimental site) was 640 mm. The area has an average maximum temperature of 24.4ºC, an average minimum temperature of 11.3ºC, and an annual potential evaporation of 1904 mm obtained at Alula Aba Nega airport station (approximately 25 km away from the experimental site).

The dominant soil texture in the study area is clay, with physical properties shown in Table 1.

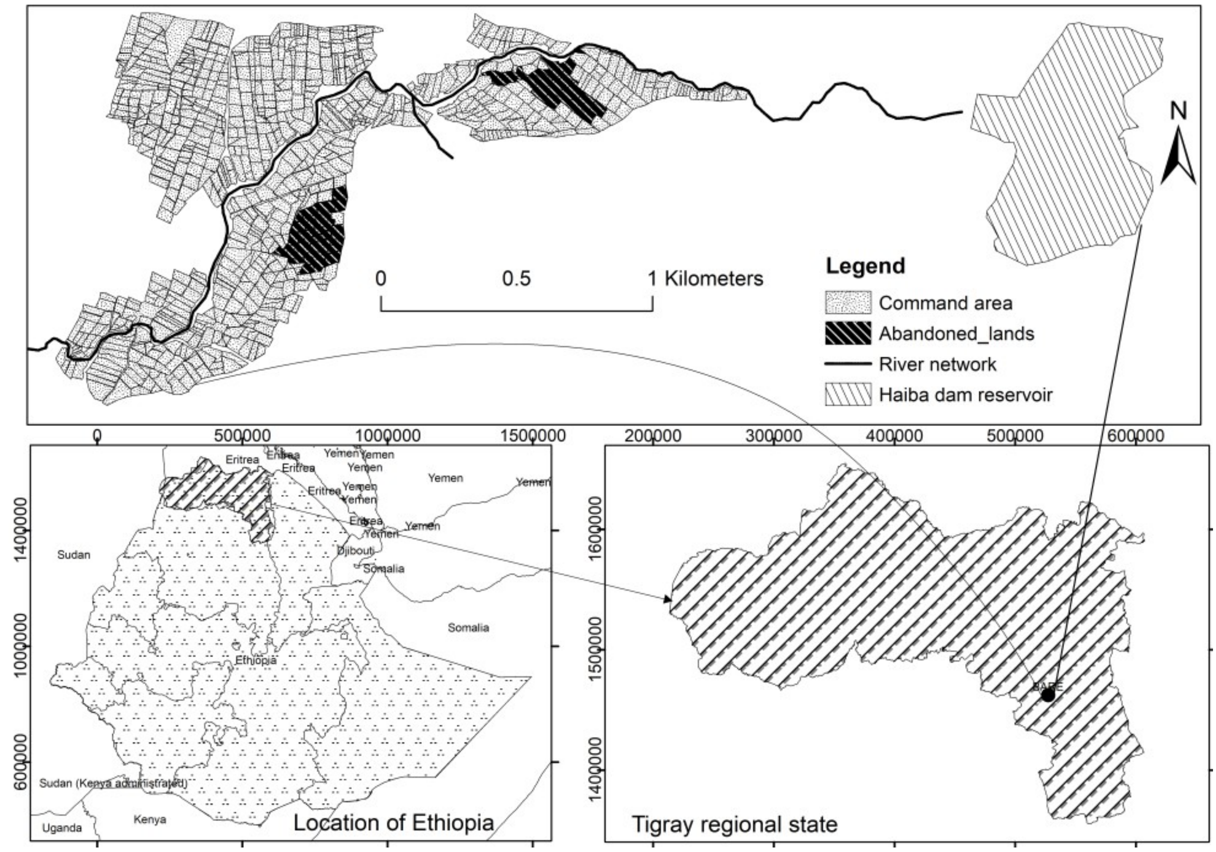


Figure 1: Location of the study area.

Table 1: Soil physical properties at the experimental field

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture class	Saturation (%)	FC (%)	PWP (%)
0-30	27	28	45	Clay	51.36	40.37	28.51
30-60	27	31	42	Clay	51.39	41.61	26.98
60-90	31	25	44	Clay	47.50	39.74	22.14
90-120	25	31	44	Clay	51.01	42.85	28.99
120-150	19	23	58	Clay	52.48	40.98	27.87

FC – field capacity on a volume basis; PWP – permanent wilting point on a volume basis.

