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Toward a better understanding of the environmental impacts of expanding farmer-led irrigation in Sub-Saharan Africa: an exploratory assessment of irrigation-induced risk of nutrient water pollution in Ethiopia

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Abstract

Irrigation, and especially farmer-led irrigation, is considered to be a promising option for enhancing agricultural productivity in Sub-Saharan Africa. However, there is a lack of thorough understanding of the impacts of irrigation development on environment. Past discussions are mainly limited to the water depletion and hydrological regime change effect of irrigation. This paper presents a study to narrow the knowledge gap by assessing nutrient water pollution risk induced by the expansion of farmer-led irrigation in Ethiopia. Using household survey data collected from four woredas in Ethiopia where irrigated crop production currently concentrates, we first evaluate the impact of irrigation on cropping intensity and annual consumption level of fertilizers and then use the findings of the household survey data analysis to support conceptualization of a modeling framework for assessing agricultural nutrient water pollution risk from farmer-led irrigation development in Ethiopia at national scale. We project that overall farmer-led irrigation development in Ethiopia will lead to a gentle increase in national total of agricultural nutrient loadings. This result helps justify the endeavor of promoting farmer-led irrigation in Ethiopia. On the other hand, the projected nutrient flow and nutrient loading growth rate related to the farmer-led irrigation expansion are highly heterogeneous spatially, and risk of local water quality deterioration exists. There is still need to make investment to ensure the environmental sustainability of farmer-led irrigation development.

1. Introduction

Water is an essential input for agriculture. Irrigation augments water supply for crop production and is recognized as an important means for improving agricultural productivity (Fuglie 2008). While global irrigated area has been expanding over the last several decades, the level of irrigation development remains geographically uneven. Sub-Saharan Africa lags behind other regions in the development of irrigated agriculture; currently only 4 percent of cropland in the region is equipped for irrigation. The high dependency on rainfall exposes crop production to the risks of rainfall variability, undermines investment efficiency in the agricultural sector and contributes to food insecurity (Ringler 2021).

There has been much discussion about the prospects of expanding irrigated agriculture in Sub-Saharan Africa., including its impact on environment. Like in other types of development, environmental performance has implication for investment decision for irrigation. Discussions on the environmental impact of irrigation expansion in Sub-Saharan African countries are traditionally focused on water depletion and changes in hydrological regimes, (Liu *et al* 2014, Xie *et al* 2014, Altchenko and Villholth 2015, Liersch *et al* 2019), yet in reality, irrigation development has broader impacts on the environment and there is still a lack of understanding of them. In this paper, we assess the risk of nutrient water pollution which may arise from the development of farmer-led irrigation in Ethiopia.

Nutrient elements, specifically nitrogen and phosphorus, are essential for sustaining life; but excessive amounts can cause eutrophication and other adverse impacts on aquatic ecosystem health. Due to the paucity of water quality monitoring data, it is difficult to provide a complete picture about water quality conditions across the Sub-Saharan Africa region. However, recent water quality assessments at a few locations reported concerning levels of nutrient pollutants in freshwater environments (Maghanga *et al* 2013, Tibebe *et al* 2019, Isiuku and Enyoh 2020). Past studies have established a linkage between agricultural and nutrient water pollution (Howarth *et al* 2002, Strokal *et al* 2016, Mateo-Sagasta *et al* 2018). Irrigation is an agricultural technology with potential to alter the nutrient budget of crop production; its widespread application creates additional concerns about the nutrient state of the water environment.

There are different paradigms of irrigation development in Sub-Saharan African countries. In this study, we limited our attention to farmer-led irrigation. Farmer-led irrigation—also often referred to as small-scale irrigation, smallholder irrigation or small private irrigation—denotes a collection of irrigation practices that are self-financed and self-managed by individual or small groups of farmers. Being viewed as a grassroots approach to irrigation development (Kay 2001), farmer-led irrigation has recently attracted great interest from government agencies and international donors (You *et al* 2011, de Fraiture and Giordano 2014, Woodhouse *et al* 2017, Xie *et al* 2017, Lefore *et al* 2019).

The impact of irrigation on nutrient runoff from cropland is two-fold: firstly, water is a main driver of nutrient transport. Irrigation leads to stronger water movement and influences the biophysical processes of nutrient cycling in cropland. Second, and perhaps more importantly, irrigation development can change cropping patterns and farming practices and therefore shift nutrient input flows of crop production. To be specific, Sub-Saharan Africa generally has a tropical climate with alternating rainy and dry seasons. Irrigation helps extend the production season from the rainy season into the dry season, which might well add fertilizer use. Moreover, the agricultural productivity in Sub-Saharan Africa is also often constrained by the low-level use of fertilizers. There is perception that irrigation adoption may induce higher application rates of fertilizers in order to ensure realization of improved crop yield potential and a satisfactory economic return from irrigation investment (Yilma and Berger 2006, Folberth *et al* 2013).

Thanks to advances in environmental science and computing technology, numerical nutrient models have been developed and can be applied to evaluate the effect of irrigation on the biophysical processes of nutrients transport (Dechmi *et al* 2012, Malik *et al* 2019, Zhu *et al* 2020). On the other hand, there is still no consensus on how significant the effects of irrigation development on cropping pattern and farming practices are. This issue is non-trivial since evaluations of water balance and economic feasibility in irrigation planning involve use of climate data that vary with growing season and are based on cropping pattern of irrigated production. Some irrigation planning studies over Sub-Saharan African countries or region in the past emphasized the significance of the cropping intensity change brought about by the irrigation development by presuming that dry season is the main irrigation season and defining the irrigation development potential as the estimated scale of the dry-season irrigated crop production expansion that can be achieved under combined biophysical and socioeconomic constraints (Xie *et al* 2014, Xie *et al* 2017, Xie *et al* 2021). As a contrast, there are also studies which chose to omit the dry-season farming-inducing effect of irrigation development and based the irrigation water demand calculation on the existing cropping pattern which mainly reflects the crop mix in the rainy season. (Pavelic *et al* 2012, Altchenko and Villholth 2015, Worqlul *et al* 2017). In terms of changes in fertilizer application levels with irrigation, effort has been made to examine the statistical relationship between irrigation and fertilizer use (Aregay and Minjuan 2012, Sheahan and Barrett 2017, Pandey and Diwan 2021, Haile *et al* 2022). However, no consistent conclusions were reached from these case studies, suggesting that farmers' behavior may deviate from what would be considered rational (Streletskaya *et al* 2020). Notably, a study in the Tigray region of Ethiopia by Gebregziabher and Holden (2011) reported that irrigation adoption significantly increased the probability and intensity of fertilizer use, whereas earlier studies in the same region by Pender *et al* (2002) and Hagos (2003) reported the effect of irrigation on fertilizer use to be insignificant and even negative.

