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Basin-wide productivity and livelihood analysis of flood-based agricultural systems in African drylands: A case study in the Fogera floodplain

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ABSTRACT

Flood-based Agricultural Systems (FAS), which rely on temporary floods, provide livelihoods for nearly 50 million smallholder farmers across water-stressed African basins. This paper analyses the impact of externally driven agricultural production and productivity improvement interventions in FAS, taking the Ethiopian Fogera floodplain as a case study. Ostroms' Governing the Commons Principles were used as analytical framework. Field data was gathered through focus group discussions and interviews with 266 farmers and pastoralists, and 10 local administration staff, while the AquaCrop model was used to simulate maize yield under varied floodwater management and farming practices. The interventions in the Fogera floodplain replaced vital maize and teff food crops with high-return upstream rice cultivation. It has characteristics similar to other interventions across Africa: 1) inadequate integration of local agricultural water management practices; 2) narrow focus on short-term economic gains and insufficient attention to long-term sustainability of livelihoods and environmental issues; and 3) lack of detailed ex-ante analysis of basin-wide consequences – it failed to prioritize the needs of downstream vegetable producers and pastoralists using shallow wells. The intervention missed several low-cost opportunities, including the establishment of rules to protect downstream water rights; the construction of gabion-strengthened on-farm structures to efficiently distribute floods or raised brick-walls to reinforce shallow wells; and the implementation of measures for improved soil fertility and weed management. The study establishes that these missed opportunities could have enhanced livelihoods by doubling rice yield to 6 tons/ha; increased teff and maize harvests by one-third, to 3 and 5 tons/ha respectively; and mitigated 25% vegetable yield loss and 40% reduction in grazing land. These opportunities could have also produced environmental benefits, including reduced soil moisture and fertility depletion. Lessons from the Fogera floodplain on making interventions cost-effective and considering basin-wide livelihood impacts are relevant to FAS globally.

1. Introduction

Flood-based Agricultural Systems (FAS) have received relatively little research and investment attention as compared to perennial irrigation systems (Puertas et al., 2015). They are, however, substantial: they cover an estimated 25 million ha across arid and semi-arid Africa where they provide food and fodder for nearly 50 million farmers irrigating, on average, 0.5 ha (Kool et al., 2017). There are four widely practiced FAS: (1) floodplain agriculture (flood recession and flood rise) – the cultivation of floodplains using receding and/or rising floodwater; (2) flood inundation canal systems – where canals fed by temporarily high-water levels in rivers irrigate adjacent low-lying fields; (3) spate irrigation, which makes use of short duration floods generated from mountain catchments; and (4) depression agriculture – shallow, seasonally waterlogged depressions that retain sufficient moisture for dry season grazing and crop production (Kool et al., 2017). Floodplain agriculture, complemented by flood inundation system, is the focus of this paper. It is the most extensive system covering nearly two-thirds of the total 25 million ha potential of FAS in arid and semi-arid Africa (Puertas et al., 2015).

Floodplain agriculture goes back more than 5000 years in some parts of Asia (Pakistan and Yemen in particular), and is also widely practiced

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in several African riverine environments including the Logone-Chari, Niger, Senegal and Volta Rivers (Adams et al., 2018; Saarnak, 2003; Traore et al., 2020), the Okavango delta (Motsumi et al., 2012) and Lake Victoria (Kipkemboi et al., 2007). Although floodplain agriculture and FAS in general have received little policy attention (van Steenbergen et al., 2011; Motsumi et al., 2012), several East African governments, including in Sudan, Ethiopia, and Kenya, have recently invested and are planning to invest in improving the productivity and livelihoods of 'traditional' FAS. In this paper, 'traditional' refers to 'farmer-led' FAS (Woodhouse et al., 2017), where farmers play a driving role in the design and establishment of the systems and are primarily responsible for the overall operation and maintenance of the floodwater management structures and all relevant farming practices. Traditional FAS often support subsistence food cultivation and rely on simple earthen and stone diversion and distribution structures that are frequently breached by floods. In Ethiopia, among the major local government-led interventions was the introduction of rice as a high value crop in around 40% of the 15,000 ha Fogera floodplain. Rice was envisioned to replace teff and maize, which are relatively low revenue but vital food crops, in order to boost economic growth and lift the living standards of the target communities. The significant shift to rice took place in the last decade.

Recent academic interests in FAS have focused on scheme-level technical improvements (Gebrehiwot et al., 2015; Libsekal and Mehari, 2020; Mehari et al., 2011; Zenebe et al., 2015) and impacts of environmental change (Sall et al., 2020). They have also covered farmer management practices (Singh et al., 2021) including the importance of indigenous knowledge (Motsumi et al., 2012). Few studies adequately address basin-wide floodwater management and productivity issues that impact the livelihoods of multiple varied users and uses. Castelli et al. (2018) attempted a detailed performance analysis of past interventions in the Raya Valley's FAS located in the Northern part of Ethiopia. The analyses, however, covered only one of the 17 Raya Valley schemes with relatively homogenous user groups in terms of the type of crops and the size of land they cultivated. Major basin-wide interrelated issues were not discussed. Yet, also at the local level, Castelli et al. (2018) show that participatory engagement of farmers can result in improved design of irrigation and bank erosion structures that respond to the needs of and are in line with the operation and maintenance strategy of the farmers.

In the Fogera floodplain, as is typical of FAS, various users share the same basins with seasonal or intermittent river courses. The lack of basin-wide analysis could, therefore, curtail the positive impact of interventions designed to improve traditional FAS and may increase the chance of unintended negative consequences, as the needs and priorities of some users will not be sufficiently identified and responded to. While scientific studies of the impacts of interventions are limited, there are some documented cases. One example is the Wadi Zabid spate irrigation scheme in Yemen, where the upstream expansion of a highly profitable, but hugely water demanding banana plantation eventually contributed to frequent downstream sorghum food crop failures (Zenebe et al., 2016). A second example comes from an intervention in Wadi Siham spate irrigation scheme in Yemen. The multiple offtake-system that allowed downstream water users to withdraw water directly from the river was replaced with a single upstream distribution offtake. This intervention is widely perceived as having contributed to floodwater supply scarcity in the downstream area (van Steenbergen et al., 2010). Other examples include upstream dam developments in the Senegal River (Saarnak, 2003), Tana River in Kenya (Zenebe et al., 2021) and the Mekong Delta (Ngoc, 2017) and the modernization of the spate irrigation system in Eritrea (Mehari et al., 2011).

Taking the Fogera floodplain as a case study, this paper analyses the following three questions:

- What are the strengths and limitations of traditional floodwater management practices in meeting floodwater supply needs, enhancing agricultural productivity and livelihoods of basin-wide users?
- How has the intervention that partially replaced the vital teff and maize food crops with high value rice upstream cultivation impacted traditional floodwater management practices, agricultural productivity, and basin-wide livelihoods?
- If a basin-wide intervention approach had been implemented, what technical and non-technical measures could have been introduced to further improve floodwater management practices, agricultural productivity, and livelihoods?

The Fogera floodplain is a relevant case study for two main reasons. First, the approach followed in the area – a limited scope in detailed ex ante scientific diagnosis of basin-wide issues as well as lack of attention to long-term sustainability – is representative of the characteristics of several interventions in FAS (see for instance, Zenebe et al., 2021; Ngoc, 2017; Mehari et al., 2011); Second, the Fogera floodplain is among the pioneer intervention sites to improve the productivity and livelihoods of traditional FAS; thus, it is expected to harbor rich experiences and lessons that can make a significant contribution to enhancing similar endeavors in other FAS across Africa and perhaps globally.

2. Theoretical framework

The Principles of the theory "Governing the Commons" presented in Table 1 (Ostrom, 2000) provided an analytical framework for the data and information collection across the above outlined three research questions. These Principles, drawn from extensive research, have been widely recognized as imperative benchmarks for successful collective management of a "shared" resource such as the floodwater in FAS to provide for the livelihood needs of all target beneficiary groups (Ostrom, 2002).