Description of experimental design and installation of drainage innovation

The type of drainage innovation installed in this experiment is called the “stone-trench” structure. The installation of such drainage structures in the region's irrigation schemes is new.

The innovation was conceived by the author, inspired by experiences in constructing foundations for houses. The drainage innovation is simple and can be implemented with local materials and the available skills of local farmers, compared to other imported, expensive, and sophisticated drainage technologies. This innovation is believed to be simple, easily applicable, and affordable for small-scale farmers in rural areas. It simply requires digging trenches and filling them with selected, locally available stones, as shown in Figure 2. Preferably, cobblestones with an oval shape and with no fractures are selected for effective and durable drainage service.

A subsurface (groundwater) depth of 1.5 m was set, considering the maximum root depth of maize. Of the total subsurface depth, 0.3 m from the surface was filled with soil, considering the plough depth in the area. A drain spacing of 20 m was intentionally selected to suit farmers' plot widths of 40 m, in which case three trench drains per farmer's plot would be laid.

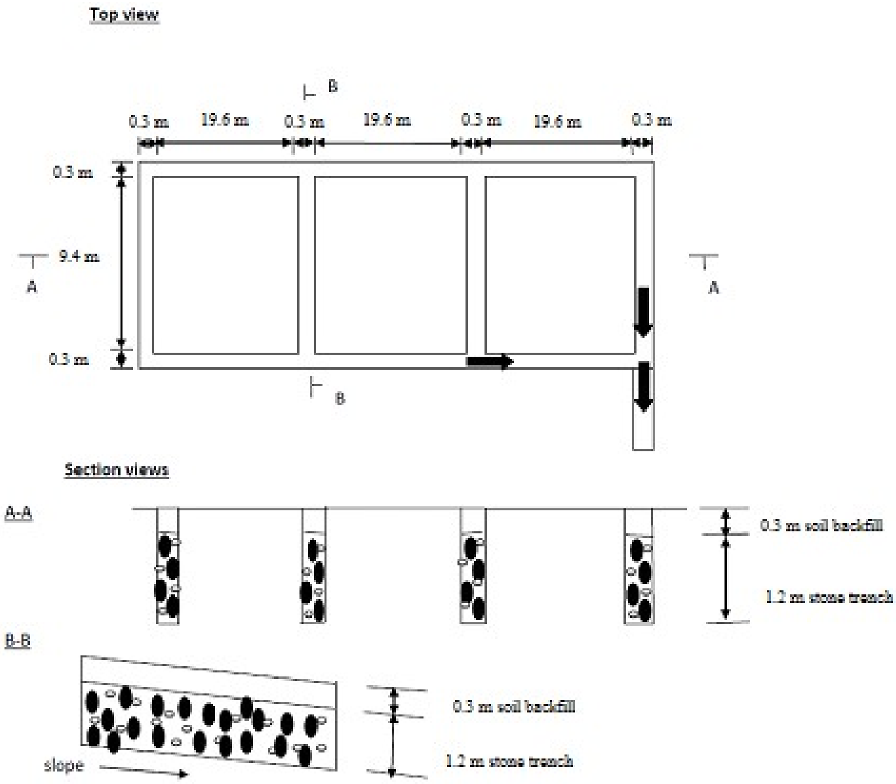


Figure 2: Layout of drainage innovation.