In the Ethiopia case study presented in this paper, we attempt to base the nutrient water pollution risk assessment on a better understanding of the impact of irrigation development on agricultural production practices. To this end, we first examine primary agricultural household survey data collected from four woredas in Ethiopia where irrigated crop production currently concentrates. The results of the household data survey analysis are presented in section 2.1 as a part of the methodology development and are used to support conceptualization of a modeling framework to assess the agricultural nutrient water pollution risk originating from farmer-led irrigation development at national scale (section 2.2). The estimated nutrient loading growth

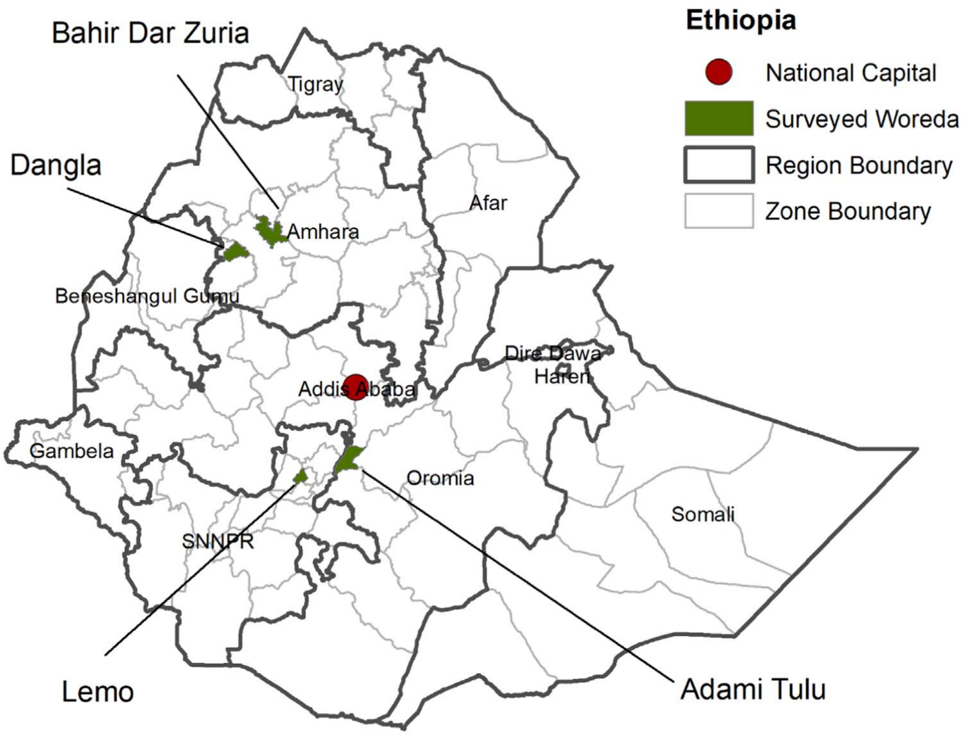

Figure 1. Surveyed woredas.

Table 1. Sample size and distribution.

Region	Zone	Woreda	Number of households	Number of irrigators
Amhara	Awi	Dangla	83	41
Amhara	West Gojjam	Bahir Dar Zuria	185	128
Oromia	East Shoa	Adami Tulu	66	31
SNNPR	Hadiya	Lemo	105	45
Total			439	245

Note: SNNPR = Southern Nations, Nationalities, and Peoples' Region.

rates are reported as indicator for the risk of agricultural nutrient pollution induced by expanding farmer-led irrigation and are presented in section 3. More discussions about the policy implications of the results of this country-scale assessment are provided in section 4.

2. Methods

2.1. Household survey data analysis for assessment approach conceptualization

The data used in the household survey data analysis presented in this paper are part of the data collected through the baseline survey in the Feed the Future Innovation Laboratory for Small-Scale Irrigation (ILSSI) project. The survey was implemented in November-December 2014. A description of survey sampling methodology can be found in Mekonnen *et al* (2019). Specifically, the sample were drawn from four woredas in three regions of Ethiopia (figure 1). Woredas are Ethiopia's third level of administration, after zones and regional states. Two of the four woredas, Dangla and Bahir Dar Zuria, are located in Amhara Region and the other two, Adami Tulu and Lemo are in Oromia and in the Southern Nations, Nationalities, and Peoples' Region (SNNPR), respectively. The four woredas were selected because each of them contains an intervention kebele (village) which is the kebele that partners with the ILSSIL project to explore various interventions for promoting farmer-led irrigation development. The four intervention kebeles have high irrigation potential and were identified through a spatial analysis using a composite irrigation suitability index proposed by Xie *et al* (2014). In the ILSSI survey, the sampling in each woreda consists of two stages. At first stage 11 additional kebeles (2 in Dangla, 6 in Bahir Dar Zuria, 2 in Lemo and 1 in Adami Tulu) were selected randomly from kebeles with similar identified irrigation suitability. The second stage involved selecting the households to be interviewed: based on the lists of household

Table 2. Number of households practicing dry season annual crop cultivation.

Woreda	Type of household	Total number of households	Number of households practicing dry season annual crop cultivation
Dangla	Irrigators	41	30
	Non-irrigators	42	1
Bahir Dar Zuria	Irrigators	128	48
	Non-irrigators	57	8
Adami Tulu	Irrigators	31	29
	Non-irrigators	35	0
Lemo	Irrigators	45	43
	Non-irrigators	60	52

Table 3. Distribution of irrigated and rainfed plots in annual crop cultivation in two seasons.

	Rainy season		Dry season	
	Rainfed	Irrigated	Rainfed	Irrigated
Dangla	386	3	7	45
Bahir Dar Zuria	880	24	35	58
Adami Tulu	215	22	2	40
Lemo	563	27	180	54

obtained from the local extension office, irrigators and non-irrigators were randomly chosen from irrigator list and non-irrigator list. Here, irrigators are defined as households that irrigated at least one plot over the recall period. In intervention kebeles, all households working with the ILSSL projection were included. The total numbers of surveyed households and a breakdown of irrigating and non-irrigating households are listed in table 1. A total of 439 households were surveyed. Since the samples are drawn from the selected kebeles with high irrigation suitability, the share of irrigating households in the four woredas is thus above the national average of irrigators.

The survey protocol includes modules on crop production and management practices, household demographics and participation of social development and protection programs. The recall period of the survey is the preceding one year, covering the full season cycle; for annual crops, up to two growing seasons are recorded. Ethiopia has a complex intra-annual rainfall pattern (Tsidu 2012). The country receives most precipitation between June and September, and this period constitutes the main crop cultivation season. The intra-annual rainfall distribution in part of the country is bimodal in that there is both a main and a short rainy season. In what follows, for convenience we refer to all crop cultivation outside the main rainy season as dry season farming.

As evidence of the effect of irrigation on cropping intensity, we present the numbers of irrigating and non-irrigating households that practice dry season annual crop cultivation (table 2), and the distribution of irrigated and rainfed plots in annual crop cultivation in two seasons (table 3).The pronounced increase in cropping intensity is observed particularly in Dangla, Bahir Dar Zuria, and Adami Tulu. In these three woredas respectively, 73 percent, 38 percent, and 93 percent of households with access to irrigation reported annual crop farming activities in the dry season; by contrast, the proportions of non-irrigator households engaged in dry-season farming activities in the three woredas were 2.4, 14, and even zero percent (table 2). At the plot level, the data show that annual crop production is concentrated in the rainy season and that in this season only a small percentage of plots are irrigated; irrigation during the dry season, on the other hand, is used in 45 of 52 plots in Dangla, 58 of 93 plots in Bahir Dar Zuria, and 40 of 42 plots in Adami Tulu. The situation is somewhat different in Lemo, where non-irrigators are more active in dry-season crop production (table 2), with a larger number of rainfed plots (table 3). This anomaly may be attributed to the fact that Lemo is located in a zone with quite strong bimodal annual rainfall distribution. Even in this bimodal rainfall distribution case, however, the share of irrigated plots is still much higher in the dry season than in the rainy season, suggesting that irrigation contributes to expanding annual crop production.