The overarching analytical question was to what extent the floodwater management rules and practices before and after the introduction of rice fulfils the requirement of the Principles and how this in turn impacts floodwater availability and productivity, and livelihoods of the Fogera farming and pastoralist communities. The operational effectiveness of the rules was further comparatively analysed against the

Table 1
Selected Ostrom's governing the commons principles relevant to floodwater management analyses.

Ostrom's principles	Analytical relevance to this paper's floodwater management system
1. Rules for managing a common resource must equally and adequately respond to all varied local priorities and needs.	Helped assess if and to what extent the operational rules meet the floodwater requirements of the three target farmer groups (upstream rice growers, midstream teff and maize cultivators, downstream vegetable producers)
2. All likely to be affected should have equal opportunity to participate in decision-making about formulation and modification of rules	Among others, this Principle informed the analyses of the 'upstream first with limitations rule' that restricted the upstream allocation to a single turn (350 mm depth) but was then modified to double this allocation to two turns following the introduction of upstream rice cultivation.
3. Use graduated sanctions and accessible, low-cost means for addressing violations and disputes	Served as the basis for evaluating the pros and cons of the operational conflict mitigation process in the study area that is being implemented by the Water-masters (farmer leaders)
4. Basin-wide institutions to manage a common resource in nested tiers from the lowest level up to the entire interconnected system	This informed the effectiveness analysis of the current water-masters (farmer leaders) led institutional arrangement as far as enforcing water distribution rules, organizing operation and maintenance and other related floodwater management practices are concerned

scope of the 'package of rules' successfully applied across some of the centuries-old FAS in Asia, Pakistan and Yemen in particular (Table 2).

3. Materials and methods

3.1. Study area description

The Fogera floodplain is in the Fogera district of the Amhara region in Ethiopia. As shown in Fig. 1, the floodplain is the area with the lowest elevation bordered on the east by the Bahir Dar-Gonder road, on the west by Lake Tana and on the north and the South by Reb and Gumara rivers respectively. The potential inundation area is nearly 40,000 ha, but the annually flood-irrigated land is estimated at 15,000 ha (Nederveen et al., 2011). The floodplain is the major source of food and fodder for 75% of the largely agrarian Fogera district population of nearly 250,000 (Gebey et al., 2012).

During the June to September rainfall season, overflows from Lake Tana, the largest lake in Ethiopia, and the Reb and Gumara rivers that ultimately discharge their flow into the lake, irrigate the Fogera floodplain (Nederveen et al., 2011). The annual average rainfall in the mountainous catchment upstream of the lake and the rivers is about 1200 mm. This gradually decreases towards the lowlands reaching its lowest amount of about 400 mm in the downstream Fogera floodplain where rainfall is more erratic in nature (Nederveen et al., 2011). The mean monthly temperature ranges from about 20–30 °C, which is favorable for the major crops grown in the study area: rice, teff, maize as well as vegetables, mainly onions and beans (Gebey et al., 2012).

For several decades, traditional food crops (teff and maize) have been grown in 8000 ha extending eastwards from the lake Tana shore in Nabega, Wagetera, Kdste hana, Shina and Shaga wards (Fig. 1). In the next Kuhar Mikael, Tihua Ena Kokit, Wereta and Kuhar Abo wards, about 4000 ha have been cultivated with vegetables using flood-recharged shallow wells. Further in the fringes of the floodplain, a vast 3000 ha grazing area supported pastoral livelihoods. The Fogera floodplain has long attracted the attention of the local government and its development partners as a potential rice hub. This is because the floodplain has flat topography and a 2–3 m deep silt loam soil profile with high water holding capacity of about 440 mm/m (Mehari et al., 2011; van Steenbergen et al., 2010). These soil conditions are favorable for the high-water demanding rice crop, but also for all the other major crops as they complete their entire growth cycle based on residual moisture harnessed with a single irrigation turn of about 350 mm depth during the preceding flood season. Although there were early attempts to introduce rice in the 1990 s, the big push by the local administration came when Ethiopia rolled out its nation-wide development program in the late 2000 s. Rice production was first piloted in the 'upstream part' of the floodplain in Wagetera and Nagega wards close to the Lake Tana shore (Fig. 1). Significant shift to rice cultivation, however, mainly happened in the last decade. There is now 6000 ha rice cropped land in Nabega, Wagetera, Kdste hana wards originally cultivated by maize and teff.

Flood inundation and flood plain agriculture systems are complementarily practiced. The floods generated when Lake Tana overflows its banks are distributed to the irrigated area through a series of field canals. Earthen bunds retain the floodwater in the irrigated fields where floodplain agriculture is practiced – flood rise for rice and flood recession for the food crops (teff and maize) and as well as the vegetables. A group of fields share a common canal, and the floodwater is distributed from one field to the next by breaking the earth bunds.

Field bunds are central to effective floodwater management at both individual farm and irrigation system levels. Fogera farmers invest time and labor to construct as strong earthen bunds as possible through compaction of 5–10 cm soil layer at a time and eventually reaching a height of about 35 cm. Unlike in perennial irrigation where multiple irrigation gifts are possible, crops in Fogera floodplain and other FAS depend on one to two irrigation turns, which must be adequately retained. Given this large amount of floodwater supply, a breaching of any field bund could lead to devastating damage to neighboring fields and structures.

The Fogera farmers often practice direct manual planting. The crop growth period for rice extends from June to September, which coincides with the flood season while the other crops complete their growth cycle from end of September to January under flood recession agriculture. Some of the large-scale farmers (0.6–3 ha) with relatively more financial resources than the small-scale (< 0.5 ha) farmers invest in weed management as well as fertilizer application. Other field management practices such as mulching are not common.

Table 2
Floodwater management rules successfully practiced in centuries-old Flood-based Agricultural Systems (FAS) across Yemen and Pakistan (Source: own compilation based on Mehari et al., 2007; van Steenbergen, 1997; Zenebe et al., 2016).

Rule on:	Objective and description
Demarcation	Protects downstream rights by prohibiting new upstream developments (canals, structures, farming systems) not supported by the majority of all users' groups
Sequence, irrigation depth and turns	Provides some predictability on which fields will be irrigated first and which ones next. It limits upstream priority to a single turn of a maximum of 500 mm irrigation depth, and grants a second turn only after all other fields are irrigated once
Special crop preferences	Aims to protect the poorest segments of the farming communities by prioritizing crops that are vital for household food security over cash crops
Small and large floods	Allocates small (5–15 m^3/s) and medium (15–25 m^3/s) floods to the upper and middle reaches - they cannot flow further downstream; large (25–40 m^3/s) and very large (> 40 m^3/s) floods to the tail-end - they can cause more damage than benefit if retained upstream
Maintenance	It stipulates that, given the unreliable and destructive nature of floods, maintenance should be taken very seriously. Accordingly, hefty penalties are enforced to start with and those who repeatedly (three or more times) fail to contribute through labor or in cash are deprived of floodwater supply altogether

3.2. Methods for data and information gathering

The analyses in this paper are derived from qualitative and quantitative data gathered from a total of 276 respondents, of which 170 (150 farmers and 20 pastoralists) participated in individual interviews and 80 (72 farmers and 8 pastoralists) were engaged in Focus Group Discussions (FGDs). In addition, 26 key informants guided the field surveys; these comprised 12 farmers and four pastoralists purposefully selected and 10 local administration staff active in the Fogera floodplain. The 150 individually interviewed farmers were selected using stratified random sampling from a database of 1282 farmers with over 10 years of experience in floodwater management and farming practices. The database consisted of 366 rice growers, 432 teff and maize cultivators, and 484 vegetables producers. To ensure equal representation, the sample sizes from each of the three farmer categories were proportional to their respective total populations. Since few pastoralists actively interact in floodwater management, 20 pastoralists relatively more familiar with the topic and were willing to be interviewed were purposively sampled. The 80 FGD participants were also selected using purposive sampling to ensure engagement of those with over 10-years farming or pastoral livelihood experiences. The sections below have further details on the three data collection methods.

