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CLIMATE CHANGE IN MALI:

AGRICULTURAL ADAPTIVE PRACTICES IMPACT MODELING ASSESSMENT – SUMMARY REPORT

NOVEMBER 2014

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ARCC

African and Latin American Resilience to Climate Change Project

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Cover Photo: *Zai* holes in Malian field, David Miller

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AFRICAN AND LATIN AMERICAN RESILIENCE TO CLIMATE CHANGE (ARCC)

NOVEMBER 2014

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ACRONYMS AND ABBREVIATIONS

ACN	*Aménagement en Courbes de Niveau*
APEX	Agricultural Policy/Environmental eXtender
ARCC	African and Latin American Resilience to Climate Change
CGIAR	The Consultative Group on International Agricultural Research
CN	Curve Number
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAI	Development Alternatives Inc.
DEM	Digital Elevation Model
DSSAT	Decision Support System for Agrotechnology Transfer
EPIC	Erosion Productivity Impact Calculator
ET	Evapotranspiration
FAO	Food and Agricultural Organization
GCM	Global Circulation Models
ICRISAT	International Crops Research Institute for the Semi-Arid-Tropics
IPSL	*Institut Pierre-Simon Laplace*
MMA	*Mali Minstère de l'Agriculture*
ODI	Overseas Development Institute
US	United States
USAID	United States Agency for International Development
USLE	Universal Soil Loss Equation
WARDA	West Africa Rice Development Association

ABOUT THIS SERIES

ABOUT THE STUDIES ON CLIMATE CHANGE VULNERABILITY AND ADAPTATION IN WEST AFRICA

This document is part of a series of studies produced by the African and Latin American Resilience to Climate Change (ARCC) project that address adaptation to climate change in West Africa. Within the ARCC West Africa studies, this document is part of the subseries Climate Change in Mali. It also contributes to the subseries Agricultural Adaptation to Climate Change in the Sahel. In addition, ARCC has produced subseries on Climate Change and Water Resources in West Africa and Climate Change and Conflict in West Africa.

THE SUBSERIES ON CLIMATE CHANGE IN MALI

Upon the request of the United States Agency for International Development (USAID), ARCC undertook the Mali series of studies to increase understanding of the potential impacts of climate change in rural Mali and to identify means to support adaptation to these impacts. Other documents in the Climate Change in Mali series include: A Country Vulnerability Map; Climate Change Agricultural Adaptive Practices Impact Modeling Assessment; Key Issues in Water Resources; Expected Impacts on Pests and Diseases Afflicting Livestock; Expected Impacts on Pests and Diseases Afflicting Selected Crops; and An Institutional Analysis of l'Agence de l'Environnement et du Développement Durable and l'Agence Nationale de la Météorologie.

AGRICULTURAL ADAPTIVE PRACTICES IMPACT MODELING ASSESSMENT

ARCC produced the report summarized here, *Climate Change in Mali: Agricultural Adaptive Practices Impact Modeling Assessment*, to understand the impact of selected water conservation practices under current and future climate change scenarios. This Modeling Assessment was also produced to demonstrate one step of a process developed by ARCC and described in the document *An Approach to Evaluating the Performance of Agricultural Practices*, which is found in the ARCC subseries on Agricultural Adaptation to Climate Change in the Sahel. The object of the ARCC process is to assess how climate change may impact the effectiveness of field-level practices currently employed by farmers the Sahel. It consists of three basic components: defining expected changes in climate; defining adaptation objectives and identifying the practices to be assessed; and conducting the evaluation of the defined practices. *Profiles of Agricultural Management Practices* contributes to the definition of adaptation objectives, and *Organizational Survey and Focus Groups on Adaptive Practices* identifies practices to be assessed. The document summarized here forms part of the third of these steps, the evaluation of the performance of specific practices.

The full report, of which this is the summary, can be found in Annex A to this report.

INTRODUCTION

Agriculture is a major source of livelihood in Mali, but agricultural production is limited by variable precipitation, high temperatures, and sandy soils with low water holding capacity and low organic matter content. To overcome the constraints to producing crops — the most important of which are maize, millet, sorghum, and rice (MSU, 2011) — farmers use a variety of practices, including rainwater harvesting, soil fertility enhancement, and supplemental irrigation. About 84 percent of the farm land in Mali has water-related constraints, so rainwater harvesting measures such as soil or rock bunds, contour plowing, vegetative filter strips, or *zai* holes are particularly important. Irrigation water drawn from the Niger River is also used to supplement rain-fed agriculture.

Annual rainfall in Mali is highly variable, ranging from less than 200 millimeters to 1,300 millimeters. The rainfall is unevenly distributed between the north and south. Northern Mali gets 200–350 millimeters annual rainfall and southern Mali, which accounts for much of the country's agricultural activity, gets 350–600 millimeters. The rainy season is short and lasts only 3–4 months, from June to September. The potential evapotranspiration exceeds 2,000 millimeters per year (ICRISAT, 1999). Poor harvests due to drought create frequent food shortages for Malians, especially in northern regions of the country.

Climate change threatens to increase air temperatures and evapotranspiration, increase the risk of intense rainstorms, and increase the risk of heat waves associated with drought (Baptista, et al., 2013). The literature on climate change in Mali makes a variety of predictions about the specific changes that will occur (Diarra et al., 2007, Butt et al., 2005, Jalloh et al., 2013). The impacts of climate change on precipitation in Mali vary depending on which combination of global and regional climate models are used. Some reports also attempt to estimate the impact of the changing climate on crop yields (Schlenker & Lobell, 2010, and Sultan et al., 2013). All present a bleak picture for the future of agriculture in Mali.

Given these predictions, there is an urgent need to develop adaptive practices to maintain or increase crop production in Mali. Hence, this study evaluates traditional water conservation practices that can optimize soil water retention and alleviate the soil fertility constraints for improved crop productivity. For the evaluation four practices were selected, contour ridges, *zai* holes (planting pits), bunds and vegetative filter strips. Their impact was tested in combination with four crops, millet, maize, sorghum and rice. The study uses a modeling approach to understand the impacts these water conservation practices under current and future climate change scenarios.

Broadly, this study concludes that all of the water harvesting practices evaluated can significantly improve soils and yields under some conditions, yet none of them can improve soils and yields more than the others under all conditions. None of them is "better than nothing" under all conditions. To be effective, a practice must be used with the appropriate crop, on the appropriate soil and slope, with the right climate. While it is likely that climate change will increase the importance of these and similar water harvesting practices, it will not relieve the need to improve our understanding of how conditions affect their performance. None of the water harvesting practices evaluated will be the universal solution to the challenges farmers can be expected to face managing rainwater in the Sahel under the projected climate conditions.

METHODOLOGY

The site selected for modelling was in the Sahelian agro-ecoregion of Mali, in the Bankass District of the Mopti Region. This is an agricultural area with a wide range of slope steepness and soil types that can affect the effectiveness of water conservation practices.

The modelled area has highly weathered soils typical of Sub-Saharan Africa. The soils have very low organic matter content and shallow depth, which adversely affect crop yields. The major physical and chemical characteristics of the soils are described in Annex A.

The most common soil types in the region are arenosols, luvisols, regosols, and lithosols. The four soil types were evaluated for each combination of crop and soil water conservation practice. The effectiveness of the practices is expected to vary with soil texture and soil physical characteristics that affect infiltration and water holding capacity. The key characteristics of the four soils are as follows:

- Arenosols are sandy in texture, and have shallow and weakly developed soils. They are easy to till, but have poor fertility and need amendments of organic matter to improve productivity. Most arenosols are used for animal grazing, but they could be used for arable cropping if irrigated.
- Luvisols are loamy sand in soil texture that commonly occur in flat or gently sloping land. They contain clays and are generally fertile and suitable for a wide range of agricultural uses. Luvisols on steep slopes require erosion control measures.
- Regosols are common in arid areas. They have low water holding capacity and are prone to erosion. After intense rain, surface crusts form in these soils, which impede emergence of seedlings and lead to runoff. Some regosols are used for irrigated farming, but the most common land use is low-volume grazing.
- Lithosols generally occur at higher elevations on steep slopes. They are shallow soils with abundant weathered rock fragments. Lithosols are cultivable through the removal of stones by hand and terracing.

The study used the Agricultural Policy/Environmental eXtender (APEX) model. The model was chosen because it can:

- simulate the dynamics of soil fertility and soil moisture content status for a variety of crops and conservation practices;
- simulate impacts of management practices and crop production at multiple scales;
- subdivide farms or fields by soil type, landscape position, surface hydrology, or management configuration;
- link each subarea with other subareas based on water routing on the landscape; and
- generate future climate change scenarios.

The crop database of the APEX model contains information needed to simulate the growth of the selected crops. Parameters define plant growth under ideal conditions and quantify the impact of environmental stresses on plant growth. The simulations conducted here addressed the four most important staple food crops of Mali. Each crop was characterized using a set of standard growth parameters. A literature review of modeling studies for these crops in the Sahelian region (Kihara et al., 2012) provided initial estimates for crop growth parameters.

A literature review was also used to establish an initial set of crop management operations and management dates. Input to the model included data for planting, harvest, irrigation applications, manure and fertilizer applications, and hand or animal-based tillage operations.

Four rainwater harvesting measures were evaluated for their effect on soil moisture storage, soil erosion control, and soil fertility improvement: vegetative filter strips, contour bunds (soil or stone), planting pits (*zai*), and contour planting. Simulating the effects of these practices involved representing each one with a combination of factors. Those factors and initial estimates of their parameters were based on a modeling study of the same practices in Niger (Kihara et al., 2012).

Simulation scenarios were developed based on the combinations of crop, soil type, and slope with which farmers use each conservation practice, as shown in Table 1. Scenarios with the lowest slope (0-3%) included supplemental irrigation for rice.

To calibrate APEX software for projections based on future climate scenarios, model parameters were first set so that they simulated yields resembling those recorded for the study zone during the baseline years of 1991 to 2000. Each of the scenarios was then run with each of the selected soil and water conservation practices using historical climate data (1991–2000). Both crop and conservation practice parameters in the APEX model crop database were then recalibrated as necessary to achieve annual yields of each crop close to the FAO (2014) reported annual yield for Mali.

TABLE 1: MODEL SCENARIOS TESTED*

Scenario description	Slope and soil combination			
	6–12% slope/ Regosols	**3–6% slope/ Lithosols**	**3–6% slope/ Arenosols**	**0–3% slope/ Luvisols/ Irrigated**
Crop	**Maize**	**Sorghum**	**Millet**	**Maize**
Water conservation practices	Vegetative filter strips	Vegetative filter strips	Vegetative filter strips	Vegetative filter strips
	Soil bunds	Stone bunds	Soil bunds	Soil bunds
	Zai	*Zai*	*Zai*	*Zai*
	Contour farming	Contour farming	Contour farming	Contour farming

*Scenario 1 tested Rice at a 0-3% slope/Luvisols/Irrigated for soil bunds and contour farming.

After the calibration exercise, the model was able to accurately estimate surface runoff, water balance, and crop yield for the climate and soils typically found in the Mopti region of Mali. Overall, the calibrated APEX model had good predictive capability for the soils, crops, management, and climate scenarios used in the baseline period.

PERFORMANCE OF RAINWATER HARVESTING PRACTICES UNDER CURRENT CONDITIONS

The performance of the four rainwater harvesting practices was first evaluated for each crop, slope and soil using the climate data from 1990 - 2000. Performance was evaluated on the impact of the practices relative to performance on surface runoff, soil organic carbon content, soil loss, and crop yield without the rainwater harvesting practices.

Surface runoff

The rainwater harvesting practices caused changes in the water balance in comparison to the baseline for all crops. The changes differed most by soil and slope. For maize, sorghum and millet, the practices significantly reduced surface runoff on the three finer textured soils: luvisols, regosols, and lithosols. They were less effective on the more permeable arenosols, which are so sandy that they have inherently high infiltration rates. For rice, both contour ridges and bunds were effective at reducing surface runoff on the luvisols.

Soil loss

The rainwater harvesting practices were effective at slowing the loss of topsoil, which has higher fertility and moisture holding capacity than subsoil, except on the sandy arenosols, which had minimal soil loss to start with. Under maize, the practices reduced soil loss on lithosols the most. Under sorghum, the practices were less effective at reducing rates of erosion on the steepest slopes (regosols) than on the flatter slopes. When planted with rice, soil loss was effectively reduced by contour ridges and on the relatively flat luvisols. Overall, contour ridges gave the highest percent reductions.

Soil organic carbon

Reductions in soil loss under all crops helped improve soil fertility through preservation of soil organic carbon. However, this effect differed by crop and soil type. For maize, millet, and sorghum, the greatest gains occurred on one of the two soils with the highest initial fertility, lithosols and luvisols. Gains were greatest under maize. Under rice cultivation, reductions in erosion caused only small gains in soil organic carbon.

Crop yield

The use of rainwater harvesting practices improved yields for all four crops, but varied substantially by soil type and crop. For maize, sorghum and millet, the water harvesting practices improved yields most substantially on the two soils with higher organic carbon content, the lithosols and luvisols. On these soils, there was little difference in the effectiveness of the water harvesting practices in improving maize yield, while, of the four practices, contour ridges gave the highest sorghum and millet yields. The addition of water harvesting practices had little positive impact on rice yields because water supply was adequate even under baseline conditions due to irrigation.

TABLE 2: PERCENT CHANGE IN YIELD UNDER BASELINE CLIMATIC CONDITIONS (MOPTI MEASURED 1991–2000)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	13	-2.4	13.4	
	Lithosols	44.2	21.1	10.9	
	Arenosols	2.4	-5.6	9.4	
	Luvisols	40.6	61.7	17.1	2.2
VFS	Regosols	14.4	-5.8	11.7	
	Lithosols	45.8	14	9.6	
	Arenosols	4.4	-5.6	10.2	
	Luvisols	36.5	55.3	17.1	
Contour Ridges	Regosols	15.7	4.7	16.5	
	Lithosols	47	35.4	24.4	
	Arenosols	4.6	-1.2	14.8	
	Luvisols	36.6	76.1	23.3	2.6
Zai	Regosols	14	1	13.4	
	Lithosols	51.7	28	10	
	Arenosols	2.4	-5.2	10.9	
	Luvisols	45.8	66.3	17.1	

Green = Top 20% of crop category
Red = Bottom 20% of crop category

PERFORMANCE OF RAINWATER HARVESTING PRACTICES UNDER FUTURE CONDITIONS

Web-based software called MarkSim was used to generate climate data for 2030 and 2050 for input into the APEX crop model. (Annex A describes the software and process used to generate these scenarios.) Of the multiple sets of data generated, four were selected to provide input to the Apex model. They were selected to represent the range of future climate scenarios projected. The selected data came from two global climate models (GCMs). The two scenarios selected from the first model (IPSL-CM5A-MR) were characterized by slight warming and a significant increase in rainfall (2030) and significant warming, and no change in rainfall (2050). The two scenarios selected from the second model (CSIRO-MK3-6-0) were characterized by no warming, increase in rainfall (2030), and significant warming, significant decrease in rainfall (2050).

TABLE 3: COMPARISON BETWEEN CLIMATIC PARAMETERS FOR BASELINE (1991-2000) VERSUS FUTURE CLIMATE SCENARIOS

	IPSL-CM5A-MR		CSIRO-MK3-6-0	
	2030	2050	2030	2050
Increase in avg. daily temp (°C)	0.24	1.5	No change	1.0
Increase in avg. annual rainfall (millimeters)	102.26	No change	37.26	-25.34
Increase in frequency of heavy rain events (percent of rainy days)	9	3	3	3

The performance of the four rainwater harvesting practices was evaluated for each crop and soil using the conditions for the IPSL and CSIRO scenarios. Performance was evaluated on the impact of the practices relative to the baseline on surface runoff, soil loss, soil organic carbon content, and crop yield.

Surface runoff under 2030 scenarios

Regarding surface runoff, the effectiveness of a particular water harvesting practice was generally greater under the dryer CSIRO scenario, but varied by crop. Under maize, effectiveness decreased in the following order: contour ridges, *zai,* bunds, vegetative filter strips. Under sorghum, contour ridges and *zai* were equally effective at reducing runoff and more effective than either bunds or vegetated filter strips, which were about equally effective. Under millet, contour ridges, *zai*, and bunds were equally effective at reducing runoff, and all three were more effective than vegetative filter strips. Under rice, bunds and contour ridges were both effective at decreasing surface runoff.

The effectiveness of practices also varied by soil type. For both maize and millet, the practices decreased surface runoff most for finer textured soils, while for sorghum, the addition of water harvesting practices reduced surface runoff on all soils.

Soil loss under 2030 scenarios

The use of water harvesting practices reduced soil loss on all soils under both scenarios. Their effectiveness differed by crop. For maize, contour ridges were most effective, followed by *zai*, bunds, and vegetated filter strips. Under millet, contour ridges and *zai* were equally effective and both were more effective than bunds, which were more effective than vegetated filter strips. For sorghum, contour ridges and *zai* were equally effective at reducing soil loss, and both practices were more effective than bunds, which, in turn, were more effective than vegetated filter strips. Soil loss with irrigated rice was reduced by contour ridges and bunds.

Soil organic carbon under 2030 scenarios

Water harvesting practices generally increased soil organic carbon but varied by crop and soil. For maize, the biggest gains occurred with contour ridges, particularly on steep regosols, and to a lesser extent on flatter luvisols and lithosols. Vegetated filter strips were also effective at increasing soil organic carbon, while *zai* and bunds were the least effective practices. Under millet, the practices had mixed and relatively small impacts on soil organic carbon levels, while under sorghum increases were more significant. The biggest gains occurred with contour ridges on lithosols. *Zai* and bunds were reasonably effective at increasing soil organic carbon, while vegetated filter strips were the least effective. Reductions in erosion with rice caused very small gains in soil organic carbon under ISPL conditions, and negligible gains or losses under CSIRO conditions.

Crop yield under 2030 scenarios

Maize: Under the IPSL scenario, (slight warming, significant increase in rainfall), rainwater harvesting practices were relatively ineffective at improving maize yields on the more fertile lithosols and luvisols. On lithosols, bunds and *zai* decreased yield due to waterlogging effects. Contour ridges increased yields most consistently, with slight increases on all soils. Under the CSIRO scenario, (no warming, increase in rainfall), under some conditions the practices improved yields more effectively. Contour ridges improved yields significantly on the luvisols and the less fertile regosols. Vegetative filter strips also significantly improved yields on regosols. On all soils, change was negligible with bunds and *zai*.

Millet: Rainwater harvesting practices were only effective at improving millet yields on the more fertile lithosols for the IPSL scenario, (slight warming, significant increase in rainfall). As was the case with maize, the water harvesting practices decreased yields on the other soils due to waterlogging effects. However, where *zai* decreased maize yields on lithosols, they increased millet yields on these same soils. Water harvesting practices had a similar impact on millet yields under the CSIRO scenario, (no warming, increase in rainfall). Practices increased yields on lithosols, but reduced them on other soils.

Sorghum: Rainwater harvesting practices were most effective at improving sorghum yields. They increased yields on all soils for both the IPSL and the CSIRO scenarios relative to yields without these practices.

Rice: Rainwater harvesting practices resulted in relatively insignificant impact relative to yields without these practices, because water supply was generally adequate even under baseline conditions due to supplemental irrigation.

Surface runoff under 2050 scenarios

Under the 2050 IPSL and CSIRO scenarios surface runoff generally was less than under the baseline runoff for 1991–2000, mainly due to differences in annual temperatures and the frequency of heavy rain events rather than differences in annual precipitation. The effectiveness of a particular water harvesting practice was generally greater under the IPSL model than under the CSIRO model.

For maize, millet and sorghum, the effectiveness of water harvesting practices was the same order of effectiveness observed using 2030 data. Under IPSL and CSIRO 2050 climatic conditions, the practices significantly decreased surface runoff, with bunds and contour ridges being most effective. Contour ridges, *zai* holes, and bunds were more or less equally effective at reducing surface runoff, and all three were more effective than vegetative filter strips.

Soil loss under 2050 scenarios

The use of water harvesting practices reduced soil loss on all soils under both models. For maize, contour ridges and *zai* holes were most effective, followed by bunds and vegetated filter strips. Under millet and sorghum, the effectiveness of water harvesting practice decreased in the following order: contour ridges and *zai* holes were equally effective; both were more effective than bunds, which were more effective than vegetated filter strips. The use of bunds and contour ridges significantly decreased erosion losses under rice.

Soil organic carbon under 2050 scenarios

For maize and sorghum, the biggest gains occurred with contour ridges, particularly on lithosols, and to a lesser extent, on flatter luvisols and steeper regosols. *Zai* were also effective at increasing soil organic carbon, while bunds and vegetated filter strips were the least effective practices. Under millet, the biggest gains occurred with contour ridges, bunds, and *zai*, particularly on the steeper regosols and lithosols. Vegetated filter strips were the least effective conservation practice for improving soil fertility. The use of bunds and contour ridges reduced erosion with rice, resulting in a small gain in soil organic carbon under both models. Gains in soil organic carbon with all water harvesting practices were smallest on steeper regosols that had higher erosion rates, and on low fertility arenosols.

Crop yield under 2050 scenarios

Maize: Under the IPSL scenario, (significant warming, no change in rainfall), rainwater harvesting practices marginally improved maize yields on lithosols and luvisols, and were even less effective on the less fertile regosols and arenosols. The effectiveness of water harvesting practices on maize yield was strongly affected by soil type under the CSIRO scenario, (significant warming, significant decrease in rainfall), under which water harvesting practices were very effective at improving maize yields for all but the sandiest soils (arenosols).

Millet: Rainwater harvesting practices were relatively ineffective at improving millet yields on all soils for the both scenarios. The ineffectiveness of water harvesting practices is likely related to a large increase in mean annual temperature, combined with the lack of sufficient precipitation that characterizes these scenarios.

Sorghum: Rainwater harvesting practices improved sorghum yields on all soils, under both scenarios. They were very effective at improving sorghum yields on lithosols and least effective at increasing sorghum yield on the sandy arenosols.

Rice: Water harvesting practices had a relatively insignificant impact on rice yield.

TABLE 4: CHANGES IN CROP YIELD (PERCENT) WITH WATER HARVESTING PRACTICES (2030)

SLIGHT WARMING, SIGNIFICANT INCREASE IN RAINFALL (IPSL)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	1	-1	13.1	
	Lithosols	-12	7.7	22.9	
	Arenosols	1	-2.7	15.4	
	Luvisols	1	-2.2	23.1	-0.6
VFS	Regosols	1	-3.1	12.1	
	Lithosols	4	6	27.8	
	Arenosols	1	-6.1	15.4	
	Luvisols	3	-5.6	22.5	
Contour Ridges	Regosols	2	-1	22.9	
	Lithosols	3	11.6	36.2	
	Arenosols	3	-1.7	16.4	
	Luvisols	5	-0.7	30	-0.4
Zai	Regosols	1	-1.8	13.1	
	Lithosols	-11	7.3	23.2	
	Arenosols	1	-2.5	15.4	
	Luvisols	1	-2.7	21.1	

Green = Top 20% by crop
Red = Bottom 20% by crop

NO WARMING, INCREASE IN RAINFALL (CSIRO)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-2	-4.2	16.5	
	Lithosols	0	11.1	12.5	
	Arenosols	-0.2	-4.3	13.6	
	Luvisols	-0.4	-0.9	14.4	-3.2
VFS	Regosols	20.6	0.6	16.5	
	Lithosols	1.3	9	18.6	
	Arenosols	3.8	-5.1	13.2	
	Luvisols	13.4	-3	16.6	
Contour Ridges	Regosols	22.4	-19.5	24.8	
	Lithosols	1.1	12.7	23.1	
	Arenosols	4.6	-6.8	19.8	
	Luvisols	16	-5.6	25.3	-1.5
Zai	Regosols	-1.7	-19.2	16.5	
	Lithosols	0.3	13.4	12.9	
	Arenosols	-0.2	-7.4	13.6	
	Luvisols	-0.9	-7.3	14.4	

Green = Top 20% by crop
Red = Bottom 20% by crop

TABLE 5: CHANGES IN CROP YIELD (PERCENT) WITH WATER HARVESTING PRACTICES (2050)

SIGNIFICANT WARMING, NO CHANGE IN RAINFALL (IPSL)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	2.8	1	27.4	
	Lithosols	8	1.3	39	
	Arenosols	-1.5	-4.4	1.5	
	Luvisols	2.1	-1.5	18.4	0.7
VFS	Regosols	2.3	-2.3	17.1	
	Lithosols	8.4	-0.5	39	
	Arenosols	-0.6	-5.2	1.5	
	Luvisols	4.1	-4	16.7	
Contour Ridges	Regosols	6.5	-0.7	35	
	Lithosols	11.5	2	54.7	
	Arenosols	1.5	-6.5	4.6	
	Luvisols	7.7	-1.1	21.8	0.9
Zai	Regosols	4.1	-2	28.2	
	Lithosols	7.4	0.8	40.6	
	Arenosols	-1.2	-6.5	1.5	
	Luvisols	2.5	-1.5	18.7	

Green = Top 20%
Red = Bottom 20%

SIGNIFICANT WARMING, SIGNIFICANT DECREASE IN RAINFALL (CSIRO)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	8.8	5.9	12.8	
	Lithosols	33.1	3.6	42.3	
	Arenosols	1.7	1.3	8.9	
	Luvisols	13.5	-1.5	13.3	-0.5
VFS	Regosols	10.4	7	9.3	
	Lithosols	28.6	1	47	
	Arenosols	3.5	1.3	11.1	
	Luvisols	16.1	-1.7	9.2	
Contour Ridges	Regosols	17	2.2	17.4	
	Lithosols	33.5	2.3	64.3	
	Arenosols	3.5	-1.9	11.1	
	Luvisols	22	-5.4	26.5	0.3
Zai	Regosols	9.9	2.2	14	
	Lithosols	34.3	2	43.2	
	Arenosols	1.2	-1.9	8.9	
	Luvisols	11.5	-5.8	13.3	

Green = Top 20% by crop
Red = Bottom 20% by crop

CONCLUSIONS

A few broad conclusions can be drawn regarding the effectiveness of the four water harvesting practices evaluated. Generally, they improved sorghum yields most consistently, and on average, contour ridges proved to be most effective. The use of contour ridges on sorghum significantly raised yields in all climate scenarios and all soils, with the exception of arenosols under the IPSL 2050 scenario. Across all climate scenarios and crops, the practices were least effective on the sandy, less fertile arenosols, and produced the smallest impact on the yields of rice under supplemental irrigation. The practices also resulted in the greatest improvements in yield under the harsh CSIRO 2050 scenario.

However, an overall absence of pattern in the results overshadows these isolated conclusions. Clearly, the impact of each water harvesting practice depends on the crop, soil type, slope, and climate scenario under which it is being used. The same practice influences surface water runoff, soil loss, surface organic carbon and yields differently under different conditions.

All of the water harvesting practices evaluated can significantly improve soils and yields under some conditions, yet none of them can improve soils and yields more than the others under all conditions. None of them is "better than nothing" under all conditions. To be effective, a practice must be used with the appropriate crop, on the appropriate soil and slope, with the right climate. While it is likely that climate change will increase the importance of these and similar water harvesting practices, it will not relieve the need to improve our understanding of how conditions affect their performance. None of the water harvesting practices evaluated will be the universal solution to the challenges farmers can be expected to face managing rainwater in the Sahel under the projected climate conditions.

ANNEX A. MALI AGRICULTURAL ADAPTIVE PRACTICES MODELING ASSESSMENT – FULL REPORT

EXECUTIVE SUMMARY

The major objective of this study is to evaluate traditional water conservation practices that can alleviate the soil fertility constraints and optimize soil water retention for improved crop productivity in the Sahelian region of Mali. The Agricultural Policy/Environmental eXtender (APEX) model is used to evaluate the impacts of selected water harvesting practices on yield of common crops grown in Mali (maize, millet, sorghum and upland rice) under current and future climate change scenarios.

The study focuses on a hypothetical site in the Sahelian agro-ecoregion of Mali, in the Mopti region and Bankass District. This hypothetical site consists of four soil types commonly found in this region, namely; regosols, lithosols, arenosols, and luvisols. Each soil occurs on a characteristic slope; the order, from steepest to least steep, is as follows: regosols; lithosols; arenosols; and luvisols.

Arenosols correlate with the Entisols of the U.S. Taxonomic System. They are sandy in texture, and have shallow and weakly developed soils. Regosols are poorly developed, low-water-holding-capacity soils that are prone to erosion. Lithosols are shallow soils with abundant rock fragments, but they have relatively high soil organic matter content. Arenosols are very sandy in soil texture and have poor water holding capacity and soil fertility. Luvisols are loamy sand or coarser in texture, have relatively high soil organic matter content, and commonly occur in flat or gently sloping land near rivers where upland rice is grown.

The APEX model was calibrated with measured climatic data for the Mopti region from 1991–2000 against FAO reported values for yield of maize, millet, sorghum, and upland rice as well as typical reported values for runoff from soils of Western Africa. Literature surveys were used to establish initial values for APEX model parameters that describe soil properties, crop phenological characteristics, and soil or crop management practices for the Mopti region of Mali. The calibrated APEX model provided a satisfactory representation of maize, millet, sorghum, and upland rice yields, as well as runoff amounts during the baseline climatic period.

Four rainwater harvesting practices, based on farmer surveys in Mali, were selected for evaluation using the APEX model. These include soil or stone bunds, vegetated filter strips, contour ridges, and *zai* holes. APEX model parameters for these practices were initially selected from literature reviews and adjusted to obtain reasonable crop yields and runoff amounts. The performance of rainwater harvesting practices was evaluated for each crop and soil based primarily on the impact of rainwater harvesting practices on surface runoff, crop yield, soil organic carbon content, and soil loss. Each of these indicators was compared with the value of the same indicator when no rainwater harvesting practices were used to grow crops.

Under the baseline climatic data measured from 1991–2000, the daily average temperature was 29.7 °C and the average annual rainfall was 525.7 millimeters. Rainfall mainly occurs during the growing season (June–September). A literature search showed wide variability in future precipitation amounts generated by different climate models. To better represent the effects of this variability on performance of rainwater harvesting practices, we used predictions from two distinctly different climate models that gave a range of contrasting precipitation conditions. Four additional future climatic scenarios were developed using the MarkSim daily third order Markov process climate simulator for the years 2025–2035 and 2045–2055. MarkSim has the option of generating climate data using any or all of 17 global climate models (GCMs) using a stochastic process that produces any desired number of realizations for each of the 17 GCM models. Future climatic data output of one realization from each of two GCM models (Institut Pierre-Simon Laplace, IPSL-CM5A-MR and CSIRO-MK3-6-0) were chosen as input data for the APEX model. The IPSL-CM5A-MR GCM model realization chosen exhibited an average temperature of 29.9 °C and 31.2 °C, and an increase in temperature of 0.24 °C and 1.5 °C for 2030 and

2050, respectively, relative to the baseline period of 1991–2000. Precipitation for the IPSL climate averaged 628 and 524 millimeters in the 2030 and 2050 future time periods, respectively. The CSIRO-MK3-6-0 GCM model realization chosen exhibited an average temperature of 29.6 °C for 2030, which is essentially unchanged from baseline conditions. It also predicted an average temperature of 30.9 °C around 2050, an increase in temperature of 1.0 °C relative to the baseline period. Annual precipitation around the year 2030 averaged 563.0 millimeters and then decreased to 500.4 millimeters for the years before and after 2050. In summary, compared with the baseline (current) climate, the four future climatic scenarios evaluated exhibited 1) a slight warming in 2030 along with a significant increase in precipitation; 2) no significant warming in 2030 along with a moderate increase in precipitation; 3) a significant rise in temperature for 2050 along with no change in precipitation; and 4) a significant rise in temperature for 2050 along with a significant decrease in precipitation. The IPSL and CSIRO scenarios evaluated also included some realizations that were characterized by an increased frequency of very hot days or an increased frequency of very intense precipitation events.

Results for future climate scenarios showed interesting and complex changes relative to pre-2000 climatic conditions in runoff, crop yield, soil erosion, and soil organic matter. The changes differed depending on which combination of soil, slope, crop, climate, and water harvesting practices were being considered. Yields of maize and millet generally increased for climatic scenarios with increased annual precipitation and decreased for scenarios with decreased precipitation relative to pre-2000 climatic conditions. The yield response to precipitation was greater for more fertile lithosols and luvisols than less fertile regosols or arenosols. Yield decreased in response to increased temperature or decreased precipitation for sorghum. Yield of irrigated rice increased moderately with increases in precipitation, and decreased moderately in response to decreases in precipitation. Runoff increased as precipitation increased, and decreased as precipitation decreased, as expected. Decreases in runoff did not always result in increased crop yield, as much of the infiltrated water was unavailable for crop uptake due to deep percolation and subsurface lateral flow. Changes in soil loss were proportional to changes in runoff, in general, but tended to be larger on steeper regosols or on soils where changes in crop yield and biomass affected soil cover. Changes in soil fertility were controlled by gains or losses of soil organic carbon in response to changes in soil erosion. As soil erosion decreased, soil organic carbon content was preserved and gains in soil fertility were observed relative to soils that had greater rates of soil erosion.

Performance of rainwater harvesting practices was affected by climate, soil type, slope steepness, and crop. Rainwater harvesting practices were generally not effective at improving yield of upland rice on flat luvisols because of the availability of supplemental irrigation. Similarly, rainwater harvesting practices were generally not effective at improving maize or millet yields on very sandy arenosols, which have very high inherent infiltration rates. These practices also did not generally improve (e.g., 1–5 percent gains for maize) and often diminished maize or millet yields (e.g., approximately 11 to 12 percent losses for maize due to asphyxiation) under climatic scenarios with high annual precipitation (IPSL 2030). Rainwater harvesting practices were most effective at improving crop yield (gains of 12–34 percent for maize and 9–64 percent for sorghum) on more fertile lithosols and luvisols under climatic scenarios with low annual precipitation (CSIRO, 2050). Water harvesting practices were not very effective at improving yield of millet during years with low precipitation (CSIRO, 2050). Yield increases due to water harvesting practices were generally better with sorghum (1–64 percent increased yield) than maize or millet on all soils and under all climatic scenarios considered. Overall, contour ridges and *zai* improved crop yield more than bunds, which, in turn, were more effective than vegetated filter strips.

Surface runoff was decreased significantly (e.g., by 40–66 percent for maize) through the use of rainwater harvesting practices for all combinations of soil and climate. As mentioned previously, reductions in surface runoff did not always translate into gains in crop yield, because the soils studied have inherently high rates of deep percolation and lateral subsurface flow. In general, contour ridges and *zai* were more effective at decreasing runoff than bunds, which were more effective than vegetated filter strips.

Soil loss decreased significantly (by 28–100 percent) through the use of rainwater harvesting practices across all combinations of crop, soil, and climate. In general, contour ridges and *zai* were more effective at decreasing erosion than bunds, which were more effective than vegetated filter strips. Although the magnitude of soil erosion was affected by amount of annual precipitation, the reductions in soil erosion with water harvesting practices were relatively uniform for a given practice across all soil types and climatic scenarios. As soil loss decreased through the installation of water harvesting practices, there was also reduced loss of soil organic carbon associated with topsoil. Thus, practices that reduced soil erosion also helped preserve soil fertility by conserving soil organic carbon relative to the situation without water harvesting practices. Gains in soil organic carbon with water harvesting practices, relative to levels of soil organic carbon without these practices, averaged 0.1–45 percent for maize and 4–41 percent for sorghum across soil types and climatic scenarios. Gains in soil organic carbon were small and inconsistent for millet. Contour ridges and *zai* helped preserve soil organic carbon more than bunds or vegetated filter strips, particularly for maize and sorghum. Reductions in loss of soil organic carbon with these practices were largest under climatic scenarios with the least rainfall (CSIRO 2050), and least under climatic scenarios with the most rainfall (IPSL 2030). Overall, gains in soil organic carbon helped maintain soil fertility, leading to improved crop yields, especially on the inherently more fertile lithosols and luvisols.

This study shows that water harvesting practices generally have benefits for improving crop yield and soil fertility under various possibilities for future climate change. However, the extent of these benefits depends on specific combinations of crop, soil, slope, and water harvesting practice. Benefits are small for irrigated upland rice on luvisols and for maize and millet on very sandy arenosols. Benefits are greatest for maize and sorghum on more inherently fertile lithosols and luvisols, especially for climatic scenarios which involve decreased precipitation. In general, contour ridges and *zai* were more effective at improving crop yield, reducing runoff and erosion and preserving soil organic carbon than bunds and vegetative strips.

Several challenges were encountered during completion of this project. First, parameterization of the APEX model was affected by a paucity of site-specific information concerning soil or climatic characteristics and historical crop yields near Mopti. Parameterization of the water harvesting practices was similarly affected. Despite these challenges, the APEX model seemed able to adequately represent relative differences and changes that resulted from installing water harvesting practices on different soil, slope, crop, and climatic combinations.