When it comes to fertilizer-use intensity, we did not find consistent evidence for increased fertilizer-use probability and intensity among the four woredas. Using irrigation and fertilizer-use decisions as binary variables, the charts in figures 2(a) and (b) display the number of plots with individual and combined use of two inputs during the two growing seasons for annual crops. We observed extensive use of fertilizers in both seasons and under both rainfed and irrigated production conditions. The per hectare fertilizer uses in irrigated and

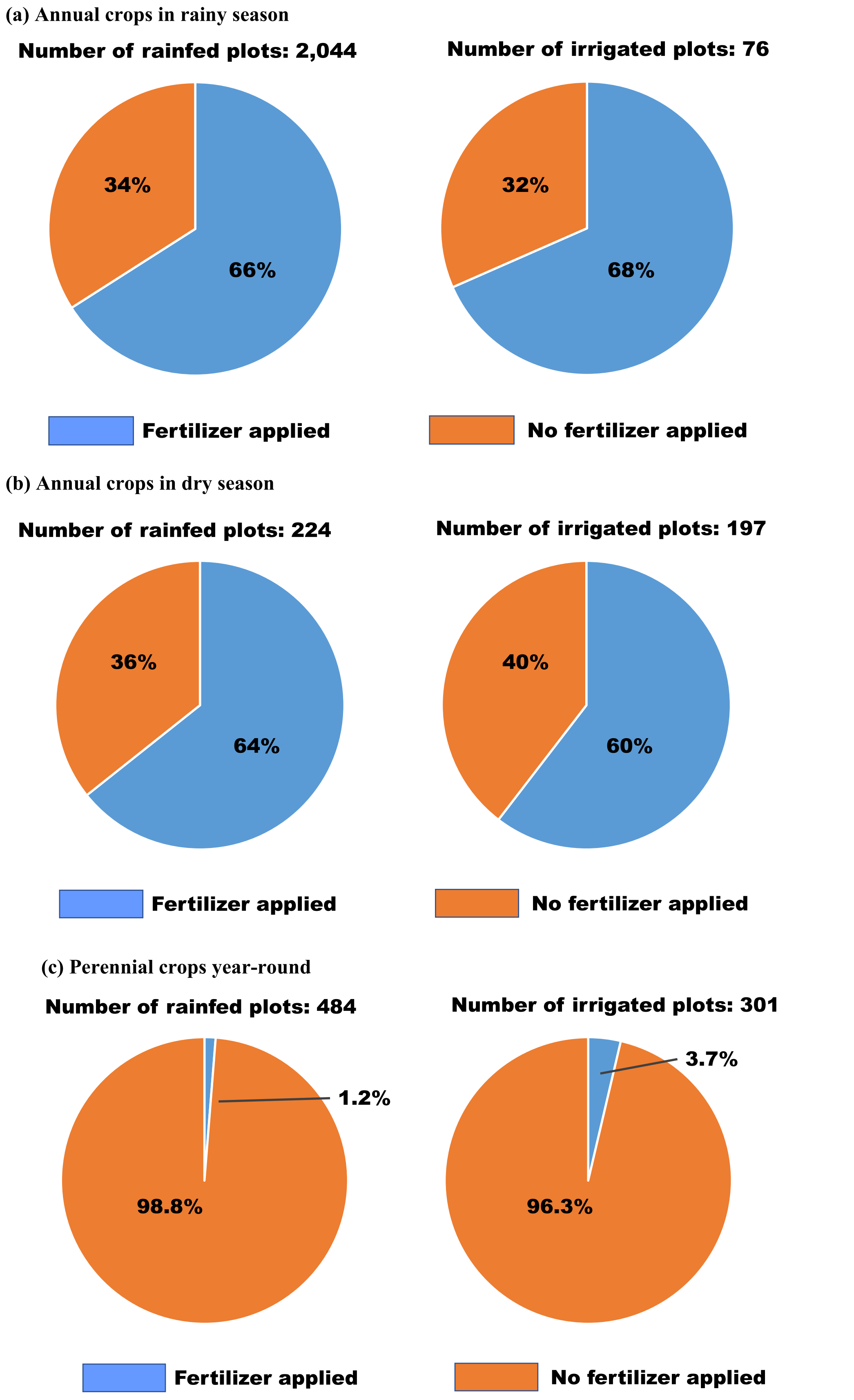

Figure 2. Plot-level decisions on irrigation and fertilizer use.

rainfed plots are shown in table 4. They are calculated by dividing the total quantities of fertilizer used on all irrigated and rainfed plots by the total areas of rainfed and irrigated plots in each woreda. Compared to the calculated fertilizer application rates in rainfed plot group, the per hectare fertilizer use for irrigated plot group is

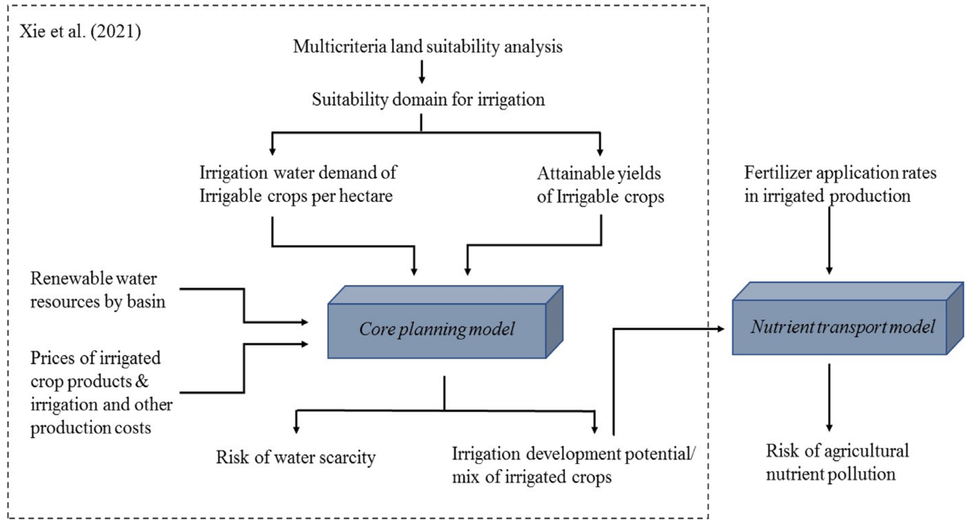

Figure 3. A methodological framework for assessing farmer-led irrigation development potential in sub-Saharan African countries, with extended functionality to evaluate risk of agricultural nutrient pollution.

Table 4. Per hectare fertilizer consumption in rainfed and irrigated plots with annual crop cultivation.

	Irrigated (kg/ha)	Rainfed (kg/ha)
Dangla	137	150
Bahir Dar Zuria	107	149
Adami Tulu	353	38
Lemo	37	143

higher in Adami Tulu but lower in three other woredas, indicating that farmers' fertilizer-use behavior under irrigated conditions differs from woreda to woreda.

The heterogeneity of farmers' fertilizer-use behavior is further tested econometrically by fitting the data from each woreda to double-hurdle model (Cragg 1971). The double-hurdle model is widely applied to consumption data consisting of zero values (Newman *et al* 2003, Aristei and Pieroni 2008, Adusah-Poku and Takeuchi 2019); in this study, the zero value indicates no use of fertilizers. In the double hurdle model, the consumption is modeled as a two-stage process. At the first stage, the model predicts the individual's yes/no decision with regard to fertilizer consumption; in the case of an affirmative decision, the second stage models consumption quantity. The double-hurdle model used in this study comes with a probit equation for fertilizer-use decision, and a linear regression equation for fertilizer intensity; the latter is expressed in kilograms per hectare (kg/ha) at the plot level. The explanatory variables used in the double-hurdle modeling are listed in the first column of table 5 and their descriptive statistics are shown in table S1 in supplementary data section. Among them, the adoption status of irrigation is indicated by a binary variable *irrigation* (0 = rainfed; 1 = irrigated); the variable *season*, *fertility* and *erosion* represent cultivation season, level of soil fertility and erosion , or biophysical environment of the crop production; the sociodemographic characteristics of households are represented by the age of household head, the education level of household head measured in years in school and the family size; considering the possible synergies between agricultural technologies, the indicator variables for the pesticide use of and the use of improved seeds, which are typically obtained through purchase, are included; finally, plot size, land tenure and financial service environment (e.g., access to credit) may also potentially influence the adoption of the agricultural technologies (Soule *et al* 2000, Barrett *et al* 2010, Girma 2022). Data on these factors were gathered in the survey and are also used in the analysis.

Table 5 shows the estimated values of coefficients for independent variables in two equations, and their level of significance. For Adami Tulu, consistent with what is seen from the descriptive statistics on fertilizer use per hectare (table 4), the coefficients for irrigation indicator variable in both the decision equation and the intensity equation are positive, and the effect is significant at the 1 percent level; this implies that irrigation leads to an increased probability of fertilizer use and fertilizer-use intensity. In the model for Dangla, the estimated coefficient values in both equations are also positive but are not statistically significant. The predicted fertilizer-

Table 5. Estimation results of double-hurdle model.