3.2.1. Field survey

The field survey combined transect walks and key informant interviews (Kawulich, 2005). Fourteen transect walk days were organized: four days to each of the upstream rice, midstream teff and maize, and

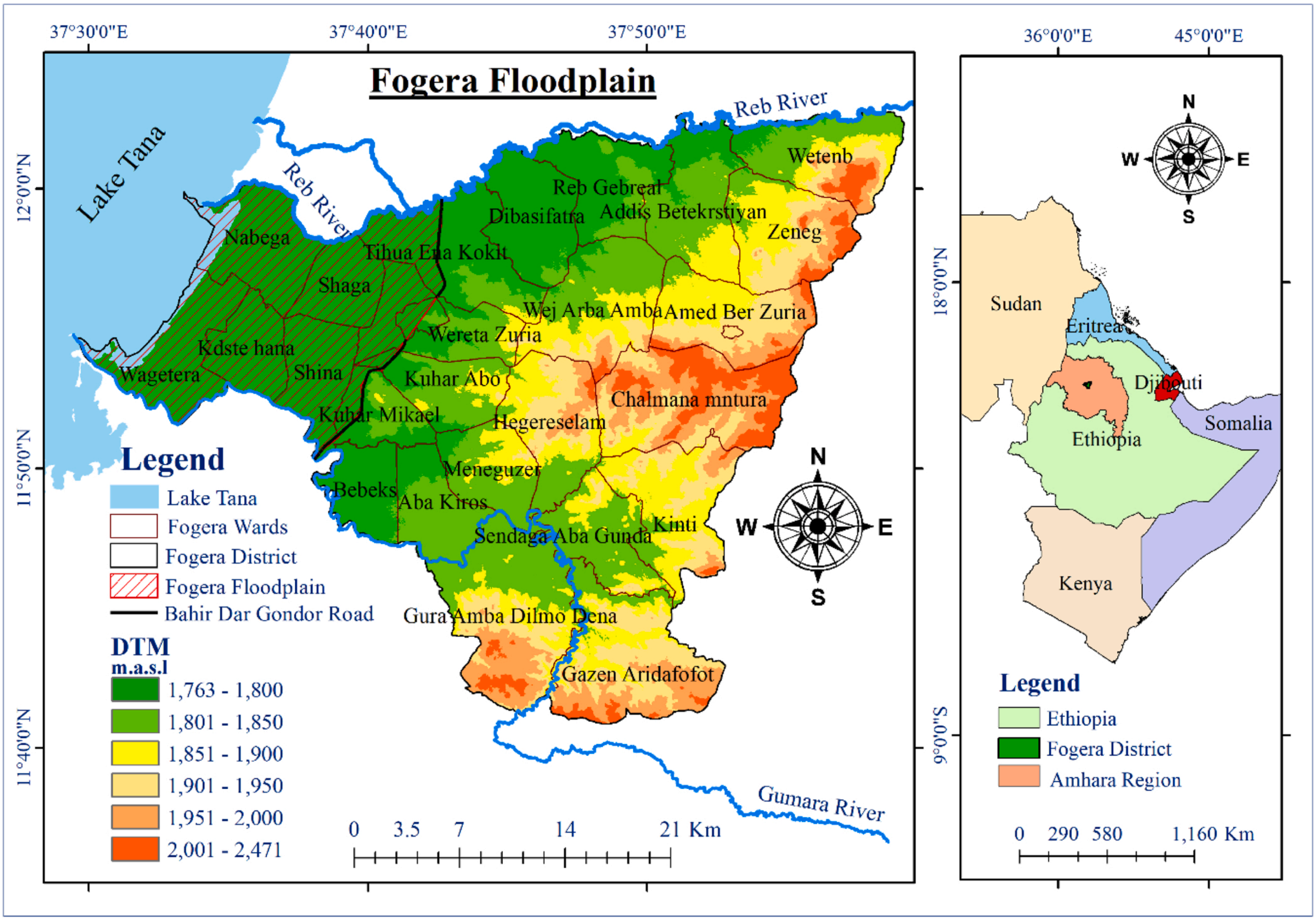

Fig. 1. Location map of the Fogera floodplain within the Fogera district, Amhara region, Ethiopia.

downstream vegetable farming systems; and two days to the grazing areas. Sites with good and poor floodwater management and farming practices were identified and visited together with 16 key farmer informants (four representing each of the three category of farmers and the pastoralists) who guided the transect walks. Each transect walk day started with an early morning preparatory meeting, followed by 3–5 h walking in the field and an evening wrap-up session to summarize main observations and findings. The key informant farmers, selected in consultation with the community leaders and the local administration, met two criteria: (1) over 15-year experience as active farmers or pastoralists; and (2) good relations with the wider Fogera community, which was critical for having access to all the selected field visit sites. The transect walks generated information on a range of issues: floodwater sharing; organization of repair and maintenance activities; farming practices and actual harvest, and the main factors that impact agricultural productivity. Follow-up discussion with the key farmer informants further elaborated on the rules and enforcement mechanisms that governed floodwater management before and after the introduction of rice. The discussions with the 10 local administration staff generated policy insights on why rice was introduced, and the population and characteristics of the farming and pastoral communities. These data and information established the basis for the detailed analyses during the FGDs and individual interviews.

3.2.2. Focus group discussions

This widely recognized qualitative research method (Guest et al., 2017; Moon et al., 2016) engaged a total of 72 farmers and 8 pastoralists in ten homogeneous eight-member focus groups that share similar challenges and priorities: six farmer groups respectively representing small-scale (< 0.5 ha) and large-scale (0.6–3 ha) operators from either: (a) upstream rice growers, (b) midstream food crop (teff and maize) cultivators, and (c) tail-end vegetable producers; one pastoralist group that have grazing land at the downstream fringes of the floodplain; and three 'water-masters' groups - farmer leaders responsible for enforcing floodwater management practices in the rice, food crops and vegetable production areas.

The homogeneity of the focus groups, as also discussed by Smithson (2000) and Cassell and Symon (2004), enabled candid interactions in a public setting. The FGDs started with 25 min brainstorm sessions that introduced the participants to and made them comfortable with the discussion theme: floodwater management practices before and after the introduction of rice. Using colored post-it cards, the participants were asked to write three short phrases that best expressed their priority floodwater management issues. The cards were displayed in a large paperboard and all participants gave 2–3 min elaborations. This was followed by 60–80 min discussions guided by 10–12 major questions and facilitated using the cards system. All participated by either directly responding to the questions raised or expressing their views on the answers provided by their fellow group members. In the concluding session, each participant was given about two-minutes to share new thoughts or elaborate on points that were not fully addressed. The moderator then wrapped-up the session with highlights of the important issues discussed.

This approach of conducting FGDs is informed by previous experiences of the first author (Zenebe et al., 2016, 2021) and was also found to be effective during the two pilot FGDs conducted with a farmer and a pastoralist group. The FGDs generated rich data across three priority themes: (a) floodwater sharing rules and their impact on floodwater management (b) strengths and weaknesses of institutional floodwater management arrangements; and (c) basin-wide approach for efficient and productive floodwater utilization. These thematic areas informed the individual interviews conducted.

3.2.3. Individual interviews

Individual interviews are a well-recognized method to harvest individual perspectives, including on issues that are perceived to be sensitive for public discussion (Bryman, 2016). In this study, individual interviews were employed to generate quantitative data across the three thematic areas identified by the FGDs. The interviews were conducted with 20 pastoralists and 150 farmers (Fig. 2). The database was compiled using a household survey conducted as part of this study. The local administration had a list of farmers who regularly cultivate their land and have experience of over 10 years, which is imperative as livelihood and yield comparisons have to be made for the periods before and after the introduction of rice. The list, however, lacked data on the size and location of the irrigable land and the crops grown, which was completed during the household survey.

The questionnaire that guided the individual interview was prepared with the 'laddering technique' (Schultze and Avital, 2011), an approach that facilitates harnessing detailed individual viewpoints on a specific issue through a set of subsequent interconnected questions. For example, the following questions captured the Fogera farmers' livelihood perspectives: (1) how do you compare your living standard before and after introduction of rice: (a) significantly improved, (b) slightly improved, (c) remained the same, (d) got slightly worse, and (e) became significantly worse; (2) Can you explain why there was a slight deterioration in your living standard? (3) What do you suggest needs to be done to address the issues you outlined?