Parameters used in drain spacing

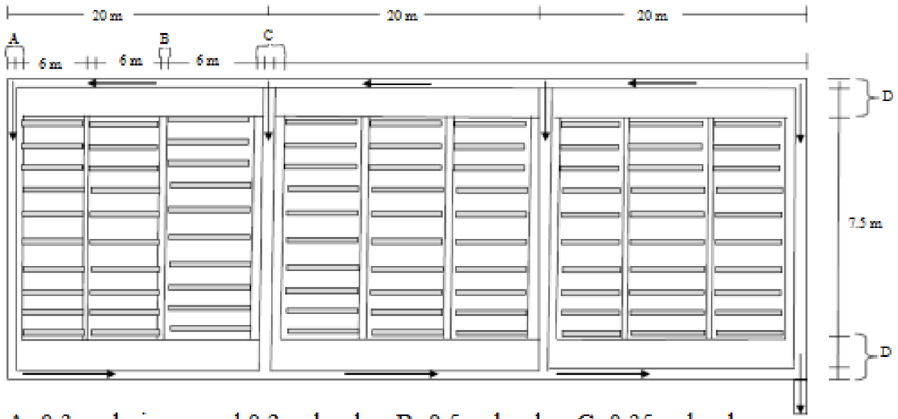
A drain spacing of 20 m was verified using the Hooghoudt procedure (Ritzema, 1994) under a homogeneous soil profile of clay, with a trench width of 0.3 m, a topsoil trench backfill depth of 0.3 m, and a trench depth with a stone envelope of 1.2 m. The input parameters for verification included the drainage requirement (0.0096 m day^{-1}), soil moisture holding capacity at field capacity (40.98%) and saturation (52.48%), hydraulic conductivity (K = 0.256608 m day^{-1} at 1.5 m), groundwater level from the surface (0.5 m), and drain depth based on the maximum root depth of maize (1.5 m).

Experimental design and treatments

A completely randomized experimental design with three replications was adopted. The study combined three soil amendments (dam silt, no dam silt and manure, and manure) with two drainage conditions (with drainage and without drainage). The experimental treatments were: i) T1 – application of a deposited silt material collected from a dam reservoir to the experimental plots at a rate of 34.32 tons ha

-1, as per the recommendation of Girmay et al. (2009); ii) T2 – the existing farmers' practice of no application of dam silt and manure; and iii) T3 – application of manure collected from farmers' backyards at a rate of 12.00 tons ha^{-1}, as per the recommendation of Assefa et al. (2015). These treatments were combined in drained and non-drained conditions. The selected soil amendments were locally available compared to imported chemical fertilizers.

Maize (*Zea mays*) variety Melkassa-II, the main crop grown at the experimental site, was planted with a spacing of 75 cm between rows and 30 cm between plants, based on the standard for maize, in all 18 plots (nine in drained and nine in non-drained) with each plot area of 45 m^2 (7.5 m × 6.0 m) and 10 furrows spaced at 0.75 m. Figure 3 shows the detailed layout of each plot along with the drainage network.



A=0.3 m drainage and 0.2 m border; B=0.5 m border; C=0.35 m border, 0.3 m drainage and 0.35 border; D=0.3 m drainage and 0.95 m border

Figure 3: Top view of drained field layout.

Land management

Harrowing and weeding were carried out three times, while Diazinon, a pesticide to prevent the American bollworm, was applied four times. The soil moisture level was kept between saturation (under non-drained condition) and field capacity (under drained condition). Consequently, the crop directly accessed the available soil moisture to meet its water requirement without the need for additional irrigation water from the canal system.

Data collection

The data on germination, flowering, silking, cob length, and grain yield were collected following the field guide developed by CIMMYT (2013). Accordingly, from every row of a plot, germination, silking, and flowering were monitored by recording the starting date and the number of daily germinated, silked, and flowered plants until it reached 50% of the total number of plants per plot. Based on these collected data, it was possible to analyse the days to 50% germination, starting date and days to 50% flowering, starting date and days to 50% silking. Cob length (cm) was measured using a ruler on randomly selected sample plants per plot. At the end of the season, the harvest was threshed and grain was separated. Grain yield was weighed using a balance from every plot area of 2.56 m^2 and converted to kg ha^{-1}.

Demonstration day

A field day was organized at the maturity stage of the crop. A total of 21 participants, including two extension experts and 19 farmers who own plots within the scheme, were invited to evaluate each experimental plot condition. Each participant ranked all of the plots based on growth indicators including stem thickness, stem height, stem colour, number of cobs per stem, length of cob, thickness of cob, number of plants per plot, and uniformity of plant height per plot.

Financial analysis

The material costs of all inputs required for installing the 'stone-trench' sub-surface drainage innovation structure were collected for cost-benefit analysis. The results were used to evaluate the feasibility of the innovation in the experimental area for further promotion in similar areas.