Another challenge involved representing the wide variability in future precipitation amounts and intensities generated by different climate models. To overcome this challenge, we evaluated the effectiveness of water harvesting practices using predictions from two distinctly different climate models that gave a range of contrasting precipitation conditions. In the future, it would be beneficial to evaluate the effectiveness of these practices using a wider range of future climate scenarios, as well as a wider range of study locations beyond the Mopti region.

INTRODUCTION

Mali is a country in West Africa whose landscape is dominated by flat or rolling terrain. It receives annual rainfall ranging from less than 200 millimeters up to 1,300 millimeters. There are two different precipitation regimes in the Sahelian zone of Mali. The northern part of the Sahel has 200–350 millimeters annual rainfall and the southern part (also called the Sahelo-Sudanian zone) has 350–600 millimeters. The rainy season is short and extends only 3–4 months, from June to September. The potential evapotranspiration (ET) exceeds 2,000 millimeters per year (ICRISAT, 1999).

The most important crops grown in Mali are maize, millet, sorghum, and rice (MSU, 2011). Production of maize and rice has increased by about 7.7 percent annually since 1990 as a result of expansion in production areas and improved crop genetics. In contrast, production of sorghum and millet only grew by 2–3 percent over the same time period. Poor harvests due to drought create vast shortages of food for Malians, especially in northern regions of the country, where armed conflict has increased recently.

Mali is located in the Sahelian region of Africa, where agricultural production is limited by several biophysical factors, including variable precipitation, warm temperatures, and sandy soils with low water holding capacity and low organic matter content. To overcome these constraints, a variety of agricultural practices are available, including those that involve rainwater harvesting measures, field management practices that improve soil fertility, and the use of supplemental irrigation. Rainwater harvesting measures often used by farmers include soil or rock bunds, contour plowing, vegetative strips, or *zai* holes. Manure application and long-term fallowing are the primary methods farmers use to improve soil organic matter. About 84 percent of the agricultural soils of Mali have water-related constraints. Application of irrigation water from the Niger River is used to supplement rain-fed agriculture.

There have been many studies documenting the benefits of various types of rainwater harvesting measures in the Sahelian region of Africa under current climate conditions. Kablan, Yost, & Brannan (2008) studied Aménagement en courbes de niveau (ACN), which are permanent contour ridges. ACN increased yields of millet, sorghum, and maize by 50 percent, while also increasing soil organic carbon content. Rainfall infiltration with ACN increased up to 10 percent, which allows for the earlier planting of crops. Belemvire, Maiga, Sawadogo, Savadogo & Ouedraogo (2008) and Botoni & Reij (2009) studied rainwater harvesting measures in Burkina Faso. At least 300,000 hectares of stone bunds, vegetated strips, half cuvettes and *zai* have been installed for water harvesting in Burkina Faso (Belemvire et al., 2008). These measures helped to reduce soil erosion, improve soil moisture, and maintain soil fertility. Stone bunds increased crop yields by 13–34 percent for millet and sorghum (Belemvire et al., 2008; Botoni & Reij, 2009), while *zai* increased yields by 86 percent in a low rainfall region of Burkina Faso. Rainwater harvesting measures also increased crop residue production in millet and sorghum by 39–44 percent (Botoni & Reij, 2009), which has important benefits for animal feed, soil mulch, and soil organic matter content.

Spaan, Sikking, & Hoogmoed (2005) studied the impact of 1-meter-wide contour vegetative filter strips on soil erosion in Burkina Faso. Research was conducted on a sandy loam (luvisol) located on a 2 percent slope during three years in which rainfall received on the plots varied from 51 to 224 millimeters. Vegetative filters were composed of either perennial grass, a shrub or a succulent plant, the latter was less effective at controlling erosion or runoff than the former two types of plant because of its open clumped structure. Soil loss was reduced 70–90 percent with vegetative bands consisting of perennial grass or shrubs, and by 50 percent for succulent plants. Most of the runoff and erosion occurred during the most intense rainstorms.

Samaké, Smaling, Kropff, Stomph, & Kodio (2005) showed that millet yields in the Bankass region of Mali increased significantly as soil organic carbon content increased. This shows that practices that improve both water and fertility status of soils are important. Tied ridging systems were studied in Mali by Kouyaté, Franzluebbers, Juo, & Hossner (2000). Yields with tied ridging systems were better on loamy soils than on loamy sands, and crop yields increased when tied ridging was practiced in combination with the growth of green manure. Conversely, Moustapha (2010) showed that there are also some disadvantages to rainwater harvesting measures in Niger. Installation of *zai* increased the risk of asphyxiation of young crops after intense rainstorms due to ponding of water for an extended duration.

FAO (2001) organized a conference to discuss the performance and suitability for adoption of a wide variety of rainwater harvesting measures in West Africa. Overall, the fewest constraints to adoption occur for stone bunds, followed by vegetative bands, with *zai* being less acceptable than either of these options due to heavier labor and maintenance requirements. Stone bunds, *zai,* and vegetated bands were all equally effective at reducing soil erosion and conserving soil moisture. However, *zai* performed better on sandy soils than rocky soils, while stone bunds performed better on rocky soils than sandy soils.

A few studies have used computer modeling to evaluate the impact of rainwater harvesting measures on crop yield. Worou, Gaiser, Saito, Goldbach, & Ewert (2012) studied production of rain-fed upland rice in Benin with and without soil bunds using the EPIC model. Soil bunds significantly increased soil moisture content, but there were no increases in rice yield with soil bunds as compared to without soil bunds. Fatondji, Bationo, Tabo, Jones, Adamou, & Hassane (2012) studied the impact of *zai* on water use and millet yield in Niger using the DSSAT model. For *zai* with manure amendments, millet yields increased from 705 kg/ha without *zai* to about 1,175 kg/ha with *zai*. Crop yields were not increased with *zai* that did not receive manure amendments. There apparently have not been any modeling studies to evaluate the performance of rainwater harvesting measures under future climate change scenarios.

Climate change threatens to increase the risk of growing crops in the Sahelian region of Africa. Climate change threatens to increase air temperatures and evapotranspiration, increase the risk of intense rainstorms, and increase the risk of heat waves associated with drought (Baptista, S., et al., 2013). Impacts of climate change on precipitation vary depending on which combination of global and regional climate models are used.

A brief literature review of climate change in Mali showed quite a bit of variation in predictions. Diarra, Diakite, & Macina et al. (2007) showed that from 1961-1990 the average maximum temperature in Mali was 30.5 °C, and temperatures higher than this occurred 50 percent of the time. By 2050, the average maximum temperature is expected to increase to 32.5 °C, with temperatures higher than this occurring 40 percent of the time. Butt, McCarl, Angerer, Dyke, & Stuth (2005) stated that climate change in Mali is expected to increase temperature from 1-3 C by 2030, while precipitation will change from -0.17 to +0.03 millimeters/year. Crop yields under this scenario are predicted to decrease by about 12 percent for maize, 14 percent for sorghum and 9 percent for millet (Butt et al., 2005). Schlenker & Lobell (2010) used a simple regression model to estimate the impacts of climate change by 2050 on yields of maize, millet and sorghum in Mali. On average, yields of these crops decreased by 10-20 percent. Jalloh, Nelson, Thomas, Zoubmoré, & Roy-Macauley (2013) found that precipitation in West Africa is likely to rise slightly by 2025, while there is no predictable trend by 2050. However, the frequency of extreme events (droughts, floods) is likely to increase for both 2025 and 2050. In a comprehensive study, Sultan et al. (2013) evaluated the impacts of climate change on sorghum and millet yields in Mali using 35 individual combinations of global and regional climate models. For the period from 2031-2050 temperatures generally increased from 0.7 to 2.5 °C, while changes in precipitation ranged from -15 percent to +15 percent. Although there was quite a bit of variability in climate predictions, when warming exceeds 2 °C, yield reductions in these crops could not be compensated by any increases in precipitation. Sultan et al. (2013) found that crop yields in southern Mali were more sensitive to temperature change, whereas yields in the Mopti region were more sensitive to changes in rainfall.

Based on this literature review, there is a pressing need to develop agricultural adaptive practices to maintain or increase production of maize, millet, sorghum, and rice in the Sahelian region of Africa as the climate warms and, if it occurs, rainfall declines. Approaches that have merit for accomplishing this goal include practices that harvest rainwater, improve soil fertility, or provide supplemental irrigation water.

OBJECTIVE

The major objective of this study is to evaluate traditional water conservation practices and other technologies that can alleviate the soil fertility constraints and optimize soil water retention for improved crop productivity in the Sahelian region of Mali. A modeling approach will be used to understand the impacts of selected water conservation practices under current and future climate change scenarios.

METHODOLOGY

Site selection

The study model was based on the Bankass District of the Mopti Region in the Sahelian agro-ecoregion of Mali (Figure A.1). The site is an agricultural area that has representative sloping landscapes. Agricultural land in the Mopti region of Mali has a wide range of slope steepness distributions (Table A.1). The variation in slope steepness (along with soil type) interacts with the effectiveness of a particular type of water conservation practice. Generally, water conservation practices are less effective at harvesting water on steeper slopes as compared with flatter slopes.

FIGURE A.1: LOCATION OF THE STUDY SITE

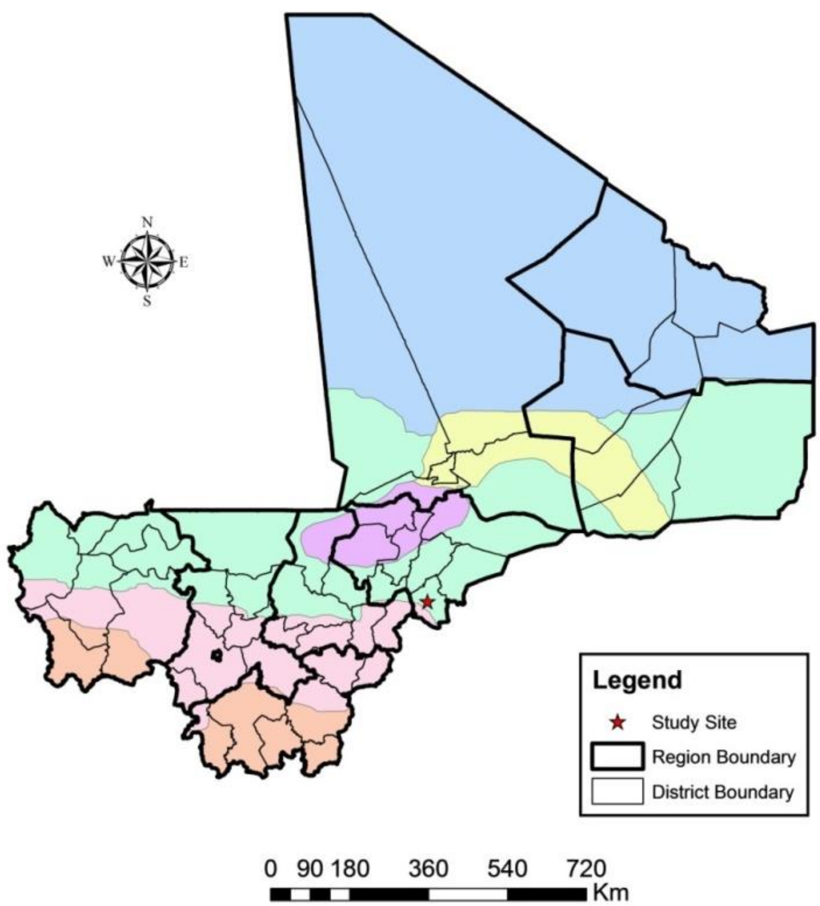


TABLE A.1: SLOPE STEEPNESS DISTRIBUTION IN THE MOPTI REGION OF MALI

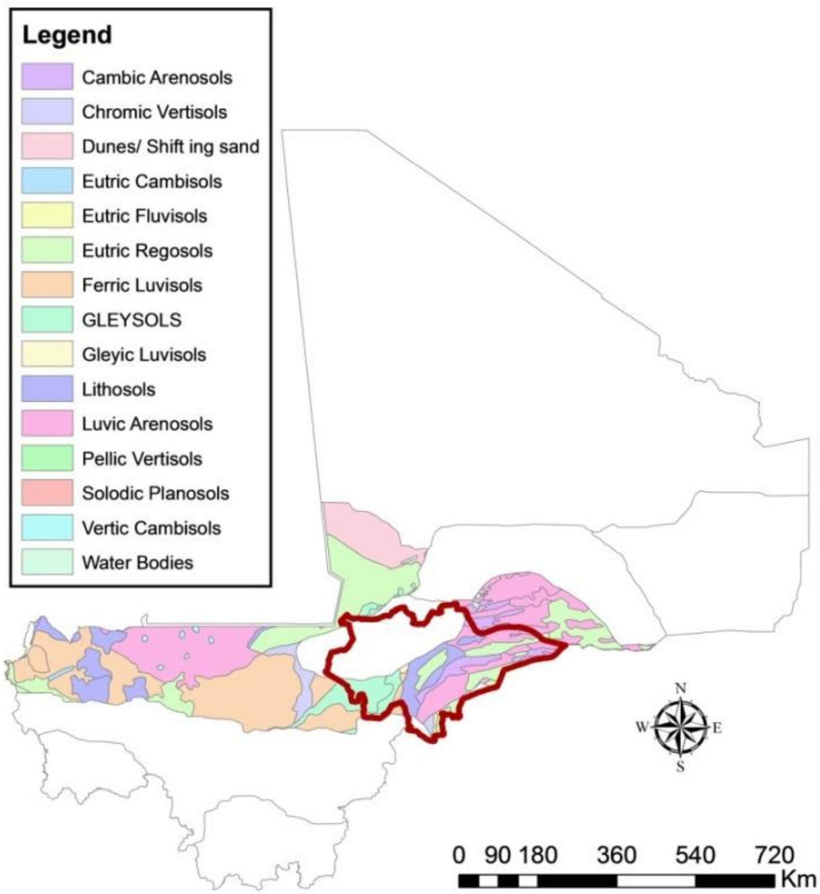
Area (percent)	Slope Steepness (percent)
<3	57
3-6	32.5
6-12	10
>12	0.5

There are 11 major FAO soil groups in the Sahelian agro ecoregion (Table A.2, Figure A.2). The most common (four) soils are arenosols, luvisols, regosols, and lithosols. These four soil types will be evaluated for each of the crop and soil water conservation practice combinations that are modeled. Evaluating performance of rainwater harvesting practices on different soil types is important. Effectiveness of these practices is expected to vary with soil texture and soil physical characteristics that affect infiltration and water holding capacity.

TABLE A.2: SOIL DISTRIBUTION IN THE MOPTI REGION OF MALI

Soil Type	Area (km^2)	Percent Area
Arenosols	8212166	30.70
Luvisols	6709443	25.09
Regosols	5420117	20.26
Lithosols	2274303	8.50
Dunes	1800000	6.73
Gleysols	1468768	5.49
Vertisols	585319	2.19
Cambisols	133982	0.50
Water	84996	0.32
Fluvisols	47850	0.18
Planosols	9426	0.04
Total	26746370	100.00

FIGURE A.2: SOILS IN THE MOPTI REGION OF MALI



The area upon which the modeling exercise was based site has highly weathered soils typical of Sub-Saharan Africa. The soils have very low organic matter content and shallow depth, which adversely affect crop yields. The major physical and chemical characteristics of the soils are shown in Table A.3 below.

Arenosols correlate with the Entisols of the US Taxonomic System. They are sandy in texture, and have shallow and weakly developed soils. Arenosols are easy to till in agricultural areas, but have poor fertility. They need amendments of organic matter to improve productivity. Most arenosols in the dry zone are used for little more than animal grazing, but they could be used for arable cropping if irrigated. Luvisols are loamy sand in soil texture. They have argillic horizons where clay accumulates in the subsurface B horizon, and commonly occur in flat or gently sloping land. These soils have clays with high cation exchange capacity, and are generally fertile soils which are suitable for a wide range of agricultural uses. Luvisols on steep slopes require erosion control measures. Regosols are common in arid areas and, as with arenosols, are classified as Entisols in the US Taxonomic System. They have low water-holding capacity and are prone to erosion. After intense rain, surface crusts form in these soils, which impede emergence of seedlings and lead to runoff. Some regosols are used for irrigated farming, but their most common land use is for low-volume grazing. Lithosols generally occur at higher elevations on steep slopes. They are shallow soils with abundant weathered rock fragments. Lithosols are cultivable through the removal of stones by hand and terracing.

TABLE A.3: SOIL PROPERTIES OF THE STUDY SITE

Parameters	Horizon 1				Horizon 2			
	Lithosol	Luvisol	Arenosol	Regosol	Lithosol	Luvisol	Arenosol	Regosol
Soil depth (mm)	300	300	300	300	580	810	1000	1000
Hydrologic group	C	C	B	C	C	C	B	C
Soil texture	Loam	Sandy loam	Sand	Loamy sand	Loam	Sandy loam	Sand	Loamy sand
Bulk density (gm/cm^3)	1.1	1.4	1.4	1.7	1.2	1.4	1.5	1.5
Soil available water capacity	0.098	0.087	0.125	0.125	0.098	0.087	0.125	0.125
Soil erodiblity	22.4	22.2	226.8	28.4	13.0	14.0	194.3	44.3
Organic carbon content (percent)	0.9	0.6	0.2	0.3	0.7	0.4	0.1	0.2
Clay (percent)	22	15	5	8	27	23	5	10
Silt (percent)	33	18	3	9	29	16	3	9
Sand (percent)	44	67	92	83	43	61	92	81
Soil pH	6	6	6	6	5.4	5.4	5.4	5.4
Saturated conductivity (mm/hr)	22.4	22.2	226.8	28.4	22.4	22.2	226.8	28.4

Model selection

The Agricultural Policy/Environmental eXtender (APEX) model is selected for this study (Gassman et al., 2009; Steglich & Williams, 2008; Waidler, White, Steglich, Wang, Williams & Srinivasan, 2011; Wang, Gassman, Williams, Potter, & Kemanian, 2008; Williams, Izaurralde, & Steglich, 2008). The major reasons for applying this model are:

It can simulate the dynamics of soil fertility and soil moisture content status for a variety of crops and conservation practices.

It can simulate impacts of management practices and crop production at whole farm and small watershed scales.

APEX has a unique ability to subdivide farms or fields by soil type, landscape position, surface hydrology or management configuration to represent crop diversity and landscape characteristics within a field or farm.

Each subarea may be linked with other subareas based on water routing on the landscape, starting from the most distant subarea towards the watershed outlet.

APEX can generate future climate change scenarios with its weather generator.

APEX has been successfully used in previous studies of soil and water conservation in Mali and other West African countries, (Folberth, Gaiser, Abbaspour, Schulin, & Yang, 2012).

Crop model growth and management parameter specification

Crop management and simulation models can be used to understand and predict the phenological development of crops. The APEX model crop database contains information needed to simulate the growth of crops typically cultivated in Mali. The growth parameters in the plant growth database define plant growth.

Simulations addressed the most important staple food crops of Mali, namely; millet, sorghum, maize, and upland rice. According to FAOSTAT (2014), in the year 2010, millet was grown on 1,873,644 ha in Mali, sorghum on 858,698 ha, maize on 598,833 ha, and rice on 617,109 ha. Each crop is characterized with growth parameters such as those shown in Table A.4 below. A literature review of modeling studies for these crops in the Sahelian region (Kihara, Fatondji, Jones, Hoogenboom, Tabo & Bationo, 2012) provides initial estimates for crop growth parameters (Table A.5).

TABLE A.4: CROP GROWTH PARAMETERS NEEDED FOR APEX MODEL

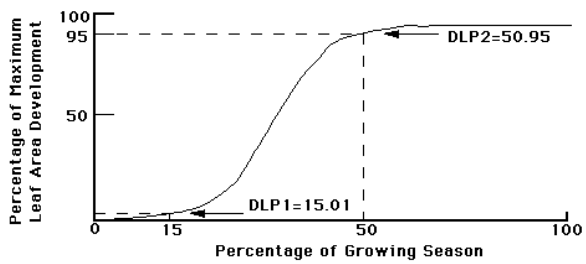
Variable	Description
CPNM	*Crop Name*. A four character name to represent the crop.
WA	*Biomass-Energy Ratio. Also called* radiation use efficiency
HI	*Harvest index*
TG	*Optimal temperature for plant growth.*
TB	*Minimum temperature for plant growth.*
DMLA	*Maximum potential leaf area index.*
DLAI	*Fraction of growing season when leaf area declines*
DLAP1	*First point on optimal leaf area development curve.*
DLAP2	*Second point on optimal leaf area development curve.* 
RLAD	*Leaf area index decline rate parameter*

TABLE A.5: MODEL CROP GROWTH PARAMETERS FOR THE STUDY SITE

Parameter	Description	Corn	Sorghum	Rice	Millet
WA	Biomass-Energy Ratio	40	37	25	35
HI	Harvest index	0.5	0.5	0.25	0.25
HI-Mopti		0.35 (Folberth et al., 2013)	0.28 (Zaongo et al., 1997)		0.2 (Vadez et al., 2012)
TOP	Optimal temperature for plant growth	25	27.5	25	30
DMLA	Maximum potential leaf area index	6	5.5	6	2.5
DMLA-Mopti		4.47 (Oguntunde et al., 2004)	4 (Zaongo et al., 1997)	3.95 (Akinbile, 2013)	1.8 (Vadez et al., 2012)
DLAI	Fraction of growing season when leaf area declines	0.8	0.8	0.8	0.85
DLAP1	First point on optimal leaf area development curve	15.05	15.01	15.01	15.01
DLAP2	Second point on optimal leaf area development curve	50.95	60.95	50.95	50.95
RLAD	Leaf area index decline rate parameter	1	0.5	0.5	1
RLAD-Mopti		0.01 (Folberth et al., 2013)	0.01 (Folberth et al., 2013)	0.01 (Folberth et al., 2013)	0.01 (Folberth et al., 2013)
RBMD	Biomass-energy ratio decline rate parameter	0.1	0.5	0.5	1
GSI	Maximum Stomatal Conductance	0.007	0.007	0.008	0.012
SDW	Seeding rate (kg/ha)	20	5	50	5
SDW-Mopti		22 (FAO, 2014)	6 (FAO, 2014)	55 (FAO, 2014)	4 (Payne et al., 1990)
HMX	Maximum crop height, m	2	1.4	0.8	2.5
HMX-Mopti		1.8 (Oguntunde et al., 2004)	2.6 (Zaongo et al., 1997)	0.89 (Akinbile, 2013, Warda,	1.8 (Oguntunde et al., 2004)

Parameter	Description	Corn	Sorghum	Rice	Millet
				2006)	
RDMX	Maximum root depth, m	2	2	2	2
RDMX-Mopti		1.2 (Payne et al., 1990, Zaongo et al., 1994)	1.1 (Zaongo et al., 1997)	0.23 (Akinbile, 2013, Warda, 2006)	1.2 (Payne et al., 1990, FAO, 2014)
	Grain Yield, t/ha	1.6 (FAO, 2014)	1.4 (FAO, 2014)	2.2 (FAO, 2014)	0.9 (FAO, 2014)
	Biomass Yield, t/ha	4.5 (Oguntunde et al., 2004)	6.2 (Zaongo et al., 1997)	5.2 (Akinbile, 2013)	2.9 (Bacci et al., 1999)
	Cultivar	Sotubaka (Omanya et al., 2007)	Bakari Kuruni (Akinbile, 2010)	NERICA (Warda, 2006)	SOSAT-C88 (Lacy et al., 2006)

The primary file used to parameterize crop management practices in APEX is the subarea management operation schedule file. This file contains input data for planting, harvest, irrigation applications, manure and fertilizer applications, pesticide applications, and hand- or animal-based tillage operations. An initial set of crop management operations (FAO, 1993; Xie et al., 2011) and management dates was gleaned from a literature review (Table A.6).

TABLE A.6: INITIAL MANAGEMENT OPERATIONS SCHEDULE

Crop	Maize	Millet, pearl	Rice	Sorghum
Scientific name	*Zea mays* L.	*Pennisetum glaucum* (L.) R. Br.	*Oryza sativa* L.	*Sorghum bicolor* (L.) Moench
Additional Information	Wet season	Wet season	Irrigated, wet season	Wet season
Primary Tillage	Hoe (Manual)	Hoe (Manual)	Hoe (Manual)	Hoe (Manual)
Secondary Tillage	Cultivator (Manual)	Cultivator (Manual)	Cultivator (Manual)	Cultivator (Manual)
Planting period – onset	June 1	June 1	May 1	July 1
Planting period – end	July 31	July 31	August 31	July 31
Planting rate, kg/ha	20-25	4-5	50-60	6-7
Length of the cropping cycle	75-90 days	75-90 days	90-145 days	90-100 days
Harvesting period – onset	August 1	August 1	September 1	October 1
Harvesting period – end	August 31	September 30	December 20	October 30
Manure Application	May 24	April 23	May 24	May 24
Fertilizer Application	June 1	June 1	June 1	July 1

Rainwater harvesting practices model parameter specification

The primary goal of this modeling study is to assess the impact of the different water conservation practices on soil moisture retention for agricultural production systems in the Sahelian region of Mali.

Four rainwater harvesting measures were evaluated for their effect on soil moisture storage, soil erosion control and soil fertility improvement. These practices are:

Vegetative strips

Contour stone or soil bunds, depending on availability of rocks

Planting pits (*zai*)

Contour planting

Simulating the effects of vegetative strips, stone or soil bunds, contour farming and *zai* involved representing each practice using a combination of factors shown in Table A.7. The primary factors include the Universal Soil Loss Equation (USLE) P factor, Curve Number CN-2 and Crop Cover factor

(USLE C factor). Initial parameter estimates were based on a modeling study of these practices in Niger (Kihara et al., 2012). Adjustments were made based on baseline climate scenario runs to obtain reasonable crop yields (FAO, 2014) and runoff amounts (Senay & Verdin, 2004).

TABLE A.7: RAINWATER HARVESTING PRACTICE MODEL PARAMETERS

Conservation Practice	Factor	Maize	Sorghum	Millet	Rice
Vegetative strips	USLE_P	0.7	0.7	0.7	0.8
	CN-2	Depends on soil/slope	Depends on soil/slope	Depends on soil/slope	Depends on soil/slope
	Crop Cover-C	Model calculated	Model calculated	Model calculated	Model calculated
	Land use #	+4	+4	+4	+4
Stone bunds	USLE_P	0.8	0.8	0.8	
	CN-2	Depends on soil/slope	Depends on soil/slope	Depends on soil/slope	Depends on soil/slope
	Crop Cover-C	Model calculated	Model calculated	Model calculated	Model calculated
	Land use #	+2	+2	+2	+2
Soil bunds	USLE_P	0.7	0.7	0.7	
	CN-2	Depends on soil/slope	Depends on soil/slope	Depends on soil/slope	Depends on soil/slope
	Crop Cover-C	Model calculated	Model calculated	Model calculated	Model calculated
	Land use #	+2	+2	+2	+2
Zai	USLE_P	0.6	0.6	0.6	
	CN-2	Depends on soil/slope	Depends on soil/slope	Depends on soil/slope	Depends on soil/slope
	Crop Cover-C	Model calculated	Model calculated	Model calculated	Model calculated
Contour Farming	USLE_P	0.8	0.8	0.8	0.9
	CN-2	Depends on soil/slope	Depends on soil/slope	Depends on soil/slope	Depends on soil/slope
	Crop Cover-C	Model calculated	Model calculated	Model calculated	Model calculated

Conservation Practice	Factor	Maize	Sorghum	Millet	Rice
	Land use #	+2	+2	+2	+2

Baseline model scenarios

Baseline model simulation scenarios are developed based on possible combinations of land use or types of crops grown, soil type, topographic settings, type of conservation practices, and rain-fed versus irrigated agriculture. We ran 13 baseline simulation scenarios (without water harvesting structures) with measured climate data from 1990–2000 (described below) for various combinations of slope, soil, and crop scenarios as shown in Table 8. In scenario one, rice production was simulated on the flat luvisols, the only soil type where supplemental irrigation water can be simulated. Scenarios 2-13 are in groups of four by crop and soil type. For example, scenario 2 evaluated the impact of the four practices on maize fields in regosols. This set of simulations was used to calibrate the model so that it gives accurate historical (1991–2000) predictions of crop yield (FAO, 2014) and runoff (Senay & Verdin, 2004). Then we ran each of the 13 basic scenarios with each of the selected soil and water conservation practices (Table A.8) using baseline measured historical climate (1991–2000).

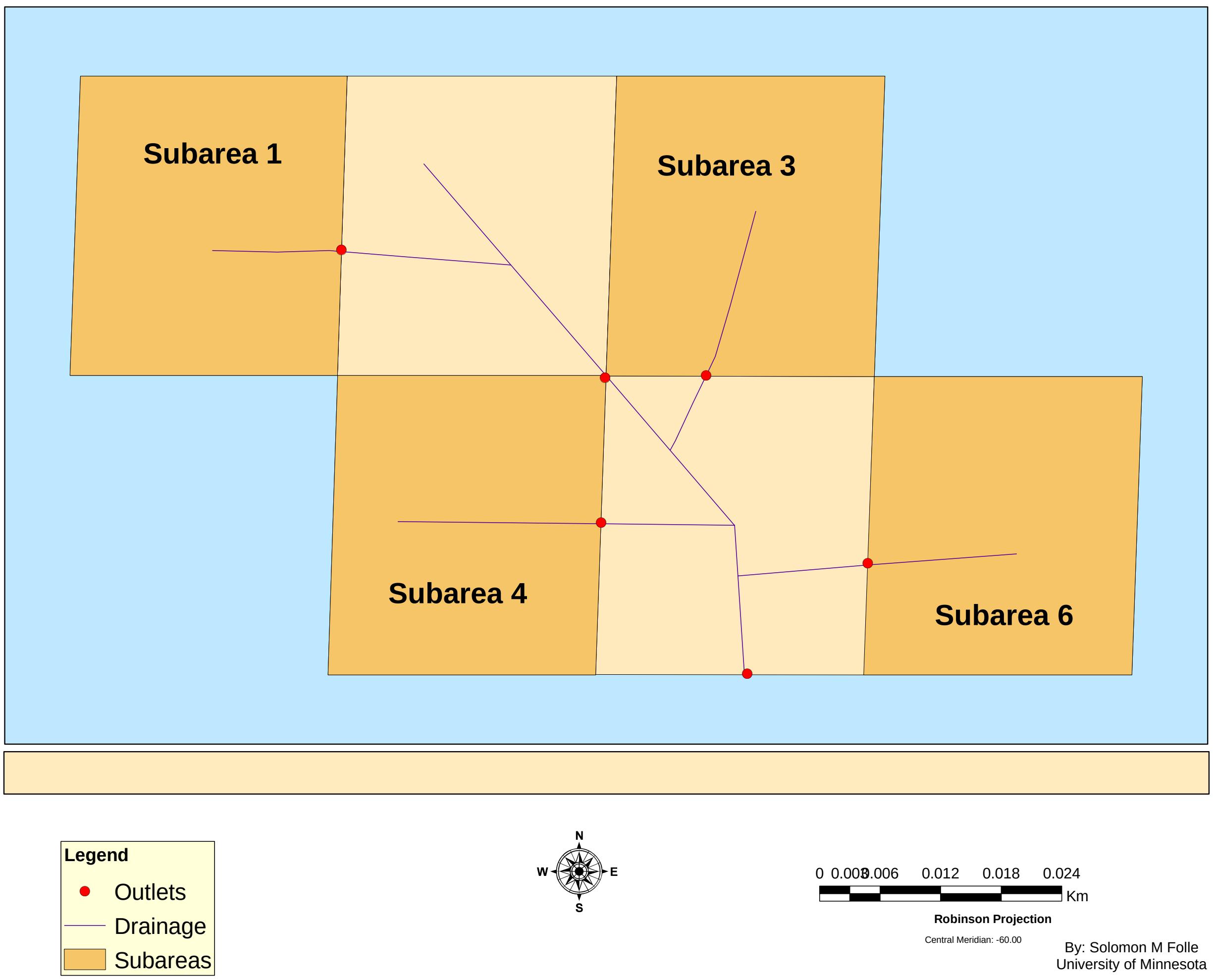
Production of the first three crops was tested in all the four subareas, and rice production was simulated under luvisols at the bottom slope region only, where supplemental irrigation water can be simulated.

TABLE A.8: MODEL SCENARIOS TESTED

	Description of Scenarios	Slope and Soil Combinations			
		6-12 percent slope/ Regosols	3-6 percent slope/ Lithosols	3-6 percent slope/ Arenosols	0-3 percent slope/ Luvisols/Irrigated
	Subarea	**1**	**3**	**4**	**6**
Scenario 1	**Crop**				**Rice**
	Water Conservation Practices				Soil bunds
					Contour farming
Scenarios 2-5	**Crop**	**Maize**	**Sorghum**	**Millet**	**Maize**
	Water Conservation Practices	Vegetative strips	Vegetative strips	Vegetative strips	Vegetative strips
		Soil bunds	Stone bunds	Soil bunds	Soil bunds
		Zai	*Zai*	*Zai*	*Zai*
		Contour farming	Contour farming	Contour farming	Contour farming
Scenarios 6-9	**Crop**	**Sorghum**	**Millet**	**Maize**	**Sorghum**
	Water Conservation Practices	Vegetative strips	Vegetative strips	Vegetative strips	Vegetative strips
		Soil bunds	Stone bunds	Soil bunds	Soil bunds
		Zai	*Zai*	*Zai*	*Zai*
		Contour farming	Contour farming	Contour farming	Contour farming
Scenarios 10-13	**Crop**	**Millet**	**Maize**	**Sorghum**	**Millet**
	Water Conservation Practices	Vegetative strips	Vegetative strips	Vegetative strips	Vegetative strips
		Soil bunds	Stone bunds	Soil bunds	Soil bunds
		Zai	*Zai*	*Zai*	*Zai*
		Contour farming	Contour farming	Contour farming	Contour farming

Subareas in Table A.8 above refer to specific combinations of slope and soil that are modeled. A 30-meter digital elevation model (DEM; ASTER GDEM v2) from the United States National Aeronautics and Space Administration (NASA) was used to represent topography at the study site. ArcGIS archydro tools were used to generate concentrated flow paths. Flow accumulation from the 30 m DEM was estimated and a cutoff value of 100 meters (flow path length) was applied in the process of routing flows from one subarea to another. The study simulated six subareas (fields), of which four subareas (1, 3, 4, and 6) with head water discharge were used for further analysis (Figure A.3). Subareas 2 and 5, in light tan in Figure A.3, were excluded from modeling.

FIGURE A.3: SOIL/SLOPE COMBINATION SUBAREAS USED IN APEX MODELING



BASELINE MODEL CONFIGURATION

The APEX model calibration was conducted using climate data for the years 1991–2000 on a site located in southern Mopti in the Bankass District of Mali. The first year (1991) was used for model warm up and the remaining nine years were used to establish the calibration scenarios. Of the four subareas selected for modeling, each subarea represented a different major agricultural soil of the Mopti region of the Sahelian agro-ecoregion (Table A.9). Production of the first three crops was tested in all the four subareas, and rice production was simulated under luvisols at the bottom slope region only, where supplemental irrigation water can be simulated.

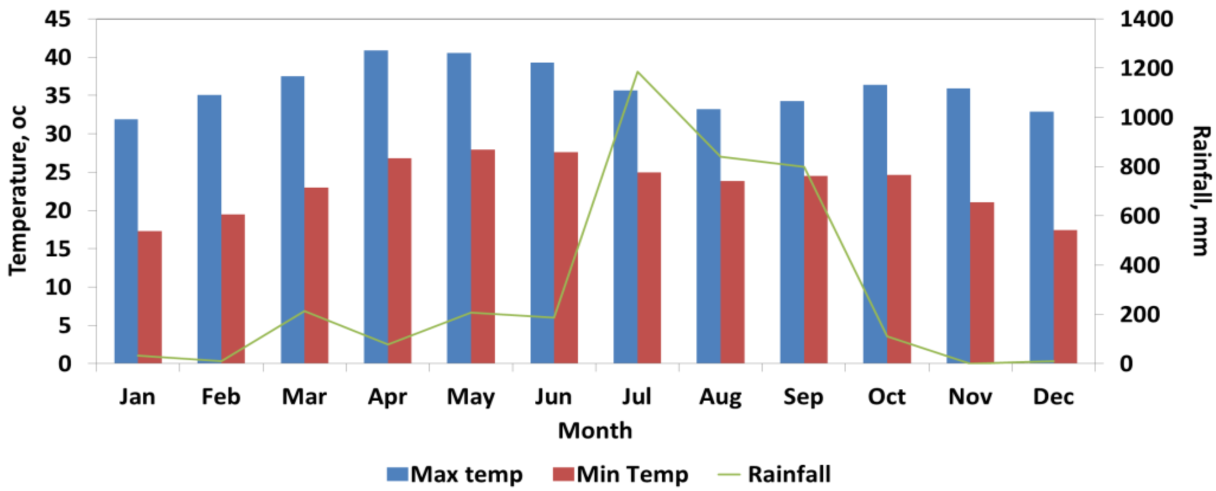
TABLE A.9: DESCRIPTION OF THE SUBAREAS

Subarea	Slope (percent)	Soil Type	Crops Simulated
1	12	Regosols	Maize, sorghum, millet
3	8	Lithosols	Maize, sorghum, millet
4	6	Arenosols	Maize, sorghum, millet
6	3	Luvisols	Maize, sorghum, millet, rice

Baseline weather input data

Observed daily temperature and precipitation data from 1991–2000 (http://www.tutiempo.net/en/Climate/Mopti/01-1991/612650.htm) were obtained for a meteorological station near Mopti, Mali. The average daily maximum and minimum temperatures at the study site are 36.1 °C and 23.2 °C, respectively (Figure A.4), with a daily average temperature of 29.7 °C. The highest daily temperature of 51.5 °C was recorded in April 1994. The average annual rainfall is 525.7 millimeters. However, there is a huge variability in rainfall, ranging from 335 millimeters/year (1993) to 1,119 millimeters/year (1994). The rainfall mainly occurs during the growing season (June–September). The maximum number of rainy days was 48 (1994), and the minimum number of rainy days was 21(1999). The months of July and August have an average of nine rainy days, and the months of June and September have five and six rainy days, respectively.