3.3. Data analysis methods

The 'thematic method' (Braun and Clarke, 2006; Nowell et al., 2017) was employed to systematically organize the FGDs and generate the three main thematic areas outlined in Section 3.2.2. This was achieved in a three-stage process: (1) *observation during FGD data collection*, (2) *data familiarization* (reading through the text and listening to audio recordings), and (3) *searching for themes* – taking a much deeper look at the data to identify patterns and eventually themes. These thematic areas, as mentioned earlier, informed the individual interview. Descriptive statistics and frequency criteria guided the analyses of the individual interview data that was systematically organized in a spreadsheet.

Ostrom's' Governing the Commons Principles (see Section 2), provided the analytical framework for all the data and information gathered through FGDs and individual interviews covering floodwater management practices and rules, agricultural productivity and livelihood impacts. The rules that were operational before introduction of rice and those functional now were further analysed against the scope of the 'package of rules' detailed in Section 2. The analytical questions included: to what extent have the rules contributed to protecting downstream floodwater rights, limiting excessive upstream floodwater use, facilitating timely operation and maintenance and mitigating flood damage? How has this in turn affected agricultural productivity and livelihoods of the Fogera farmers and pastoralists?

3.4. AquaCrop modeling

AquaCrop model was employed for detailed yield analyses. This model simulates crop and water productivity (kg/ha and kg/m^3) under various water scarcity conditions, but it can also assess the impacts of farming practices (Ranjbar et al., 2019; Steduto et al., 2009). Maize was singled out for analysis based on inputs from the farmers who participated in the FGDs and the individual interviews: (a) maize and teff are the two crops that have suffered the most from increased water scarcity following the introduction of rice – of which maize is more sensitive to water stress; (b) farmers are interested in enhancing their maize harvests, because the crop has more market value in the region than teff.

AquaCrop has been widely evaluated and found to be reliable for maize yield analyses (Hammer et al., 2009; Ranjbar et al., 2019). Although validating the model was not the objective in this paper, good correlation was found between the model results and the individual interview data with regard to the impact of fertilizer deficiency and floodwater losses on maize yield (see Section 4.3.2). These results further confirm the model is reliable.

Seven scenarios (Table 3) formulated by the FGD participating farmers assessed impacts on maize yield of various combinations of four factors: (a) floodwater scarcity; (b) floodwater losses caused by earthen field bund failures; (c) soil fertility stress; and (d) non-optimal weed management. The farmers were interested to know the yields that correspond to the scenarios in order to make an informed investment decision of their limited resources. The scenarios reflect the varied floodwater management and farming realities on the ground. Three in four of the individually interviewed farmers informed that floods often breach earthen field bunds and 30–40% of the maximum 350 mm irrigation depth supplied to the fields is lost. All individually interviewed farmers agreed that there is a medium soil fertility stress – this corresponds to 20% deficiency in the quantitative categorization of AquaCrop model. The weed management ranged from good to fairly poor, which is equivalent to 10% and 35% weed infestation rates in the model. Although waterlogging occurs during the flooding period, it was not considered in the modeling because maize planting takes place after the floodwater has fully receded (infiltrated) and the soil is not wet and can allow proper tillage. Hence, the soil is at near field capacity during the planting period. The model input parameters are detailed in the Appendix.

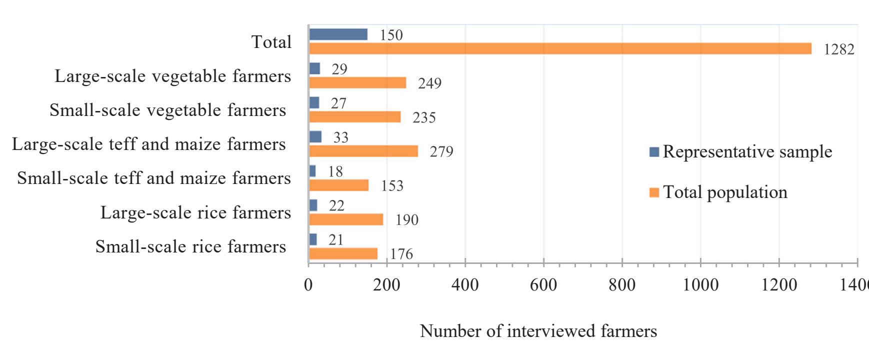

Fig. 2. Breakdown of Fogera floodplain farmers engaged in the individual interview. The sample sizes of each farmer category are proportional to their respective total populations.
(Source: Household survey).

Table 3
AquaCrop scenarios formulated by Fogera floodplain farmers for maize yield analyses.

Scenarios	Floodwater supply	Floodwater management	Fertility stress	Weed management
1	Maximum available 350 mm irrigation depth	Well-maintained field bunds: negligible floodwater loss	Farmers apply fertilizers: no stress	Good: 10% weed infestation
2	Same as above	As in the above	No fertilization-modest, 20% stress	Good
3	Same as above	As in the above	None	Fairly-poor: 35% weed infestation
4	245 mm irrigation depth	Poor field bund maintenance: 30% of the 350 mm is lost	None	Good
5	210 mm irrigation depth	Poor field bund maintenance: 40% of the 350 mm is lost	None	Good
6	As in scenario 4	As in scenario 4	Modest (20%)	Good
7	As in scenario 5	As in scenario 5	Modest (20%)	Good

4. Results and discussion

The socio-demographic descriptions of the total population of 1282 farmers and the corresponding 150 sample of individual interview participants are summarized in Table 4. The sample is representative of the total population as can be inferred from the closely correlated mean ages and irrigated areas. The very low Standard Deviation (STDEV) values across the six farmer categories are also an indication that the intra-variability in the irrigated areas and ages of the farmers is largely insignificant.

4.1. Traditional floodwater management

At a conceptual level, as gathered from the FGDs, the traditional floodwater management system that existed for over two hundred years before the introduction of rice promoted equitable floodwater distribution between the upstream maize and teff growers and the downstream vegetable (onion and beans) producers. This fulfils Ostrom's 1st Principle (Table 1). The practical effectiveness of the traditional system was, however, curtailed as it lacked some imperative rules presented in Table 2.

4.1.1. Traditional floodwater distribution rules

The strengths and limitations of the two rules that guided the traditional floodwater management are as discussed below.

Upstream first, but with restrictions rule: The FGD participants informed that this rule dates back nearly two hundred years. It grants the upstream farmers the priority for a single irrigation turn of 350 mm depth, and a second turn only after all the other fields have secured the same single turn. Floods are guided from field to field by breaking earthen bunds, which are restricted by this very upstream first rule to a maximum height of 35 cm to avoid excessive floodwater retention. The first irrigation turn is less than the minimum 500 mm depth required for optimum maize productivity (Steduto et al., 2012), a fact also recognized by the FGD participating farmers. Given the unpredictable nature of floods in timing and volume, there is no guarantee of a second turn. The upstream first rule does, therefore, in principle, facilitate some fairness in floodwater sharing and hence fulfils Ostrom's 1st Principle (Table 1). Its practical impact was, however, limited due to absence of the rule on 'small and large floods' (Table 2). This rule could have restricted the diversion of large floods to the upstream, which, as observed during the field surveys, often damaged the earthen field bunds and resulted in floodwater losses. On the other hand, letting these large floods flow downstream, where they are relatively less destructive, could have sufficiently recharged the shallow-wells that irrigate vegetables and water the grazing area.

A third of the interviewed farmers managed to properly construct and timely maintain their field bunds, but there were many instances of floodwater losses due to field bund damage. This was also several decades back a major challenge in Yemen and Pakistan, but it has been addressed by introducing gabion-reinforced field intakes that mitigated field bund failures (Mehari et al., 2005; van Steenbergen, 1997). The FGD participating farmers agreed that these improved intakes would also be useful in the Fogera floodplain. Introducing such floodwater management structures and effective water distribution rules are also considered priority interventions for the Shire Valley flood recession and the Eritrean Western Lowlands spate irrigated areas (Malota and Mchenga, 2020; Mehari et al., 2011).

In a new year, dry fields first rule: This rule does not exist in the centuries old FAS in Yemen and Pakistan outlined in Table 2. According to the FGDs participants, it was introduced some 50 years after the upstream first rule to further increase fairness in floodwater sharing. It

Table 4
Descriptive statistics of the total and sampled farmer populations engaged in individual interviews.