Independent variables	Dangla	Bahir Dar Zuria	Adami Tulu	Lemo
Decision model				
Season (0 = rainy season; 1 = dry season)	−0.754 (0.573)	−1.618 (0.25)***	0.672 (0.588)	0.074 (0.128)
Irrigation (0 = rainfed; 1 = irrigated)	0.995 (0.613)	0.633 (0.249)**	1.369 (0.472)***	−0.804 (0.178)***
Plot size (hectares)	0.971 (0.394)**	0.72 (0.19)***	0.955 (0.466)**	3.987 (0.552)***
Land tenure (0 = less secured; 1 = secured)	−0.414 (0.227)*	−0.305 (0.13)**	−0.326 (0.218)	−1.067 (0.358)***
Pesticide (0 = not applied; 1 = applied)	1.374 (0.265)***	0.435 (0.119)***	0.12 (0.198)	0.929 (0.164)***
Seed (0 = non-purchased; 1 = purchased)	1.098 (0.169)***	1.272 (0.103)***	0.675 (0.217)***	0.077 (0.125)
Fertility (1 = fertile; 2 = medium fertile; 3 = less fertile)	0.045 (0.123)	−0.197 (0.075)***	−0.109 (0.15)	0.13 (0.096)
Erosion (1 = no erosion; 2 = mild erosion; 3 = severe erosion)	0.108 (0.147)	0.231 (0.089)**	0.426 (0.204)**	0.32 (0.125)**
Age of family head (years)	0.002 (0.006)	−0.005 (0.004)	−0.005 (0.011)	0.008 (0.006)
Education/years in school (years)	0.008 (0.031)	−0.014 (0.02)	0.016 (0.03)	0.025 (0.016)
Family size (number of people)	−0.074 (0.053)	0.059 (0.025)**	0.006 (0.043)	−0.012 (0.029)
Credit access (0 = no; 1 = yes)	−0.204 (0.324)	−0.145 (0.202)	0.856 (0.678)	0.281 (0.195)
Constant	0.45 (0.522)	−0.311 (0.334)	−2.117 (1.039)**	−0.535 (0.553)
Intensity model				
Season (0 = rainy season; 1 = dry season)	−48.171 (60.535)	−43.577 (42.473)	52.874 (31.936)*	−80.245 (18.504)***
Irrigation (0 = rainfed; 1 = irrigated)	5.974 (59.794)	−89.293 (35.427)**	133.992 (34.169)***	−119.29 (40.207)***
Plot size (hectares)	−57.87 (36.031)	−282.708 (34.546)***	−81.413 (48.449)*	−128.797 (29.548)***
Land tenure (0 = less secured; 1 = secured)	−10.379 (17.369)	−4.525 (14.181)	14.165 (28.897)	31.762 (17.635)*
Pesticide (0 = not applied; 1 = applied)	9.495 (14.643)	−21.321 (13.328)	68.943 (28.875)**	112.127 (15.057)***
Seed (0 = non-purchased; 1 = purchased)	114.254 (14.428)***	63.316 (11.434)***	115.6 (53.017)**	−36.496 (12.955)***
Fertility (1 = fertile; 2 = medium fertile; 3 = less fertile)	−7.806 (10.558)	0.718 (8.913)	−22.066 (22.843)	−20.546 (10.247)**
Erosion (1 = no erosion; 2 = mild erosion; 3 = severe erosion)	9.875 (11.957)	−2.298 (10.459)	−22.845 (31.35)	11.539 (11.698)
Age of family head (years)	0.232 (0.493)	−0.936 (0.535)*	4.615 (1.391)***	0.191 (0.685)
Education/years in school (years)	3.042 (2.401)	1.543 (2.219)	9.356 (4.319)**	0.647 (1.637)
Family size (number of people)	7.905 (4.508)*	4.411 (3.103)	−5.938 (5.568)	3.786 (2.875)
Credit access (0 = no; 1 = yes)	−43.897 (28.676)	8.658 (24.168)	136.308 (207.989)	−36.99 (21.609)*
Constant	94.213 (45.725)**	277.268 (40.218)***	−329.332 (252.948)	115.741 (47.527)**

Note: *, **, and *** indicate statistical significance at the $p < 0.1$, $p < 0.05$, and $p < 0.01$ levels.

use probability and intensity do not move in the same direction in the Bahir Dar Zuria model as the value of the irrigation indicator variable changes from 0 to 1. In this woreda, a positive coefficient value is found in the decision equation, but a negative coefficient value is shown in the intensity equation; both of these are significant at the 5 percent level. Finally, the relationship between irrigation use and fertilizer use in the Lemo model is opposite to the one found in the Adami Tulu model. The estimated coefficient values for the irrigation indicator variable in the two equations are both negative and significant at the 1 percent level, indicating that irrigation adoption negatively affects fertilizer-use probability and intensity.

The analysis of irrigated and rainfed farming presented above is focused on annual crops. The data show that about 25 percent of the plots in the four woredas are used to cultivate perennial crops; these crops include chat, coffee, eucalyptus, and enset. As shown in figure 3(c), the perennial crop cultivation is characterized by substantial use of irrigation but only sparse use of fertilizer. Although the application of fertilizers on irrigated plots is more frequent than on rainfed plots (3.7 percent versus 1.2 percent), the absolute value of percentage of irrigated plots with fertilizer use in perennial crop production is still very low.

In summary, the household survey data show that access to irrigation boosts annual crop cultivation in the dry season. Although there is a lack of consistent evidence that irrigation increases the fertilizer use intensity in the irrigated production, the hecterage expansion of annual crop production in the dry season alone is sufficient to result in increased fertilizer consumption at annual time scale, This, plus the observations from the household data that the application of irrigation in rainy season production is limited and fertilizer application rate in irrigated perennial crop production is very low, suggest that the additional cultivation of annual crops in the dry

Table 6. Fertilizer application rates assumed in planning analysis.

Crop	Urea (kg/ha)	DAP (kg/ha)
Vegetables	100	50
Pulses	0	0
Fodder	0	50

Note: DAP = Diammonium phosphate.

Table 7. Estimated development potential of dry season farmer-led irrigation in Ethiopia, and agricultural nutrient loading increments associated with irrigation development (with a comparison to agricultural nutrient loading under baseline conditions).

	Potential area (1,000 hectares)				Total nitrogen (1,000 tons/year)**		Total phosphorus (1,000 tons/year)**	
Region*	Vegetables	Pulses	Fodder	Total	Baseline	Increased	Baseline	Increased
Affar	0.04	0	0.03	0.07	0.09	0.002	0.02	0
Amhara	48	284	139	471	243	23.7	32.6	1.9
Benishangul-Gumuz	3	11	2	16	14.3	1.5	2.3	0.2
Gambella	1	0	0	1	0.4	0.02	0.10	0.003
Harari	0	0	0.1	0.1	0.04	0	0	0
SNNPR	39	43	41	123	92.4	6.7	11.6	0.49
Tigray	0.4	3	11	15	21.3	0.71	2.4	0.01
Oromiya	58	218	172	447	273	23.1	37.3	1.4
Somali	0	0	1	1	1.6	0.006	0.39	0
Total	149	560	365	1,074	644	55.7	86.4	4

Source: Data in Columns 2 to 5: Xie *et al* (2021); replicated under a Creative Commons license.
Note: * = irrigation potentials in Addis Ababa and Dire Dawa are negligible and are not listed in the table.
** = subject to rounding error; SNNPR = Southern Nations, Nationalities, and Peoples' Region.

season constitutes a main source of nutrient pollution risk to water environment during development of irrigated agriculture.