FIGURE A.4: AVERAGE MONTHLY RAINFALL AND TEMPERATURE FOR THE CALIBRATION YEARS (1991-2000)



Model parameterization and calibration

The crop database of APEX model contains unique information needed to simulate the growth of the selected crops. Parameters in the plant growth database define plant growth under ideal conditions and quantify the impact of environmental stresses on plant growth. To calibrate APEX software for projections based on future climate scenarios, model parameters were first set so that, using observed climate data derived from Tu Tiempo (2014), they simulate yields resembling those recorded for the study zone during the baseline years of 1992–2000. Initial parameters and their values were obtained from a review of reports and research studies conducted locally or within the region. Model parameters for the purpose of this study are calibrated in two categories: general parameters that represent overall conditions in the area and apply to all subareas; and crop types versus crop specific calibration. General calibration parameters for the study area are shown in Table A.10 below.

TABLE A.10: GENERAL CALIBRATION PARAMETERS

Parameter	Default Value	Calibrated value
Potential Evapotranspiration Equation	Penman-Monteith	Penman-Monteith (for windy conditions)
Runoff Peak Rate Estimate	Modified Rational EQ Rigid Peak Rate Estimate	Modified Rational EQ Rigid Peak Rate Estimate
Curve Number	Variable daily CN nonlinear CN/SW with depth soil water weighting	Variable daily CN SMI (soil moisture index)
Runoff (Q) Estimation Methodology	CN estimate of Q	Green and Ampt equation
Manure application	Auto application	Variable limits
Saturated Conductivity adjustment factor	0	0.15
Irrigation Code		Only for Rice Production; minimum application interval of three days

Both crop and hydrological parameters in the APEX model crop database were selected and calibrated to achieve annual yields of each crop close to but lower than the FAO (2014) reported annual yield for Mali as shown in Table A.11 (FAO, 2014). These measured yields are generally higher than crop yields in the Mopti region, but in the absence of Mopti-specific crop yields, they provide a useful benchmark for model performance. Crop specific parameter calibration is discussed in greater detail in the analysis of individual crop simulation efforts below.

TABLE A.11: CROP YIELD IN MALI, TONS/HA

Year	Maize	Millet	Rice	Sorghum
1992	1.0	0.5	1.8	0.6
1993	1.1	0.5	1.7	0.8
1994	1.1	0.6	1.7	0.8
1995	1.3	0.5	1.5	0.8
1996	1.6	0.8	1.9	1.0
1997	1.7	0.7	1.8	1.0
1998	1.6	0.9	2.2	1.0
1999	1.5	0.9	2.2	0.9
2000	1.3	0.7	2.1	0.8
Average	**1.4**	**0.7**	**1.9**	**0.9**

Baseline model results for maize

Agricultural production in Mali is largely derived from rain-fed subsistence farming, where recurring droughts are the major limitation for crop production (MMA, 2007–2008). Maize producing areas of Mali are concentrated in parts of the country where there is a 20 to 40 percent drought risk probability (MMA, 2007–2008). Recurring droughts have seriously limited maize production in the country. The average increase in maize yield over the years 1980–2012 was 0.41 tons/hectare. Studies show that increases in maize yields are driven by farmer adoption of higher levels of fertilizer use, rather than improvements in variety and management (Foltz, Aldana, & Laris 2012). Figures A.5 and A.6 show maize production (tons, hectare, and tons/hectare) in Mali for the years 1991–2000, as summarized by FAO (2014). These are the baseline years for our study.

In order to initiate APEX modeling of maize production in the study area, representative maize management operations were set with details on tillage operations and fertilizer applications (Table A.12). Nine major crop input parameters were calibrated based on a review of local research findings, shown in Table A.13.

FIGURE A.5: MAIZE PRODUCTION AND AREA HARVESTED IN MALI

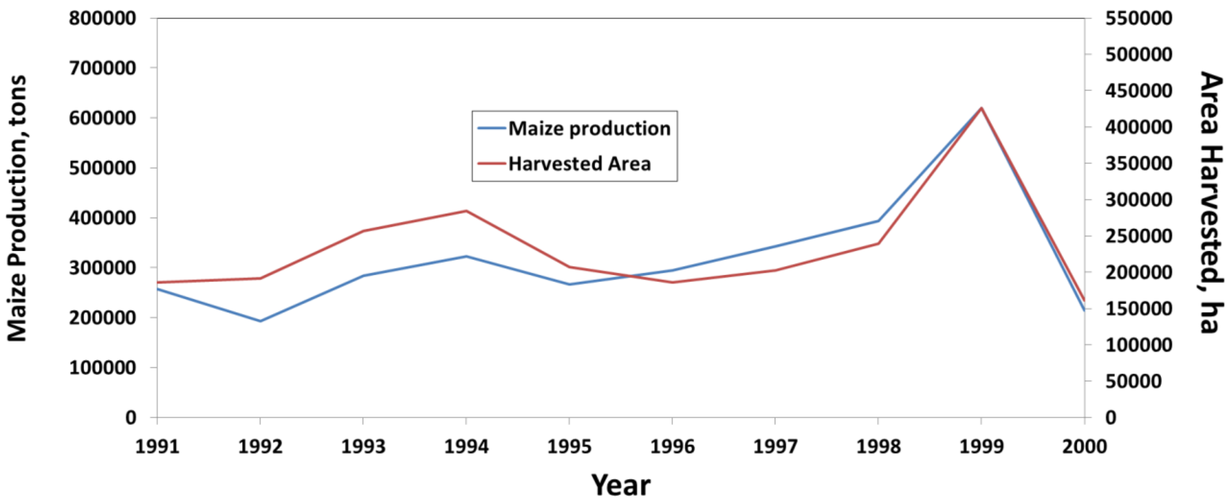


FIGURE A.6: MAIZE YIELD IN MALI

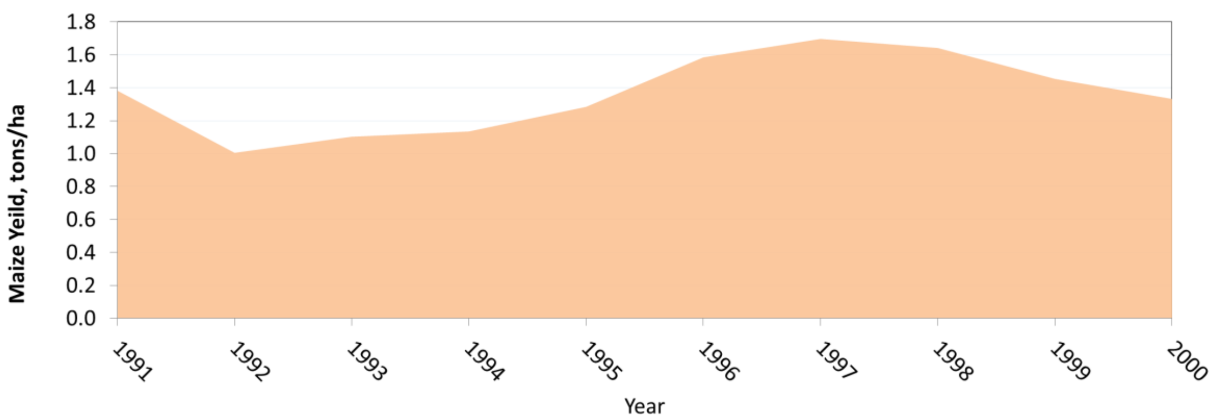


TABLE A.12: MAIZE PRODUCTION MANAGEMENT OPERATIONS SCHEDULE

Ag Operation	Date	Description
Primary tillage	April 2	Hand hoe as tillage tool
Manure application	May 21	Compost equivalent to 1000 kg/ha fresh manure
Field cultivation	May 30	Manual hand Cultivator
Planting	June 1	
DAP Fertilizer application	June 1	25 kg/ha
Cultivation	June 30	Manual hand Cultivator
Cultivation	July 30	Manual hand Cultivator
Harvest	August 30	

TABLE A.13: PARAMETERIZATION OF INPUT PARAMETERS FOR MAIZE

Parameter	CPNM	Units	Default	Calibrated
Biomass-Energy Ratio	WA	[ ]	60	40
Harvest Index	HI	[ ]	0.50	0.35
Optimal temperature for plant growth	TOP	^0C	25.00	30.00
Maximum potential leaf area index	DMLA	[ ]	6.00	4.75
Seeding rate	SDW	kg/ha	20.00	22.00
Maximum crop height	HMX	m	2.00	1.80
Maximum root depth	RDMX	m	2.00	1.20
Soil Evaporation Coefficient	PARM 12	[ ]	1.5	1.5
Soil Evaporation – Plant Cover Factor	PARM 17	[ ]	0.1	0.1

The national average and simulated yield of maize for the four subareas are shown in Table A.14. Results of simulated yield show that the highest maize yields average 0.93 and 0.78 ton/hectare under lithosols and luvisols, respectively. Regosols and arenosols have the lowest yields. These differences are largely driven by the higher organic matter content and better fertility of the lithosols and luvisols. The average simulated yield across all the four soil types is 0.72 ton/hectare, which is 47 percent less than the national average (Table A.14 and Figure A.7). As shown in Figure A.8, the annual average maize yield was less than the national average after 1996. This could be associated with severity of the drought condition in the Mopti area as compared with maize producing southern parts of the nation. In Mopti, over the years 1996–2000 (with the exception of year 1998), the rainfall started early in June and there was not enough rain in July when the crop is about five weeks old. This happened repeatedly in four different years and was a major reason for the decline in yield.

TABLE A.14: AVERAGE MAIZE YIELD* BY SUBAREA/SOILS (TONS/HA)

Year	Subarea-1/ Regosols	Subarea-3/ Lithosols	Subarea-4/ Arenosols	Subarea-6/ Luvisols	*Simulated Average Yield	National Average Yield
1992	0.92	2.03	0.67	1.44	1.11	1.01
1993	1.25	0.09	1.2	0.46	0.90	1.10
1994	0.58	2.41	0.53	1.12	1.00	1.13
1995	1.23	0.9	1.19	0.86	1.11	1.28
1996	0.65	0.16	0.48	0.77	0.50	1.58
1997	0.54	1.36	0.4	0.8	0.68	1.70
1998	0.59	0.19	0.54	0.47	0.48	1.64
1999	0.22	0.41	0.17	0.36	0.26	1.45
2000	0.39	0.85	0.29	0.71	0.48	1.33
Average	**0.71**	**0.93**	**0.61**	**0.78**	**0.72**	**1.36**

* The simulated average yield is calculated using a weighted average of soils areas based on their occurrence (percent) in the Mopti region (Regosols =21 percent, Lithosols =20 percent, Arenosols = 46 percent, and Luvisols = 14 percent).

FIGURE A.7: AVERAGE MAIZE YIELD BY SOIL TYPE

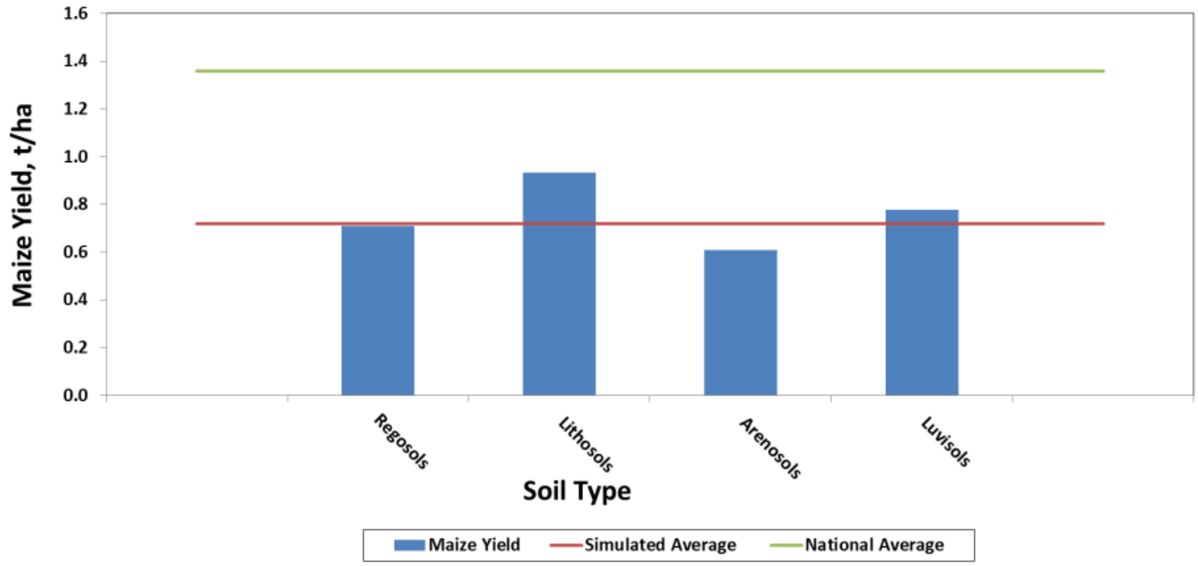
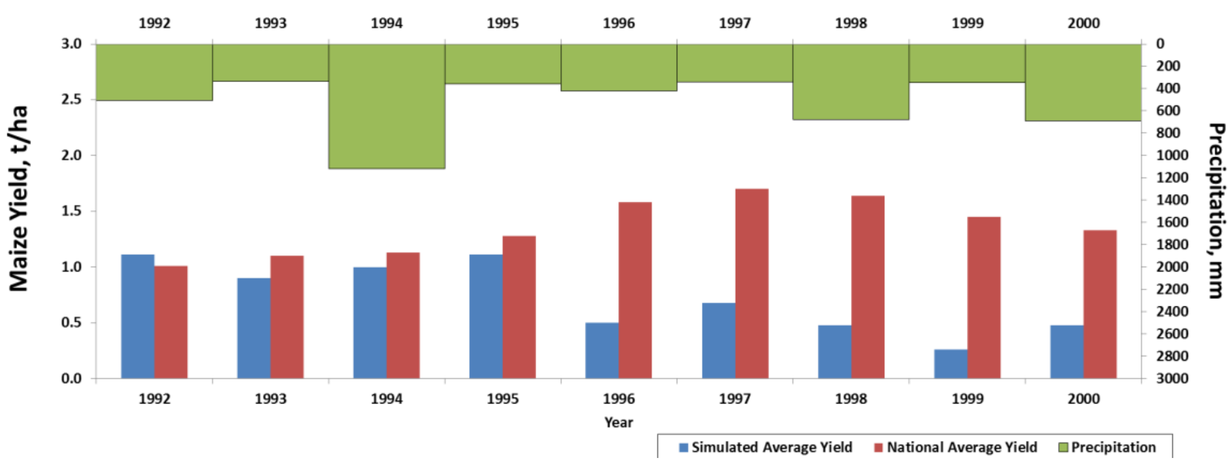


FIGURE A.8: AVERAGE MAIZE YIELD AND PRECIPITATION IN THE MOPTI REGION FROM 1992-2000

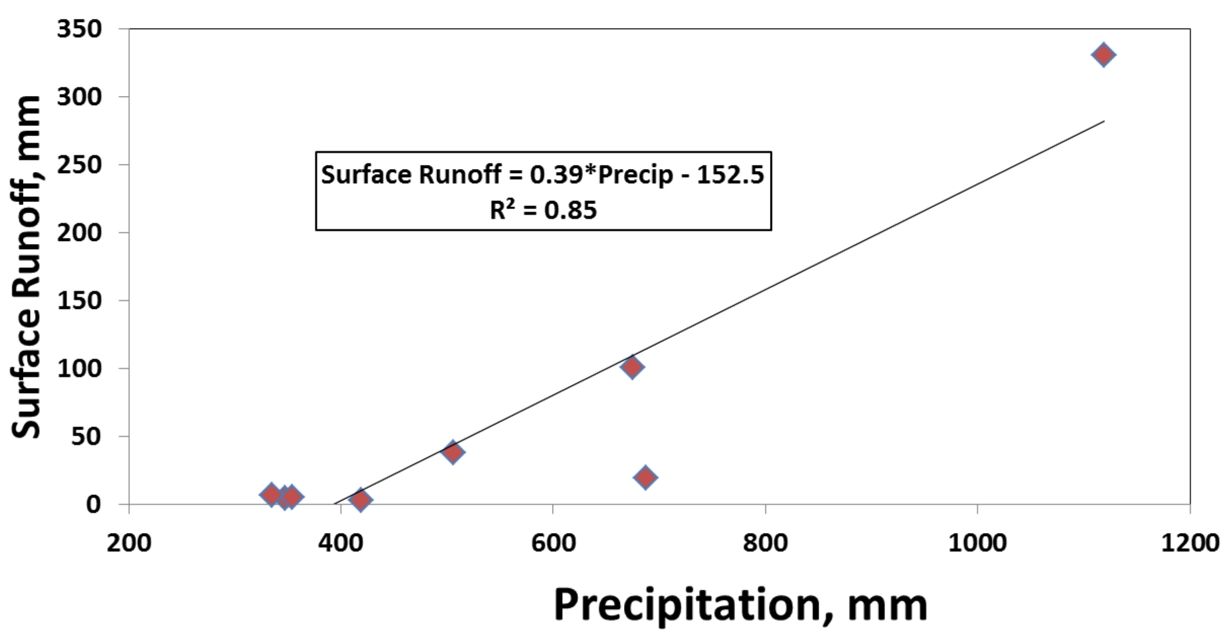


Analysis of water balance was made to quantitatively describe percolation and runoff averaged over the entire simulation period. As shown in Table A.15 below, evapotranspiration, deep percolation, and surface runoff are the major components, accounting for about 71 percent, 11 percent, and 10 percent of the water balance, respectively. Surface runoff increases with precipitation (Figure A.9). The average annual surface runoff from the maize field under the four soil types is about 54 millimeters (Figure A.10), or 10 percent of the annual rainfall, which is consistent with previous studies (Senay & Verdin, 2004). Arenosols have the lowest runoff because these are very sandy soils.

TABLE A.15: WATER BALANCE UNDER MAIZE PRODUCTION

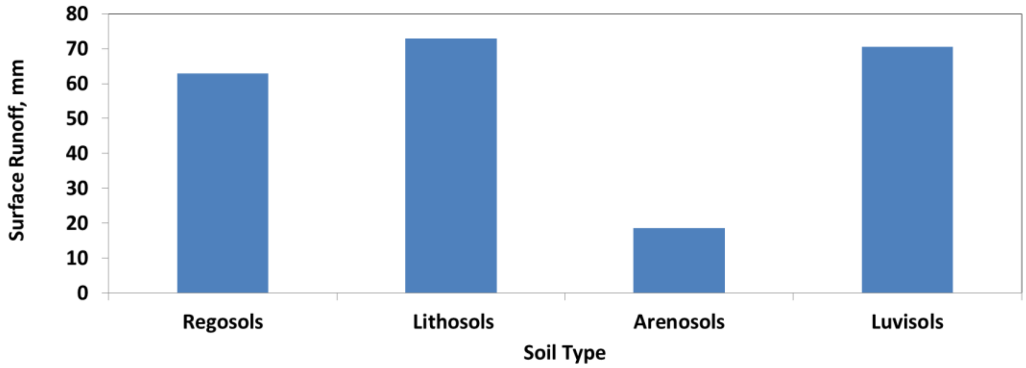
Water Balance	mm	Percent of Rainfall
Inputs	525.7	100
Irrigation	0.00	0.0
Precipitation	525.7	100.0
Outputs	525.7	100
Evapotranspiration	371.2	70.6
Subsurface Flow	39.4	7.5
Deep Percolation	58.5	11.1
Surface Runoff	54.1	10.3
Change in Storage	2.5	0.5

FIGURE A.9: SURFACE RUNOFF RELATION TO PRECIPITATION WHEN SUBAREAS ARE UNDER MAIZE[1]



[1] The low runoff outlier in this figure occurred during a year (2000) with about 690 mm of precipitation. The exceptionally low runoff was a result of an even distribution of rainfall events, leading to low antecedent soil moisture and good vegetative growth that prevented runoff.

FIGURE A. 10: SURFACE RUNOFF UNDER THE DIFFERENT SOIL TYPES



Baseline model results for sorghum

Total sorghum production in Mali was stagnant during the years before 1986. It only began increasing after 1986. The increase in production was due to an increase in harvested area (Ndjeunga, 2002; Yapi, Kergna, Debrah, Sidibe, & Sanogo, 2000). The average annual increase of sorghum production from 1986-2012 was about 58,000 tons. The average annual yield increase for the same time was only 0.06 tons/hectare. Figures A.11 and A.12 show sorghum production (tons, hectare, and tons/hectare) in Mali during 1991–2000, as tabulated by FAO (2014). These are the baseline years for our study.

FIGURE A.11: SORGHUM PRODUCTION AND AREA HARVESTED IN MALI

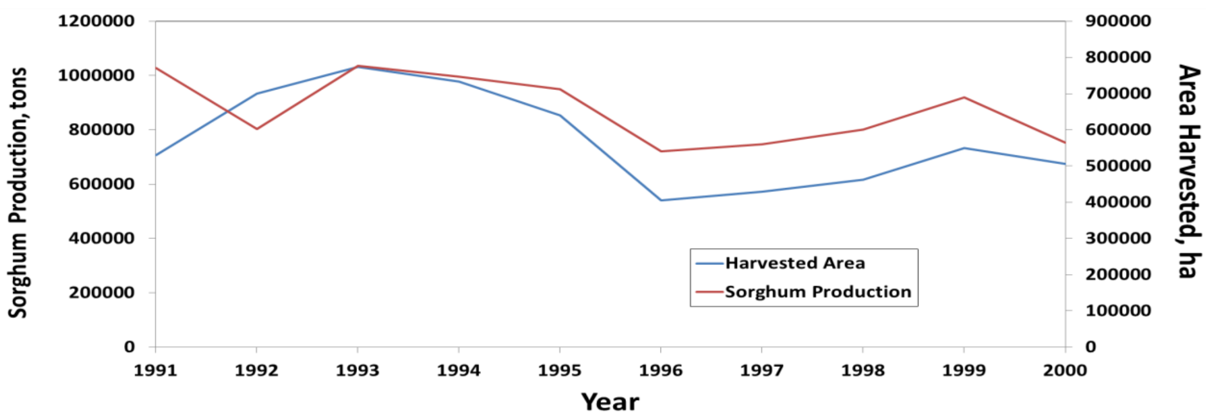
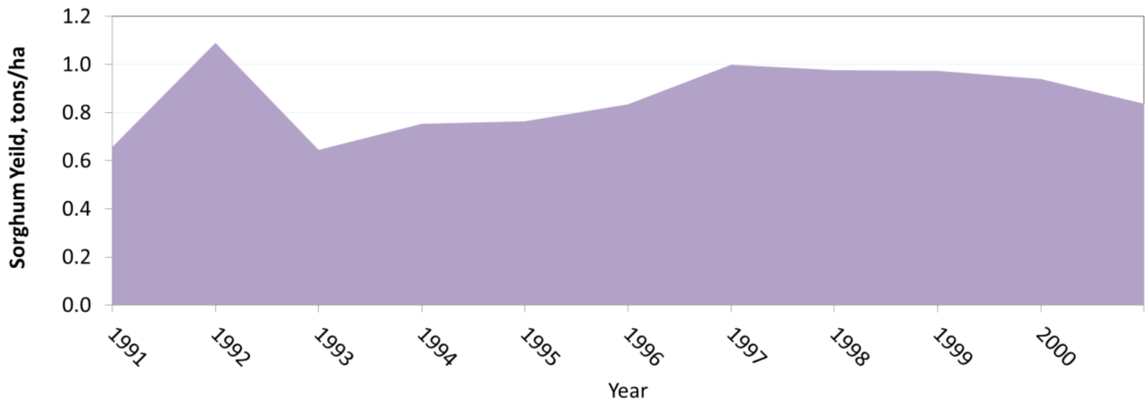


FIGURE A.12: SORGHUM YIELD IN MALI



The sorghum production management schedule for the study site is shown in Table A.16 below. Calibration of input parameters is vital to better represent the local agronomic and hydrologic conditions. The calibrated parameters of the APEX model for sorghum production are shown in Table A.17. Every effort was made to use input parameters from published studies in order to minimize the number of parameters used for calibration. When parameters were calibrated, only slight changes were made from default values.

TABLE A.16: SORGHUM PRODUCTION MANAGEMENT OPERATIONS SCHEDULE

Ag Operation	Date	Description
Primary tillage	April 25	Hand hoe as tillage tool
Manure application	May 21	Compost equivalent to 600 kg/ha/year fresh manure
Field cultivation	June 30	Manual hand Cultivator
Planting	July 1	
DAP Fertilizer application	July 1	12 kg/ha
Cultivation	July 30	Manual hand Cultivator
Cultivation	August 30	Manual hand Cultivator
Harvest	October 30	

TABLE A.17: PARAMETERIZATION OF INPUT PARAMETERS FOR SORGHUM

Parameter	CPNM	Units	Default	Calibrated
Biomass-Energy Ratio	WA	[ ]	37	37
Harvest Index	HI	[ ]	0.50	0.28
Optimal temperature for plant growth	TOP	^{0}C	27.5	27.5
Maximum potential leaf area index	DMLA	[ ]	5.5	4.0
Seeding rate	SDW	kg/ha	5	6.0
Maximum crop height	HMX	m	1.4	2.0
Maximum root depth	RDMX	m	2.00	1.10
Soil Evaporation Coefficient	PARM 12	[ ]	1.5	1.5
Soil Evaporation – Plant Cover Factor	PARM 17	[ ]	0.1	0.4

Simulated average sorghum yield for the four subareas is 0.47 ton/hectare. This is 45 percent less than the national average sorghum yield of Mali, 0.86 ton/hectare (Table A.18). Simulated annual average sorghum yield was quite similar to the national average up to the year 1996 (Figure A.13). Yield in the wet year of 1994 decreased due to the fact that 47 percent of the rainfall occurred in about three days (from 07/02/1994 to 07/10/1994), when plants were susceptible to water logging. The decline of yield after 1997 was due to the decrease in rainfall. Simulated sorghum yields were highest under lithosols and luvisols (0.91 ton/hectare and 0.62 ton/hectare, respectively). These soils have higher soil organic carbon contents that release more nitrogen than the other two soils. Regosol (0.32 tons/hectare) and arenosol (0.28 tons/hectare) yields were lower (Table A.18 and Figure A.14) because of poorer soil fertility.

TABLE A.18: AVERAGE SORGHUM YIELD BY SUBAREA/SOILS (TONS/HA)

Year	Subarea-1 (Regosols)	Subarea-3 (Lithosols)	Subarea-4 (Arenosols)	Subarea-6 (Luvisols)	Simulated Average Yield	National Average Yield
1992	0.31	0.69	0.29	0.51	0.41	0.64
1993	0.52	1.21	0.46	1.08	0.71	0.75
1994	0.28	0.65	0.26	0.52	0.38	0.76
1995	0.53	0.9	0.48	0.63	0.60	0.83
1996	0.26	1.38	0.23	1.2	0.60	1.00
1997	0.23	1.56	0.16	0.43	0.49	0.98
1998	0.24	0.57	0.23	0.37	0.32	0.97
1999	0.31	0.72	0.22	0.49	0.38	0.94
2000	0.23	0.51	0.23	0.39	0.31	0.84
Average	0.32	0.91	0.28	0.62	0.47	0.86

FIGURE A.13: AVERAGE SORGHUM YIELD AND PRECIPITATION FROM 1992-2000

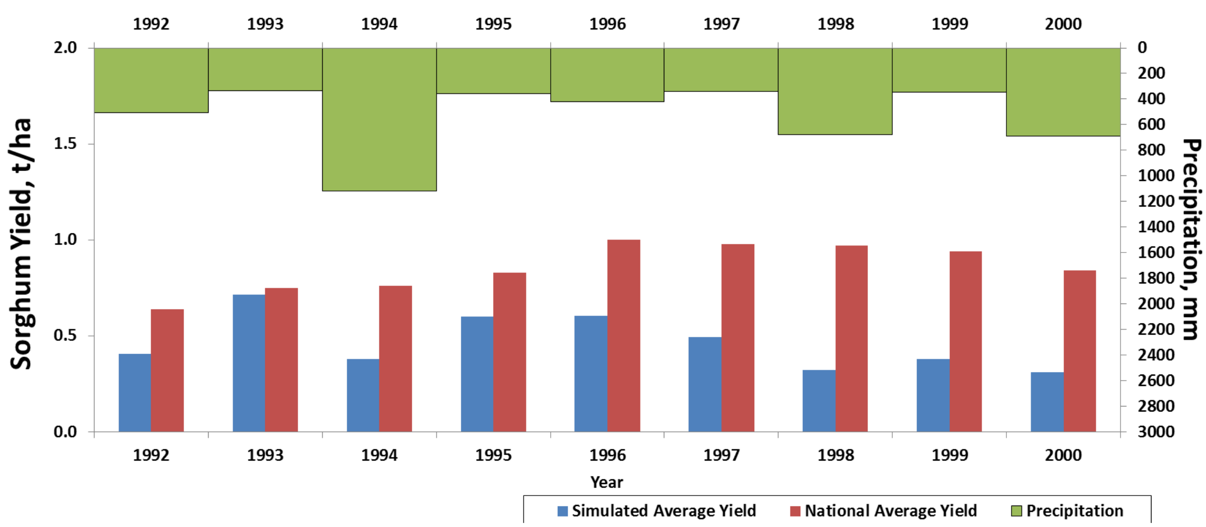
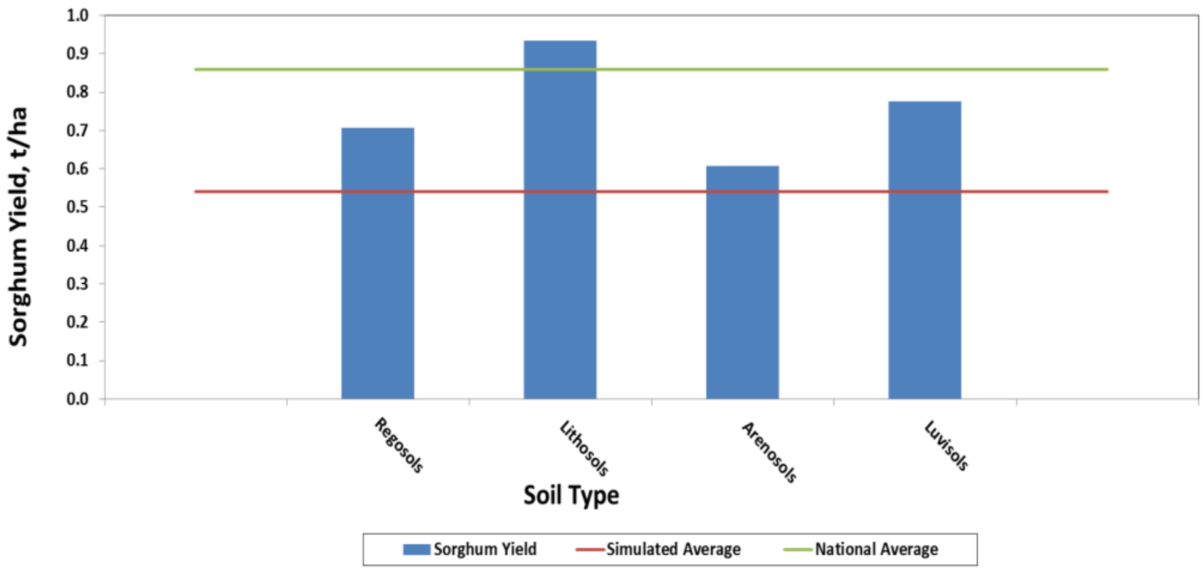


FIGURE A.14: AVERAGE SORGHUM YIELD BY SOIL TYPE



Sorghum showed 5 percent less evapotranspiration, and 3.1 percent more deep percolation as compared to maize (Table 19). As shown in Figure 15, there is a strong linear relationship between surface runoff and precipitation, with a 0.85 coefficient of determination. The average annual surface runoff is about 52 millimeters (Figure 16). Runoff was lowest in the sandiest soil (arenosols).

TABLE A.19: WATER BALANCE UNDER SORGHUM PRODUCTION

Water Balance	mm	Percent of Rainfall
Input	525.70	100.00
• Irrigation	0.00	0.00
• Precipitation	525.7	100.00
Output	525.7	100.00
• Evapotranspiration	343.7	65.4
• Subsurface Flow	52.2	9.9
• Deep Percolation	74.6	14.2
• Surface Runoff	52.1	9.9
• Change in Storage	3.1	0.60
Balance = Input-Output	0.00	0.00

FIGURE A.15: SURFACE RUNOFF RELATION TO PRECIPITATION WHEN SUBAREAS ARE UNDER SORGHUM[2]

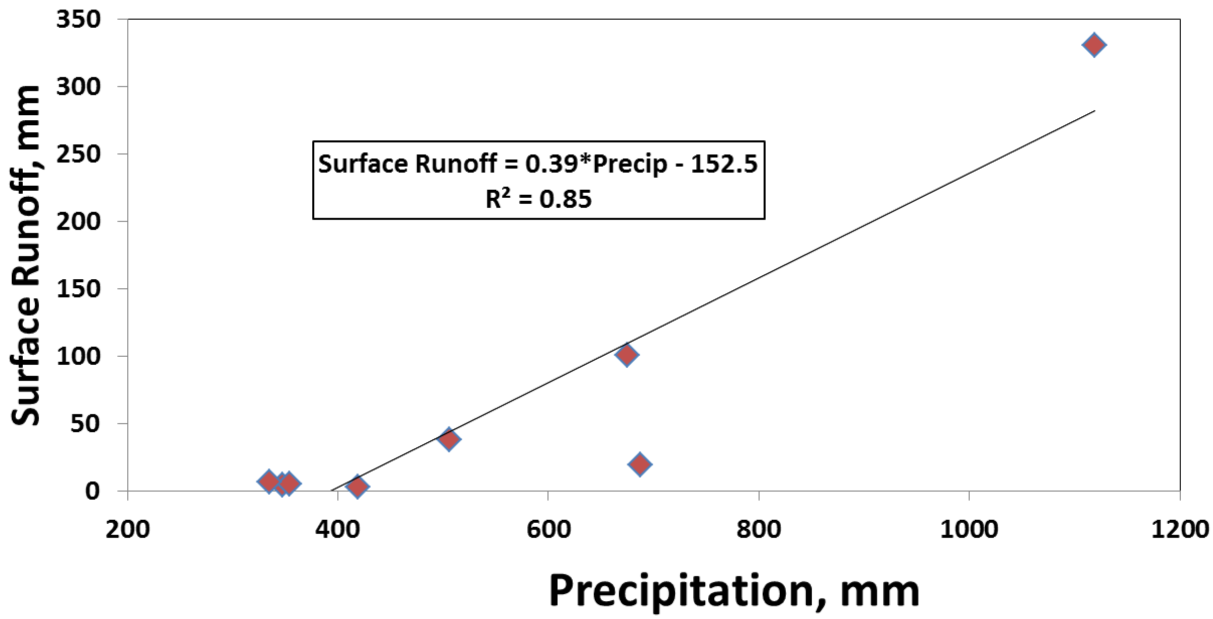
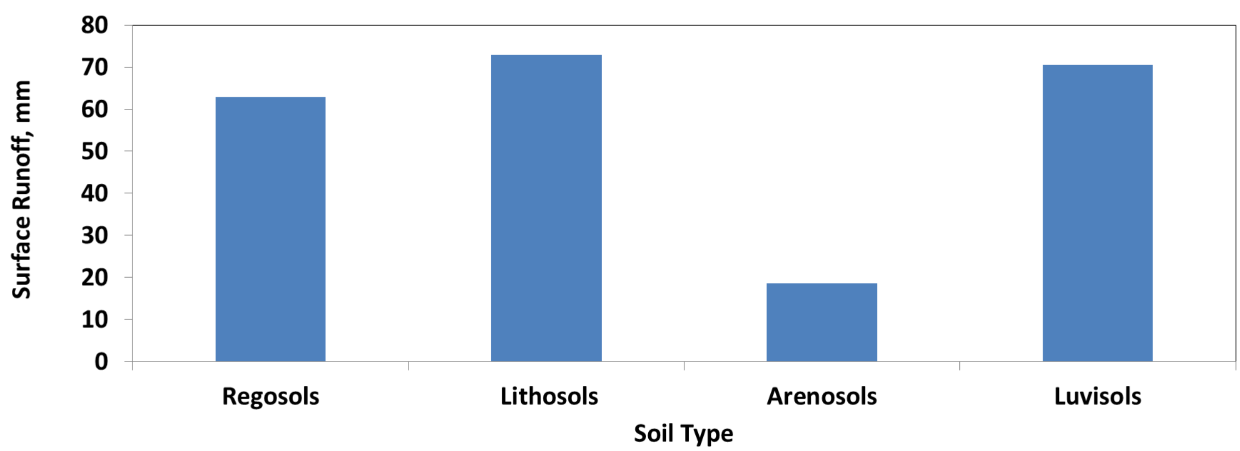


FIGURE A.16: SURFACE RUNOFF WITH SORGHUM FOR DIFFERENT SOIL TYPES



Baseline model results for millet

Millet is the leading cereal crop of the Sahel, providing food grain to households living in areas with low soil fertility and erratic rainfall, averaging 300–600 millimeters (Ndjeunga et al., 2002; Yapi et al., 2000). It

[2] The low runoff outlier in this figure occurred during a year (2000) with about 690 mm of precipitation. The exceptionally low runoff was a result of an even distribution of rainfall events, leading to low antecedent soil moisture and good vegetative growth that prevented runoff.

is grown in the harsh semi-arid tropics of Africa where inadequate rainfall and lack of irrigation make production of other cereal crops difficult to sustain (Maredia, Byerlee, & Pee, 2000).