Descriptive statistics		Farmer categories					
		Small-scale rice	Large-scale rice	Small-scale teff and maize	Large-scale teff and maize	Small-scale vegetable	Large-scale vegetable
A. ***Total population***							
No. of farmers		176	190	153	279	235	249
Farming experiences		All farmers had more than 10 years farming experiences					
Age (Yrs.)	Range	36–73	34–74	32–72	30–83	22–72	32–72
	Mean	50	49	50	49	45	48
	STDEV	9.7	9.4	9.66	10.3	9.4	7.2
Irrigated area (ha)	Range	0.01–0.5	0.6–2.6	0.01–0.5	0.6–2.5	0.01–0.5	0.6–1.75
	Mean	0.23	1.29	0.23	0.89	0.19	0.79
	STDEV	0.12	0.48	0.11	0.35	0.10	0.21
A. ***Total sample***							
No. of farmers		21	22	18	33	27	29
Farming experiences		All farmers had more than 10 years farming experiences					
Age (Yrs.)	Range	40–73	37–58	38–72	37–60	32–68	38–68
	Mean	55	45	48	47	45	47
	STDEV	10.5	6.5	9.49	6.3	8	7.8
Irrigated area (ha)	Range	0.03–0.5	0.6–2.5	0.06–0.5	0.6–2.04	0.06–0.35	0.635–1
	Mean	0.21	1.3	0.25	0.88	0.17	0.75
	STDEV	0.13	0.55	0.13	0.31	0.11	0.1

directs that in a new flood season, irrigation should start with the fields that did not receive floodwater the previous year. While the rule has a powerful equity principle, enforcing it is near impossible. First, it requires that upstream farmers let the floodwater flow downstream while their fields are dry – a difficult ask. Second, small and medium floods may dominate the start of the flood season and even if allowed to travel downstream to drier fields, they may not have the necessary velocity and volume to reach there. All farmers engaged in the FGDs agreed that the rule on 'small and large floods' is more practical and a better replacement.

4.1.2. Institutional floodwater management arrangements

The FGD participating farmers explained that a group of three to five farmer leaders, locally known as 'water-masters', enforced the rules and the Operation and Maintenance (O&M) of field bunds and canals in their respective villages inhabited by between 200 and 600 farmers. They are elected in a village meeting for a single 3-year term, which can be renewed once for the same duration. Any farmer above the age of 25 years is eligible for election. Water-masters do not receive salary, but there is one strong incentive: irrigation priority as per the provisions and restrictions of the upstream first rule.

The water-masters have the mandate to respectively sanction 400–1200 ETB (about 10–26 Euros) for 1st and 2nd time violations of rules or failure to physically participate in O&M activities. Farmers who repeatedly (three times or more) disobey water-masters' orders are brought before the local administration, a 'scenario' that usually leads to a payment of about €50, a hefty amount for any Fogera farmer. The money collected is used for food and drinks during O&M and other events such as when the community supports elderly farmers during the labor-intensive harvesting period. The FGD participants emphasized that the hefty penalty was sparingly imposed as farmers often cooperated.

The water-masters led enforcement mechanism is very much akin to the 'graduated sanctions approach' advocated by Ostrom's 3rd Principle (Table 1). It was evaluated as being successful by nearly 80% of the interviewed farmers. While it did not go as far as depriving farmers of floodwater supply as required by the rule on 'maintenance' (Table 2), the threat of hefty sanction combined with the strong collaboration between the community-respected water-masters and the legally powerful local administration has achieved a high degree of discipline in abiding by the rules, and conflicts were rare.

The traditional institutional arrangement does not fulfill Ostrom's 4th Principle (Table 1) as there is not any higher-level organization that coordinates the activities of the water-masters. Three in four of the interviewed farmers do not see the need for such an organization – nearly 90% believe that it is financially unsustainable. In their opinion, the water-masters across the villages are well-connected and have the necessary coordination capacity. Lessons from other FAS including the Tana River in Kenya (Zenebe et al., 2021) and the Mekong Delta (Ngoc, 2017), however indicate that it is imperative to have a Fogera floodplain wide institution to partly represent the farming communities' priorities more effectively during external development interventions.

The analyses of Institutional Alternatives for African Smallholders (Shah et al., 2002) confirms that collaborative institutional arrangement between farmers and irrigation agencies is the most effective. Farmers alone may not adequately manage irrigation systems because they often do not invest into long-term sustainability of irrigation systems – a role that can be fulfilled by the public institutions. To ensure that farmer organizations adequately pay their share of O&M cost, however, the objective of institutional reforms should shift from 'just irrigation water management improvement' to 'enhancing productivity and income.' This implies that Water Users Associations (WUAs) may not be appropriate farmers organizations – 'producers groups' with a mandate that goes beyond just managing water distribution and includes agronomic and marketing aspects may be necessary.

4.2. Floodwater management in the rice era

The FGDs revealed that the traditional *upstream first rule* was modified to grant upstream rice farmers two irrigation turns of 350 mm depth each instead of the single turn, which was the case in the traditional floodwater management system. This modification is contrary to Ostrom's 1st Principle (Table 1) that advocates for equally and adequately responding to the needs and priorities of all target beneficiaries. It has to be noted, however, the two irrigation turns is much less than the 1000 mm water requirement of early maturity (100–120 days) rice varieties (FAO, 2019) common in Fogera floodplains. Despite its strong economic growth drive, the local administration did not insist that upstream rice fields be fully irrigated first. This compromise was mainly influenced by the interest of the local administration to maintain the good institutional collaboration they established with the water-masters in the pre-rice era, which they believed was essential for the successful enforcement of the modified upstream first rule. During the FGDs, the water-masters informed that they did not play a decision-making role in the modification of the rule as required by Ostrom's 2nd principle (Table 1). In principle, the water-masters agreed that they might have had a stronger influence if the rules on 'special crop preference' and 'demarcation' (Table 2) were part of the traditional floodwater management system. This could have led to a fairer floodwater sharing arrangement, such as equally dividing the 3-month (June to August) flood period between the upstream rice growers and the downstream farmers and pastoralists. This floodwater sharing arrangement was widely perceived as a good compromise by small and large-scale FAS farmers in Kenya (Zenebe et al., 2021). The second traditional rule, 'in a new year, dry fields first' was scrapped to eliminate the risk posed by the rule on significant floodwater supply reduction to upstream rice fields.

From the above, it can be deduced that the floodwater management intervention did not follow a basin-wide approach – it narrowly focused on mainly increasing floodwater supply to the upstream rice cultivation. Little attention was given to analyses of downstream farming and pastoral livelihoods' priorities, flood mitigation measures and environmental needs. As a result, some opportunities were missed including: a) the introduction of the rule on 'small and large floods', which could have increased irrigation supply to the midstream food crops (teff and maize) and the downstream vegetable (onion and beans) cultivation by prohibiting the diversion of large floods to the upstream where they often cause more damage and are less productive, and b) low-cost improved (gabion re-enforced) field intakes, which as discussed, could significantly reduce breaching of earthen field bunds and floodwater losses. Some FAS farmers in the Tigray Northern region of Ethiopia are already using gabion structures (Libsekal and Mehari, 2020) – cost may not therefore be a barrier for introducing it to Fogera floodplain.

Investing in the food and vegetable crops is not only essential to respond to midstream and downstream agricultural productivity and livelihood needs. It can also contribute to shifting from monoculture rice farming to profitable diversified agricultural system, which is more resilient to climate change impacts. The Fogera floodplain and all other FAS are inherently vulnerable to climate change as they depend on floods highly unreliable in timing and volume.

4.3. Floodwater productivity and livelihood analyses

Drawing from the individual interviews, Fig. 3 summarizes the comparative livelihood analyses for the periods before and after introduction of rice. All teff and maize farmers were negatively impacted with about half reporting significant worsening of their living standards. About two-third of the vegetable producers experienced slight livelihood deterioration. The majority (80–90%) rice farmers who previously cultivated teff and maize slightly improved their livelihoods, the rest significantly.