As noted above, the ultimate goal of the study is to provide an assessment of nutrient water pollution risk associated with the future development of farmer-led irrigation in Ethiopia all over the country. Logically, this assessment is supposed to be based on knowledge of farmer-led irrigation development potential of the country, which can be generated via irrigation planning. Also as mentioned earlier, different irrigation planning approaches have been proposed which build on various notions on dynamics behind the development of irrigated agriculture. The conclusion from the household survey data analysis actually has broader implications and highlights the need to consider the expansion of dry-season farming driven by the irrigation development in irrigation planning. In this study on nutrient pollution risk assessment, we thus extend a modeling approach we developed in a recent irrigation planning study in Ethiopia (Xie *et al* 2021), in which we focused on estimating the farmer-led irrigation development potential of the country in the dry season. We extend the modeling approach and equip it with additional capacity for assessing nutrient water pollution risk.

2.2. Nutrient loadings from expansion of dry-season farmer-led irrigation in Ethiopia—a modeling framework for national assessment

The full modeling framework with the extended capacity for nutrient water pollution risk assessment developed for the national-scale nutrient water pollution risk assessment in this study is shown in figure 3. The components that come from our 2021 study are displayed in bounded area. Below is an outline of how they work. More details can be found in Xie *et al* (2021).

- We consider the land suitability, renewable water resources conditions and economic feasibility in the evaluation of the farmer-led irrigation development potential. As a first step, a GIS-supported multicriteria land suitability analysis is implemented. Sites that are identified as suitable for irrigation are taken as an initial estimate of the potential spatial extent of irrigation development. The land suitability layer used by Xie *et al* (2021) in the case study on Ethiopia was provided by Worqlul *et al* (2017). Moreover, the geographic suitability domain delineated using GIS multi-criteria approach was further adjusted by considering current cropping pattern and the distribution of existing irrigated cropland area. It was assumed that irrigation development will be limited to current rainfed cropland used for cultivating annual crops. There are various techniques to

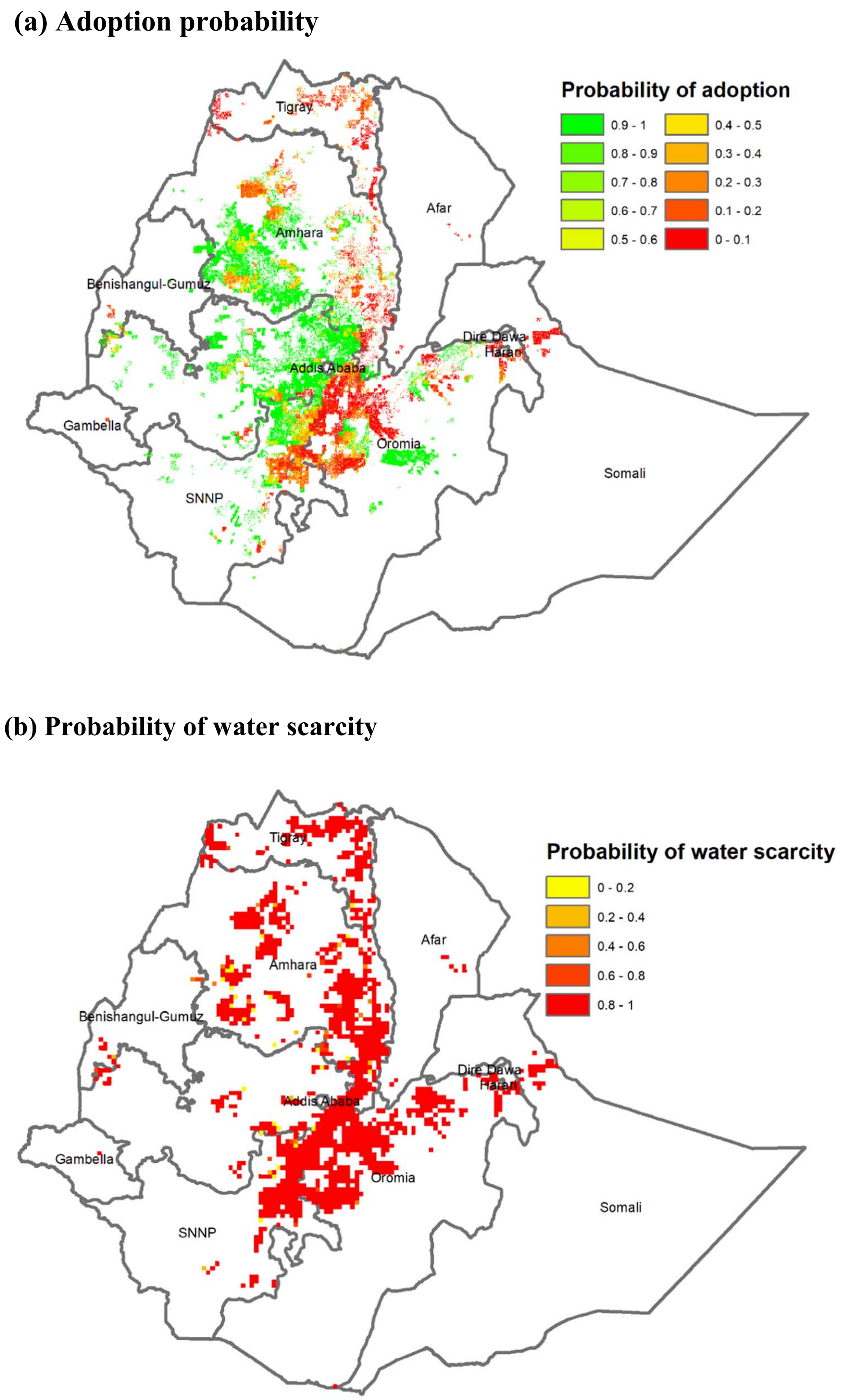

Figure 4. Estimated development potential of dry season farmer-led irrigation and associated risk of water scarcity in Ethiopia. Source: Xie *et al* (2021); replicated under a Creative Commons license. Reproduced from Xie *et al* (2021); CC BY 4.0.

map the spatial distribution of rainfed/irrigated crop production (Thenkabail *et al* 2009, Ajaz *et al* 2019). The area of rainfed cropland for annual crop cultivation in the Ethiopia study was estimated at a 1 km x 1 km spatial resolution by using the Spatial Production Allocation Model (SPAM) (You *et al* 2014) to downscale agricultural statistics gathered at region or sub-region level.