According to FAO reports for the base years 1991–2000, average grain yields of millet on farmer fields of Mali were only about 709 kg/hectare (Figure A.17). The total production and harvested area during this period was stable (Figure A.18).

FIGURE A.17: MILLET YIELD IN MALI

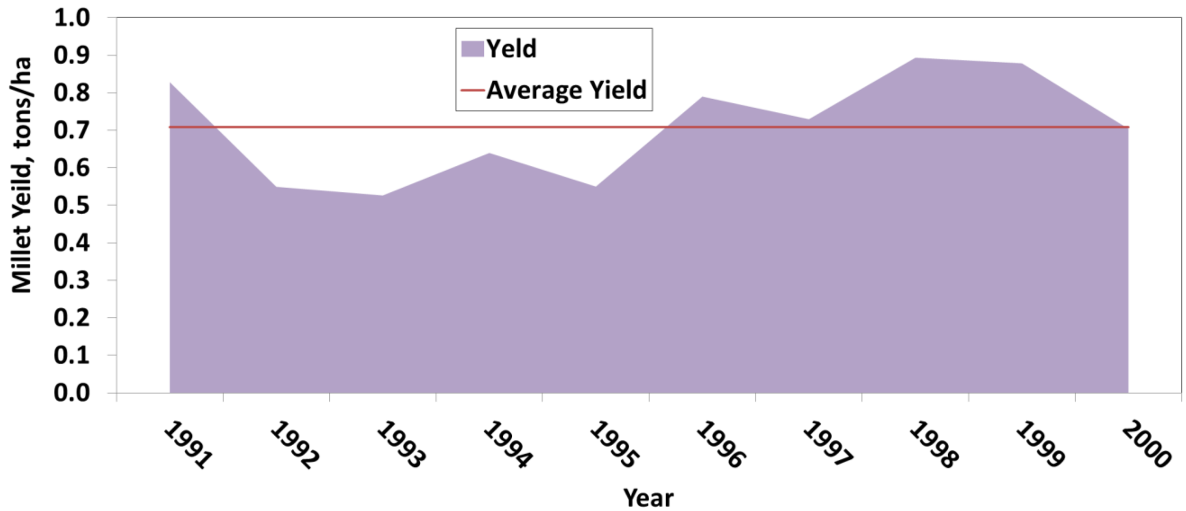
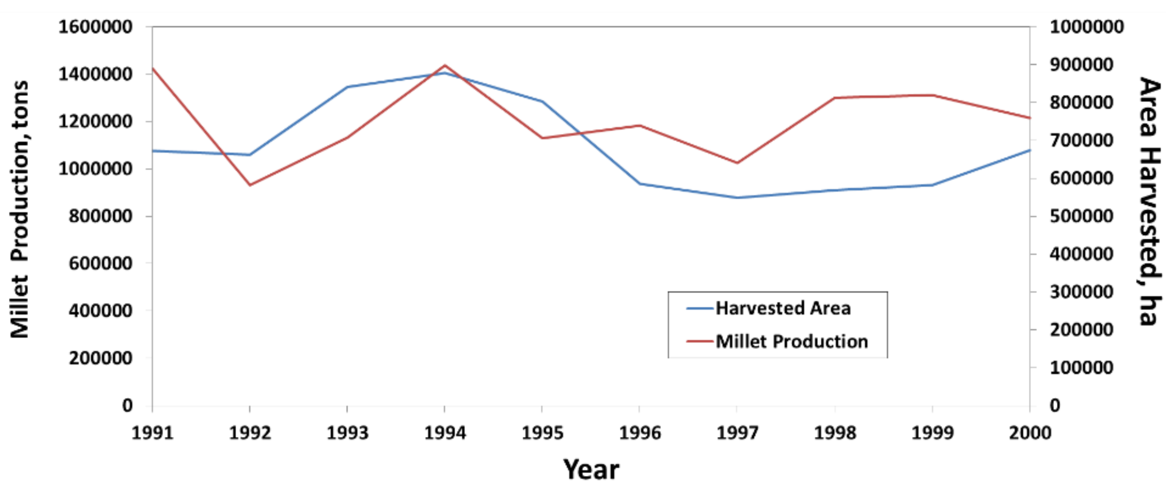


FIGURE A.18: MILLET PRODUCTION AND AREA HARVESTED IN MALI



Model parameterization for millet was based on the management operation calendar shown in Table A.20 as well as crop specific parameters in Table A.21. The crop is propagated from seed. Millet is generally grown on less fertile soils (Maredia et al., 2000). It is deep-rooted and can use residual nitrogen, phosphorus, and potassium and, therefore, may not need the levels of fertilization required by other summer grains (Lee et al., 2004). As millet seed is small, hand tools can be used for cultivation and ploughing without compromising good seed-to soil contact (Lee, Hanna, Buntin, Dozier, Timper, & Wilson, 2004).

TABLE A.20: MILLET PRODUCTION MANAGEMENT OPERATIONS SCHEDULE

Ag Operation	Date	Description
Primary tillage	April 15	Hand hoe as tillage tool
Field cultivation	May 21	Manual hand Cultivator
Planting	May 22	
DAP Fertilizer application	May 21	8 kg/ha
Cultivation	June 30	Manual hand Cultivator
Cultivation	July 29	Manual hand Cultivator
Harvest	August 30	

TABLE A.21: PARAMETERIZATION OF INPUT PARAMETERS FOR MILLET

Parameter	CPNM	Units	Default	Calibrated
Biomass-Energy Ratio	WA	[ ]	35	35
Harvest Index	HI	[ ]	0.25	0.25
Optimal temperature for plant growth	TOP	^{0}C	30	27
Maximum potential leaf area index	DMLA	[ ]	2.5	1.7
Seeding rate	SDW	kg/ha	5	5
Maximum crop height	HMX	m	2.5	1.8
Maximum root depth	RDMX	m	2.00	1.2
Soil Evaporation Coefficient	PARM 12	[ ]	1.5	1.5
Soil Evaporation – Plant Cover Factor	PARM 17	[ ]	0.1	0.4

The national average yield of millet is 0.7 tons/hectare (FAO, 2014). Simulated millet yield as grown over the four major soils of the Sahelian Agro-ecoregion near Mopti are less than the national average yield by about 33 percent (Figure A.19). Lithosol yields (0.75 tons/hectare) are higher than the other three soil types (due to higher soil fertility), while arenosols have the lowest yields (Table A.22) due to poor soil fertility. The predicted yield over the initial six years (1992–1997) was fairly similar to the national average (Figure A.20). However, the model under-predicts yield over the last three years (1998–2000). Poor distribution and low annual rainfall resulted in crop water stress for these years. Moreover, the model results showed that there was also nitrogen and temperature stress in these years that caused the low yield.

TABLE A.22: AVERAGE MILLET YIELD BY SUBAREA/SOILS (TONS/HA)

Year	Subarea-1/ Regosols	Subarea-3/ Lithosols	Subarea-4/ Arenosols	Subarea-6/ Luvisols	Simulated Average Yield	National Average Yield
1992	0.41	0.77	0.33	0.59	0.53	0.55
1993	0.43	0.77	0.4	0.54	0.54	0.53
1994	0.26	0.68	0.24	0.48	0.42	0.64
1995	0.46	0.79	0.41	0.6	0.57	0.55
1996	0.52	1.1	0.3	0.78	0.68	0.79
1997	0.57	1.2	0.26	0.91	0.74	0.73
1998	0.19	0.77	0.22	0.42	0.40	0.89
1999	0.08	0.25	0.07	0.14	0.14	0.88
2000	0.17	0.43	0.15	0.29	0.26	0.70
Average	0.34	0.75	0.26	0.53	0.47	0.70

FIGURE A.19: AVERAGE MILLET YIELD BY SOIL TYPE

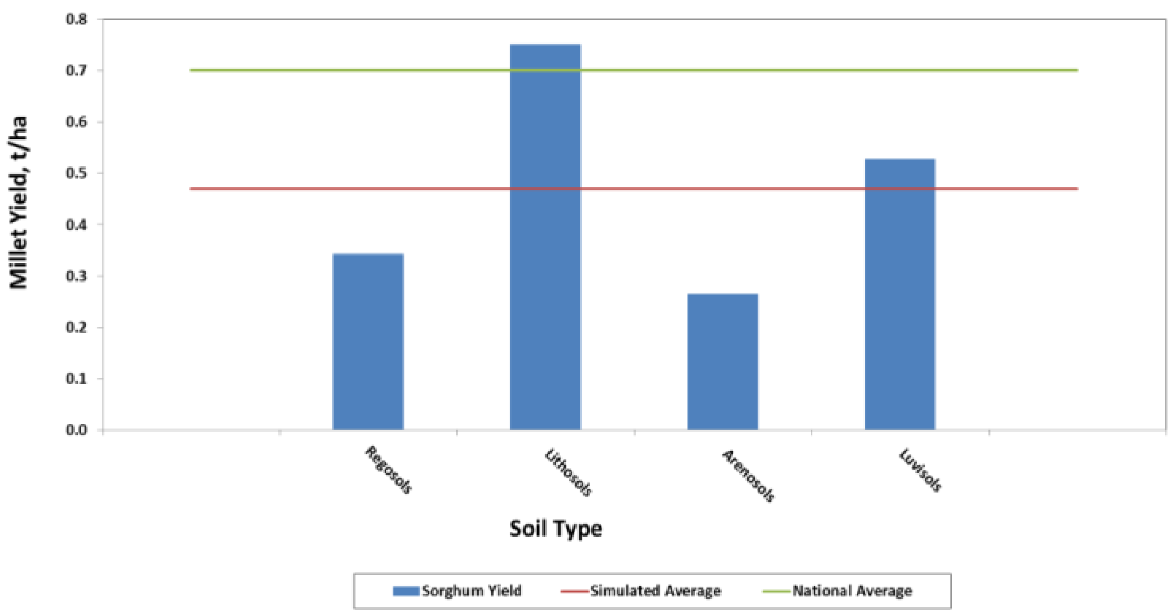
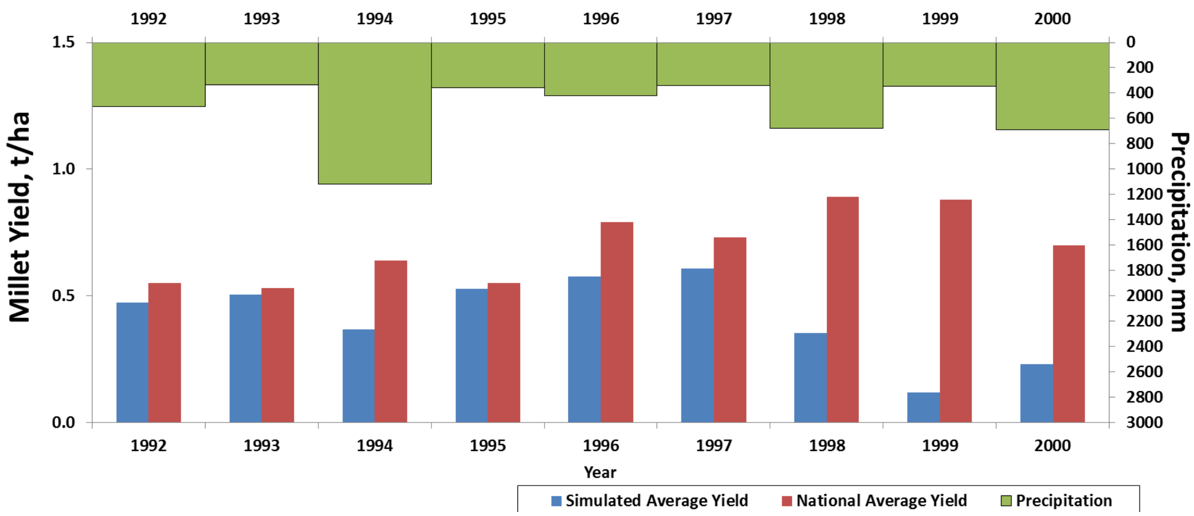


FIGURE A.20: AVERAGE MILLET YIELD AND PRECIPITATION FROM 1992-2000



The water balance of millet is very similar to that of maize, but there are slight differences. Evapotranspiration is the major component of the water balance, accounting for about 56 percent of the total. Millet has much lower evapotranspiration than either maize or sorghum. Deep percolation and subsurface flow are the next biggest components of the water budget, accounting for about 19 percent and 15 percent of the total, respectively (Table A.23). These losses reduce the amount of water available for crop uptake. There is a positive relation between surface runoff and precipitation (Figure A.21). Arenosols (very sandy soils) have the least surface runoff, and the remaining three soil types have very similar surface runoff (Figure A.22).

TABLE A.23: WATER BALANCE UNDER MAIZE PRODUCTION

Water Balance	mm	Percent of Rainfall
Inputs	525.7	100.00
• Irrigation	0.00	0.0
• Precipitation	525.7	100.00
Outputs	525.7	100.00
• Evapotranspiration	292.6	55.6
• Subsurface Flow	77.1	14.7
• Deep Percolation	102.2	19.4
• Surface Runoff	51.8	9.5
• Change in Storage	3.8	0.7

FIGURE A.21: SURFACE RUNOFF RELATION TO PRECIPITATION WHEN SUBAREAS ARE UNDER MILLET[3]

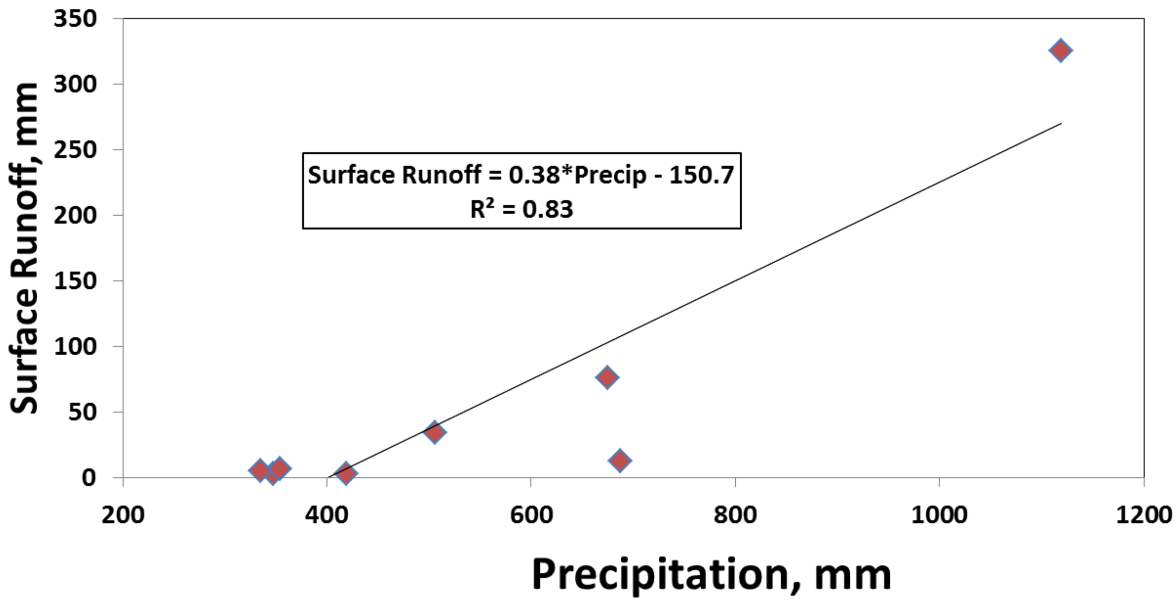
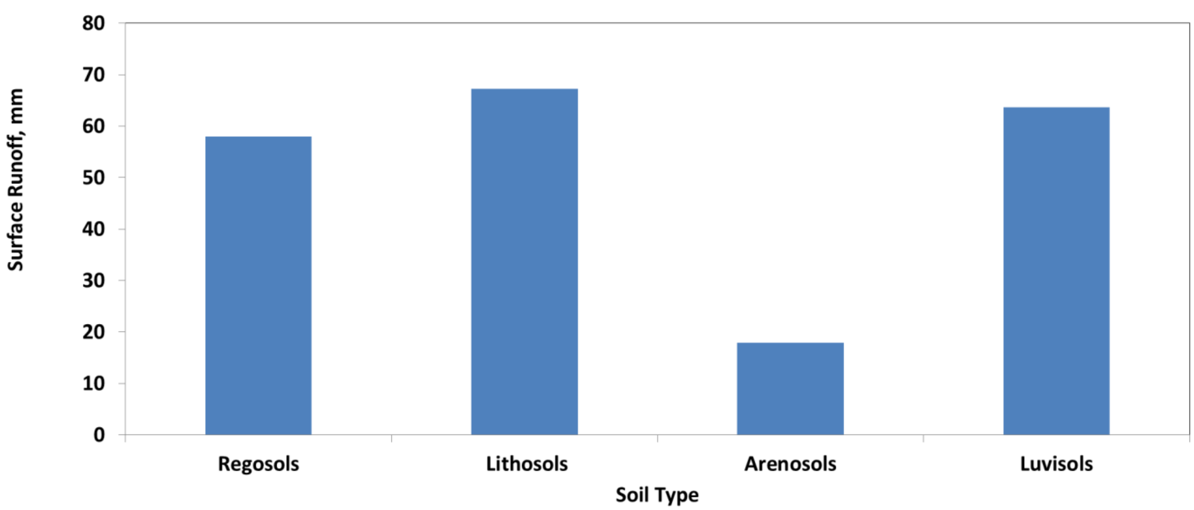


FIGURE A.22: SURFACE RUNOFF WITH MILLET FOR DIFFERENT SOIL TYPES



[3] The low runoff outlier in this figure occurred during a year (2000) with about 690 mm of precipitation. The exceptionally low runoff was a result of an even distribution of rainfall events, leading to low antecedent soil moisture and good vegetative growth that prevented runoff.

Baseline model results for rice

Mali is one of the four highest rice-producing countries in West Africa, along with Nigeria, Guinea, and Ivory Coast (WARDA, 2008). Rice production is found virtually throughout Mali, except in the true desert areas. The Niger River and its tributaries are the basis of a variety of larger scale rice production schemes in Mali and provide supplemental irrigation water to the majority of smallholder rice farmers (ODI, 2000).

In the year 2000, Mali's rice production was only 0.74 million tons (FAO, 2014). Supplemental irrigation systems accounted for nearly half of the rice production (273,560 tons). The rest of the rice production came from naturally flooded rice production systems (DAI, 2009).

According to FAO reports, average rice yield from Mali farmer fields (both irrigated and upland farms receiving supplemental irrigation) was about 1.9 tons/hectare for the simulation base years 1991–2000 (Figure A.23). The total production and harvested area during this period was stable at about 0.6 million tons and 0.3 million hectares, respectively (Figure A.24).

FIGURE A.23: RICE YIELD IN MALI

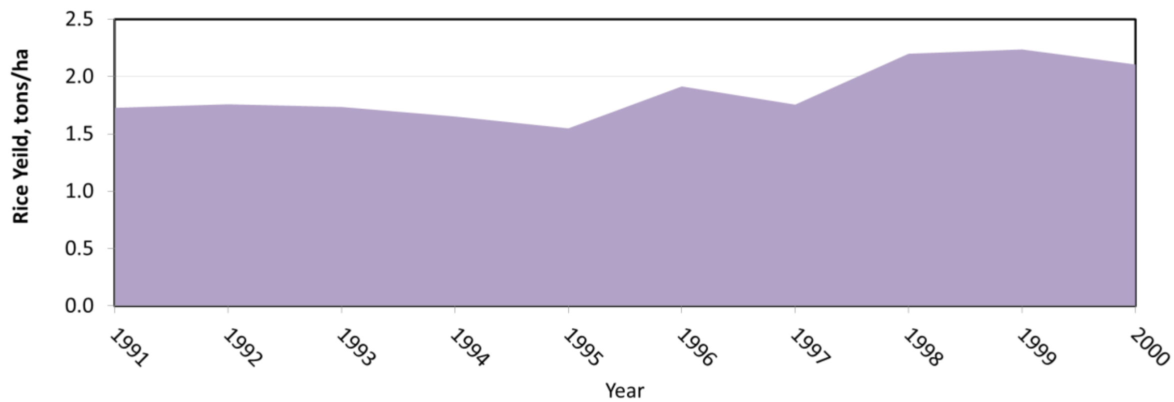
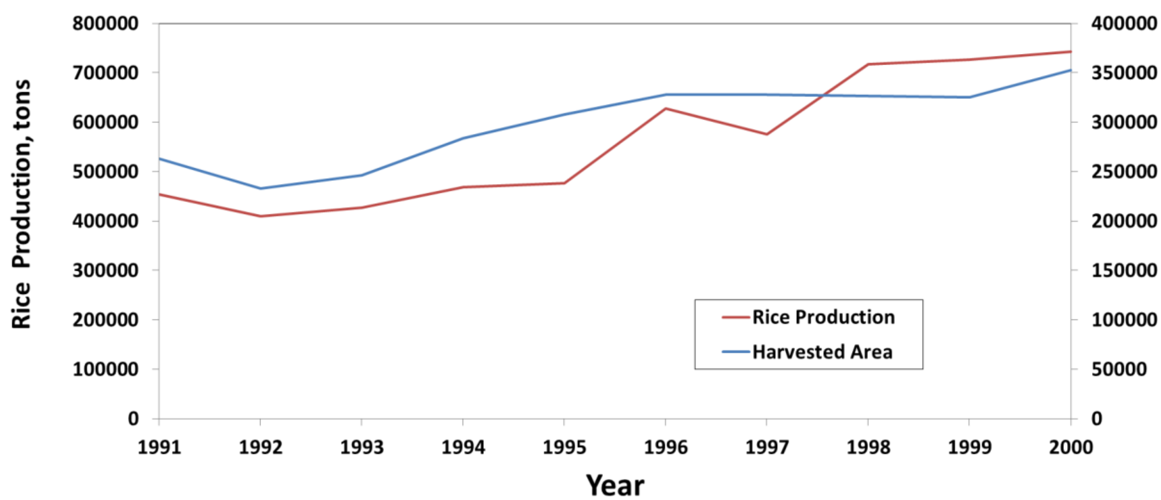


FIGURE A.24: RICE PRODUCTION AND AREA HARVESTED IN MALI



Simulation of upland rice production under supplemental irrigation was initiated by generating the management operation calendar shown in Table A.24. Organic and mineral fertilizers are applied to provide crop nutrients. Supplemental irrigation water is applied to keep the soil moist, but not flooded. The default APEX model upland rice crop input parameters are calibrated with some changes as shown in Table A.25.

TABLE A.24: UPLAND RICE PRODUCTION MANAGEMENT OPERATIONS SCHEDULE

Ag Operation	Date	Description
Fertilizer application	May 1	Compost (500 kg/ha)
Field cultivation	May 30	Manual hand Cultivator
Planting	June 1	
Irrigation water application	June 1	Irrigation water is applied every three days
DAP Fertilizer application	June 1	25 kg/ha
Cultivation	June 30	Manual hand Cultivator
Harvest	October 12	
Primary tillage	October 25	Hand hoe as tillage tool

TABLE A.25: PARAMETERIZATION OF INPUT PARAMETERS FOR RICE

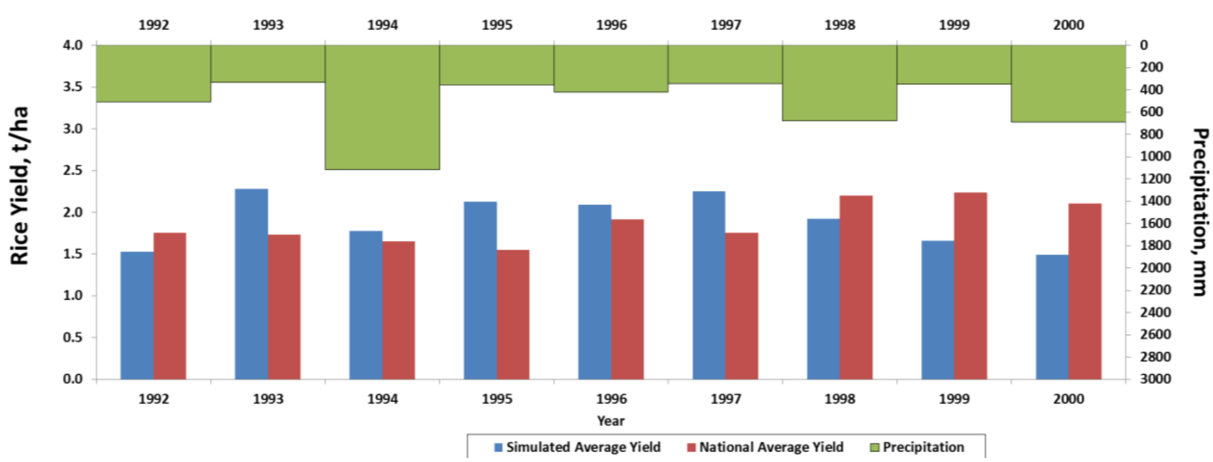
Parameter	CPNM	Units	Default	Calibrated
Biomass-Energy Ratio	WA	[ ]	25	30
Harvest Index	HI	[ ]	0.25	0.35
Optimal temperature for plant growth	TOP	^{0}C	30	30
Maximum potential leaf area index	DMLA	[ ]	6	6
Seeding rate	SDW	kg/ha	50	55
Maximum crop height	HMX	m	0.8	0.8
Maximum root depth	RDMX	m	2	2

The national average yield of rice over the base years (1992–2000) was 1.9 tons/hectare. APEX simulated rice yield under supplemental irrigation for the same period was exactly the same. Good agreement between predicted and measured rice yields was expected, because this crop tends to be irrigated, thereby reducing water stress. This was tested only on luvisols, whose landscape position is the only one suitable for application of irrigation water (Table A.26).

TABLE A.26: AVERAGE UPLAND RICE YIELD (WITH SUPPLEMENTAL IRRIGATION) (TONS/HA)

Year	Subarea-6/ Luvisols	National Average Yield
1992	1.5	1.8
1993	2.3	1.7
1994	1.8	1.7
1995	2.1	1.5
1996	2.1	1.9
1997	2.3	1.8
1998	1.9	2.2
1999	1.7	2.2
2000	1.5	2.1
Average	**1.9**	**1.9**

FIGURE A.25: AVERAGE UPLAND RICE YIELD (WITH SUPPLEMENTAL IRRIGATION) AND PRECIPITATION FROM 1992-2000



The water balance of upland rice is different from the other crops for it has an irrigation component that supplements the rainfall. Irrigation provides 14 percent of the total water input, the rest (86 percent) comes from rainfall. Evapotranspiration takes the largest share of the output side, accounting for 66 percent of the water balance. Deep percolation and surface runoff are the next biggest components of the water budget, accounting for about 13 and 12 percent of the total, respectively (Table A.27). Surface runoff is not strongly correlated with the depth of irrigation water applied. However, there is a strong positive relation between surface runoff and the total water input, which is the sum of precipitation and irrigation (Figure A.26). Irrigation applications were made based on crop water requirements, resulting in up to 215 millimeters of water application in the dry year of 1999 (Figure A.27).

TABLE A.27: WATER BALANCE UNDER SUPPLEMENTAL IRRIGATION OF UPLAND RICE

Water Balance	mm	Percent of Rainfall
Inputs	612.4	100
• Irrigation	87.7	14.3
• Precipitation	525.7	85.7
Outputs	612.4	100
• Evapotranspiration	405.7	66.1
• Subsurface Flow	48.4	7.9
• Deep Percolation	80.1	13.1
• Surface Runoff	71.4	11.6
• Change in Storage	7.8	1.3

FIGURE A.26: SURFACE RUNOFF RELATION TO TOTAL WATER INPUT (PRECIPITATION AND IRRIGATION) FOR IRRIGATED RICE

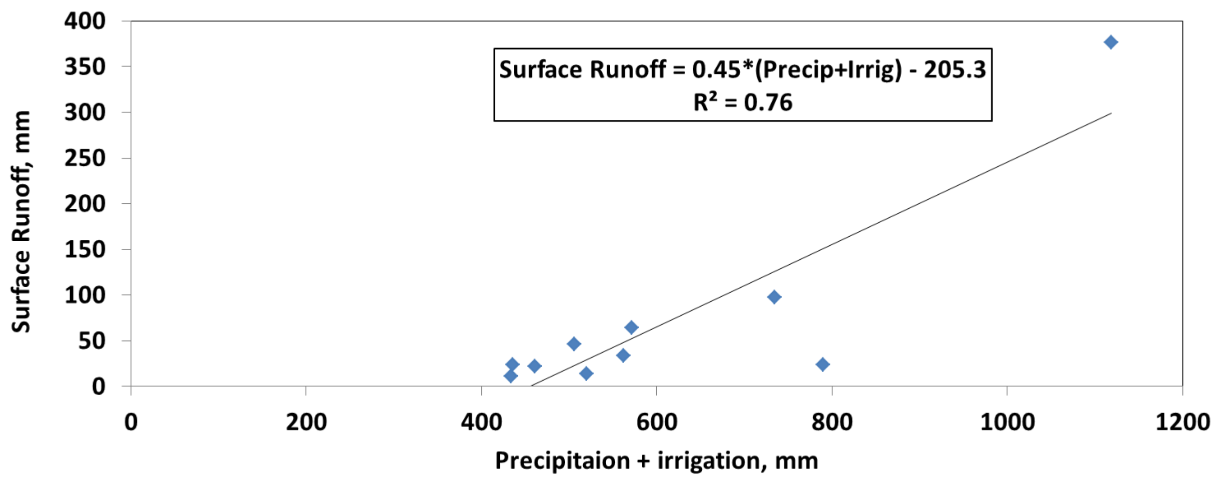
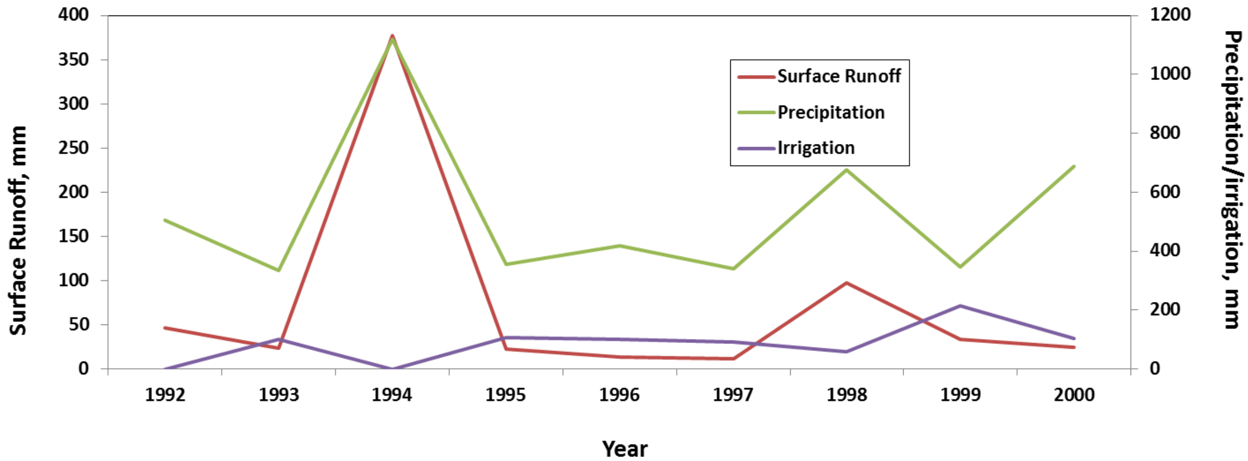


FIGURE A.27: IRRIGATED RICE SURFACE RUNOFF, PRECIPITATION AND IRRIGATION 1992-2000



Summary of baseline calibrated crop model results

APEX model calibration was able to accurately estimate surface runoff, water balance, and crop yield for the climate and soils typically found in the Mopti region of Mali. The calibration simulation period was from 1991–2000, the first year (1991) being used for model warm up. The next nine years of data (1992–2000) were used for model calibration purposes. The calibrated model simulation results for predicted annual crop yields for the four crops evaluated are similar to the national yield values for the same crops prior to 1996, but lower than national values after 1996. This is most likely due to lower precipitation in the Mopti region after 1996 relative to the rest of the country, and evaluation of the four crops on two very low fertility soils for the Mopti region. Modeled crop yields were decreased both in years of excess water and drought. Simulated surface runoff was in the range of expected values (10–15 percent of precipitation) for the study area. The calibrated model also provided a reasonable partitioning for other components of the water budget. Differences in crop yield and runoff across soil types were controlled by differences in soil organic matter content (fertility) and soil texture. Overall, the calibrated APEX model seems to have good predictive capability for the soils, crops, management, and climate scenarios used in the baseline period.

PERFOMANCE OF RAINWATER HARVESTING PRACTICES UNDER BASELINE CLIMATIC CONDITIONS

Impact of rainwater harvesting practices on maize

Rainwater harvesting practices caused changes in the water balance in comparison to baseline conditions without water harvesting. For maize, surface runoff decreased relative to runoff without water harvesting practices, particularly for finer textured soils (Figure A.28). Decreases in surface runoff were minimal (2–7 percent) for most practices on the sandiest soil (arenosols), which had low surface runoff losses even during baseline conditions without rainwater harvesting practices. On finer texture soils, contour ridges, *zai* and bunds decreased surface runoff (23–33 percent) more than vegetative filter strips (15–20 percent). The effectiveness of rainwater harvesting practices at reducing surface runoff, in decreasing order, are as follows: contour ridges; *zai;* bunds; and vegetative filter strips.

Water harvesting practices caused decreases in surface runoff, especially on finer textured soils, but not all of this harvested water was subsequently used by the crop. Much of the harvested surface runoff was lost to deep percolation, especially on sandier soils, and most of the remainder was lost to subsurface lateral flow, especially on steeper landscapes. For example, on lithosols, rainwater harvesting practices reduced surface runoff by 10–19 millimeters, depending on the practice (Figure A.28). In response to increased infiltration, deep percolation on the lithosol increased from 1–10 millimeters relative to baseline conditions without water harvesting (Figure A.29), while subsurface lateral flow increased from 1–7 millimeters. As a result, a large portion of the additional water harvested was not available for use by the crop, and gains in crop yield were not as large as might be expected (Figure A.30), especially on arenosols (2–5 percent) and regosols (13–16 percent).

FIGURE A.28: SURFACE RUNOFF FOR MAIZE GROWN ON DIFFERENT SOILS WITH AND WITHOUT RAINWATER HARVESTING PRACTICES SUCH AS BUNDS, VEGETATIVE FILTER STRIPS (VFS), CONTOUR RIDGES AND *ZAI*.