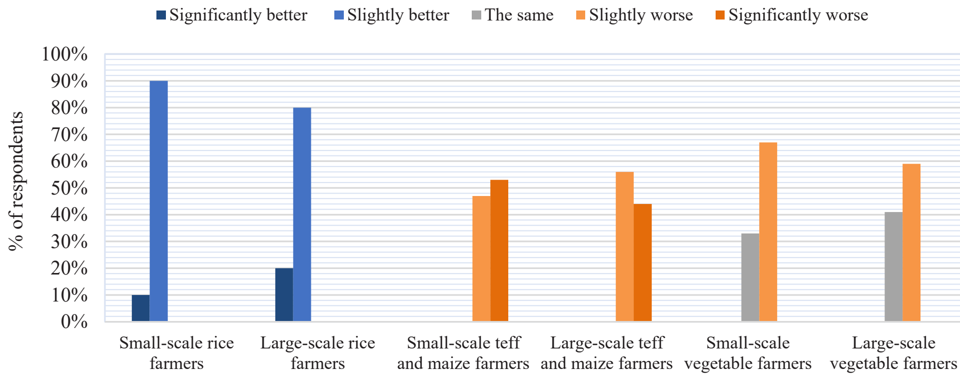

Fig. 3. Fogera floodplain farmers' perspectives on the status of their livelihoods after the introduction of upstream rice cultivation as compared to the previous era. (Source: Interview data).

4.3.1. Rice irrigating farmers

The assertion by the overwhelming majority of current rice irrigating farmers that the shift they made from teff and maize food crops to high value rice production only 'slightly' improved their livelihoods (Fig. 3) is informed by a combination of the high expectations set by the local administration (above 5 tons/ha) and the relatively low rice crop harvests obtained. Fig. 4 summarizes the yield obtained in 2019 by the interviewed 22 large-scale and 21 small-scale farmers. Even the highest reported yields of about 4 tons/ha, are far below the optimum 9 tons/ha (FAO, 2019) when irrigation, soil fertility and other field management practices are not limiting factors. The highest yields are also much less than the 6 tons/ha achieved by small-scale farmers in Kenya with irrigation applications and soil profiles similar to that in the Fogera floodplain (Ndiiri et al., 2013).

Comparatively, the large-scale farmers obtained higher rice yields. Their median productivity (3.3 tons/ha) is 30% higher than that of the small-scale farmers (Fig. 4). Further, the Inter Quartile Range (IQR) or the box width, which measures data intra-variability, is 44% greater in the case of small-scale farmers. The majority of the small-scale farmers are concentrated on the lower yield range as shown by the 'positive skewness' of the data: a median closer to the bottom of the box, and a 'whisker' (line) shorter on the lower end of the box. This indicates the large-scale farmers were more consistent in realizing their relatively higher yields.

All of the interviewed small-scale farmers and 90% of the large-scale farmers informed that the low rice harvest is the main constraint for better livelihoods as there is a vibrant and high market demand for rice in Fogera district, and the Amhara region with about 20 million population (Nederveen et al., 2011). The grain is both staple and cash crop while the straw provides nutritious livestock feed. The farmers explained that there is no added value of leaving the straw in the field or integrating it into the soil as it does not quickly degrade and does not improve soil condition and fertility. This assertion is supported by a field research conducted in Thailand that concluded rice straw did not improve rice productivity (Maneepitak et al., 2019). Similar findings were reported by Hanafi et al. (2012).

The individual interviews identified two key factors that contributed to the low rice yields: (1) *Poor on-farm floodwater management:* Nearly 75% of the participating farmers explained that although there is some shortage in physical floodwater supply, lack of effective field techniques to better manage floods and reduce losses was the more significant and frequent problem that reduced yield. As discussed, the intervention in Fogera did not introduce improved (gabion re-enforced) field intakes and the earthen bunds are often breached leading to significant irrigation losses. The small-scale farmers are more vulnerable as they lack resources to timely and properly maintain their field bunds (2) *Soil fertility stress*: the 71% and 24% of the interviewed large and small-scale farmers who managed 3.0 tons/ha and above (Fig. 4), applied between 25 and 50 kg of urea/ha (12–23 kg/ha of nitrogen fertilization, N). The four best performing large-scale farmers who obtained at least 4 tons/ha used 100 kg of urea/ha (46 kg/ha N). These facts back the claim by 80% of the interviewed farmers that the Fogera floodplain has some soil fertility deficiency. There was no significant difference in floodwater management and other farming practices among the interviewed large and small-scale farmers.

Nearly a third of the large-scale and three quarters of the small-scale farmers could not use fertilizers due to limited supply and high cost. Among those who managed, the application rates are much less than the 60 kg/ha of N recommended for rice cultivation in the lowland region of Ethiopia (Bado et al., 2018). A field experiment conducted in the region (Tamene et al., 2017) has also shown positive yield response up to 75 kg/ha of N. There is therefore opportunity to further increase

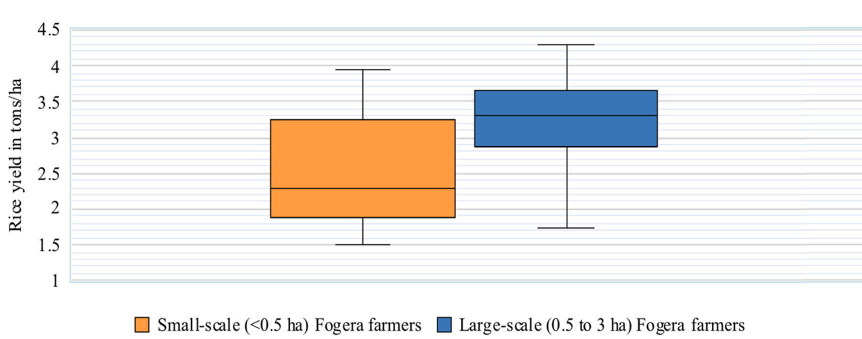

Fig. 4. Boxplot of Fogera floodplain rice yields. The median, the central line of the box, is the midpoint value of the yield dataset. The upper and lower boundaries of the box display the yields higher than 25% and 75% of the dataset whereas the minimum and maximum yields are shown in the respective lowest and highest datapoints of the whiskers.
(Source: Interview data).

productivity by making fertilizers widely available and affordable. It is important, though, to learn from Mekong Delta experience where nitrogen fertilizer overuse in rice fields has caused environmental degradation including soil acidification and water pollution (Tran et al., 2018). A more sustainable approach would be to use organic (compost) fertilization. What is relevant here, as also discussed by Motsumi et al. (2012) and Nguyen et al. (2020), is to have supportive policies from national to local levels that encourage farmers participation and promote sustainable productivity and livelihoods.

Rice planting practices were identified as yield impacting factors by just 15% of the rice interviewed farmers. However, all farmers practice direct broadcast sowing, which often leads to high planting density, poor germination, and reduced seed setting. A field experiment conduced in Kenya has shown that transplanting of younger seedlings with wider spacing significantly increased productivity (Ndiiri et al., 2013). These practices were also reported to have increased yield under flood recession in Mali by about 40% (Traore et al., 2020). Seedling preparation is a well-known practice in Ethiopia (see for example Thijssen et al., 2008). The local administration staff informed that the practice was not given attention, but that it can be piloted in some farmers' fields and then further upscaled.

Finally, spatial variability linked to the location of fields across the Fogera floodplain was not identified by the rice farmers as a yield determining factor. As mentioned earlier, this may be due to the fact that for the majority of the farmers, the major challenge is floodwater losses caused by poor management practices, not physical water scarcity. There is also no significant spatial variability in the soil type and depth (Nederveen et al., 2011).

4.3.2. Traditional food crop farmers

The data gathered from individual interviews with 51 teff and maize cultivating farmers indicates that the yield of both crops was low under the traditional system (before introduction of rice) at an average of about 40% of the attainable 7.5 tons/ha and 3 tons/ha maize and teff productivities respectively – see the medians in Figs. 5 and 6. 'Attainable yield' refers to yields obtained in Ethiopia with sufficient irrigation and fertilizer application (Clarke et al., 2017; Yihun et al., 2013). It can also be inferred from Figs. 5 and 6 that the maize yield gap between large and small-scale farmers is much bigger. This is because 40% of the large-scale maize farmers applied fertilizers to boost their harvest beyond their household requirements to generate income. Due to financial constraints, maize fertilization was given preference, as teff is relatively widely available and hence has much lower market value. Roughly 80% of the interviewed small-scale farmers could not afford to use fertilizers.