Statistical analysis

The data were subjected to statistical analysis using F-test ($p \leq 0.05$) of the analysis of variance. All the datasets were first arranged and checked for compliance with the analysis of variance.

Results and Discussion

Benefits of drainage

The benefits of drainage include: creation of better soil aeration, higher soil temperatures, improved soil structure, enhanced root development, higher yields, and improved crop quality (Cooke and Christianson, 2021). Drainage is considered the most effective technology for enhancing soil productivity and the sustainability of agriculture (Abdel-mageed and El-Hazek, 2013), providing agronomic and environmental benefits such as improved crop yield, enhanced soil trafficability, and better field operations (Tiwari and Goel, 2017). However, inadequate drainage can result in injury and death to crops due to insufficient oxygen supply for normal root growth, as well as delayed planting and harvesting, affecting overall yield (Haszler, 1989).

For instance, excess soil moisture, caused by a lack of drainage, results in a 25-30% annual loss of maize production in India on average (Zaidi et al., 2003), while installing drainage systems in the Midwestern 'Corn Belt' region has increased productivity in the USA (Christianson et al., 2013). Avoiding waterlogged conditions in soils through agricultural drainage can contribute to efficient and sustainable crop production (Gurovich and Oyarce, 2015).

Effect of stone-trench drainage on growth and grain yield of maize

The germination, flowering, and silking dates were recorded and analysed. There was no variation in the starting date for germination between drained and non-drained conditions. However, there were variations in the days to 50% germination, starting date and days to 50% flowering, and starting date and days to 50% silking. On average, there was a 4.2-day delay to 50% germination, a 22.8-day delay to the starting date of flowering, a 7.8-day delay to silking, and a 27.9-day delay to 50% silking in the non-drained condition compared to the drained condition. Similarly, Kuang et al. (2012) reported that the dates of corn jointing, tasseling, silking, and harvesting were delayed under non-drained condition. One possible justification for this is that prolonged soil saturation leads to a reduction in air content and a slowed rate of gas diffusion through the soil, creating a deficiency in oxygen. This deficiency in oxygen, in turn, hinders root growth and the plant's ability to absorb nutrients (Stephan, 1997).

Effect of drainage on cob length and grain yield

Table 2 presents the average cob length and grain yield obtained in the experimental plots under drained and non-drained conditions. Accordingly, the mean cob length ranged from 15.33 cm in T2 to 19.00 cm in T3 under drained conditions, while shorter cob lengths were observed in non-drained conditions, ranging from 6.53 cm in T2 to 9.60 cm in T1. This indicates that the average cob length under drained condition was twice that of the average cob lengths under non-drained condition.

The mean grain yield ranged from a minimum of 5,338.54 kg ha^{-1} in T2 to a maximum of 6,022.92 kg ha^{-1} in T3 under drained conditions. In the nearby Gumsalasa scheme, maize yields ranged from 5,100 kg ha^{-1} (Jiru and Van Ranst, 2010) to 6,100 kg ha^{-1} (Habtu et al., 2018) under normal drainage condition. However, under non-drained conditions in the experimental area, grain yield ranged from a minimum of 888.33 kg ha^{-1} under T2 to 1,100.00 kg ha^{-1} under T1.

The farmers within the same scheme, encountering drainage problems, also reported even lower harvest yields in the same year (2017/18), ranging from 250 to 667 kg ha^{-1}. This implies that the average maximum grain yield in the drained condition of the experimental area was 5-fold greater than non-drained condition.

The analysis of variance indicated no significant variations ($p > 0.05$) among treatments for cob length, implying that the addition of manure or dam silt did not have significant effect on cob length (Table 2. However, highly significant variation ($p \leq 0.01$) of cob length was observed between drained and non-drained conditions. Similarly, highly significant variation ($p \leq 0.01$) in grain yield was observed among treatments as well as between drained and non-drained conditions, in agreement with Haszler (1989). Besides, similar research conducted on maize in other parts of the world indicated that the average grain yield obtained under drained conditions ranged from 10,482 to 10,984 kg ha^{-1}, exceeding the yield under non-drained conditions, which was 10,294 kg ha^{-1} (Helmers et al., 2013). Nolte and Duvick (2010) also found that average maize yields under drainage ranged from 5,774 to 7,595 kg ha^{-1}, exceeding yields under non-drained conditions (3,766 kg ha^{-1}).