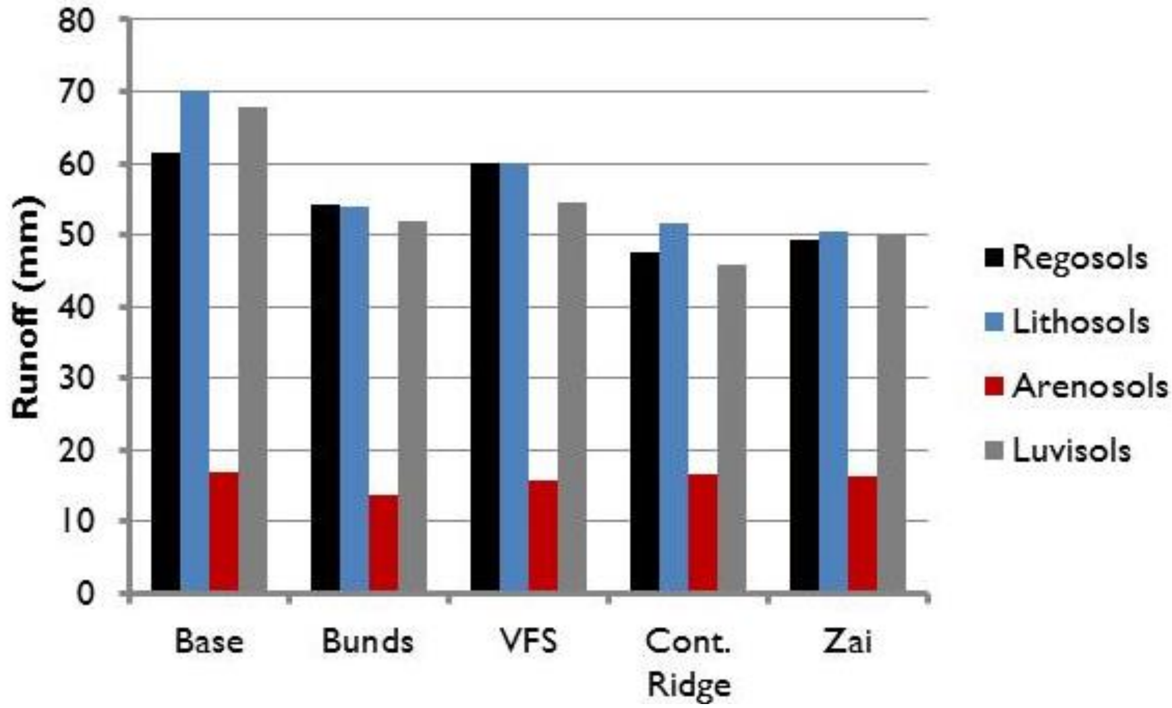
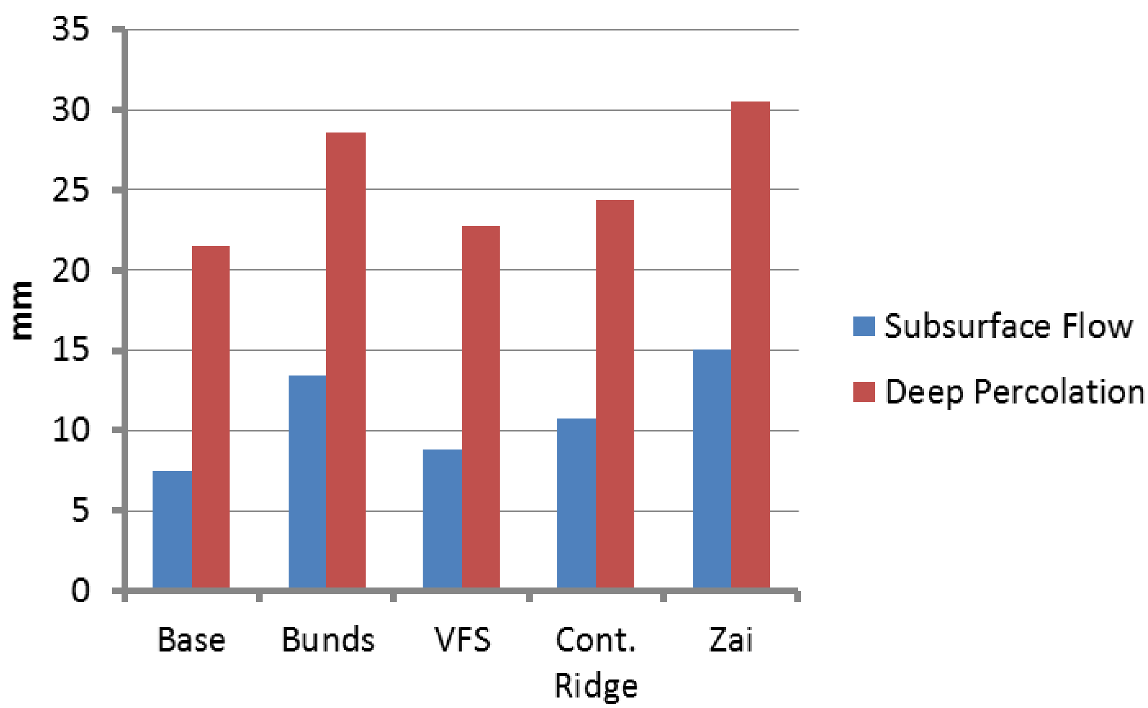
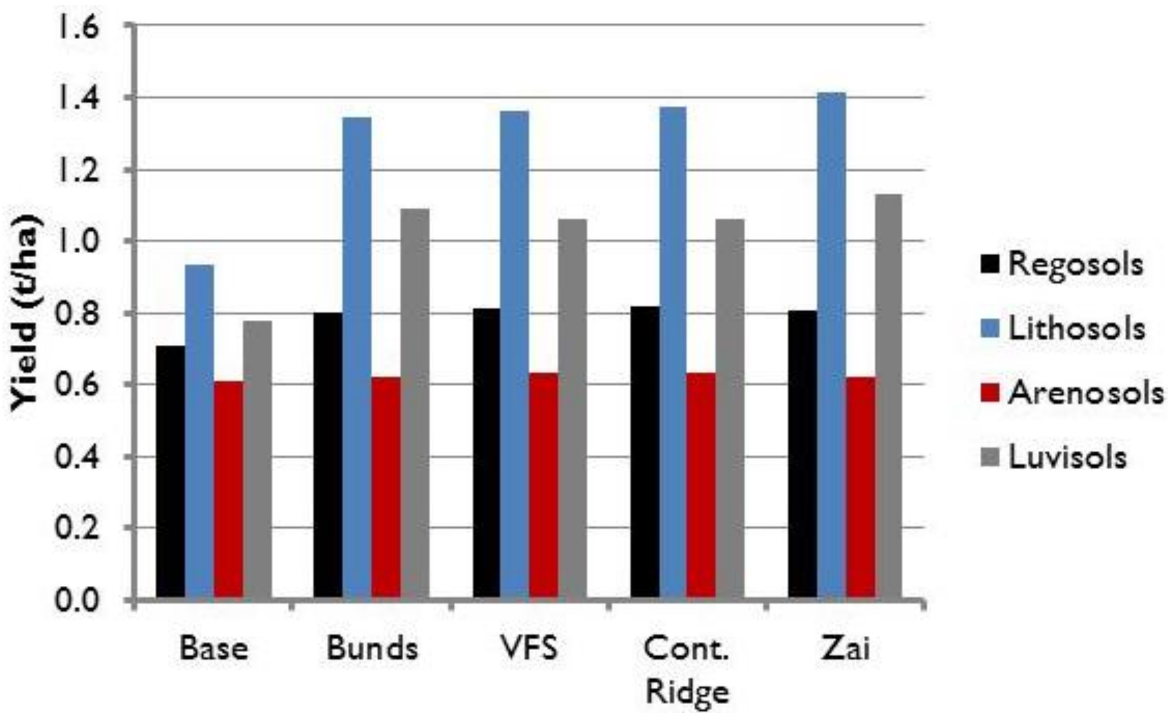


FIGURE A.29: SUBSURFACE FLOW AND DEEP PERCOLATION FOR MAIZE GROWN ON LITHOSOLS WITH AND WITHOUT RAINWATER HARVESTING PRACTICES.



Despite losses in harvested water to deep percolation and subsurface flow, gains in yield of maize with rainwater harvesting practices were substantially larger on lithosols and luvisols (Figure A.30) as compared to yields without these practices. Maize yield on luvisols increased from 0.78 tons/hectare without water harvesting practices to between 1.06 and 1.13 tons/hectare with vegetated filter strips, bunds, contour ridges, and *zai*. These gains in yield range between 36–46 percent relative to baseline conditions without water harvesting. On lithosols, maize yield increased from 0.93 tons/hectare without water harvesting to between 1.35 and 1.42 tons/hectare with rainwater harvesting practices, a gain of between 44–52 percent. The effectiveness of rainwater harvesting practices at improving maize yield was best on lithosols and luvisols, intermediate on regosols, and poor on arenosols. On th e better performing soils (lithosols and luvisols), there was little difference in the effectiveness of *zai*, contour ridges, vegetative filter strips, and bunds at improving maize yield.

FIGURE A.30: MAIZE YIELD WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES.



In addition to reducing surface runoff, rainwater harvesting practices were effective at reducing soil loss (Figure A.31), except on arenosols, which had minimal soil loss due to high rates of infiltration on very sandy soil. Lithosols had higher rates of erosion under baseline conditions without rainwater harvesting practices than regosols or luvisols. Soil loss on steep lithosols was 5.4 tons/hectare without water harvesting practices, and decreased to 1.28, 0.76, 0.45 and 0.40 tons/hectare with vegetative filter strips, bunds, *zai,* and contour ridges, respectively. These represent reductions ranging from 76–93 percent. Thus, rainwater harvesting practices are effective at slowing the loss of topsoil, which has higher fertility and moisture holding capacity than subsoil.

Reductions in soil loss caused improvements in soil fertility through preservation of soil organic carbon relative to baseline conditions without water harvesting practices. Preservation of soil organic carbon was greatest in lithosols and luvisols (18–30 percent loss prevented), intermediate in regosols (14 percent), and smallest in arenosols (4 percent). Soil organic carbon is important for overall soil fertility, as the organic matter releases nutrients to the soil, holds water, and improves soil structure and tilth. Crop yields are generally larger in soils with higher organic carbon contents (Samake et al., 2005).

FIGURE A.31: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER MAIZE FOR THE FOUR SOILS EVALUATED.

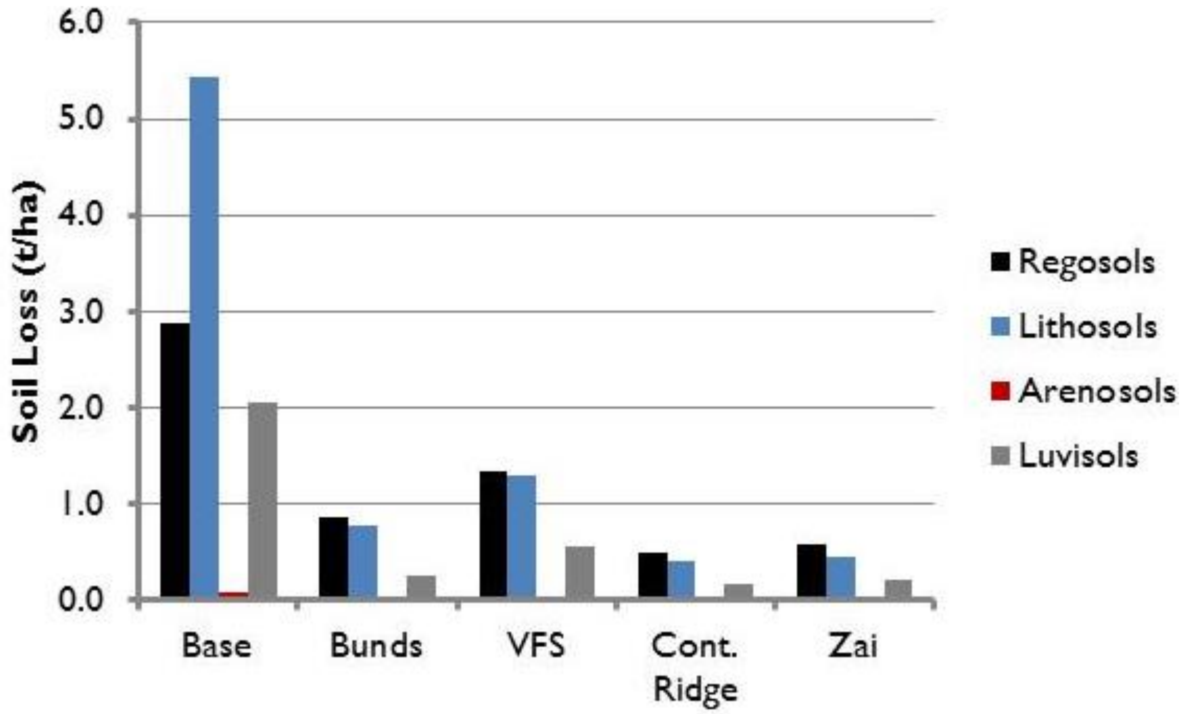
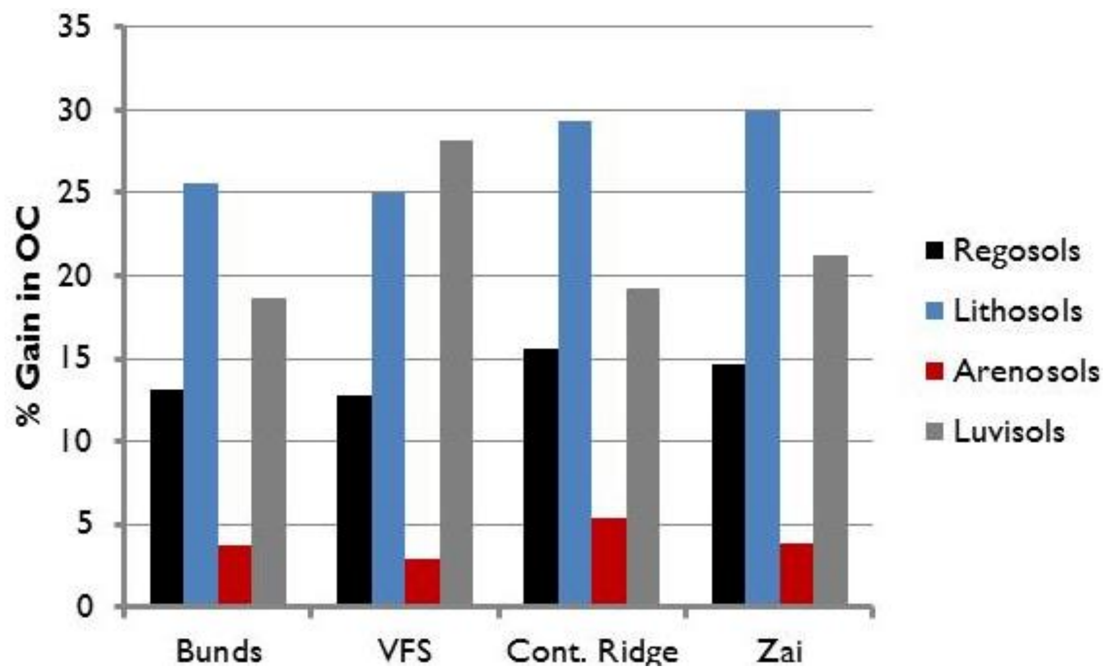


FIGURE A.32: INCREASE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM REDUCTIONS IN SOIL LOSS WITH MAIZE.



Impact of rainwater harvesting practices on sorghum

Yield of sorghum increased from 9–24 percent when rainwater harvesting practices were used on the four soils evaluated (Figure A.33) in comparison to yields without these practices. These increases are not as large as those observed with maize on the same soils (Figure A.30), so the effectiveness of water harvesting practices varies with crop type. Sorghum yields were much larger on the soils with higher organic carbon content (lithosols and luvisols) than the soils with lower organic carbon content (regosols and arenosols). Yields of sorghum without water harvesting practices on lithosols were 0.91 tons/hectare; these increased to between 1.0–1.13 tons/hectare when these practices were used, with contour ridges promoting higher crop yield than the other water harvesting practices. On luvisols, sorghum yields without water harvesting practices were 0.62 tons/hectare and increased to 0.73–0.77 tons/hectare when these practices were used, with contour ridges again giving the highest crop yield. Sorghum yields on the regosols and arenosols were less than half as large as yields on the lithosols and luvisols due to low fertility, regardless of the type of water harvesting practice installed.

Rainwater harvesting practices reduced runoff more effectively on lithosols, luvisols, and regosols than on arenosols (Figure 34), which are so sandy that they have inherently high infiltration rates. On the less permeable soils, surface runoff was reduced by 18–26 percent with bunds, *zai*, and contour ridges, whereas vegetated filter strips reduced surface runoff by only 4–17 percent.

Water harvesting practices were effective at reducing soil loss on all soils in comparison with the same soils without these practices (Figure A.35). Soil loss on steep regosols without water harvesting practices averaged 11.5 tons/hectare, and this was reduced to 5.9 or 2.2 tons/hectare with vegetative filter strips and contour ridges, respectively. Water harvesting practices were less effective at reducing rates of erosion on the steepest slopes than on the flatter slopes. Erosion rates on lithosols without these practices averaged 7.1 tons/hectare and were reduced to between 2.4 and 0.63 tons/hectare depending on the water harvesting practice. On the flatter landscapes without water harvesting practices, erosion rates were 3.6 tons/hectare (luvisols) and 1.9 tons/hectare (arenosols). With water harvesting practices erosion rates on luvisols decreased to between 0.61 and 0.9 tons/hectare, while rates on arenosols decreased to between 0.31 and 0.84 tons/hectare. Overall, decreases in erosion rates with water harvesting practices ranged between 49–91 percent, with contour ridges giving the highest percent reductions, followed by *zai*, bunds, and vegetative filter strips.

FIGURE A.33: SORGHUM YIELD WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES

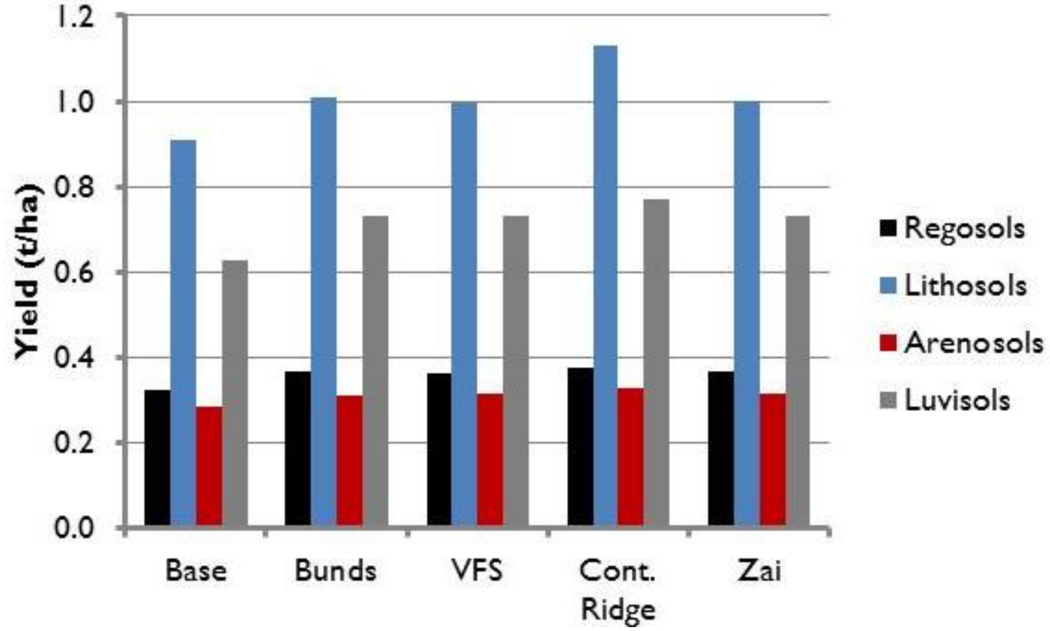


FIGURE A.34: SURFACE RUNOFF FOR SORGHUM GROWN ON DIFFERENT SOILS WITH AND WITHOUT RAINWATER HARVESTING PRACTICES.

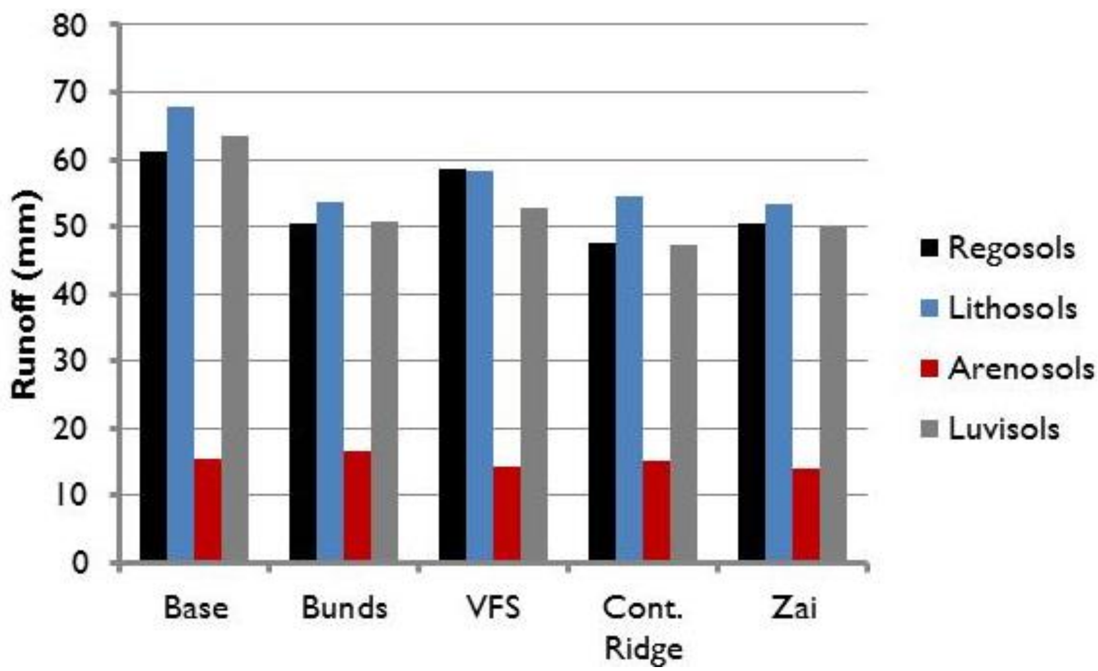
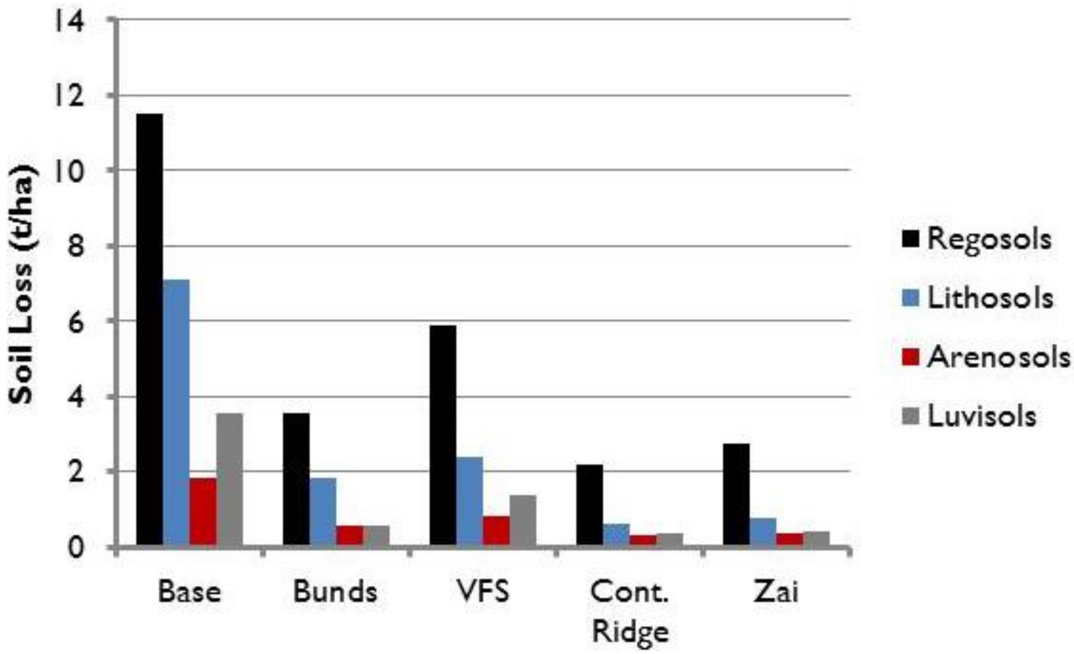
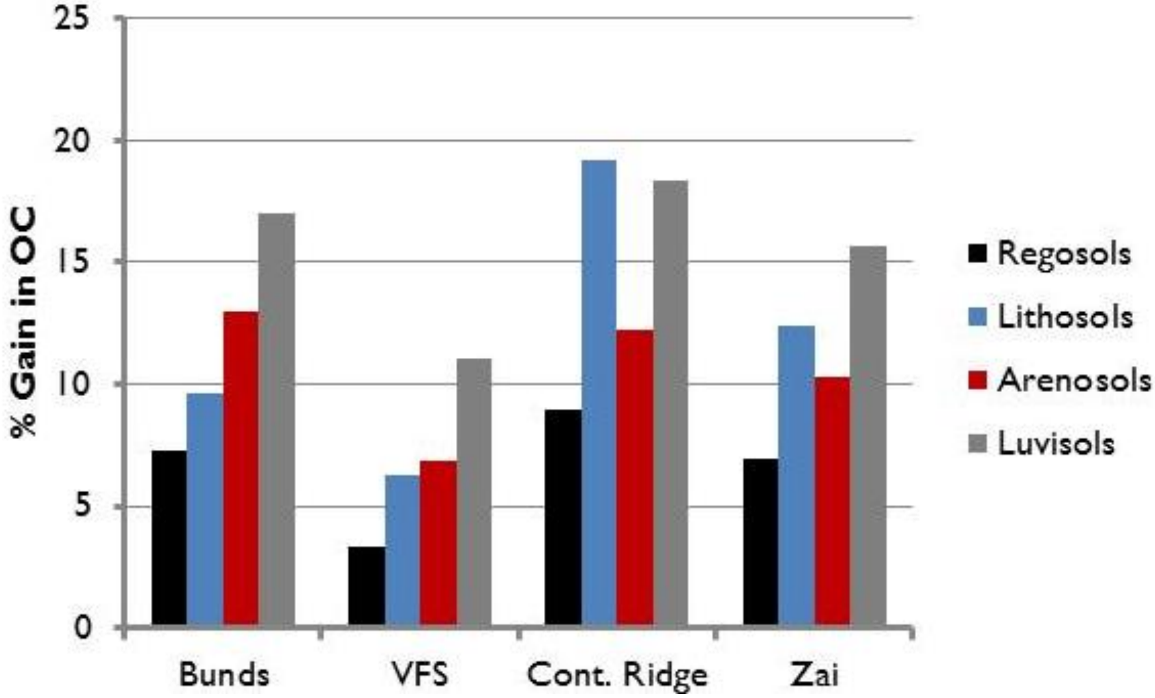


FIGURE A.35: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER SORGHUM FOR THE FOUR SOILS EVALUATED



Water harvesting practices that reduced soil erosion also tended to preserve soil organic carbon by preventing erosion of surface soil (Figure A.36). The largest gains in soil organic carbon content relative to baseline conditions without water harvesting practices occurred on luvisols, which are on relatively flat slopes and have relatively high organic carbon content. Gains in soil organic carbon content were smallest on the steepest slopes with a relatively low organic carbon content soil (regosols).

FIGURE A.36: INCREASE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM REDUCTIONS IN SOIL LOSS WITH SORGHUM.



Impact of rainwater harvesting practices on millet

Yield of millet under baseline conditions without water harvesting practices was generally low, at about 0.53 tons/hectare on lithosols, and ranging between 0.28–0.33 tons/hectare on arenosols, regosols, and luvisols. Installation of water harvesting practices had little positive impact on yield of millet (Figure A.37) relative to yields without these practices on arenosols and regosols. A significant response to water harvesting practices was observed only on the more fertile lithosols and luvisols. Millet yields with water harvesting practices increased to between 0.46 and 0.52 tons/hectare on luvisols (a 55–76 percent increase), and to between 0.61 and 0.72 tons/hectare on lithosols (a 14–35 percent increase). Yield increases were largest on these two more fertile soils with contour ridges, with smaller increases for *zai*, followed by bunds, and then vegetative filter strips.

Water harvesting practices decreased surface runoff on all soils, with decreases ranging from 7–28 percent. The largest decreases in runoff occurred on luvisols, followed by lithosols, regosols, and arenosols. Contour ridges and *zai* were the most effective at reducing surface runoff (Fig. A.38), while vegetative filter strips were the least effective. *Zai* were surprisingly effective across a range of slope steepness, whereas the effectiveness of vegetative filter strips and bunds decreased as slope steepness increased.

Soil loss was more effectively reduced by *zai* and contour ridges than by bunds for all soils and slopes, while soil loss was less effectively reduced by vegetative filter strips, especially on steeper slopes (Figure A.39). Reductions relative to those without any water harvesting practices ranged from 77–89 percent for *zai* and contour ridges, from 62–80 percent for bunds, and from 42–64 percent for vegetative filter strips. Reductions in erosion were striking on regosols and lithosols with *zai* and contour ridges.

FIGURE A.37: MILLET YIELD WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES.

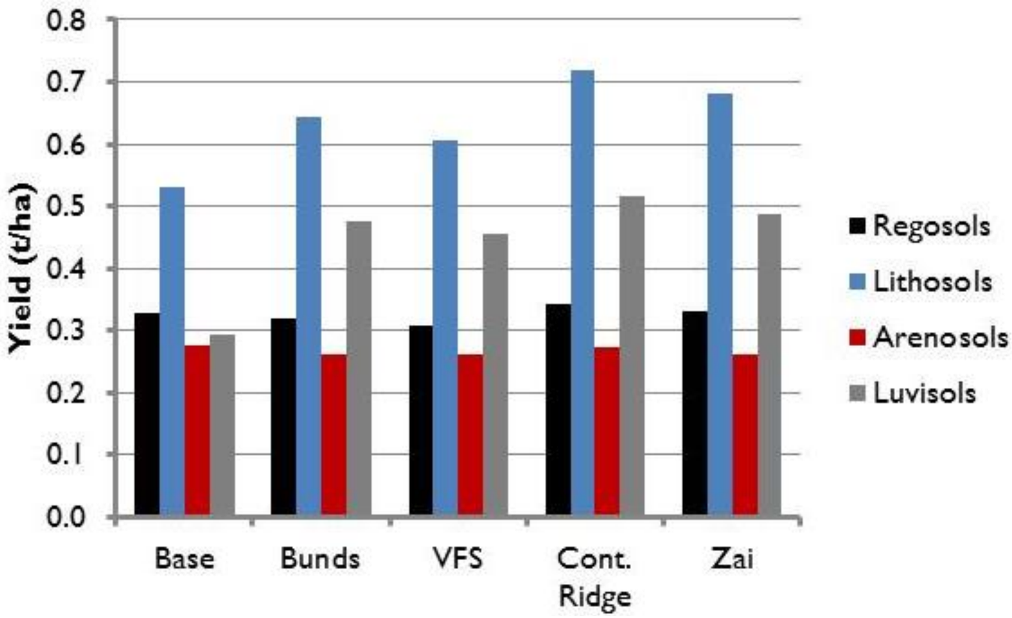


FIGURE A.38: SURFACE RUNOFF FOR MILLET GROWN ON DIFFERENT SOILS WITH AND WITHOUT RAINWATER HARVESTING PRACTICES.

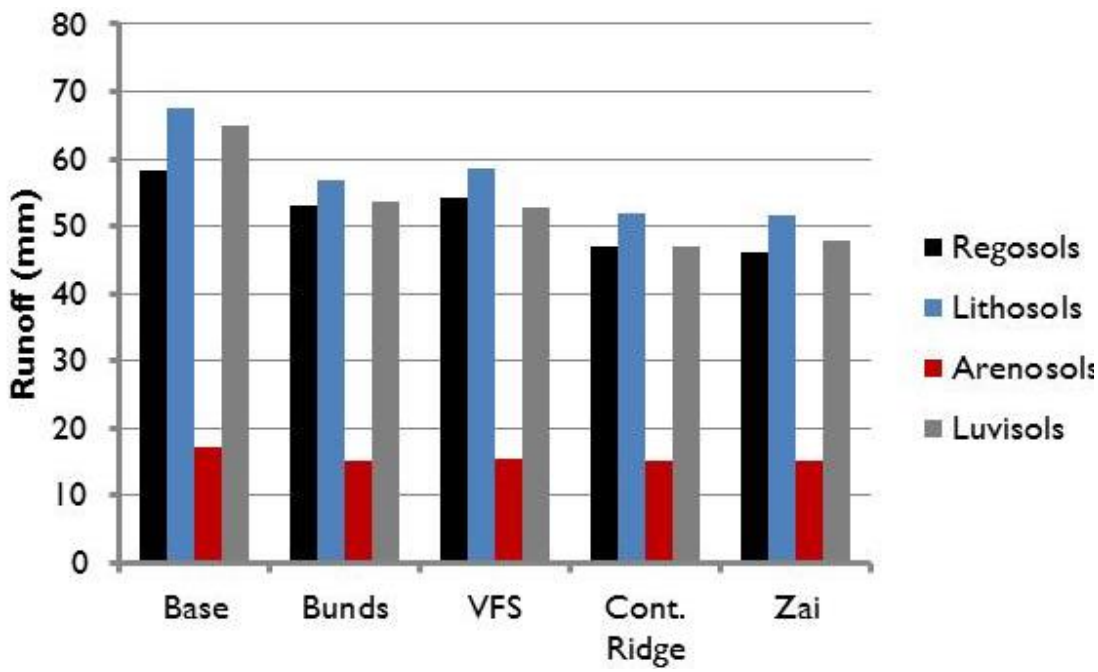
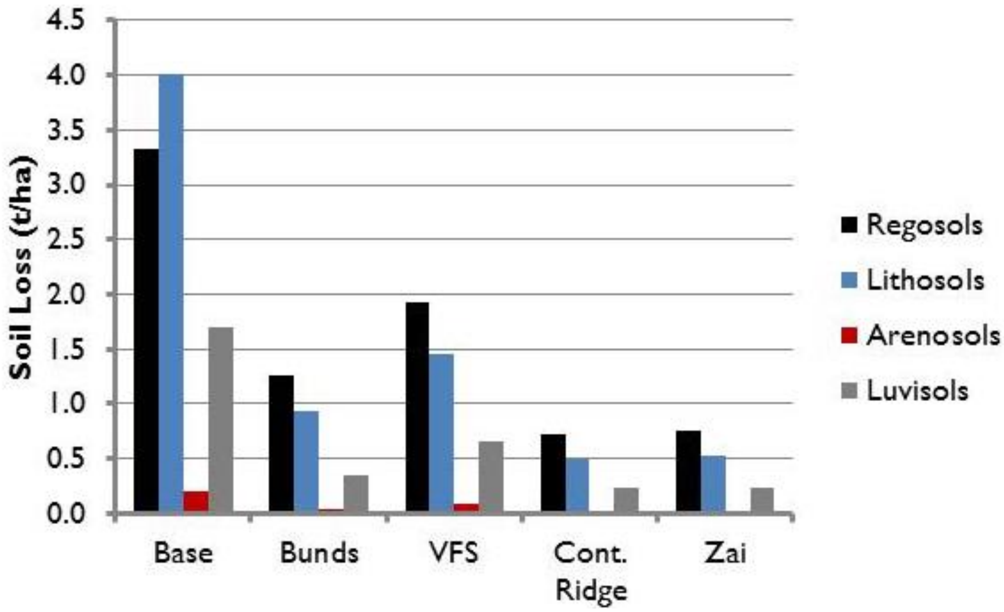
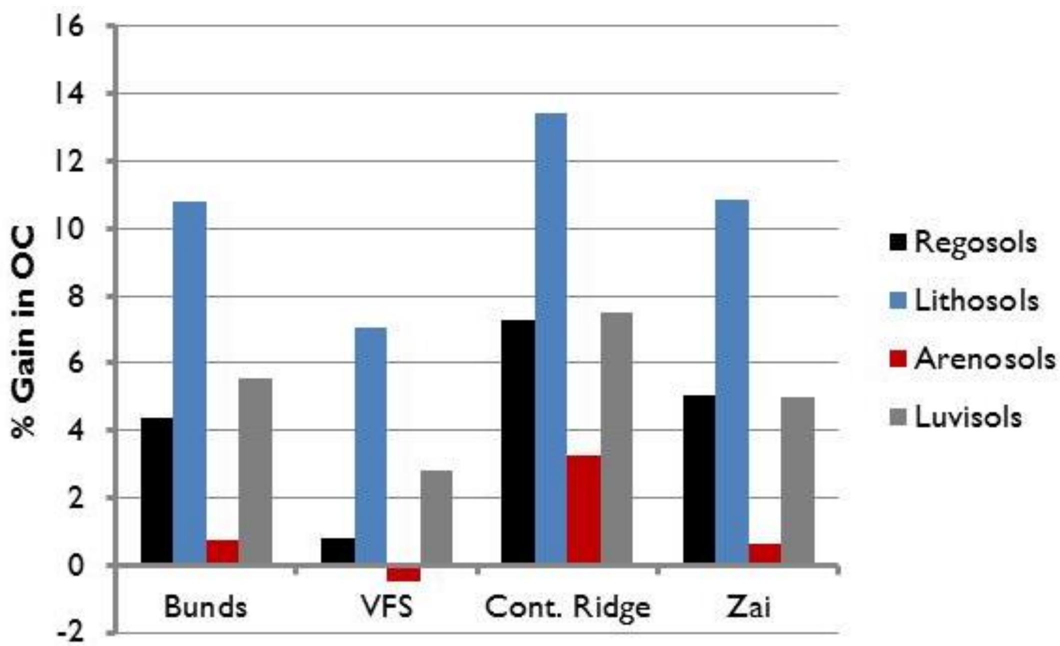


FIGURE A.39: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER MILLET FOR THE FOUR SOILS EVALUATED



Gains in soil organic carbon were greatest for conservation practices such as *zai*, bunds, and contour ridges that were also most effective at reducing soil erosion (Figure A.40). The greatest gains in soil organic carbon occurred on the soils with highest initial fertility, namely lithosols and luvisols. Vegetative filter strips were less effective at building soil organic carbon on lithosols and luvisols as a result of higher erosion rates as compared with rates of erosion with *zai*, bunds and contour ridges on these soils. Gains in soil organic carbon were moderate on regosols and minimal on arenosols.