Nearly all (95%) of the interviewed small and large-scale maize and teff farmers explained that they now (following introduction of rice) often experience floodwater scarcity, and their best-case scenario is receiving a single 350 mm irrigation depth. This would be sufficient for teff but is significantly lower than the 500–800 mm maize irrigation requirement (FAO, 2019). Furthermore, maize is more sensitive to water stress. These facts explain the greater decline in maize yield – 36% (small-scale farmers) and 25% (large-scale farmers) – compared to the 20% and 18% reductions in teff (Figs. 5 and 6).

Maize farmers are highly interested in boosting their harvest. To better understand the impact of key floodwater management and farming practices, AquaCrop model was used to simulate yield under the seven scenarios formulated by the farmers (Table 3). The objective was to support farmers make an informed decision on how best to invest their limited resources. The main results were as follows:

- The farmers who secure a single irrigation turn (350 mm) could achieve a maximum 5 tons/ha maize yield if they mitigate field bund damage, avoid floodwater losses, adequately apply fertilizers and undertake proper weed management.
- 30–40% floodwater losses, which as informed by all interviewed farmers often occur due to poor on-farm water management and flood damage to field bunds, could reduce the maximum yield by 45% and 60% respectively.
- Moderate fertility stress (20%) can decrease the maximum yield by 1.6 tons/ha or about one-third. This correlates with the 1.1–1.5 tons/ha yield increase attained by large-scale farmers who applied fertilizers (see the difference between maximum and minimum yields in Fig. 5).
- The combined effect of 30% floodwater loss and 20% fertility stress can reduce the maximum yield by 66% to about 1.8 tons/ha, which is also the maximum obtained by the small-scale farmers following the introduction of rice (Fig. 5). As indicated earlier, 80% of the small-scale farmers did not apply fertilizers due to financial constraints. For this same reason, they are also the most vulnerable to floodwater losses.

4.3.3. Vegetable producers and pastoralists

The 27 small-scale and 29 large-scale farmers who participated in the individual interviews (Figs. 7 and 8) obtained an average yield of 16.75 tons/ha (onion) and 4.3 tons/ha (fresh beans) before rice was introduced. These yields are roughly 40% and 60% of the optimum values under sufficient irrigation and fertilizer application (FAO, 2019). The onions and beans are irrigated downstream by floodwater-recharged shallow hand dug wells. Following the introduction of rice, much of the small, medium, and large floods were retained upstream, resulting in only occasional very large flood flows downstream. As a result, nearly 90% of the interviewed farmers claimed that the recharge capacity has significantly reduced and they have, over the past years, observed a decline in their well water levels while their cropping pattern and irrigated areas have not changed. The local administration staff that

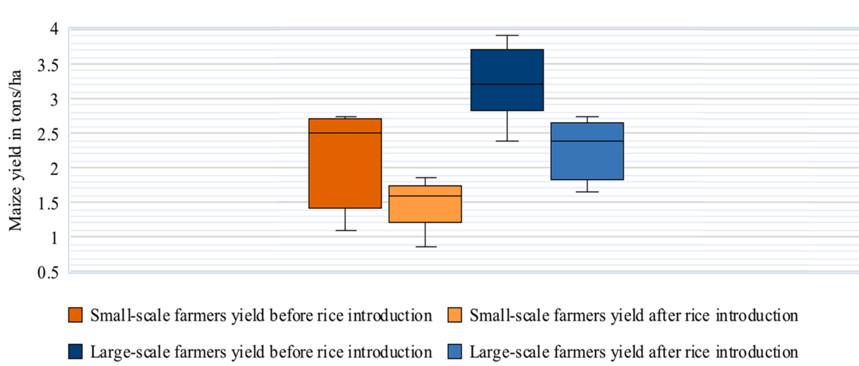

Fig. 5. Boxplot of Fogera floodplain maize yields. The median, represented by the line cutting across the box, is the center-value of the yield dataset. The lower and upper edges of the box display the yields higher than 25% and 75% of the dataset respectively whereas the whiskers indicate the minimum and maximum yields. (Source: Interview data).

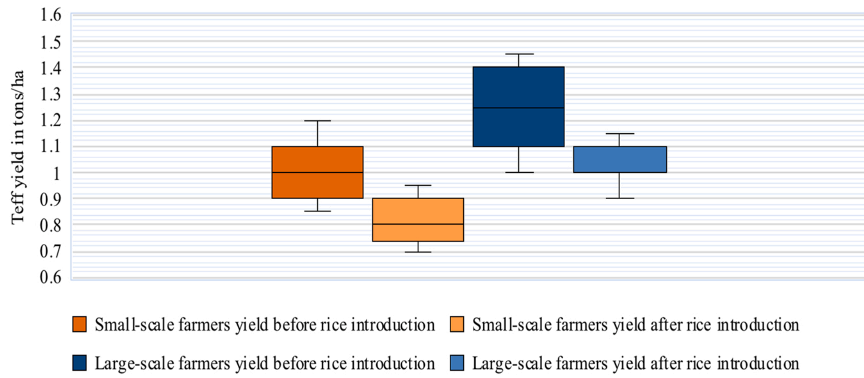

Fig. 6. Box plot of Fogera floodplain teff yields. The central line of the box represents the midpoint value (median) of the yield dataset. The upper and lower boundaries of the box indicate the yields higher than 25% and 75% of the dataset, while the whiskers show the minimum and maximum yields respectively. (Source: Interview data).

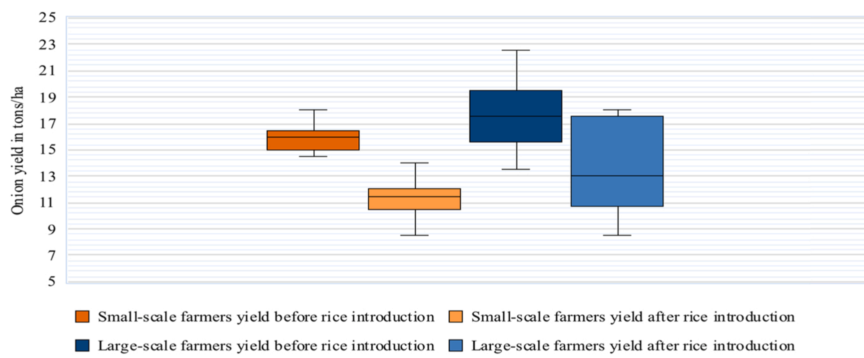

Fig. 7. Boxplot of Fogera floodplain onion yields. The median, the line dissecting the box, divides the yield dataset into two equal parts. The upper and lower edges of the box display the yields greater than 25% and 75% of the dataset while the whiskers indicate the minimum and maximum yields respectively. (Source: Interview data).

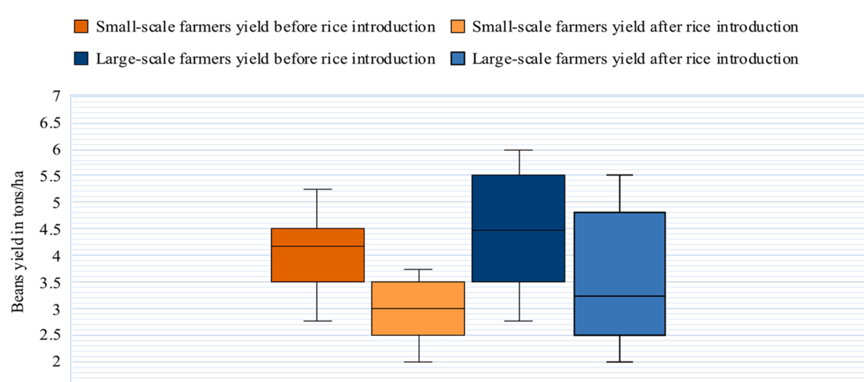

Fig. 8. Boxplot of Fogera floodplain bean yields. The median (the line cutting across the box) represents the midpoint value of the yield dataset. The lower and upper boundaries of the box display the yields greater than 25% and 75% of the dataset. The lowest whisker is the minimum yield while the highest whisker is the maximum yield.
(Source: Interview data).

participated in the key informant interviews agreed with the farmers observations, but also pointed to the absence of groundwater level monitoring data. Moreover, three in four of the interviewed farmers asserted that the very large floods frequently caused physical damage and sedimentation of the hand-dug wells. Desilting, repair, and maintenance is not always timely done due to labor and financial constraints. These factors resulted in inadequate or delayed irrigation and about 30% reduction in the average yields of both small and large-scale farmers. It should be noted here, however, that besides the introduction of rice, intensified land use and climate change may be significant contributors to the frequent large flood occurrences.