It can thus be confirmed that drainage conditions can contribute to increased crop productivity due to its capability of removing excess soil water and facilitating better oxygen circulation for plant growth (Christianson et al., 2013).

Table 2: Results of analysis of variance and means for maize cob length and grain weight under cultivation with and without soil amendments (SA) and drainage conditions (DC, drained – D and non-drained – ND)

SV	Cob length (cm)		Grain weight (kg ha^{-1})	
SA	D	ND	D	ND
T1	16.11 ± 3.15^{ns}	9.60 ± 1.78^{ns}	5802.09 ± 49.84**	1100.00 ± 50.00**
T2	15.33 ± 2.00^{ns}	6.53 ± 2.32^{ns}	5338.54 ± 225.52**	888.33 ± 85.97**
T3	19.00 ± 1.76^{ns}	8.63 ± 0.7^{ns}	6022.92 ± 202.91**	1066.28 ± 78.21**
DC				
D	16.81 ± 2.66**		5721.18 ± 339.31**	
ND		8.26 ± 2.03**		1018.20 ± 117.06**
SA × DC	12.54 ± 4.96^{ns}		3369.70 ± 2432.16*	
CV_{SA} (%)	40.82		76.59	
CV_{DC} (%)	15.82	24.59	5.93	11.50

SV – source of variation; T1 – 34.32 ton ha^{-1} dam silt; T2 – 0 ton ha^{-1} dam silt and manure; T3 – 12 ton ha^{-1} manure ; CV_{SA} and CV_{DC} are coefficients of variation of the errors in soil amendments and drainage conditions, respectively; values represent mean ± standard deviation; * – significant at $p \leq 0.05$; ** – significant at $p \leq 0.01$, and ns – not significant.

Opinion of field day participants'

Based on the evaluation criteria of the field day, up to 90% of the participants ranked plots under drained condition ranked the most performing plots. These plots had thicker stem, longer stem height, greener stem colour, more number of cobs per stem, longer and thicker cob, more number of plants per plot, and relatively uniform plant height per plot. On the other hand, up to 95% of the participants ranked plots under non-drained condition least performing plots since these plots had thinner stem, shorter stem height, lighter green stem colour, less number of cobs per stem, shorter and thinner cob, less number of plants per plot, and relatively irregular plant height per plot. These results imply that all of the best-performing plots are from the drained condition. The participants' rankings are thus in agreement with the analysed field data of grain yield. Therefore, it can be affirmed that the drained condition performed well in grain yield.

Financial feasibility of stone-trench drainage innovation

Table 4 presents a comparison of costs and benefits under three drainage scenarios: 1) installing stone-trench drainage innovation and cultivating maize crop; 2) cultivating maize crop without installing drainage innovation; 3) keeping fields with grass cover and no maize cultivation.

The results showed that the net benefit under scenario 1 becomes negative in the first two years, implying that loan arrangements may be required for farmers who don't have enough family labour force and depend on market labour for collecting locally available stones and installing the stone-trench innovation. However, the net benefit under scenario 1 turns positive and exceeds that of other scenarios as of the third year. This demonstrates that scenario 1 becomes financially feasible, and farmers would be profitable and earn more income starting from the third year should they adopt this scenario.

Conclusions

Based on the analysed results of this field research, the plots under non-drained condition had very low yield due to mainly water logging problem manifested by suppressed and delayed crop growth by 4.2, 22.8, 7.8 and 27.9 days on average in achieving 50% germination, starting of flowering, 50% flowering, starting of silking, and 50% silking, respectively, as compared to plots within the drained condition.

The "stone-trench" drainage innovation could increase the productivity of maize by about 5-fold with positive net benefit after three years since installation of the drainage innovation as compared to the non-drained condition.

The plots under drained condition had highly grin yield and got highest rank by most (up to 90%) of the field day participants'. Hence, the "stone-trench" drainage innovation could be promoted through agricultural extension systems for improving crop yield in the study site as well as in similar sites suffering of drainage problem.

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