FIGURE A.40: INCREASE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM REDUCTIONS IN SOIL LOSS WITH MILLET



Impact of rainwater harvesting practices on rice

Yield of rice under baseline conditions without water harvesting practices was generally high, at about 1.9 tons/hectare on luvisols, as a result of supplemental irrigation. Installation of water harvesting practices had little positive impact on yield of rice (Figure A. 41) relative to yields without these practices because water supply was generally adequate even under baseline conditions due to supplemental irrigation. Water harvesting practices decreased surface runoff from rice on luvisols by 11–12 percent. Both contour ridges and bunds were effective at reducing surface runoff (Figure A.42).

Soil loss was effectively reduced by contour ridges and bunds on the relatively flat luvisols (Figure A.43). Reductions relative to those without any water harvesting practices ranged from 89 percent for contour ridges, to 86 percent for bunds. Reductions in erosion caused only small gains in soil organic carbon (Figure A.44), ranging from 4.4–4.9 percent because of the inherently low soil organic carbon content on luvisols

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FIGURE A.41: RICE YIELD WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES

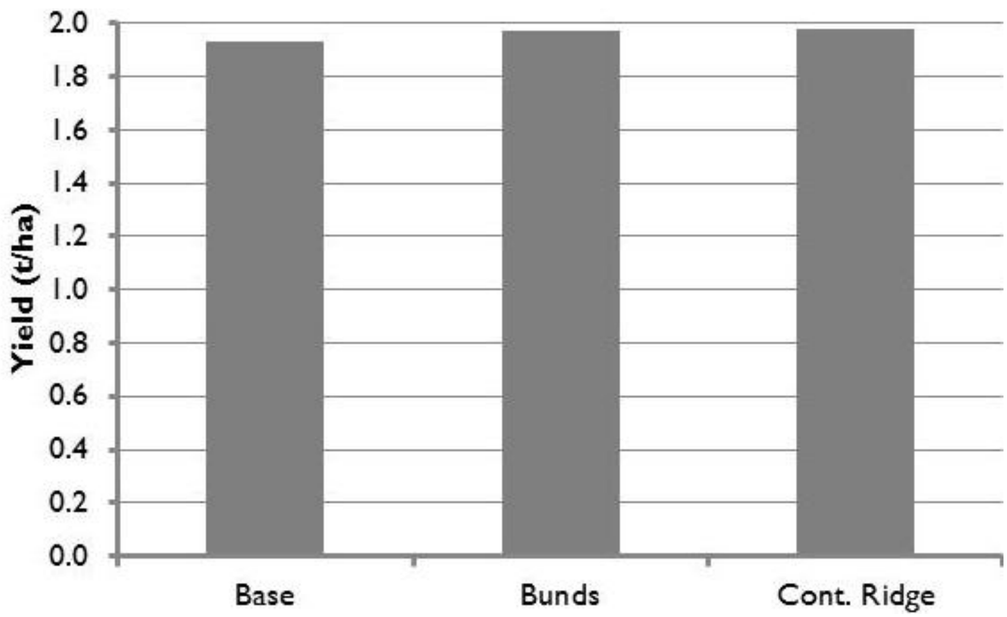


FIGURE A.42: SURFACE RUNOFF FOR RICE GROWN ON LUVISOLS WITH AND WITHOUT RAINWATER HARVESTING PRACTICES

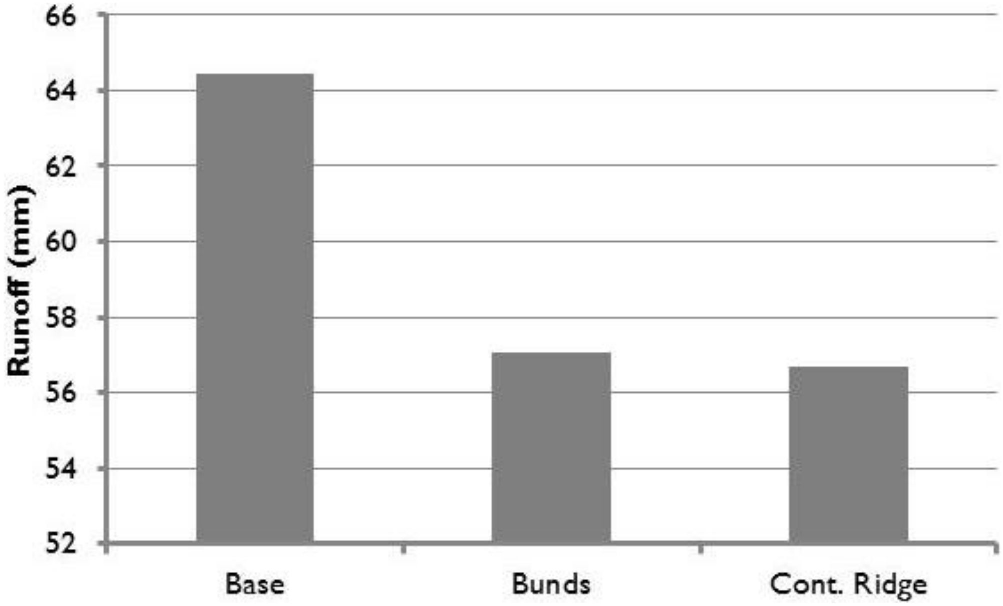


FIGURE A.43: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER RICE FOR LUVISOLS.

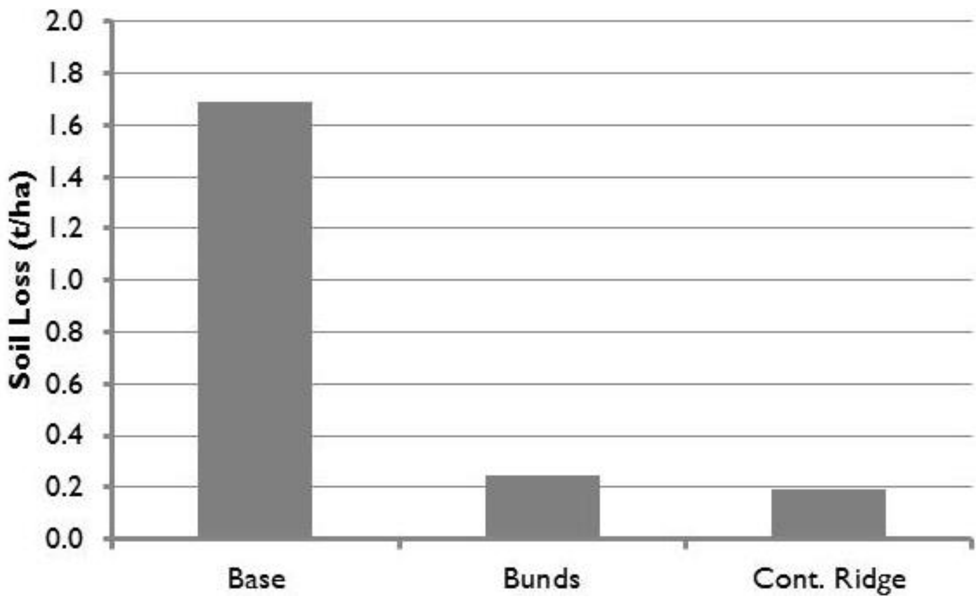
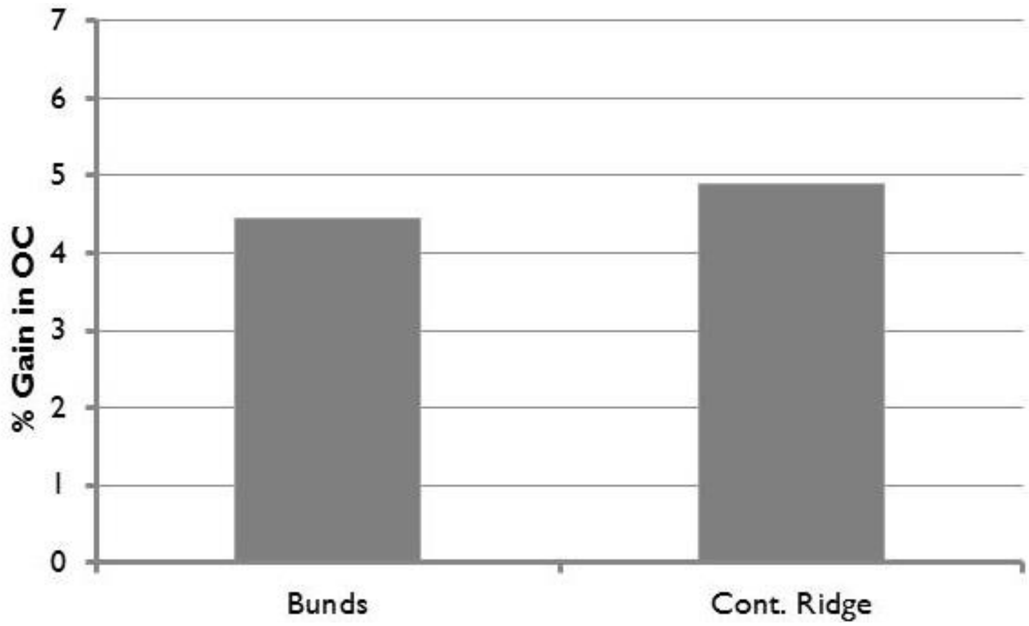


FIGURE A.44: INCREASE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM REDUCTIONS IN SOIL LOSS WITH RICE



PERFORMANCE OF RAINWATER HARVESTING PRACTICES UNDER FUTURE CLIMATIC CONDITIONS

Future climatic input data

A web-based software tool called MarkSim GCM was used to generate the future climate scenarios for the years 2025–2035 and 2045–2055. MarkSim has the option of generating climate data using any or all of 17 global climate models (GCMs) using a stochastic process that produces any desired number of realizations for each of the 17 GCM models.

MarkSim is a daily rainfall simulator that uses a third-order Markov process to predict the occurrence of a rainy day. A third-order model was shown to be necessary for tropical climates, whereas a lower-order model may suffice for temperate climates (Jones and Thornton, 1993).

Daily outputs from each of the 17 MarkSim GCM models were analyzed for 10 realizations in each year from 2025–2035 and 2045–2055. These 340 realizations were compared with the baseline measured average climate for the study area (average daily temperature 29.67 °C and average annual rainfall of 525.74 millimeters). We wanted to identify realizations that represented the range of potential future climatic conditions. Thus we selected realizations from two GCM models that had a) increased air temperature and b) a range of future mean annual precipitation amounts. Output of one realization from each of two GCM models (Institut Pierre-Simon Laplace, IPSL-CM5A-MR and CSIRO-MK3-6-0) were chosen as input data for the APEX model.

The IPSL-CM5A-MR GCM model realization chosen exhibited an average temperature of 29.9 °C and 31.2 °C, and an increase in temperature of 0.24 °C and 1.5 °C for 2030 and 2050, respectively, relative to the baseline period (Table A.28). "Hot" days occurred on 8 percent of days in the period around 2030, and 15 percent of days in the period around 2050. Days were characterized as "hot" when the temperature exceeded the threshold for the hottest 10 percent of days in the baseline period (1991–2000) for climate in the Mopti region of Mali. This realization also indicates that annual average precipitation around the year 2030 (628.0 millimeters) is expected to increase by 19 percent relative to baseline conditions, and then decrease to levels (524.0 millimeters) that are similar to the baseline period for the years before and after 2050. "Heavy" rainfall events occur on about 9 percent of the rainy days around 2030, and on 3 percent of days around 2050. Heavy events of rainfall are defined as a daily rainfall total that exceeds the threshold that occurs on the rainiest 5 percent of days in the baseline period (1991–2000). Thus, this realization is characterized by the following combination of events (relative to baseline climatic conditions):

An increase in average daily temperature around both 2030 and 2050.

An increase in the number of hot days around 2050.

A significant increase in the average annual rainfall around 2030, while the average annual rainfall around 2050 is similar to rainfall during the baseline.

An increased frequency of heavy rain events around 2030, followed by a decreased incidence of heavy rainfall events around 2050.

TABLE A.28: COMPARISON BETWEEN CLIMATIC PARAMETERS FOR BASELINE (1995) VERSUS FUTURE (2030 OR 2050) CLIMATE SCENARIOS

Climatic Period	Source	Avg. Temp (°C)	Avg. Precip. (mm)	Hottest Days			Heaviest Rain Days		
				Thresh-olds (°C)	Fre-quency (days/yr)	%	Thresh-olds (mm)	Fre-quency (days/yr)	%
1995	Measured Mopti	29.7	526	34.65	36.3	10	34	2.2	5
2030	IPSL	29.9	628	34.65	29.7	8.1	34	4.9	8.5
	CSIRO	29.6	563	34.65	11.5	3.1	34	1.8	2.9
2050	IPSL	31.2	524	34.65	55.7	15.3	34	1.9	2.9
	CSIRO	30.9	500	34.65	39.6	10.9	34	2.0	3.3

The CSIRO-MK3-6-0 GCM model realization chosen exhibited an average temperature of 29.6 °C for 2030, which is essentially unchanged from baseline conditions (Table A.28). It also predicted an average temperature of 30.9 °C around 2050, an increase in temperature of 1.0 °C relative to the baseline period. "Hot" days occurred on 3 percent of days in the period before and after 2030, and 11 percent of days in the period before and after 2050. This realization also indicates that annual average precipitation around the year 2030 (563.0 millimeters) is expected to increase by 7 percent relative to baseline conditions, and then decrease to levels (500.4 millimeters) which are 5 percent lower than the baseline period for the years before and after 2050. "Heavy" rainfall events occur in about 3 percent of the rainy days around 2030, and 3 percent of days around 2050. Thus, this realization is characterized by the following combination of events (relative to baseline climatic conditions):

No change in average daily temperature with a decrease in frequency of hot days around 2030, followed by an increase in average daily temperature for the 2050 period.

An increase in the average annual rainfall around 2030, while the average annual rainfall around 2050 is significantly lower than the baseline.

A decreased incidence of heavy rainfall events around both 2030 and 2050 relative to baseline conditions.

The performance of rainwater harvesting practices was evaluated for each crop and soil under future climate conditions consisting of climatic data for 2025–2035 and 2045–2055 from the IPSL-CM5A-MR and CSIRO-MK3-6-0 GCM models. Performance was evaluated based primarily on the impact of rainwater harvesting practices on surface runoff, crop yield, soil organic carbon content, and soil loss. Each of these indicators was compared with the value of the same indicator with or without rainwater harvesting practices in the baseline period.

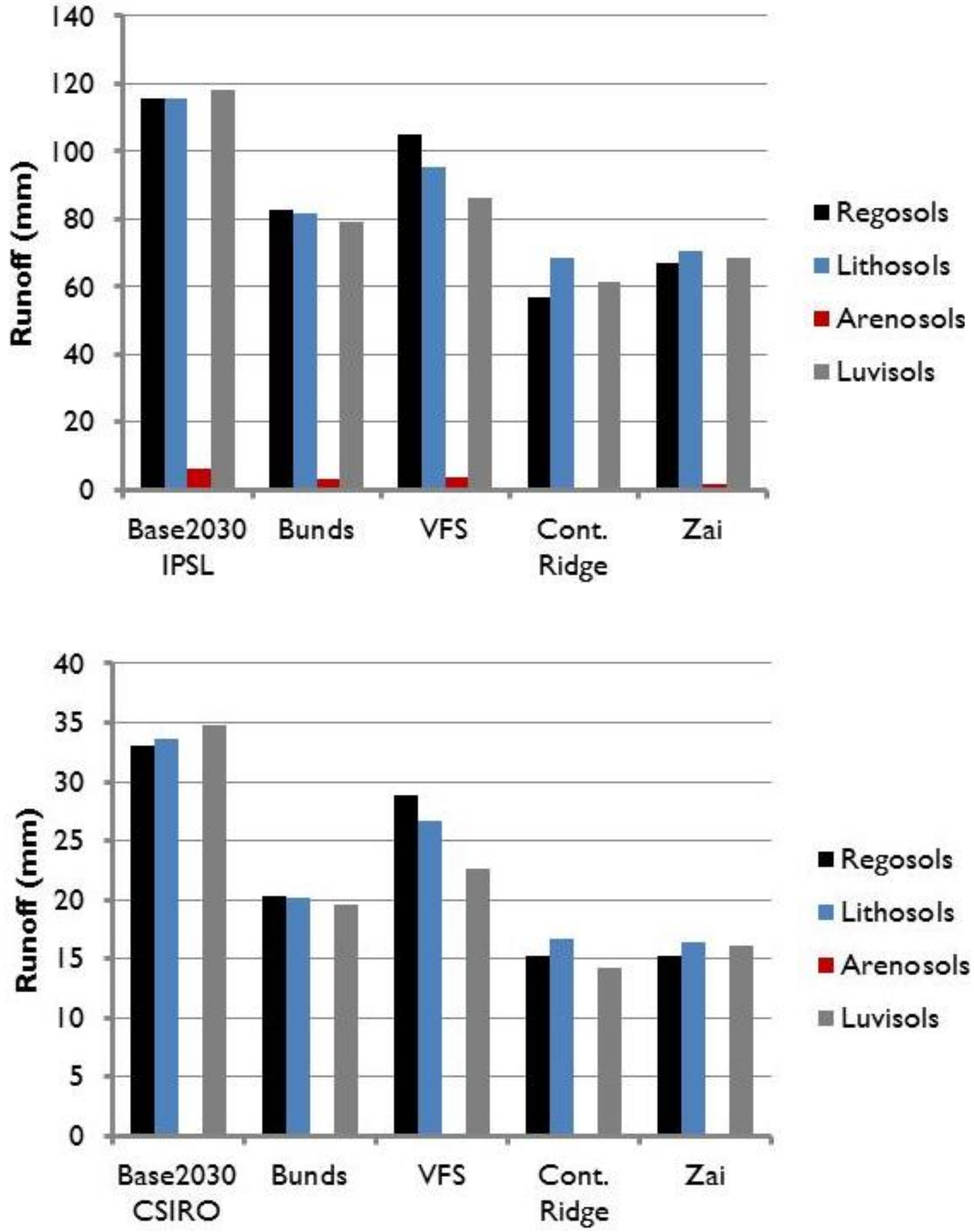
Impact of rainwater harvesting practices on maize under future climatic scenarios

Runoff on maize fields

Runoff for maize without any conservation practices on finer textured soils (the regosols, lithosols, and luvisols) with 2030 future climatic scenarios averaged from about 115 to 118 millimeters with the IPSL climatic model, and from about 33 to 35 millimeters with the CSIRO model (Figure A.45). In contrast, baseline runoff with 1991-2000 climatic data averaged from 61-70 millimeters (Figure A.28). These differences are largely driven by differences in annual precipitation, which averaged 527 millimeters using baseline data, versus 628 millimeters and 563 millimeters with the 2030 IPSL and CSIRO climate predictions, respectively. The large increases in runoff that occurred with the 2030 IPSL model are reasonable in view of the fact that annual precipitation increased by about 100 millimeters relative to baseline conditions. The decreases in runoff that occurred with the 2030 CSIRO model are largely driven by a decrease in the frequency of heavy rain events relative to baseline conditions, rather than by differences in annual precipitation between baseline and 2030 CSIRO climatic data. Runoff was extremely low on sandy arenosols with both 2030 ISPL and CSIRO climatic data (Figure A.45).

Rainwater harvesting practices caused changes in runoff in comparison to conditions without water harvesting. For maize, surface runoff decreased relative to runoff without water harvesting practices, particularly for finer textured soils (Figure A.45). The effectiveness of rainwater harvesting practices at reducing surface runoff with maize on finer textured soils decreased in the following order: contour ridges; *zai*; bunds; vegetative filter strips. Contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 41–51 percent, 39–41 percent, 28–32 percent, and 9–25 percent respectively, on finer texture soils during the relatively wet climatic conditions generated by the 2030 IPSL model. In contrast, contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 49–57 percent, 50–54 percent, 39–41 percent, and 13–32 percent respectively, on finer texture soils during the relatively drier climatic conditions generated by the 2030 CSIRO model. Thus, while the ranked order of effectiveness for water harvesting practices was the same using both 2030 climatic prediction scenarios, the effectiveness of a particular water harvesting practice was generally greater during drier years than wetter years.

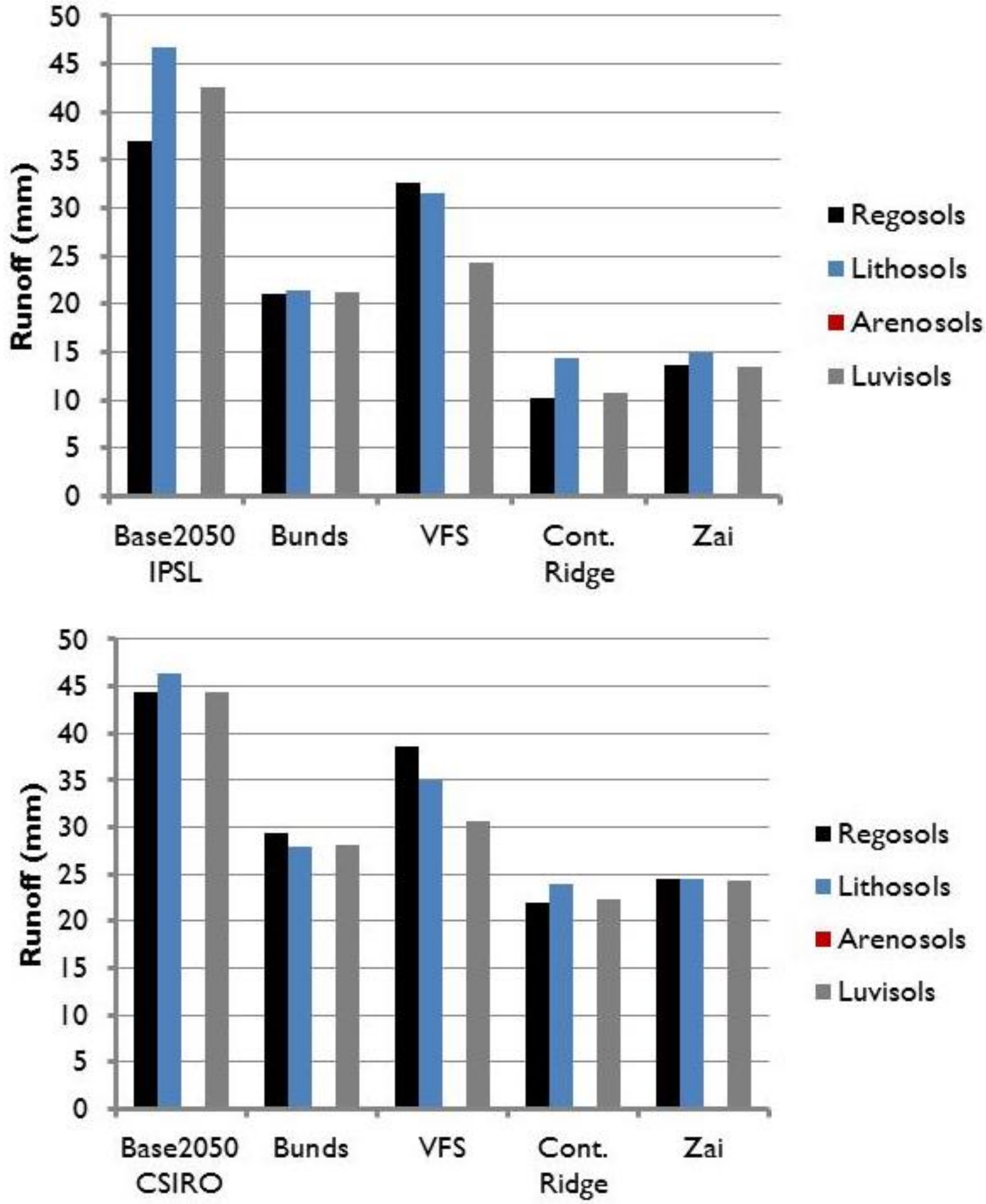
FIGURE A.45: SURFACE RUNOFF FOR MAIZE GROWN ON DIFFERENT SOILS FOR IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA WITH AND WITHOUT RAINWATER HARVESTING PRACTICES SUCH AS BUNDS, VEGETATIVE FILTER STRIPS (VFS), CONTOUR RIDGES AND *ZAI*



Runoff for maize without any conservation practices on finer textured soils with 2050 future climatic scenarios averaged from about 37 to 47 millimeters with the IPSL climatic model, and from about 44 to 46 millimeters with the CSIRO model (Figure A.46). In contrast, baseline runoff with 1991–2000 climatic data averaged from 61–70 millimeters (Figure A.28). These differences are largely driven by differences in annual temperatures and the frequency of heavy rain events rather than differences in annual precipitation, which averaged 527 millimeters using baseline data, versus 524 millimeters and 500 millimeters with the 2050 IPSL and CSIRO climate predictions, respectively. The decrease in runoff that occurred with the 2050 IPSL model are reasonable in view of the fact that annual precipitation with this scenario is very similar to precipitation under baseline conditions, but mean annual temperature was 1.5 °C warmer than baseline conditions. The decreases in runoff that occurred with the 2050 CSIRO model are largely driven by a decrease in annual precipitation relative to baseline conditions, as well as by a warming of 1.0 °C and a decrease in the frequency of heavy rain events relative to baseline climatic data. Increased temperature reduces runoff by decreasing soil moisture as a result of increased evaporation and transpiration. Runoff was extremely low on sandy arenosols with both 2050 ISPL and CSIRO climatic data (Figure A.46).

Rainwater harvesting practices caused changes in runoff with 2050 climatic data in comparison to conditions without water harvesting. For maize, surface runoff decreased relative to runoff without water harvesting practices, particularly for finer textured soils (Figure A.46). The effectiveness of rainwater harvesting practices at reducing surface runoff with maize on finer textured soils decreased in the following order: contour ridges; *zai*; bunds; and vegetative filter strips, the same order of practice effectiveness that was observed using 2030 climatic data. Contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 61–72 percent, 60–63 percent, 42–43 percent, and 12–34 percent respectively, on finer texture soils during the relatively wet climatic conditions generated by the 2050 IPSL model. In contrast, contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 46–50 percent, 45 percent, 34–37 percent, and 13–31 percent respectively, on finer texture soils during the relatively drier climatic conditions generated by the 2050 CSIRO model. Thus, while the ranked order of effectiveness for water harvesting practices was the same using both 2050 climatic prediction scenarios, the effectiveness of a particular water harvesting practice was generally somewhat greater with the IPSL generated climate than the CSIRO climate.

FIGURE A.46: SURFACE RUNOFF FOR MAIZE GROWN ON DIFFERENT SOILS FOR IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA WITH AND WITHOUT RAINWATER HARVESTING PRACTICES SUCH AS BUNDS, VEGETATIVE FILTER STRIPS (VFS), CONTOUR RIDGES AND *ZAI*



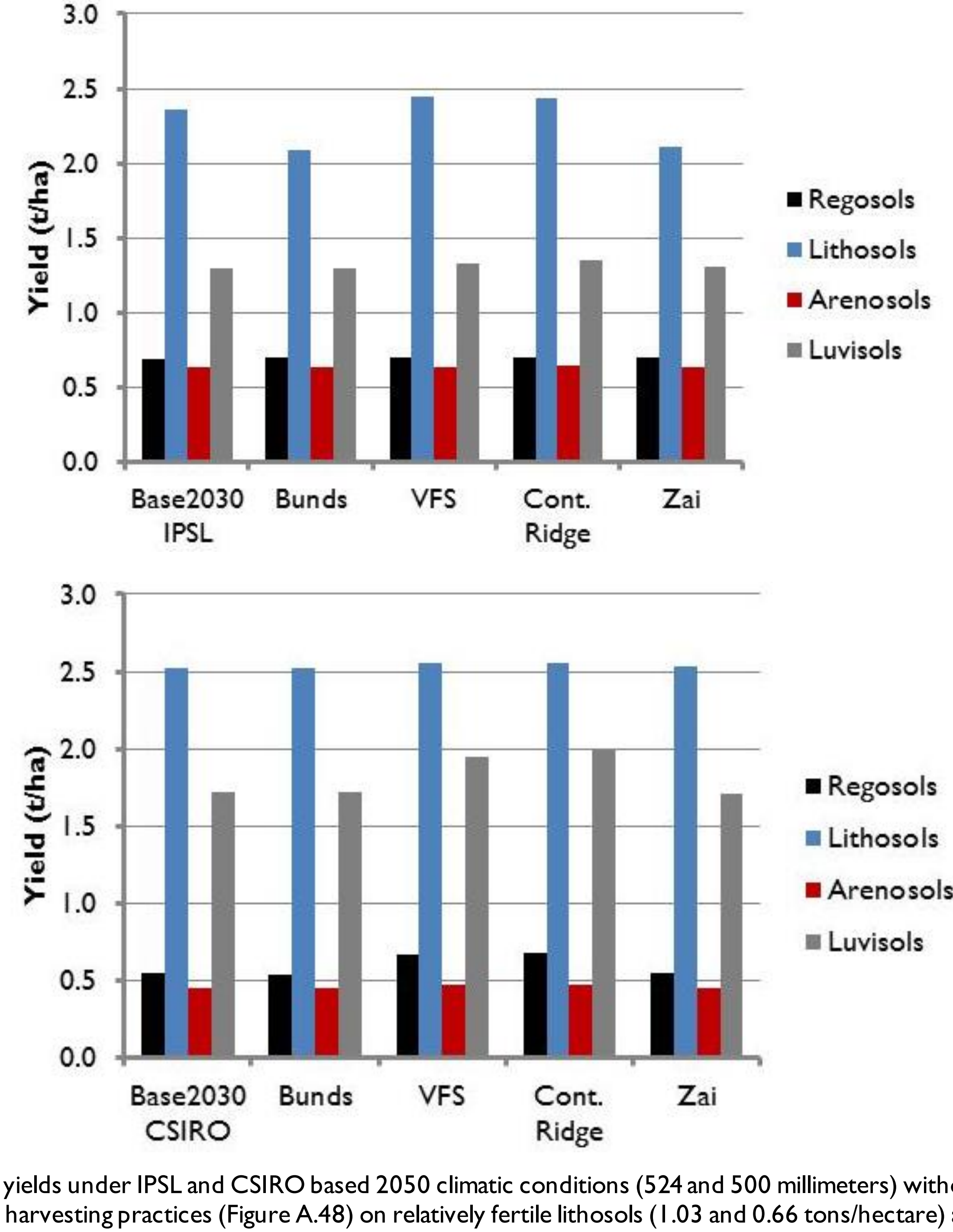
Maize yields

Maize yields under IPSL and CSIRO based 2030 climatic conditions (628 and 563 millimeters) without water harvesting practices (Figure A.47) were larger on lithosols (2.36 and 2.5 tons/hectare) and luvisols (1.29 and 1.72 tons/hectare) than yields under measured 1991–2000 climatic conditions (527 millimeters) on the same soils (0.93 and 0.78 tons/hectare) without water harvesting practices. In contrast maize yields under 2030 climatic conditions without water harvesting practices were relatively unchanged from yields on regosols and arenosols under 1991–2000 conditions without these practices. The lower yields on the more fertile lithosols and luvisols associated with the higher rainfall level of the IPSL based 2030 climate can be explained. It is reasonable for maize yields to decrease somewhat as a result of periods of excess water relative to the CSIRO based 2030 climatic conditions (563 millimeters). Maize yield responds to increases in precipitation up to a point (with CSIRO 2030 precipitation) and then excess precipitation (with IPSL 2030 precipitation) causes crops to suffer from lack of oxygen in the rooting zone. It is also reasonable for maize yields on the less fertile regosols and arenosols to exhibit no changes for 2030 climatic conditions without water harvesting practices relative to yields on the same soils with measured climatic conditions, because yields on these soils are limited by both water stress and nutrient stress. Increasing water availability does little to alleviate nutrient stress, so yields aren't affected by climate change.

Rainwater harvesting practices were relatively ineffective at improving maize yields on the more fertile lithosols and luvisols (Figure A.47) for the relatively wet IPSL generated 2030 climatic data relative to yields without these practices with the same climatic data. Maize yield on luvisols increased by 5 percent, 3 percent, 1 percent, and 1 percent with contour ridges, vegetated filter strips, bunds, and *zai*, respectively, relative to yields without these practices for IPSL 2030 climatic data. Maize yields on lithosols increased by 3–4 percent with contour ridges and vegetated filter strips, but actually decreased by 11–12 percent with *zai* and bunds due to an exacerbation of waterlogging effects, based on IPSL 2030 climatic data. On less fertile regosols and arenosols, water harvesting practices increased maize yields only by 1–3 percent using IPSL 2030 climatic data relative to yields on the same soils without these practices. To summarize, water harvesting practices were relatively ineffective, and sometimes even detrimental, to maize yields under the very wet IPSL 2030 climatic conditions.

In contrast, water harvesting practices were more effective at improving maize yields for some soils under CSIRO 2030 climatic conditions than under IPSL 2030 climatic conditions. Maize yield on luvisols changed by 16 percent, 13 percent, 0 percent, and -1 percent with contour ridges, vegetated filter strips, bunds, and *zai*, respectively, relative to yields without these practices for CSIRO 2030 climatic data. On less fertile regosols, vegetated filter strips and contour ridges increased maize yields by 21–22 percent using CSIRO 2030 climatic data relative to yields on the same soils without these practices, whereas bunds and *zai* had no effect on maize yield. Vegetated filter strips and contour ridges increased maize yield on arenosols by 4–5 percent using CSIRO 2030 climatic data, but bunds and *zai* had no effect on yield. Maize yields on lithosols increased by 1 percent with contour ridges and vegetated filter strips, and were unchanged with *zai* and bunds with CSIRO 2030 climatic data. Thus, vegetated filter strips and contour ridges were effective at increasing maize yields on only luvisols and regosols under CSIRO 2030 climatic data; maize yields on other soils were unresponsive due to already adequate rainfall.

FIGURE A.47: MAIZE YIELD FOR IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES



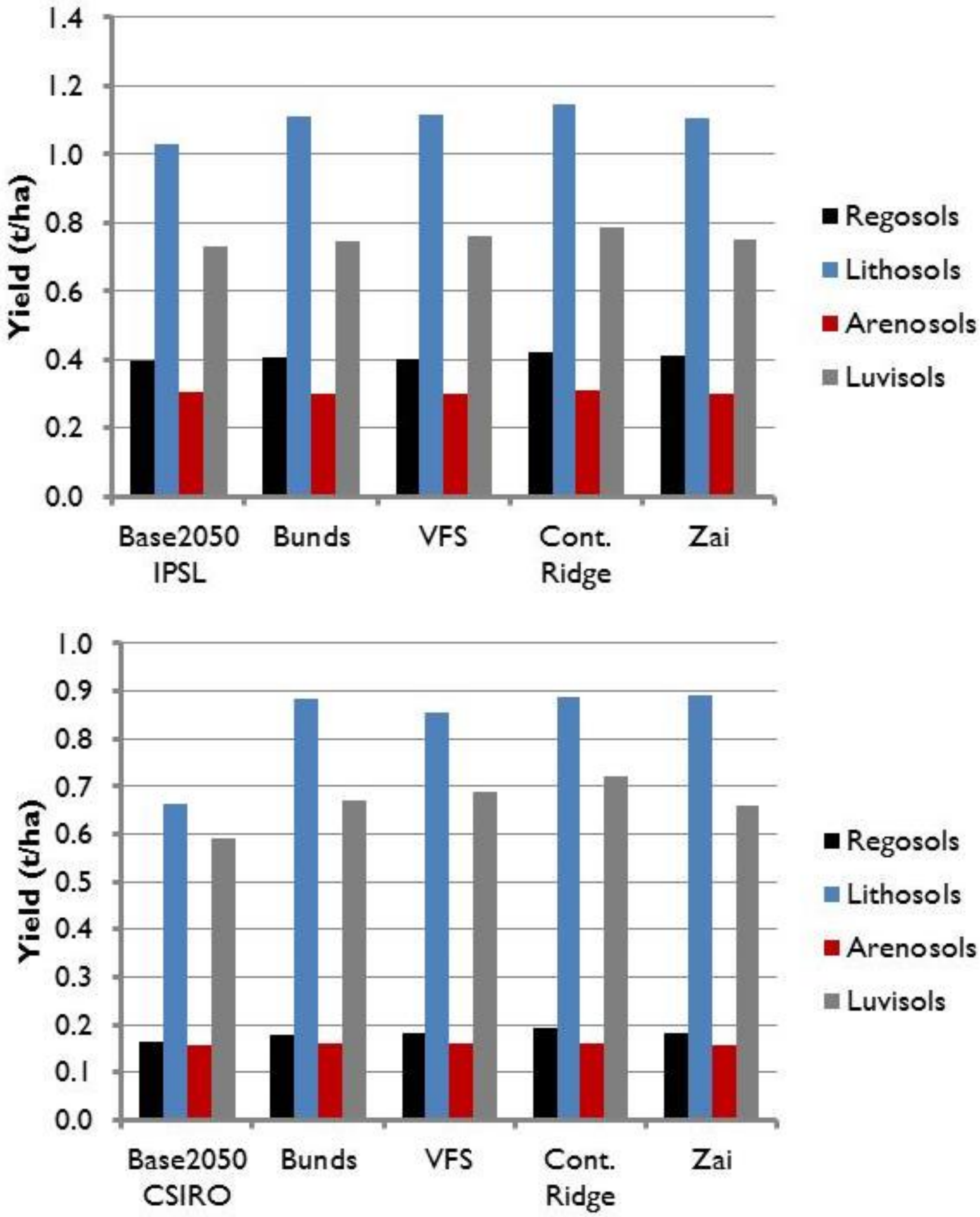
Maize yields under IPSL and CSIRO based 2050 climatic conditions (524 and 500 millimeters) without water harvesting practices (Figure A.48) on relatively fertile lithosols (1.03 and 0.66 tons/hectare) and luvisols (0.73 and 0.59 tons/hectare) were comparable to or less than yields under measured 1991–2000 climatic conditions (527 millimeters) on the same soils (0.93 and 0.78 tons/hectare) without water harvesting practices. In contrast, maize yields under 2050 climatic conditions without water harvesting practices were significantly smaller on regosols and arenosols under 1991–2000 conditions without these practices.