Unlike in the case of rice, teff and maize crops; the onion and beans yield gap between small and large-scale farmers is less significant at about 10% (Figs. 7 and 8). The large-scale farmers have better financial capacity and nearly 60% timely desilted and repaired their shallow wells, prepared their irrigation fields and harvested high yields. The other 40%, however, were less attentive to farming (they have off-farm economic activities such as small retail shops) and their productivity was low, bringing down the large-scale farmers' overall average yield. The high yield variability is reflected in the IQR of the large-scale farmers, which is three-fold that of the small-scale farmers.

In concluding the discussion on vegetables productivity, we wish to emphasize the point made in Section 4.2 that the lack of basin-wide approach in Fogera floodplain did not offer adequate prospects for detailed impact assessment of upstream rice interventions on downstream floodwater supply and management needs and priorities. This has contributed to some low-cost missed opportunities such as reinforcing the embankment of shallow-wells with raised brick-walls or stone-riprap that could have reduced the rate of flood damage and sedimentation.

Coming to the pastoralists, the 20 individual interview participants and the 8 persons engaged in the FGDs estimated that the annually irrigated pastureland has decreased by some 40%, to about 1800 ha, and the livestock (mainly cattle) population has decreased by nearly two-thirds, or roughly 1500 heads. They explained that these decreases are caused by the increase in rice production, which has resulted in the retention of floods in the upper part of the Fogera plain, including the larger floods that used to irrigate their grazing area.

5. Conclusion

The paper analysed, in detail, floodwater management and productivity of the Fogera floodplain and the livelihoods of its basin-wide users prior to and following the agricultural intervention that replaced the vital teff and maize food crops with high value upstream rice cultivation. The traditional floodwater management promoted some fairness in floodwater sharing. It, however, lacked critical agricultural floodwater management rules, techniques, and practices and remained a low-production and subsistence livelihood system.

The narrow focus of the agricultural intervention on enhancing rice harvests through primarily increasing floodwater supply, and the desire to fast-track development at the expense of long-term sustainability and detailed analyses of all basin-wide challenges and opportunities, has negatively affected Fogera floodplain agricultural productivity and hence livelihoods. Rice harvest remained low, at about 3 tons/ha, as compared to the attainable 6 tons/ha; maize and teff harvests declined by 30% and 20% respectively; vegetable (onion and green bean) productivity dropped by nearly a third; and grazing land dwindled by some 40% to about 1800 ha. Taking a basin-wide approach, a package of low-cost agricultural productivity and livelihood improvement measures could have been introduced: (a) floodwater management rules that mitigate flood damage, protect downstream rights, and give preference to food crops; (b) gabion reinforced on-farm structures for efficient floodwater distribution; (c) appropriate application of fertilizers and weed management – this has improved maize and rice yields by one-third; and (d) strengthening shallow-well embankments with raised brick-walls to decrease flood damage and sedimentation and enhance recharge capacity. These low-cost interventions can also achieve environmental benefits, including reducing water logging and salinity risk, soil erosion, moisture depletion, and soil fertility decline.

The Fogera floodplain is a pioneering agricultural intervention area. The findings of this study on cost-effective measures and the significant negative consequences of interventions that are not informed by basin-wide analyses and that narrowly focus on monoculture (rice) intensification are relevant to FAS across Africa and perhaps globally. Such interventions, as established by the study, reduce overall productivity of floodplains, cause deterioration of downstream livelihoods and the environment. Monoculture farming can also weaken the resilience of FAS, which are inherently vulnerable to climate change as they depend on floods that are highly unreliable in timing and volume.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. AquaCrop input parameters for maize yield computations under the scenarios outlined in Table 3

	Input data description	Source	Explanatory note
Climate	40-year monthly average minimum and maximum temperature (°C); rainfall (mm); relative humidity (%), windspeed (km/day) and sunshine hours	Bahr Dar Meteorological station in the vicinity of Fogera floodplain, the study area	This data set is available at CLIMWAT, FAO database: http://www.fao.org/land-water/databases-and-software/climwat-for-cropwat/en/
	ET_0, Evapotranspiration (mm/day)	Calculated using FAO CropWat 8.0 programme (http://www.fao.org/land-water/databases-and-software/cropwat/en/)	The Model uses FAO 56 Penman-Monteith equation
Maize crop	Planting date: 1–15 September	Individual interviews with farmers. Maize is planted in the first two-weeks of September after floodwater recedes, and the soil is not too wet for land tillage	1st September was used because AquaCrop only accepts a single date entry. Any date between 1 and 15 September does not change the simulated results
	Total growing period: 120 days. The mean daily temperature during the September to December growing period in Fogera is 19 °C	FGDs and individual interviews with farmers – it is within the 80–110 days range of early grain maize varieties (FAO, 2020)	Below 20 °C, maturity days could extend by 10–20 days for each 0.5 °C decrease depending on variety (FAO, 2020). 120 days is thus sufficient in Fogera
	Initial canopy cover: 0.28%	Estimated by AquaCrop based on row spacing (0.6 m) and plant spacing (0.3 m) practiced by Fogera farmers and 75% germination rate	Initial canopy cover is the area covered by maize crop after it completes the germination period, 7–20 days from planting
	Maximum canopy cover: fairly covered, which in AquaCrop ranges from 64% to 79%	Farmers estimate 70% coverage. Casa et al. (2010) reported 73%. 85–90% are also used, but these are based on 90% germination rate and high planting density of 66,000 plants/ha (Ahmadi et al., 2015)	Maximum canopy cover is the area covered by maize crop at maximum vegetative growth.
	Harvest Index (HI): 0.3–0.5.		HI is the ratio between grain yield and biomass

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(*continued*)

	Input data description	Source	Explanatory note
		The open pollinated old maize varieties in Fogera have the lowest 0.31 HI at optimum conditions (see Worku and Zelleke, 2007)	
	Rooting depth: 1–1.5 m.	As confirmed by Fogera farmers who informed maize roots grow to 1.5 m depth	1.5 m was used for the best-case scenario, 1 m for the other scenarios (Table 3)
Irrigation	Maximum floodwater available for maize crop: 350 mm	Field survey and individual farmer interviews. The amount is based on the field bund height, which is limited to 350 mm by the operational floodwater rule	The consulted farmers informed that poor maintenance of field bunds results in 30–40% floodwater loss. This is reflected in the scenarios presented in Table 3
Soil profile	Soil type: silt clay loam, soil depth (1.5–2.5 m), Soil moisture: Saturation (52%), Field Capacity (44%), Permanent Wilting Point (23%), Saturated Hydraulic Conductivity (120 mm/day)	(Gebey et al., 2012; Mehari et al., 2011; Raes et al., 2013)	Such high soil moisture holding capacity is essential as maize in Fogera grows under residual soil moisture
Field water management practices	Field bund height (0.35 m)	Field survey, interviews with farmers and farmer leaders	
	Mulching: not practiced	Field survey, interviews with farmers and farmer leaders	
	Soil fertility stress: modest	Key informant interviews with farmers and farmer leaders	Modest stress is equivalent to 20% in AquaCrop
	Weed management: Good, equivalent to 10% in AquaCrop and fairly poor to 35%	Field survey and key informant interviews with farmers and farmer leaders	The consulted farmers informed that fairly poor weed management often occurs in fields that have received relatively sufficient floodwater supply (Table 3)

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