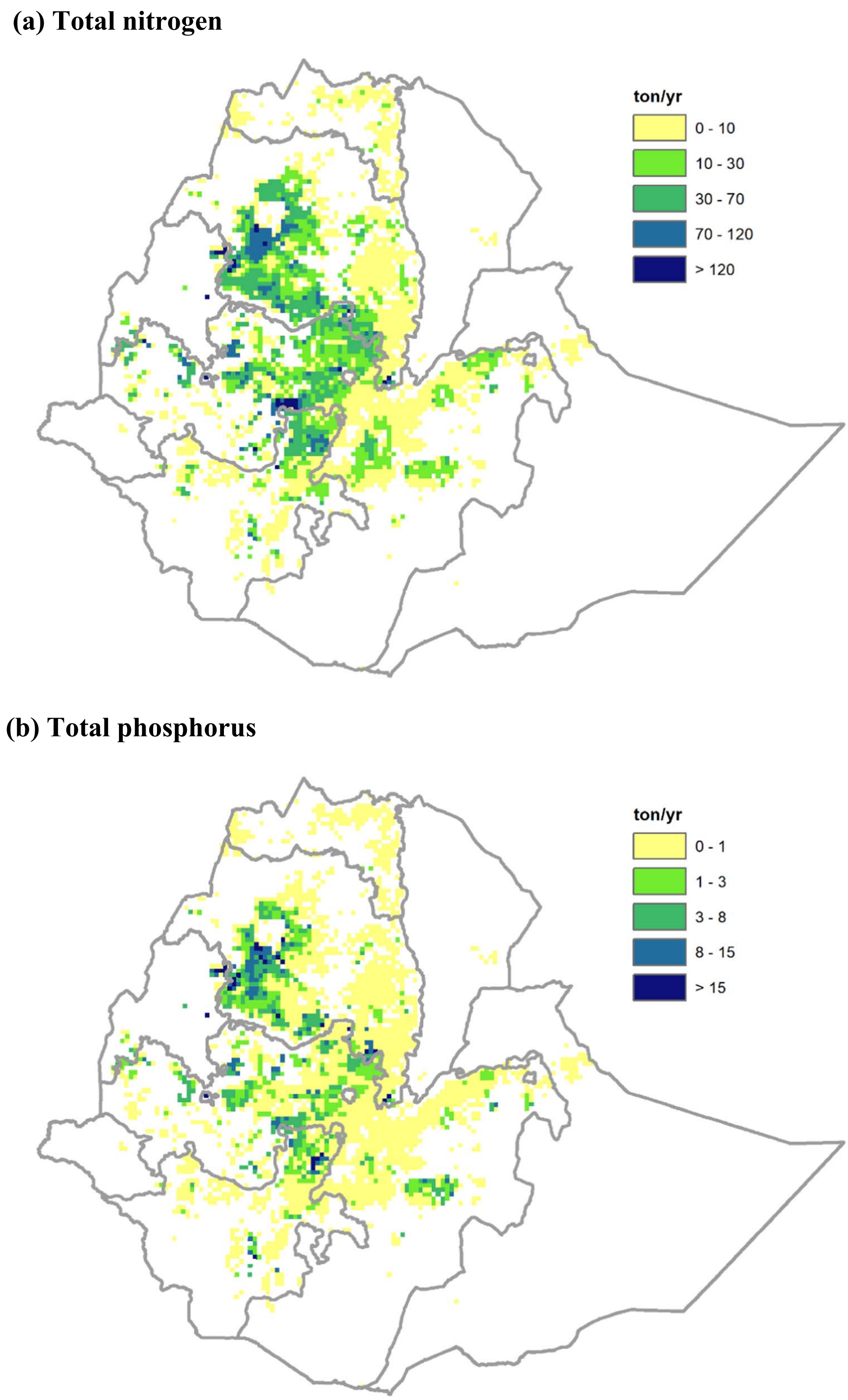

Figure 5. Increased nutrient loading of basins resulting from expanded farmer-led irrigated agriculture.

- At the core of the modeling framework is an agent-based model which is designed to simulate the process of farmer-led irrigation expansion in the dry season. The application of the agent-based modeling technique in the model design was motivated by the observation that farmer-led irrigation is essentially a decentralized paradigm for irrigation development and that as a bottom-up modeling approach agent-based modeling is more suitable to a simulation of this type of system. In agent-based modeling, each pixel on the 1 km × 1 km land grid with non-zero area suitable for farmer-led irrigation is viewed as a farm or autonomous decision-

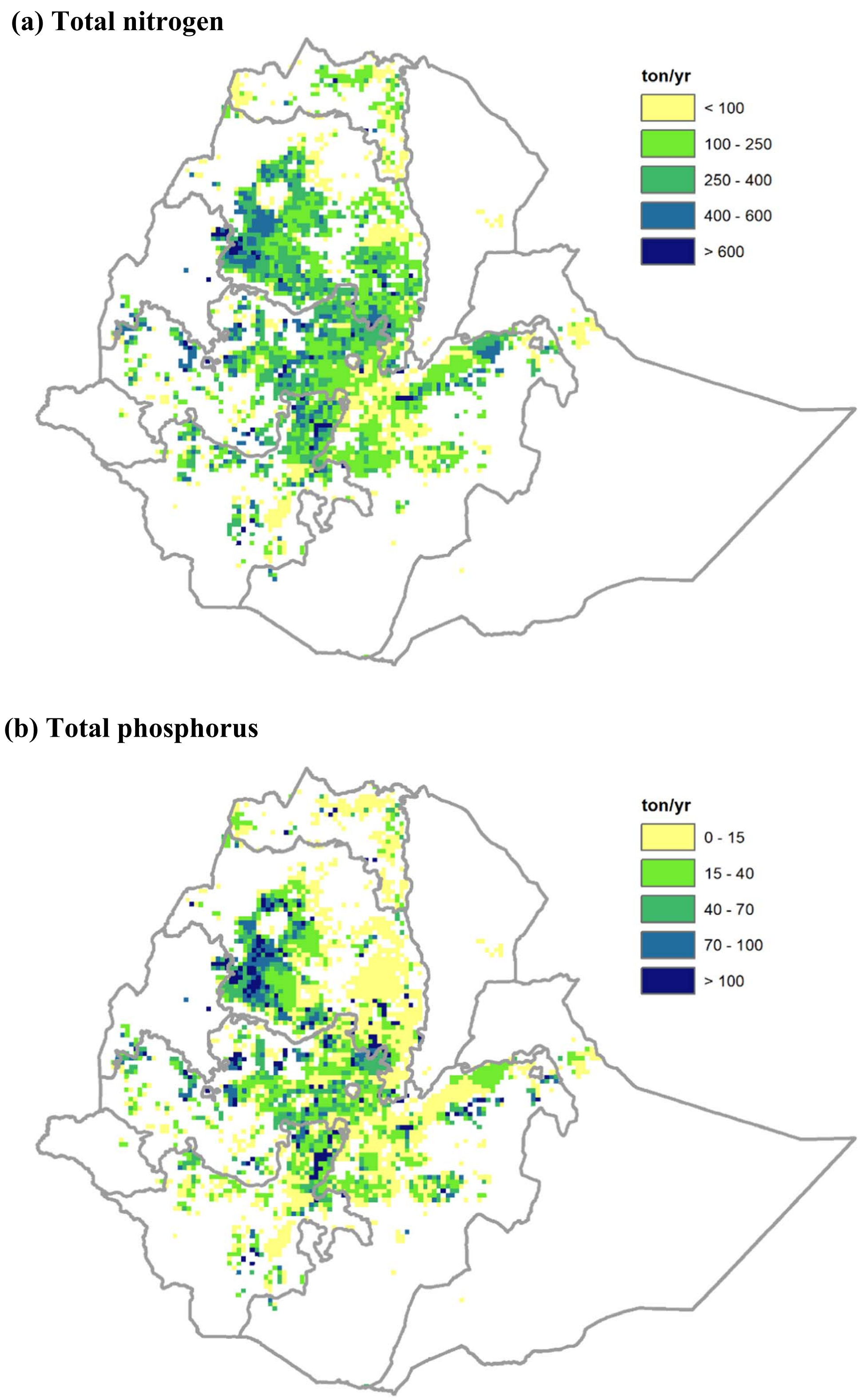

Figure 6. Nutrient loading of agricultural watersheds under current conditions.

making entity. The decision to adopt irrigation for dry season crop production is simulated at the farm level. The farmer's willingness to adopt and the success probability of the adoption are modeled as a probabilistic function of the irrigation suitability score of the farm generated in land suitability analysis and are influenced by crop prices and by the water resources conditions of the basin where the farm is located. At the macro level, this implies that the expansion of irrigation is constrained by the economic cost–benefit of the irrigated crop products and by the water balance conditions of the basin, or put it another way, the irrigation development must be economically and hydrologically sustainable.