This difference between yields on the more fertile soils under the ISPL and CSIRO conditions for 2050 can be explained. It is reasonable for maize yields on these soils under IPSL conditions (524 millimeters) to be similar to yields under baseline climatic conditions (527 millimeters). It is also reasonable for maize yields to decrease substantially relative to baseline climatic conditions (527 millimeters) as a result of decreased precipitation for CSIRO climatic conditions (500 millimeters). Maize yields decrease in response to decreases in precipitation combined with warmer annual temperatures. It is also reasonable for maize yields on the less fertile regosols and arenosols to exhibit large decreases for 2050 climatic conditions without water harvesting practices relative to yields on the same soils with baseline climatic conditions because yields on these soils are limited by a combination of water stress, heat stress, and nutrient stress.

Rainwater harvesting practices were relatively ineffective at improving maize yields on the more fertile lithosols and luvisols (Figure A.48) for the relatively wet IPSL generated 2050 climatic data relative to yields without these practices with the same climatic data. Maize yield on lithosols increased by 11 percent, 8 percent, 7 percent, and 7 percent with contour ridges, vegetated filter strips, bunds, and *zai*, respectively, relative to yields without these practices for IPSL 2050 climatic data. Maize yields on luvisols increased by 8 and 4 percent with contour ridges and vegetated filter strips, and by 2 percent with *zai* and bunds with IPSL 2050 climatic data. Water harvesting practices increased maize yields by 2–6 percent on less fertile regosols, while there were no changes in maize yield on arenosols with water harvesting practices using IPSL 2050 climatic data relative to yields on the same soils without these practices. To summarize, water harvesting practices were more effective at increasing maize yields on lithosols than luvisols or regosols, while they were ineffective at increasing maize yields on arenosols under IPSL 2050 climatic conditions.

In contrast, water harvesting practices were more effective at improving maize yields for all but the sandiest soils (arenosols) under CSIRO 2050 climatic conditions than under IPSL 2050 climatic conditions because the baseline maize yields without these practices were much lower under CSIRO 2050 than IPSL 2050 conditions. Maize yield on lithosols and luvisols increased by 29–34 percent or 12–22 percent with water harvesting practices, relative to yields without these practices for CSIRO 2050 climatic data. On less fertile regosols, water harvesting practices increased maize yields by 9–17 percent using CSIRO 2050 climatic data relative to yields on the same soils without these practices, whereas water conservation practices only increased maize yield by 1–3 percent on arenosols. Thus, the effectiveness of water harvesting practices on maize yield was strongly affected by soil type under the drier CSIRO 2050 climatic conditions, with the effectiveness of practices decreasing in the following order: lithosols, luvisols, regosols, and arenosols.

FIGURE A.48: MAIZE YIELD FOR IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES

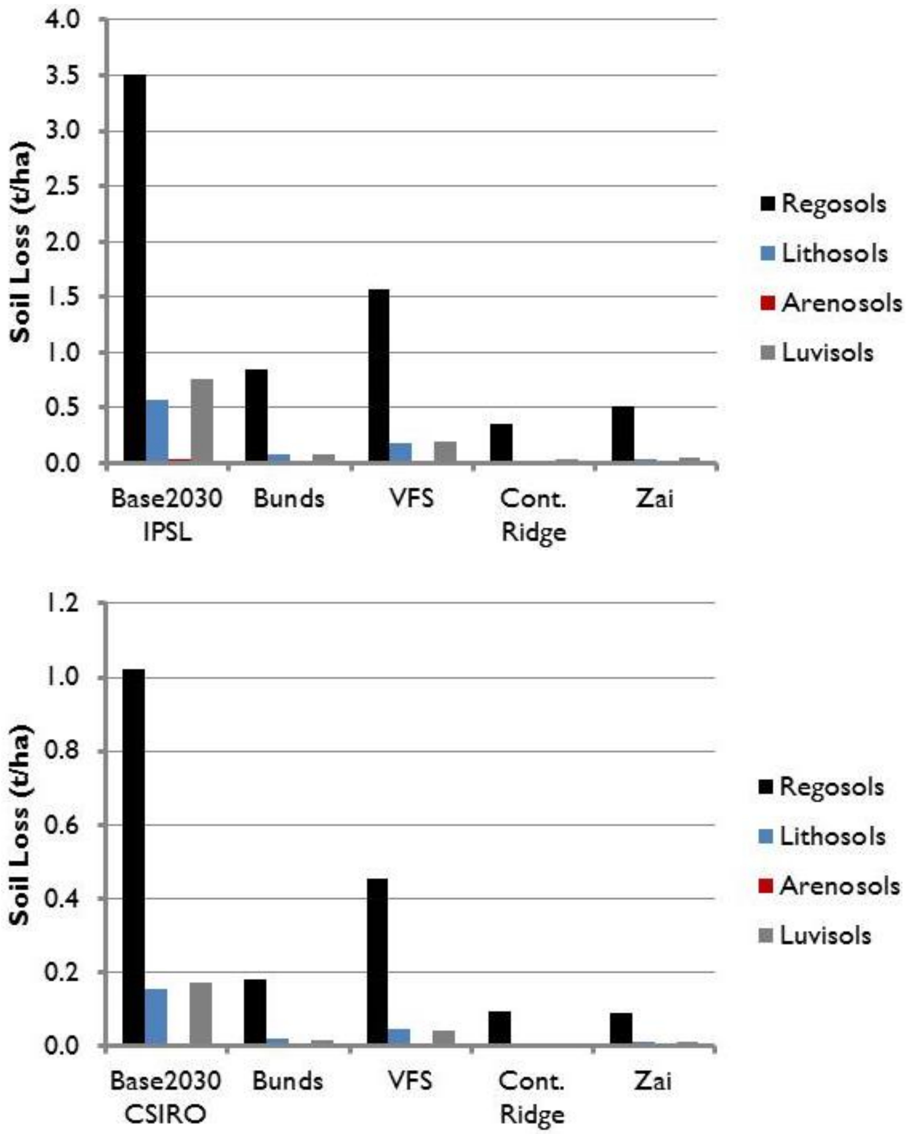


Soil loss on maize fields

Soil loss without water harvesting practices was largest on the steepest soil (regosols) for both the ISPL and CSIRO generated 2030 climatic conditions (Figure A.49). As expected, soil loss was much greater on regosols under the much wetter ISPL 2030 climate relative to the drier CSIRO 2030 climate. For the relatively fertile lithosols and luvisols, soil loss was smaller under both climatic scenarios as a result of increased crop biomass and better soil cover in comparison to the less fertile regosols. Soil loss was smallest under arenosols, which had extremely high infiltration rates and little runoff.

Water harvesting practices were very effective at reducing soil loss relative to 2030 baseline climatic conditions on all soils under both the IPSL (reductions ranged from 55–95 percent) and CSIRO (reductions ranged from 56–96 percent) generated 2030 climatic conditions (Figure A.49). Reductions in soil loss are directly related to the effectiveness of these practices at reducing runoff (Figure A.45). The most effective water harvesting practice was contour ridges, followed by *zai*, followed by bunds, and vegetated filter strips. Effectiveness of these practices was greater on lithosols and luvisols than on the steeper regosols.

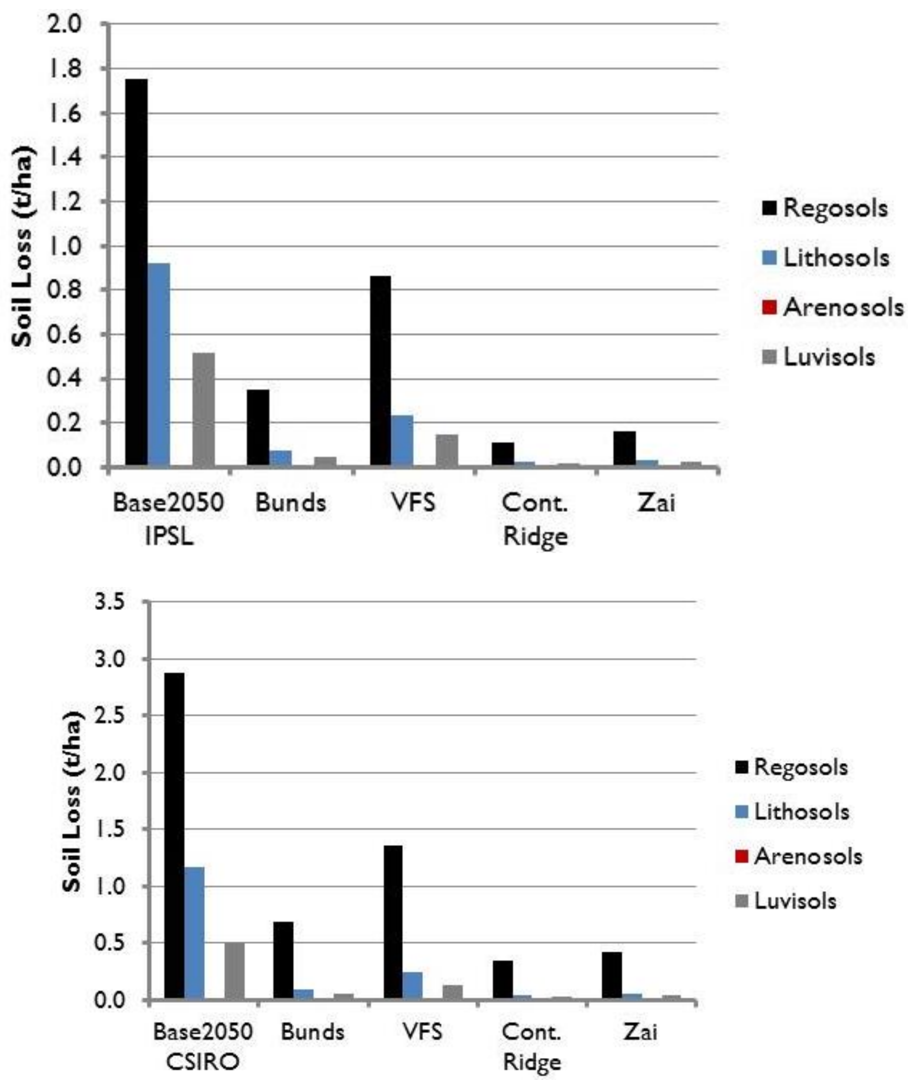
FIGURE A.49: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER MAIZE FOR THE FOUR SOILS EVALUATED USING IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA



Soil loss without water harvesting practices was largest on the steepest soil (regosols) for both the ISPL and CSIRO generated 2050 climatic conditions (Figure 50). Due to increases in crop biomass (Figure A.48), soil loss was smaller on regosols under the wetter ISPL 2050 climate relative to soil loss with the drier CSIRO 2050 climate. For the relatively fertile lithosols and luvisols, soil loss was smaller under both climatic scenarios as a result of increased crop biomass and better soil cover in comparison to the less fertile regosols. Soil loss was smallest under arenosols, which had extremely high infiltration rates and little runoff.

Water harvesting practices were very effective at reducing soil loss relative to 2050 baseline climatic conditions on all soils under both the IPSL (reductions ranged from 51–97 percent) and CSIRO (reductions ranged from 53–96 percent) generated 2050 climatic conditions (Figure A.50). Reductions in soil loss are directly related to the effectiveness of these practices at reducing runoff (Figure A.46). Contour ridges and *zai* holes were the most effective water harvesting techniques and equivalent to each other; both were more effective than bunds, which were, in turn, more effective than vegetated filter strips. The effectiveness of these practices was slightly greater on lithosols and luvisols than on the steeper regosols.

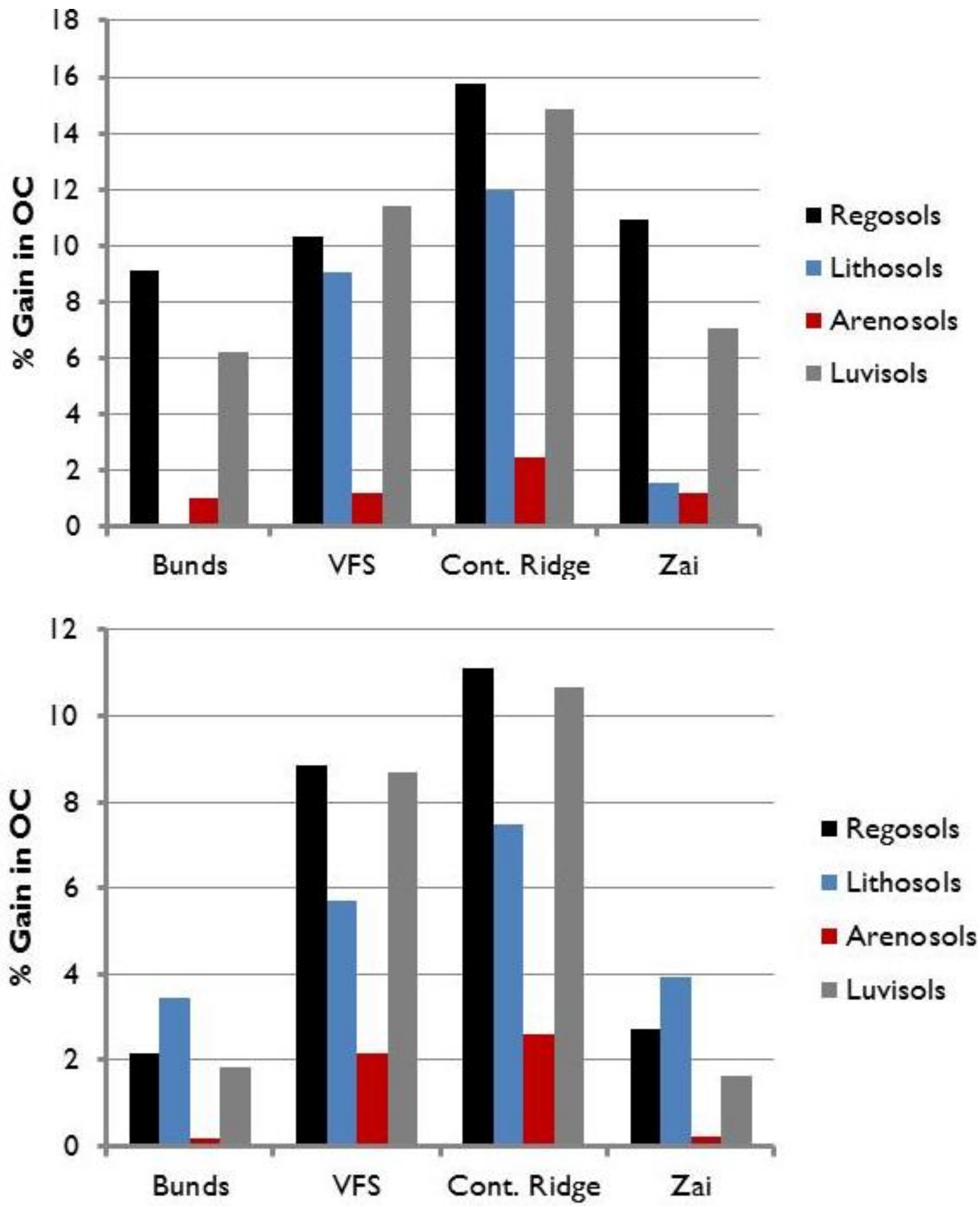
FIGURE A.50: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER MAIZE FOR THE FOUR SOILS EVALUATED USING IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA



Soil organic carbon on maize fields

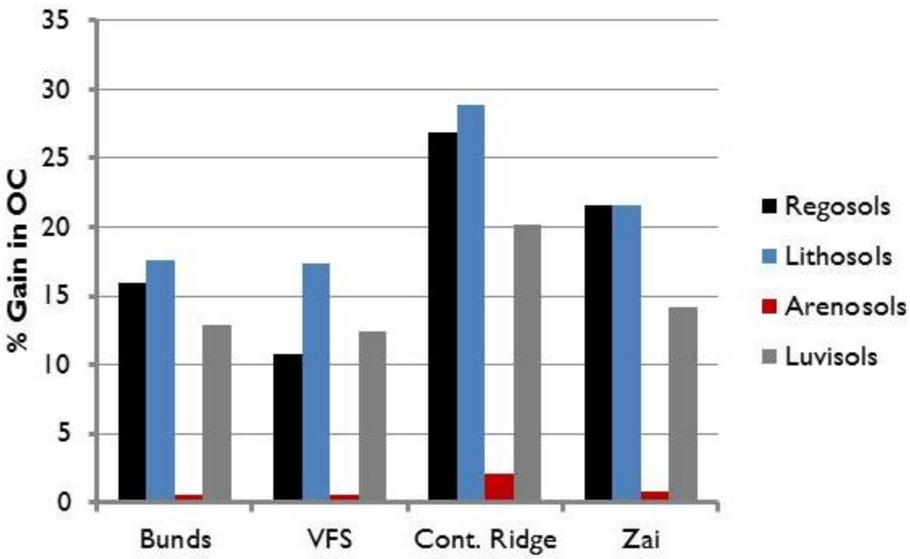
Water harvesting practices increased soil organic carbon by 0–16 percent for IPSL 2030 climatic conditions and by 0–11 percent for CSIRO 2030 climatic conditions (Figure A.51). These gains are in proportion to the level of reductions in erosion relative to reductions without these practices, as well as in proportion to increases in crop biomass returned to the soil after crop harvest. The biggest gains occurred with contour ridges, particularly on steep regosols, and to a lesser extent on flatter luvisols and lithosols. Vegetated filter strips were also effective at increasing soil organic carbon, while *zai* and bunds were the least effective conservation practices.

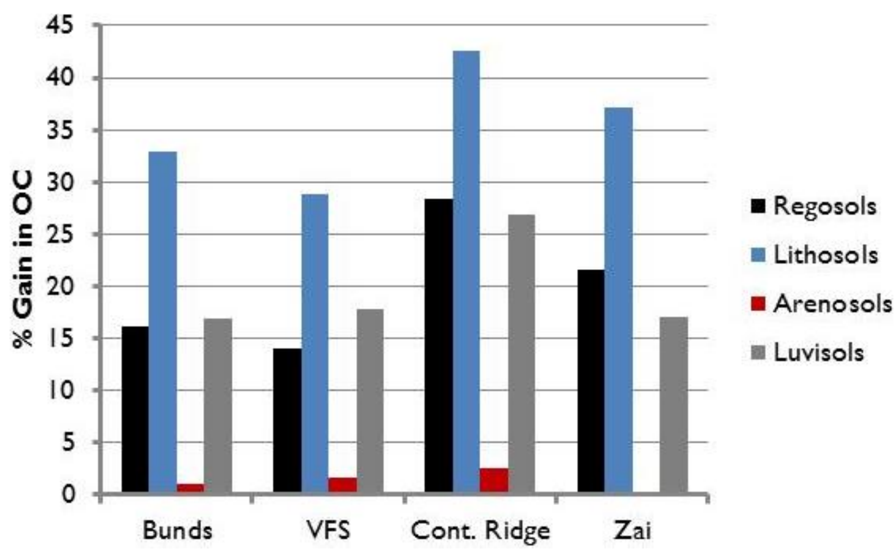
FIGURE A.51: INCREASE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM REDUCTIONS IN SOIL LOSS WITH MAIZE USING IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA



Water harvesting practices increased soil organic carbon by from 0–29 percent for IPSL 2050 climatic conditions and by 0–43 percent for CSIRO 2050 climatic conditions (Figure A.52). These gains are in proportion to the level of reductions in erosion relative to reductions without these practices, as well as in proportion to increases in crop biomass returned to the soil after crop harvest. Changes in soil organic carbon are also affected by mineralization, which tends to increase with temperature, and by decomposition of crop residue. The biggest gains occurred with contour ridges, particularly on lith osols, and to a lesser extent on flatter luvisols and steeper regosols. *Zai* were also effective at increasing soil organic carbon, while bunds and vegetated filter strips were the least effective conservation practices. Improved performance of zai and vegetated filter strips in the 2050 climatic scenarios relative to the 2030 climate scenarios were due to decreased rainfall and erosion in the 2050 scenarios.

FIGURE A.52: INCREASE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM REDUCTIONS IN SOIL LOSS WITH MAIZE USING IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA





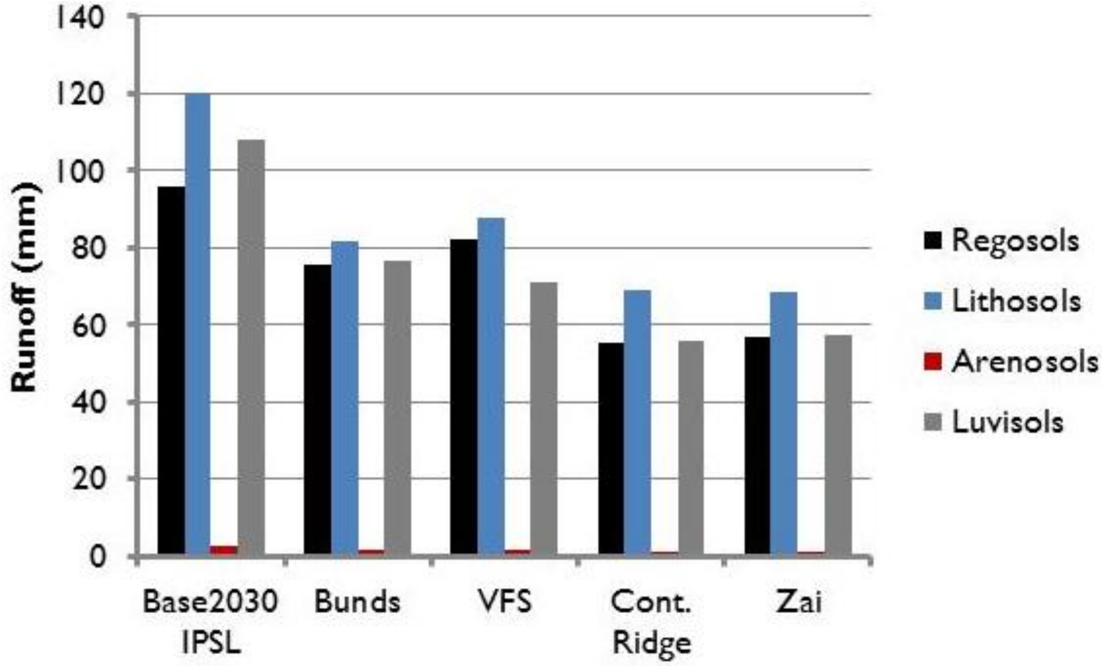
Impact of rainwater harvesting practices on millet under future climatic scenarios

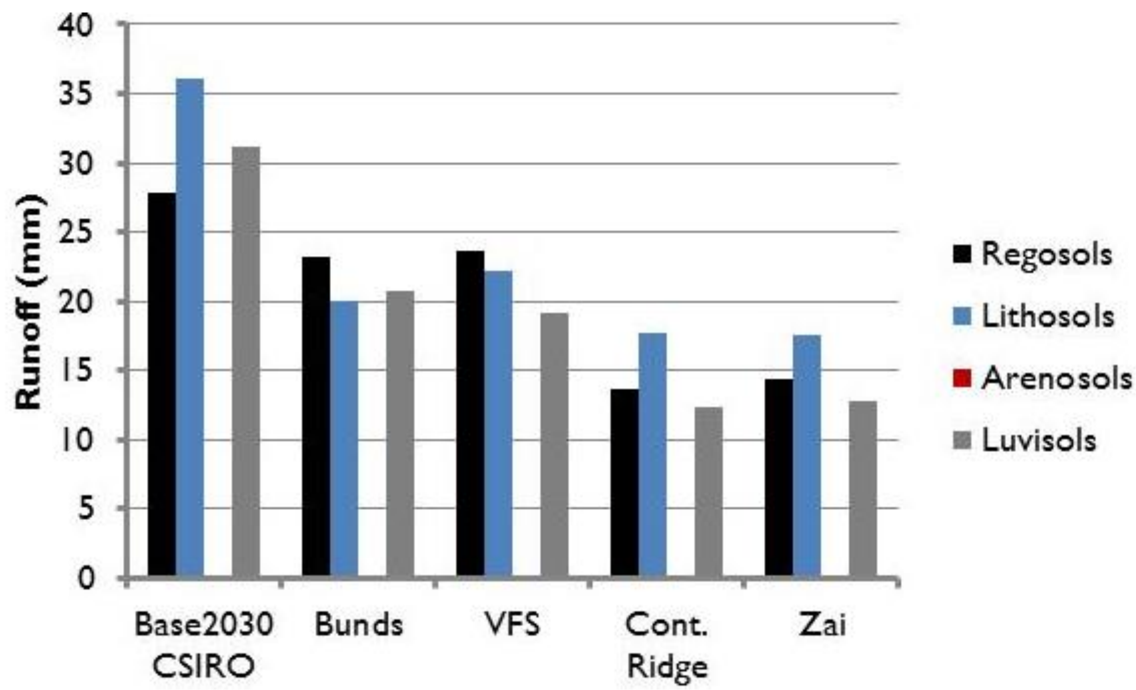
Runoff on millet fields

Runoff for millet without any conservation practices on finer textured soils (the regosols, lithosols, and luvisols) with 2030 future climatic scenarios averaged from about 96 to 120 millimeters with the IPSL climatic model, and from about 28 to 36 millimeters with the CSIRO model (Figure A.53). In contrast, baseline runoff with 1991–2000 climatic data averaged from 61–70 millimeters (Figure A.28). These differences are largely driven by differences in annual precipitation, as explained in the discussion on runoff on maize fields.

Runoff was extremely low on sandy arenosols with both 2030 ISPL and CSIRO climatic data (Figure A.45). Rainwater harvesting practices caused changes in runoff in comparison to conditions without water harvesting. As with maize, for millet, surface runoff decreased relative to runoff without water harvesting practices, particularly for finer textured soils (Figure A.53). Although, unlike when planted in maize, contour ridges and *zai* holes were equally effective at reducing surface runoff with millet on finer textured soils; these practices were more effective than either bunds or vegetated filter strips, which were roughly equivalent in their effectiveness. On finer texture soils during the relatively wet climatic conditions generated by the 2030 IPSL model, contour ridges decreased surface runoff by 28–42 percent; *zai* holes by 28–41 percent; bunds by 15–21 percent; and vegetated filter strips by 9–26 percent. In contrast, contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 37–56 percent, 37–54 percent, 17–28 percent, and 15–31 percent, respectively, on finer texture soils during the relatively drier climatic conditions generated by the 2030 CSIRO model. Thus, as with maize, while the ranked order of effectiveness for water harvesting practices was the same using both 2030 climatic prediction scenarios, the effectiveness of a particular water harvesting practice was somewhat greater during drier years than wetter years.

FIGURE A.53: SURFACE RUNOFF FOR MILLET GROWN ON DIFFERENT SOILS FOR IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA WITH AND WITHOUT RAINWATER HARVESTING PRACTICES SUCH AS BUNDS, VEGETATIVE FILTER STRIPS (VFS), CONTOUR RIDGES AND *ZAI*

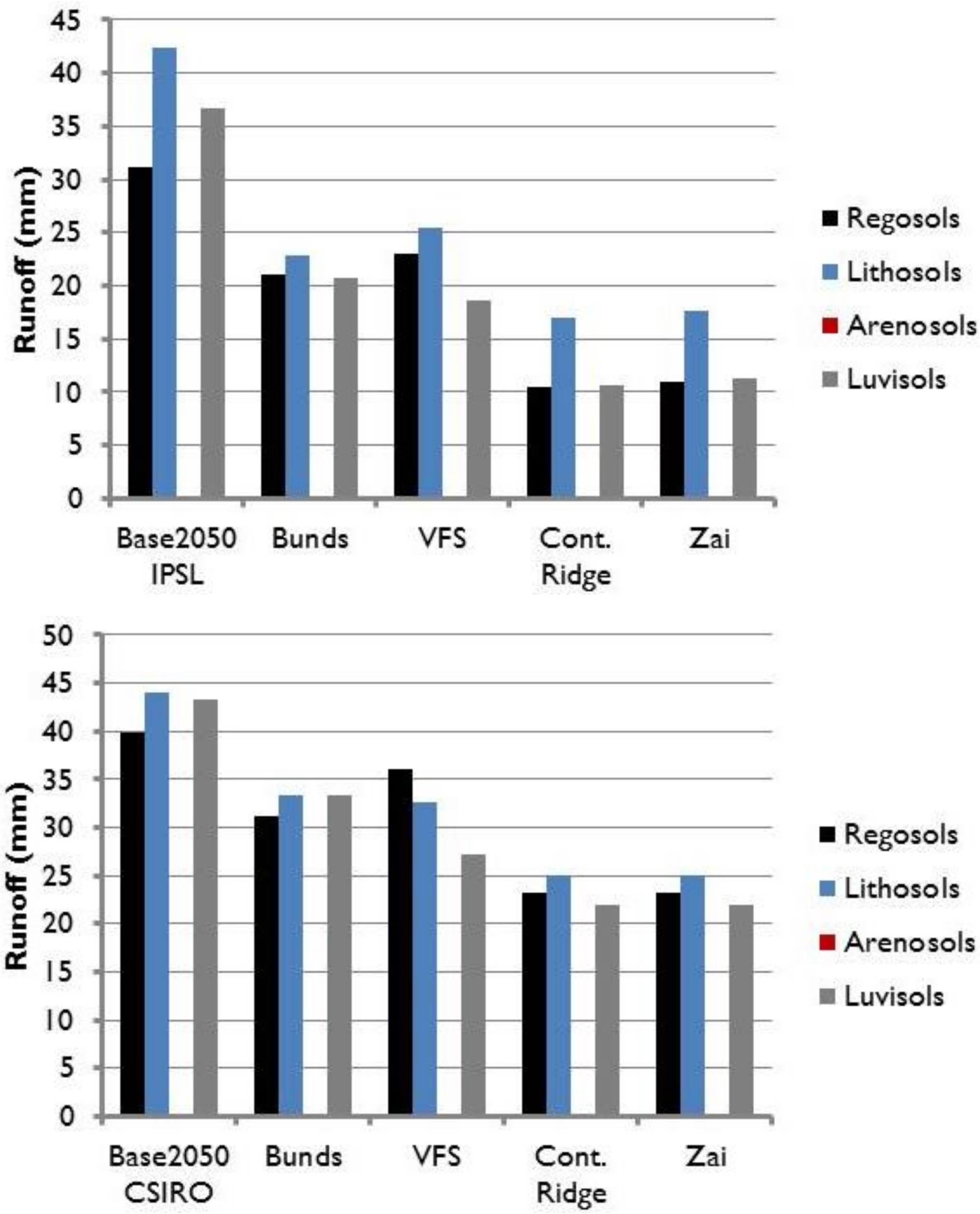




Runoff for millet without any conservation practices on finer textured soils with 2050 future climatic scenarios averaged from about 31 to 42 millimeters with the IPSL climatic model, and from about 40 to 44 millimeters with the CSIRO model (Figure A.54). In contrast, baseline runoff with 1991–2000 climatic data averaged from 61–70 millimeters (Figure A.28). These differences are largely driven by differences in annual temperatures and the frequency of heavy rain events rather than differences in annual precipitation, which averaged 527 millimeters using baseline data, versus 524 millimeters and 500 millimeters with the 2050 IPSL and CSIRO climate predictions, respectively. The decrease in runoff that occurred with the 2050 IPSL model are reasonable in view of the fact that annual precipitation with this scenario is very similar to precipitation under baseline conditions, but mean annual temperature was 1.5 °C warmer than baseline conditions. The decreases in runoff that occurred with the 2050 CSIRO model are largely driven by a decrease in annual precipitation relative to baseline conditions, as well as by a warming of 1.0 °C and a decrease in the frequency of heavy rain events relative to baseline climatic data. Runoff was extremely low on sandy arenosols with both 2050 ISPL and CSIRO climatic data (Figure A.54).

Rainwater harvesting practices caused changes in runoff with 2050 climatic data in comparison with conditions without water harvesting. For millet, surface runoff decreased relative to runoff without water harvesting practices, particularly for finer textured soils (Figure A.54). Contour ridges and *zai* holes were equally effective at reducing surface runoff with millet on finer textured soils; these practices were both more effective than either bunds or vegetated filter strips, which were roughly equivalent in their effectiveness. This is equivalent to the order of relative effectiveness that was observed using 2030 climatic data. Contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 45–66 percent, 44–65 percent, 27–34 percent, and 18–40 percent, respectively, on finer texture soils during the relatively wet climatic conditions generated by the 2050 IPSL model. In contrast, contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 37–45 percent, 37–42 percent, 16–22 percent, and 9–32 percent, respectively, on finer texture soils during the relatively drier climatic conditions generated by the 2050 CSIRO model. Thus, while the ranked order of effectiveness for water harvesting practices was the same using both 2050 climatic prediction scenarios, the effectiveness of a particular water harvesting practice was generally somewhat greater with the IPSL generated climate than the CSIRO climate.