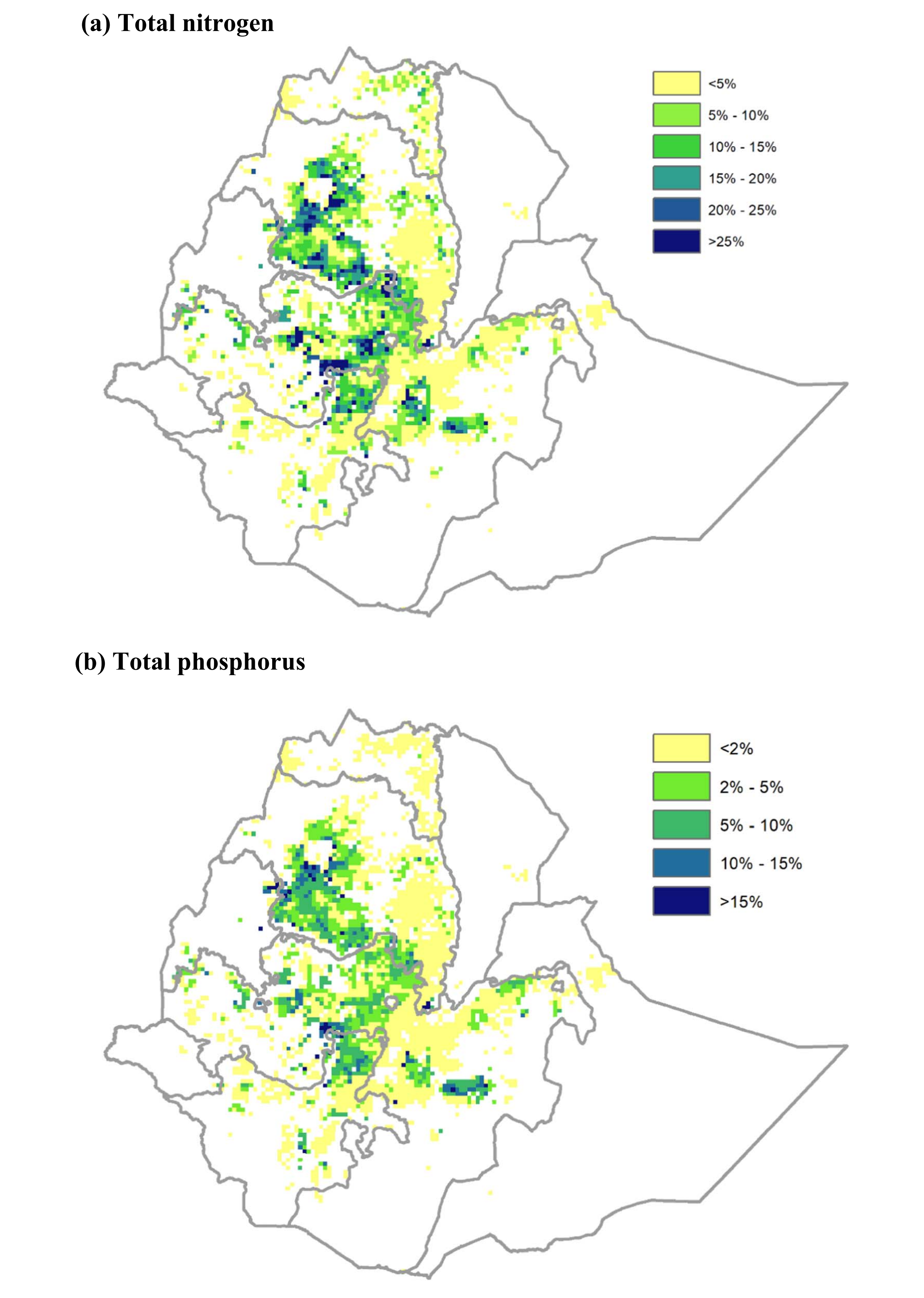

Figure 7. Percentage increase of nutrient loading resulting from expansion of farmer-led irrigated agriculture.

Extending the assessment framework to address concerns about agricultural nutrient water pollution involves introducing an additional biophysical modeling tool that is capable of tracking the fate and transport of nutrients in environment. Note that biophysical nutrient models are typically designed to simulate the processes of nutrient transport by taking crop mix and fertilizer application rates associated with the crop mix as input data. A collection of gridded data products which are generated using remote sensing or downscaling techniques to map the distribution of cropping systems at high at high spatial resolution are currently available (Monfreda et al 2008, Portmann et al 2010, Fischer et al 2013, You et al 2014);. However, these data reflect the existing crop pattern, mainly in rainy season, and cannot be directly used to determine the crop mix in the irrigated production in dry season; it is well known that famers are more likely to use irrigation to produce crops with high economic values (Domènech 2015).

The key that allows for extending irrigation planning framework for nutrient water pollution risk assessment lies in the fact that the crop mix in irrigated crop production is one of emergent phenomena generated from the agent-based simulation. Specifically, at the start of the simulation we explicitly named a subset of crops that are considered to be particularly suitable for farmer-led irrigation in the dry season; in the Ethiopian study these included vegetables, pulses, and fodder crops. The crop mix during the course of the irrigation expansion is then simulated endogenously: when the a farmer has willingness to adopt irrigation, he or she also makes decision on crop to be produced; it is assumed that farmers always choose to cultivate the most profitable crop. Based on the projected crop mix in irrigated production, the transport and fate of fertilizer nutrients in agricultural landscape can be simulated.

Figure 3 also depicts key biophysical input parameters that are used for the assessment; these include irrigation water demand and attainable yields of each irrigable crop at farm level, and quantity of renewable water resources at basin level. The spatial estimates of these input variables in the Ethiopian study were generated through hydrologic and crop modeling using a gridded national-scale Soil and Water Assessment Tool (SWAT) model for Ethiopia. SWAT is a watershed modeling tool consisting of hydrological and crop simulation modules (Arnold et al 1998). The national SWAT model for Ethiopia was set up on a 5-arc minute (~10 km) grid (Dile et al 2020); we let a farm assume values of crop attainable yields and irrigation water demand estimated in 10 km cell where the farm is located, and each 10 km × 10 km pixel on the SWAT land grid was viewed as a basin for the purposes of water balance accounting in agent-based simulation. As a comprehensive river basin modeling tool, SWAT also contains a nutrient module which has been widely applied for nutrient analysis; the SWAT nutrient module serves as the additional biophysical modeling tool introduced in this study for simulating nutrient transport. The fertilizer application rate in figure 3 is listed as an exogenous input variable, to which the assessment result is sensitive. The different results on how fertilizer application rate could vary in irrigated and rainfed production found in the household survey data from four woredas serve as a demonstration of the complexity in farmer's fertilizer use behavior. It is currently difficult to establish projection of the future fertilizer use by crop in irrigated production over the country via analytical approach. A uniform fertilizer application rate across the country for each crop is therefore proposed based on expert knowledge and used in the assessment (table 6).

2.3. Uncertainties and limitations

The modeling approach presented in the preceding section represents the first attempt to assess nutrient water pollution risk induced by farmer-led irrigation development in Sub-Saharan Africa at national scale. It is subject to the following uncertainties and limitations:

- SWAT is a process-based model. In a typical SWAT modeling exercise, initial estimates of input parameters are first generated during model setup based on prior knowledge of the physical processes, and the initial estimates can be improved through calibration (Arnold et al 2012). The SWAT model used in this case study was only partially calibrated using river discharge data and remote sensing-based evapotranspiration data (Dile et al 2020). Water quality monitoring data which could be used to further calibrate the model to improve model performance in simulating water quality processes are lacking at the time of the study. Simulation of nutrient transport in SWAT consists of two phases. The model first estimates nutrient loadings, that is, the loss rate of nutrients from land and then simulates the transport and transformation of nutrient pollutants in streams. The simulation of in-stream water quality processes can generate estimates of nutrient concentration in the surface water environment, which is a more relevant parameter for assessing water quality, but involves additional uncertainty. In this study, we choose to only report the nutrient loading or nutrient loading growth rate and to use it as a risk indicator to characterize the impact of irrigation development on the quality of the water environment.

- Fodder crops are included as irrigable crops in the Ethiopia case study. Irrigated fodder production is an emerging production activity that is expected to grow in importance in line with Ethiopia's expanding livestock production (Wondatir et al 2015). Livestock is another major source of agricultural nutrient pollution; it would thus be interesting to extend the scope of the environmental impact analysis in future to accommodate the chain of livestock production.

- It is indicated in section 2.2 that the values of fertilizer application rates used in our assessment (table 6) are proposed based on expert knowledge and therefore contain subjectivity. A future sensitivity analysis may help shed light on uncertainty arising from the subjectivity. Note that the fertilizer application rate influences crop yield. Following on the adjustments in fertilizer application rates that are made in a sensitivity analysis, the estimates of attainable irrigated crops yields that are used in the planning analysis (Xie *et al* 2021) may need to be updated as well. The sensitivity analysis can thus also be used to investigate the linkage between irrigation and nutrient management technologies.

These remarks are offered as caveats before we present the results of the model-based assessment, which are produced to provide a first insight into the nutrient water pollution risk from expanding farmer-led irrigation in Ethiopia by utilizing data and knowledge currently available. Reducing the uncertainties and limitations requires future efforts when more data supporting the assessment are available.

3. Results

As a recapitulation, the main outputs from the earlier Ethiopian study (Xie *et al* 2021) are shown in figure 4 and in Columns 2 to 5 of table 7. The study has a planning horizon to 2030. There are stochastic elements in the agent-based simulation (i.e., the farmer's initial wiliness to adopt irrigation is modeled as a probabilistic function of land suitability score), and the model reports the success probability of irrigation adoption on the 1 km × 1 km land grid (figure 4(a)) and the associated water scarcity risk at 10 km × 10 km basin level (figure 4(b)). Expected values of potential irrigation development areas at the national level as well as region by region are calculated and shown in columns 2 to 5 of table 7. According to these outputs, the national development potential of farmer-led irrigation in the dry season in Ethiopia by 2030 is around 1.1 million hectares. There is a high-adoption probability zone stretching from the central Amhara region to northern SNNPR, and it is expected that a large number of basins will be exposed to irrigation-induced water scarcity risk.

The results of the newly conducted nutrient water pollution risk assessment are presented in figures 5 to 7 and column 6 to 9 of table 7. Figure 5 displays the loadings of total nitrogen (TN) and total phosphorus (TP) exported from the expanded farmer-led irrigated production of 1.1 million hectares. These values are calculated at the basin level according to the expected values of irrigation potential area, the projected choice of irrigated crops and specified fertilizer application rate under the projected crop choice on 1 km farm grid. Figures 6(a) and (b), for comparison, show the basin-level estimates of annual nutrient loadings under baseline conditions (prior to irrigation expansion). The cropping pattern data and the data on fertilizer use by crop that are used for the baseline simulation are obtained from the SPAM database (You *et al* 2014) and EIAR Ethiopian Institute of Agricultural Research (2007). Columns 6 to 9 of table 7 list the aggregated national and region-level estimates of the incremental loading and the loadings under baseline conditions. The national totals of agricultural TN and TP loadings under baseline conditions are estimated at 644,000 tons per year and 86,400 tons per year. We project that TN and TP loading will rise by up to 55,700 and 4,000 tons, or by up to 8.6 percent and 4.6 percent, respectively as a consequence of dry season farmer-led irrigation expansion.

The projected loading growth rates at national level indicate nationally expanding farmer-led irrigation in Ethiopia will only lead to a gentle increase in annual nutrient flow from agricultural land to water environment, a conclusion that favors the development of farmer-led irrigation. However, the possibility that incremental nutrient flow from farmer-led irrigation may deteriorate local water quality significantly cannot be excluded. Figure 7 further shows the calculated percentage loading increases at the basin level. As evident, considerable spatial heterogeneity exists in the basin-wise loading growth rate. A collection of basins with high incremental nutrient loadings from expanded farmer-led irrigation, such as TN loading increases of more than 25 percent and TP loading increases of more than 15 percent, can be found. Significant water quality deterioration is more likely occur at these locations with high nutrient loading growth rate or even at sites with moderate loading growth but where the nutrient loadings are already high.

4. Conclusion and discussion

Sub-Saharan African countries has long been beset by hunger and malnutrition (FAO, IFAD, UNICEF, WFP and WHO 2020); it is an imperative to intensify the agricultural production to improve the food security in the region. The intensification in agricultural production unavoidably bring impacts to surrounding environment. With the growing environmental awareness, environmental sustainability has become an increasingly important factor that influences the policy and investment decision making for agricultural intensification (Garcia 2020, Haggar *et al* 2021).

Among various approaches proposed to intensify agricultural production in Sub-Saharan Africa, expanding farmer-led irrigation is considered to be a promising option (You *et al* 2011, de Fraiture and Giordano 2014, Woodhouse *et al* 2017, Xie *et al* 2017, Lefore *et al* 2019). However, there is a lack of thorough understanding of its impact on environment; past discussions are mainly limited to the water depletion and hydrological regime change effect of the irrigation development (Liu *et al* 2014, Xie *et al* 2014, Altchenko and Villholth 2015, Liersch *et al* 2019). In this paper, as an attempt to narrow the knowledge gap, we present a first country-scale study in Sub-Saharan Africa region to evaluate the risk of agricultural nutrient pollution from development of farmer-led irrigation.

In this case study on Ethiopia, we attempt to capture the effect of cropping pattern and farming practice changes associated with the famer-led irrigation development on nutrient inflows of crop production. The analysis on household survey data collected from four woredas offers evidence that irrigation increases cropping intensity of annual crops and that additional crop cultivation in the dry season is the main source of increased risk of agricultural nutrient pollution. We then use the observation to guide the conceptualization of a modeling framework that bases the estimation of agricultural nutrient loadings from expanding farmer-led irrigation across Ethiopia on estimated dry-season farmer-led irrigation development potential of the country.

Our assessment shows gentle increases in national totals of agricultural nutrient loadings from expanding the farmer-led irrigation. This finding undoubtedly favors choosing farmer-led irrigation as a strategy to intensify agricultural production in Ethiopia or helps justify the endeavor of promoting farmer-led irrigation by Ethiopian government and international donors (NPC National Planning Commission 2016, IFAD International Fund for Agricultural Development 2019, World Bank 2020). On the other hand, the projected nutrient flow and nutrient loading growth rates caused by farmer-led irrigation expansion are highly heterogeneous spatially; risk of local water quality deterioration exists. Thus, it is still necessary to make investments to ensure the environmental sustainability of farmer-led irrigation development. Specifically, for those sites with elevated risk of agricultural nutrient water pollution, risk mitigation can be achieved through improved land management. Various types of land management practices have been developed to reduce nutrient loading from agriculture including from irrigated crop production (Bryant and Goldman-Carter 2016). Moreover, although only low and moderate growth in agricultural loading from expanding farmer-led irrigation is projected in majority area, there is still need to set up programs to track the change in water quality during the course of irrigation development considering the uncertainty associated with the assessment. Water quality monitoring provides data of critical importance to help regulate quality of water environment. In the context of irrigation development, this means using water quality monitoring data to update the knowledge of nutrient water pollution risk so that remedy actions, if needed, can be taken in a timely manner. Most countries in Sub-Saharan Africa lack sufficient capacity to monitor water quality (Peletz *et al* 2016, Nkiaka *et al* 2021), investment is needed to strengthen the capacity of water quality monitoring in the region. At implementation level, making effective environmental investment in improved improve land management and enhancing water quality monitoring capacity may involve efforts of building appropriate institutions to incentivize farmers' adoption of land management practices and to improve performance of water monitoring programs (Drechsel *et al* 2005, Peletz *et al* 2018, Pandey 2019), exploring the application of new low-cost water quality monitoring technologies (Dube *et al* 2015, Pellerin *et al* 2016), and developing decision support systems to facilitate selection placement of land management practices for nutrient water pollution control (Yang and Best 2015, Dai *et al* 2018). All these constitute topics inviting future research.

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Data availability statement

The household survey data that support the findings of this study are available at IFPRI Dataverse at http://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/VLGMZD.

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