FIGURE A.54: SURFACE RUNOFF FOR MILLET GROWN ON DIFFERENT SOILS FOR IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA WITH AND WITHOUT RAINWATER HARVESTING PRACTICES SUCH AS BUNDS, VEGETATIVE FILTER STRIPS (VFS), CONTOUR RIDGES AND *ZAI*



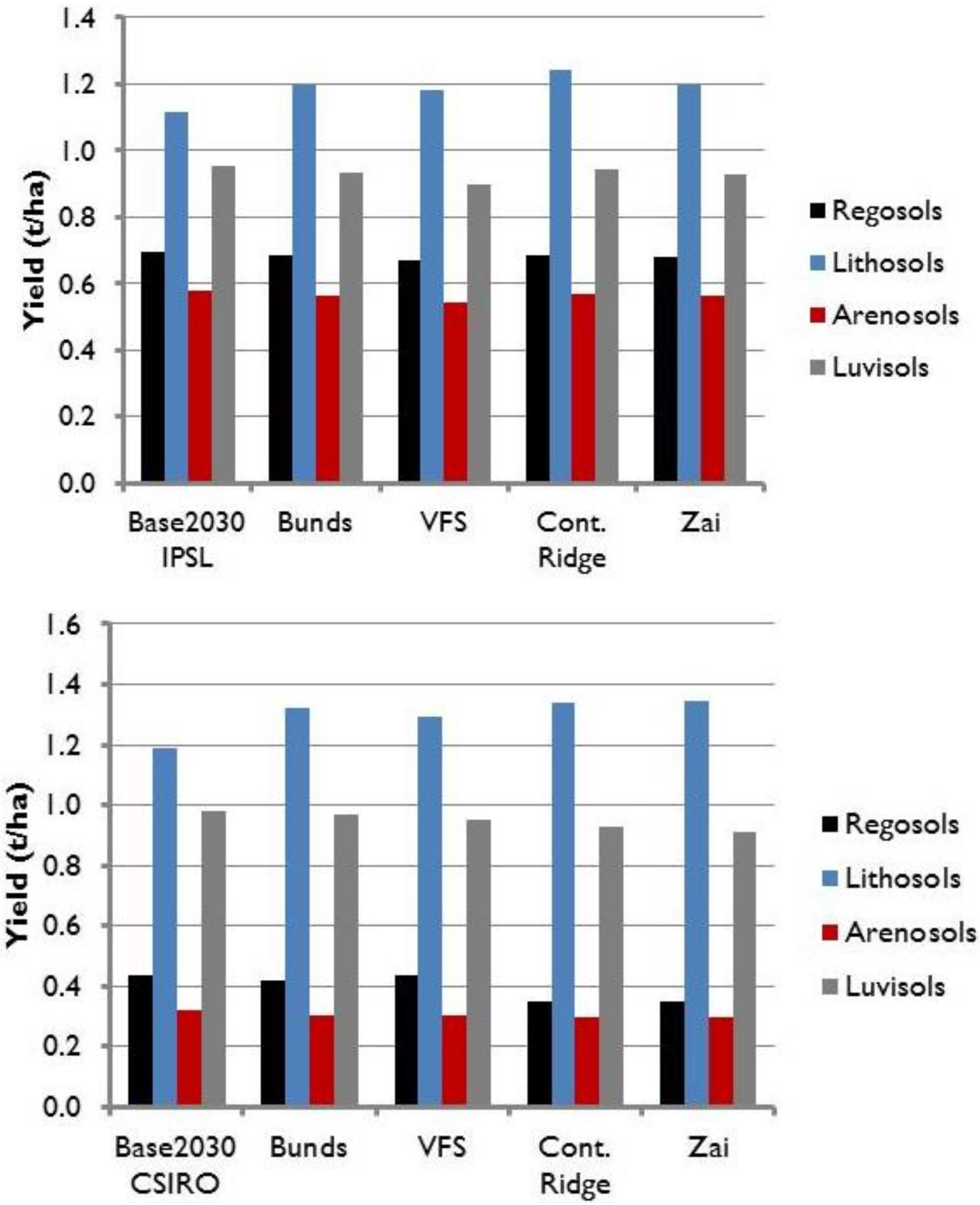
Millet yields

Millet yields under IPSL and CSIRO based 2030 climatic conditions (628 and 563 millimeters) without water harvesting practices (Figure A.55) were larger on lithosols (1.1 and 1.19 tons/hectare) and luvisols (0.95 and 0.98 tons/hectare) than yields under measured 1991–2000 climatic conditions (527 millimeters) on the same soils (0.53 and 0.29 tons/hectare) without water harvesting practices. Millet yields under 2030 climatic conditions without water harvesting practices on regosols and arenosols (0.32 to 0.69 tons/hectare) were also larger than yields under 1991–2000 conditions without these practices (0.33 and 0.28 tons/hectare) on the same soils, but not to the same extent as on the more fertile lithosols and luvisols. It is reasonable for millet yields on the more fertile lithosols and luvisols to increase under the wetter ISPL and CSIRO based 2030 climatic conditions (628 and 563 millimeters), and for millet yields to increase somewhat less on soils with poorer fertility. Millet is not as sensitive as maize to periods of soil saturation that occurred during the very wet ISPL 2030 conditions.

Rainwater harvesting practices were only effective at improving millet yields on the more fertile lithosols (Figure A.55) for the relatively wet IPSL generated 2030 climatic data relative to yields without these practices with the same climatic data. Millet yield on lithosols increased by 6–12 percent with water harvesting practices, relative to yields without these practices for IPSL 2030 climatic data. Millet yields on lithosols, regosols and arenosols decreased by 1–6 percent with water harvesting practices due to an exacerbation of waterlogging effects with IPSL 2030 climatic data. These reductions, however, were less serious than those that occurred with maize. To summarize, water harvesting practices were only effective at increasing millet yields on lithosols, and were detrimental to millet yields on all other soils under the very wet IPSL 2030 climatic conditions.

Water harvesting practices had a similar impact on millet yields under CSIRO 2030 climatic conditions as under IPSL 2030 climatic conditions. Millet yield on lithosols increased by 9–13 percent with water harvesting practices relative to yields without these practices for CSIRO 2030 climatic data. On all other soils, water harvesting practices decreased millet yields by 0–19 percent using CSIRO 2030 climatic data relative to yields on the same soils without these practices. Thus, water harvesting practices were effective at increasing millet yields on only lithosols under CSIRO 2030 climatic data: millet yields on other soils were decreased due to excess soil moisture captured by these practices.

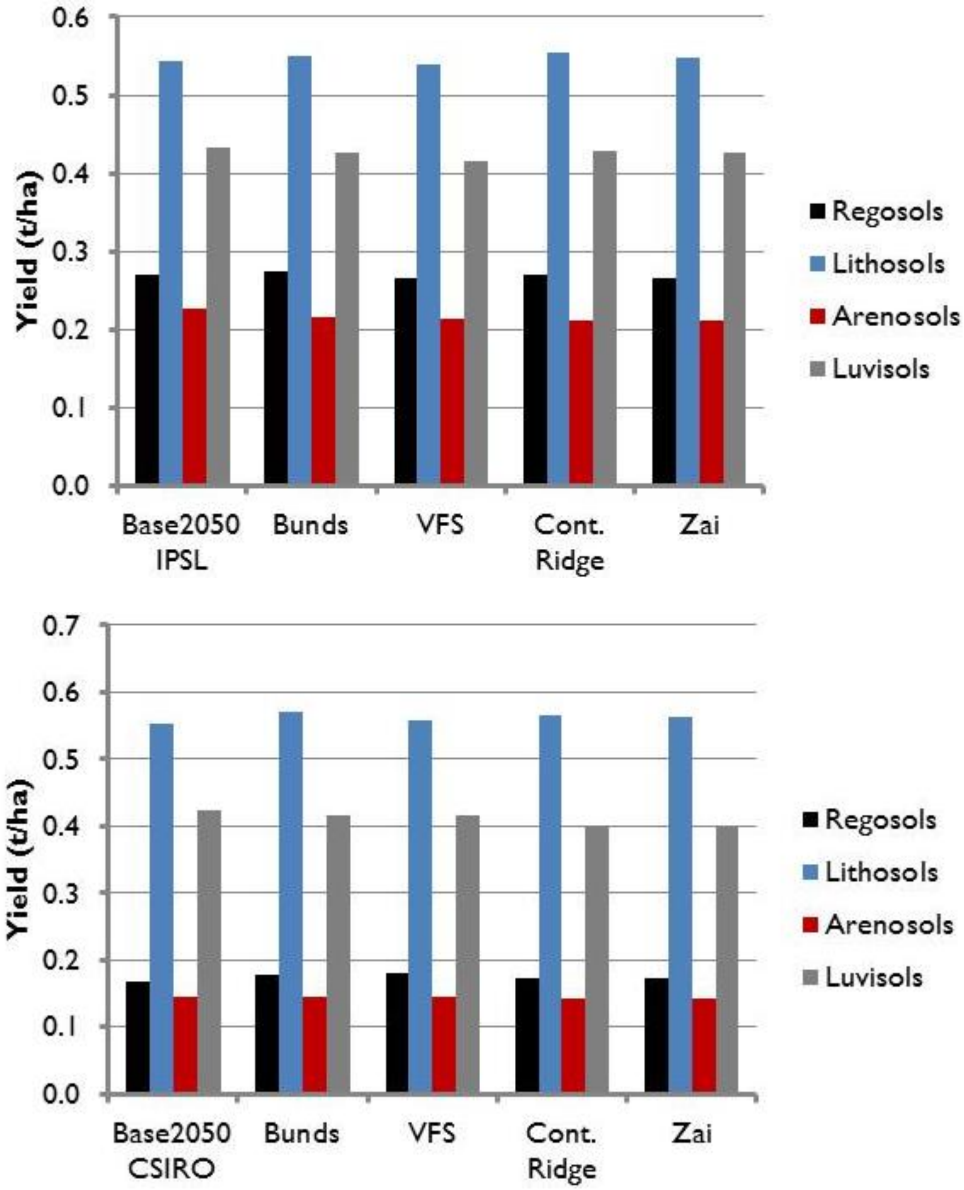
FIGURE A.55: MILLET YIELD FOR IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES



Millet yields under IPSL and CSIRO based 2050 climatic conditions (524 and 500 millimeters) without water harvesting practices (Figure A.56) on relatively fertile lithosols (0.54 and 0.55 tons/hectare) and luvisols (0.43 and 0.42 tons/hectare) were comparable to or greater than yields under measured 1991–2000 climatic conditions (527 millimeters) on the same soils (0.53 and 0.29 tons/hectare) without water harvesting practices. In contrast millet yields under 2050 climatic conditions without water harvesting practices were from 10 percent to 50 percent less than yields on regosols and arenosols under 1991 – 2000 conditions without these practices. It is reasonable for millet yields on the more fertile lithosols and luvisols to be similar to yields under baseline climatic conditions for ISPL based 2050 climatic conditions (524 millimeters), but it is surprising that millet yields for CSIRO based 2050 climatic conditions (500 millimeters) were greater than millet yields under baseline climatic conditions (527 millimeters). Millet yield with the CSIRO 2050 climate data should decrease in response to decreases in precipitation combined with warmer annual temperatures. The explanation for this surprising result is that there was an unfavorable intra-season distribution of rainfall under baseline climatic conditions relative to the 2050 climatic scenario. It is reasonable for millet yields on the less fertile regosols and arenosols to exhibit small to moderate decreases for 2050 climatic conditions without water harvesting practices relative to yields on the same soils with baseline climatic conditions, because yields on these soils are limited by a combination of water stress, heat stress, and nutrient stress.

Rainwater harvesting practices were relatively ineffective at improving millet yields on all soils (Figure A.56) for the both the IPSL and CSIRO generated 2050 climatic data relative to yields without these practices with the same climatic data. Millet yield with water harvesting practices ranged between +1 percent to -6 percent of yields without these practices for IPSL 2050 climatic data, and between +7 percent and -6 percent for CSIRO 2050 climatic data. The ineffectiveness of water harvesting practices is likely related to a large increase in mean annual temperature, combined with the lack of sufficient precipitation that characterizes these scenarios. To summarize, while millet yields demonstrated a significant response to all four practices under baseline climate conditions in lithosols and luvisols, water harvesting practices were not very effective at increasing millet yields on any soil under IPSL or CSIRO 2050 climatic conditions due to the effects of increased temperature on millet yield and soil moisture balances.

FIGURE A.56: MILLET YIELD FOR IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES

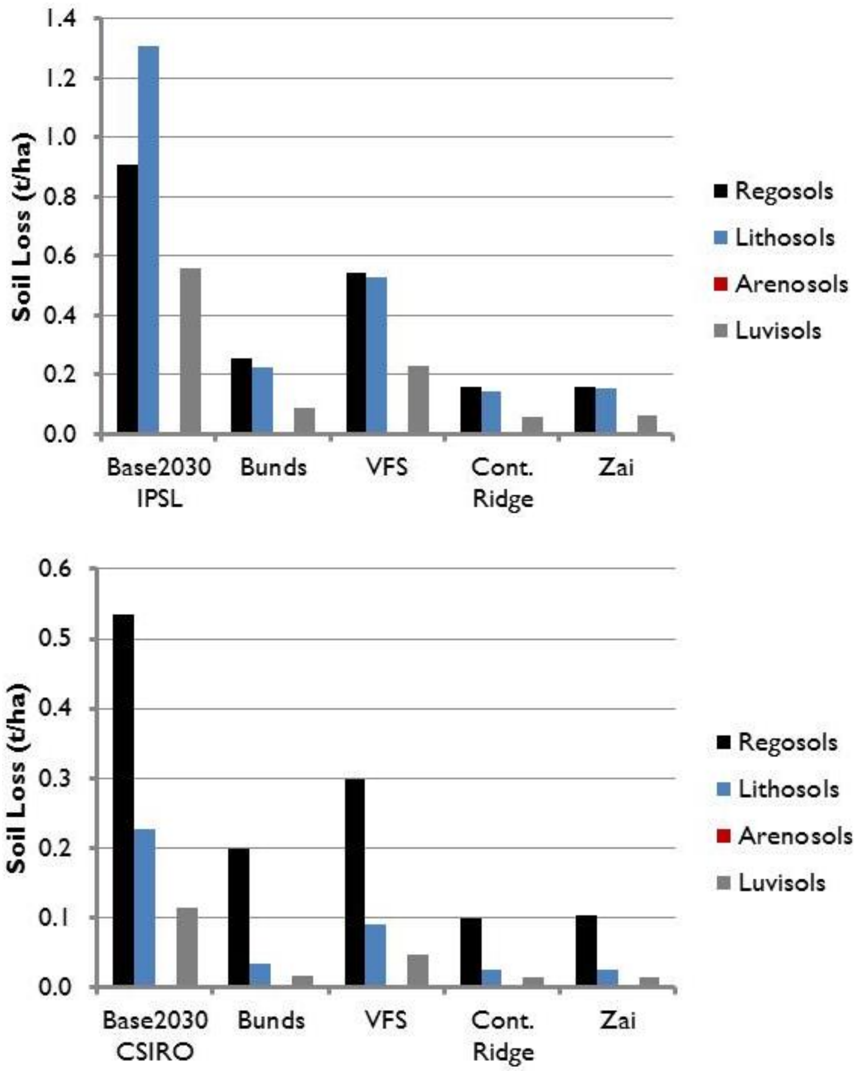


Soil loss on millet fields

Soil loss without water harvesting practices was larger on all soils for the wetter IPSL generated 2030 climatic conditions relative to soil loss under the drier CSIRO generated 2030 climatic conditions (Figure A.57). Patterns in soil loss were affected both by amounts of runoff from each soil (Figure A.53) as well as by changes in crop biomass (Figure A.55) and soil cover. Soil loss was smallest under arenosols, which had extremely high infiltration rates and little runoff. Water harvesting practices were very effective at reducing soil loss on all soils under both the IPSL (reductions ranged from 40–90 percent) and CSIRO (reductions ranged from 44–90 percent) generated 2030 climatic conditions (Figure

A.57) relative to 2030 baseline climatic conditions. Reductions in soil loss are directly related to the effectiveness of these practices at reducing runoff (Figure A.53). Contour ridges and *zai* were equally effective at reducing soil loss; both were more effective than bunds, which were, in turn, more effective than vegetated filter strips. The effectiveness of these practices was greater on lithosols and luvisols than on the steeper regosols.

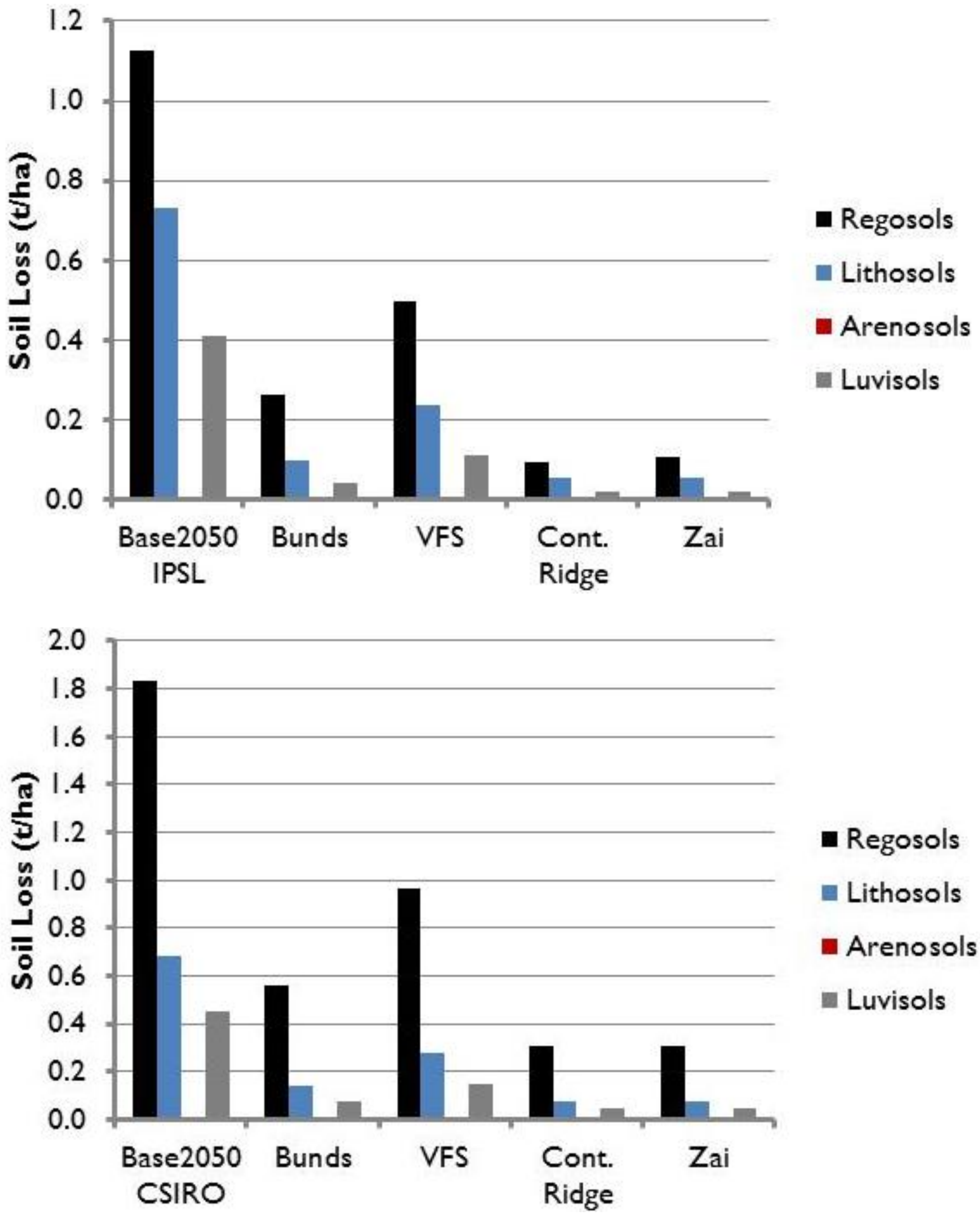
FIGURE A.57: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER MILLET FOR THE FOUR SOILS EVALUATED USING IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA



Soil loss without water harvesting practices was largest on the steepest soil (regosols) for both the ISPL and CSIRO generated 2050 climatic conditions (Figure A.58). Due to increases in crop biomass (Figure A.56), soil loss was smaller on regosols under the wetter ISPL 2050 climate relative to soil loss with the drier CSIRO 2050 climate. For the relatively fertile lithosols and luvisols, soil loss was smaller under both climatic scenarios as a result of increased crop biomass and better soil cover (even though runoff was slightly larger) in comparison to the less fertile regosols. Soil loss was smallest under arenosols, which had extremely high infiltration rates and little runoff.

Water harvesting practices were very effective at reducing soil loss relative to 2050 baseline climatic conditions on all soils under both the IPSL (reductions ranged from 56–96 percent) and CSIRO (reductions ranged from 47–90 percent) generated 2050 climatic conditions (Figure A.58). Reductions in soil loss are directly related to the effectiveness of these practices at reducing runoff (Figure A.54). The effectiveness of water harvesting practice decreased in the following order: contour ridges and *zai holes* were equally effective; both were more effective than bunds, which were, in turn, more effective than vegetated filter strips. The effectiveness of these practices was slightly greater on lithosols and luvisols than on the steeper regosols.

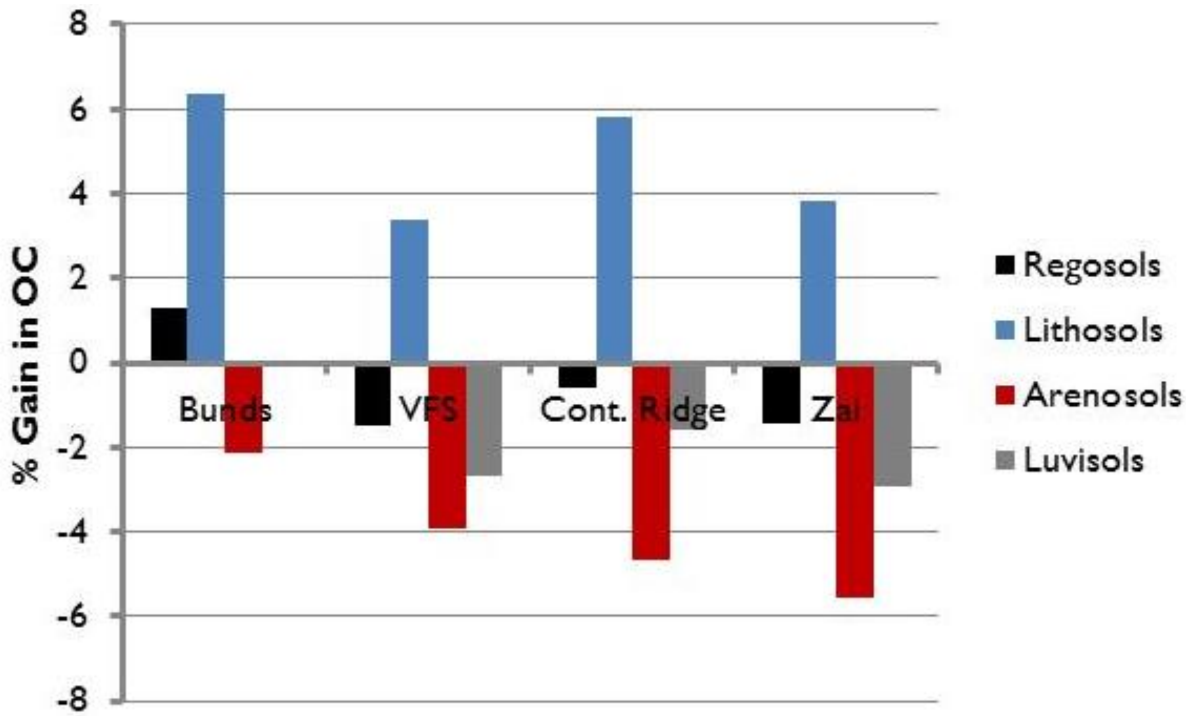
FIGURE A.58: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER MILLET FOR THE FOUR SOILS EVALUATED USING IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA

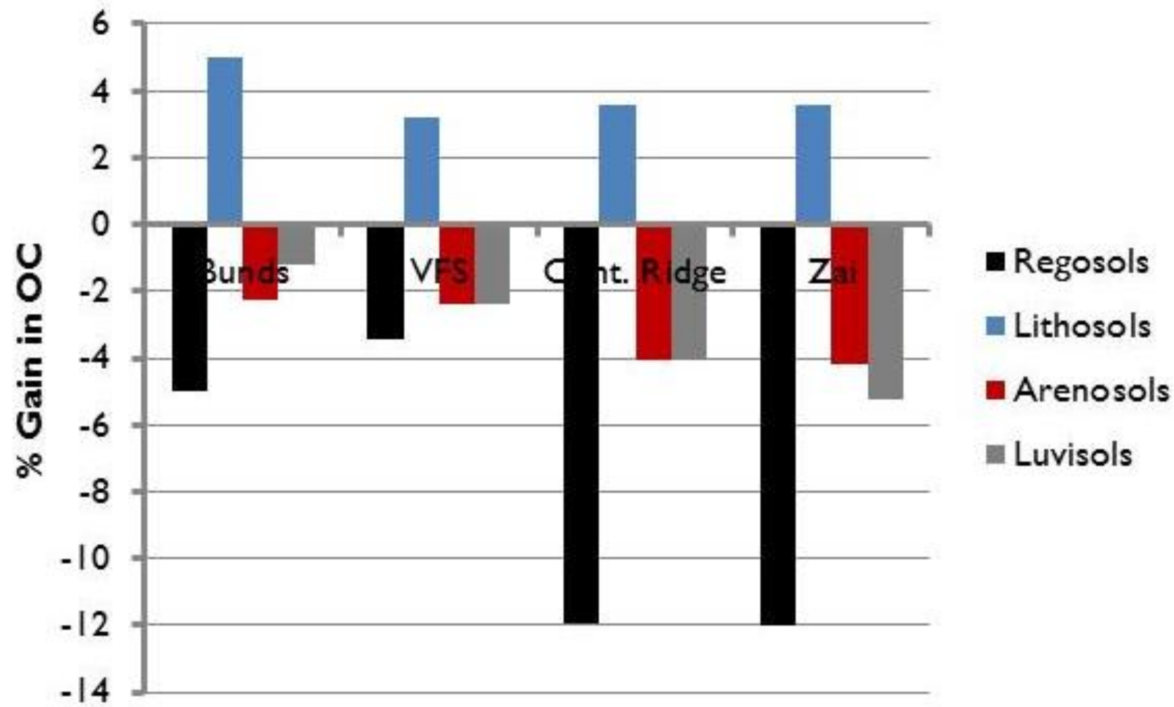


Soil organic carbon levels on millet fields

Water harvesting practices had mixed impacts on soil organic carbon levels for IPSL and CSIRO 2030 climatic conditions (Figure A.59). For lithosols there were gains in soil organic carbon on the order of 3–6 percent relative to baseline conditions without these practices. For the other soils, and in particular for regosols, there were decreases in soil organic carbon levels. Erosion losses were larger on regosols than the other soils for all water harvesting practices, leading to losses in soil organic carbon. It is not completely clear why soil organic carbon levels increased on some soils and decreased on others for millet grown under IPSL and CSIRO 2030 climatic conditions, but the changes are small. Although changes in soil organic carbon are dominated by soil erosion rates, other factors that could influence changes in soil organic carbon levels include temperature, decomposition rates of crop residue, and soil mineralization. Climate affects each of these processes. In general, the model appears to be accurate in predicting changes in soil organic carbon content and the resulting impacts of these changes on crop yield.

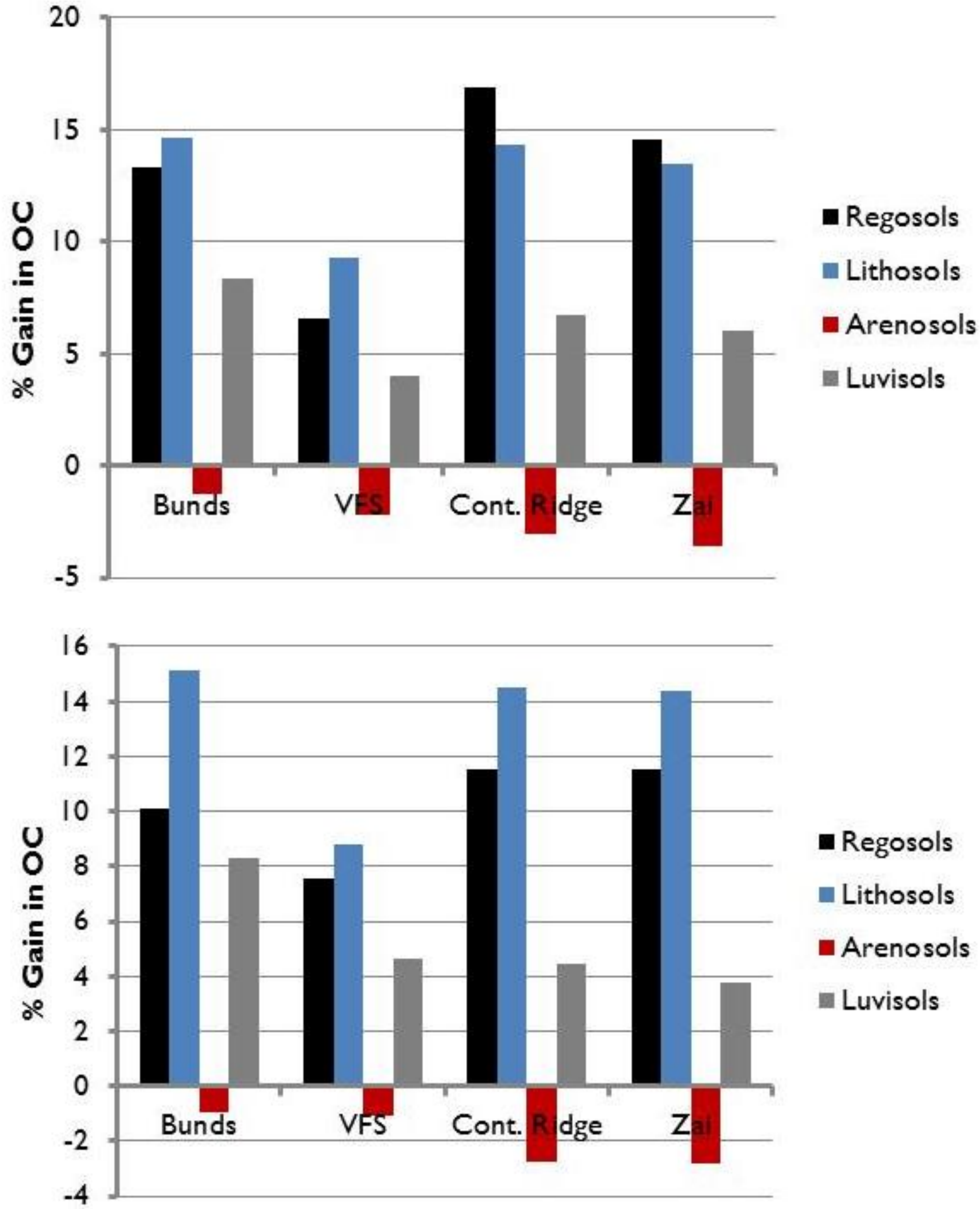
FIGURE A.59: CHANGE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM REDUCTIONS IN SOIL LOSS WITH MILLET USING IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA





Water harvesting practices were effective at increasing soil organic carbon on regosols, lithosols, and luvisols for IPSL and CSIRO 2050 climatic conditions, but were not effective at increasing organic carbon on arenosols (Figure A.60). When gains occurred, they were in proportion to the level of reductions in erosion relative to reductions without these practices, as well as in proportion to increases in crop biomass returned to the soil after crop harvest. The biggest gains occurred with contour ridges, bunds and *zai* particularly on the steeper regosols and lithosols. Vegetated filter strips were the least effective conservation practice for improving soil fertility.

FIGURE A.60: INCREASE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM REDUCTIONS IN SOIL LOSS WITH MILLET USING IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA

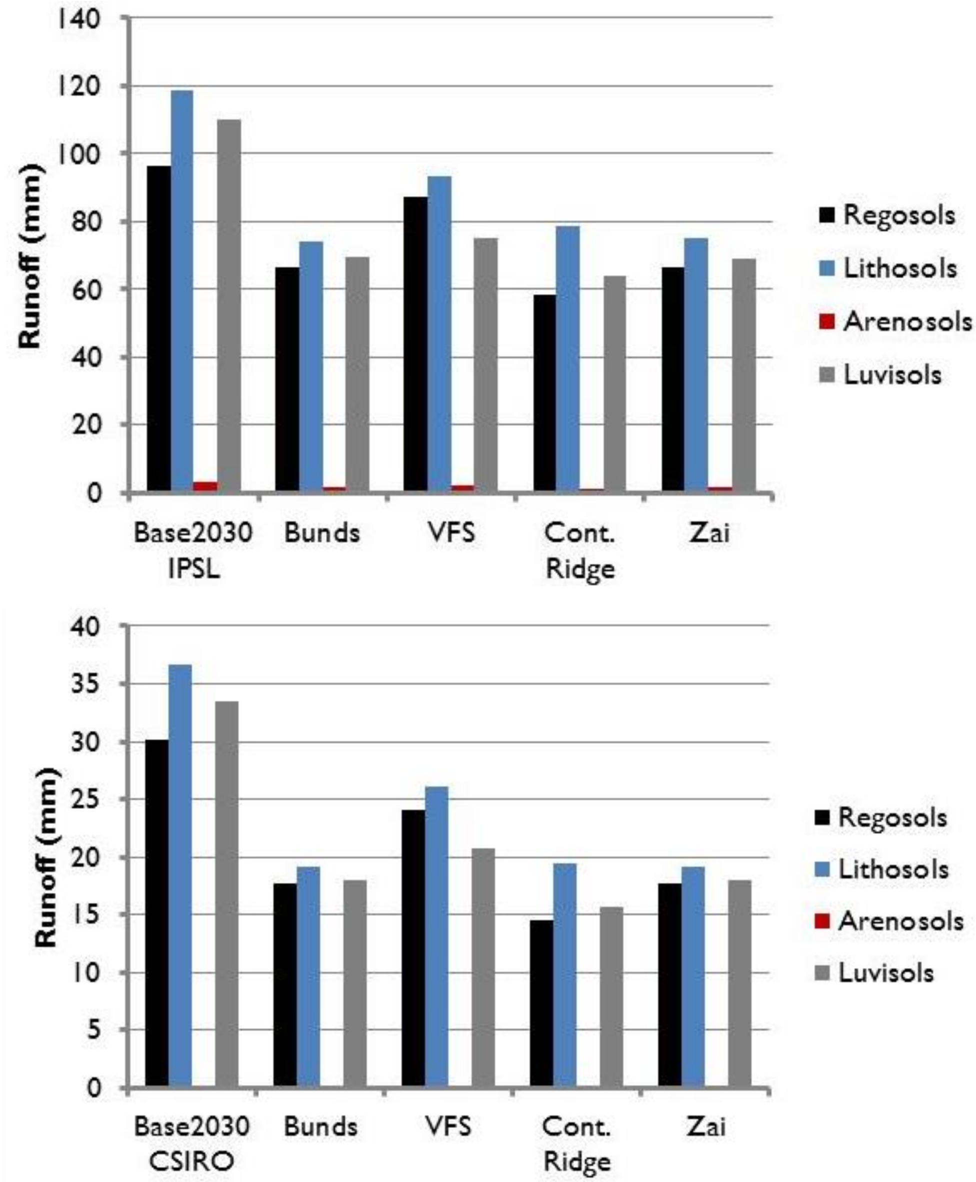


Impact of rainwater harvesting practices on sorghum under future climatic scenarios

Runoff on sorghum fields

Runoff for sorghum without any conservation practices on finer textured soils (the regosols, lithosols, and luvisols) with 2030 future climatic scenarios averaged from about 96 to 119 millimeters with the IPSL climatic model, and from about 30 to 37 millimeters with the CSIRO model (Figure A.61). In contrast, baseline runoff with 1991–2000 climatic data averaged from 61–70 millimeters (Figure A.28). These differences are largely driven by differences in annual precipitation, as explained in the discussion on runoff on maize fields. Runoff was extremely low on sandy arenosols with both 2030 ISPL and CSIRO climatic data (Figure A.61).Rainwater harvesting practices caused changes in runoff in comparison to conditions without water harvesting. For sorghum, surface runoff decreased relative to runoff without water harvesting practices, particularly for finer textured soils (Figure A.61). Contour ridges, *zai* holes, and bunds were equally effective at reducing surface runoff with sorghum on finer textured soils, and all three were more effective than vegetative filter strips. Contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 18–39 percent, 22–31 percent, 23–31 percent, and 3–22 percent respectively, on finer texture soils during the relatively wet climatic conditions generated by the 2030 IPSL model. In contrast, contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 36–52 percent, 37–42 percent, 37–42 percent, and 13–31 percent respectively, on finer texture soils during the relatively drier climatic conditions generated by the 2030 CSIRO model. Thus, while the ranked order of effectiveness for water harvesting practices was the same using both 2030 climatic prediction scenarios, the effectiveness of a particular water harvesting practice was generally greater during drier years than wetter years.

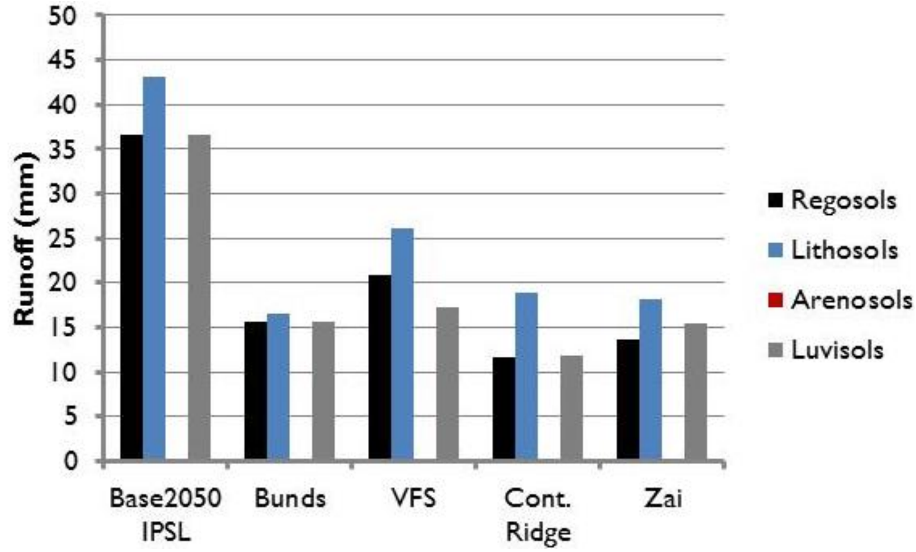
FIGURE A.61: SURFACE RUNOFF FOR SORGHUM GROWN ON DIFFERENT SOILS FOR IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA WITH AND WITHOUT RAINWATER HARVESTING PRACTICES SUCH AS BUNDS, VEGETATIVE FILTER STRIPS (VFS), CONTOUR RIDGES AND *ZAI*

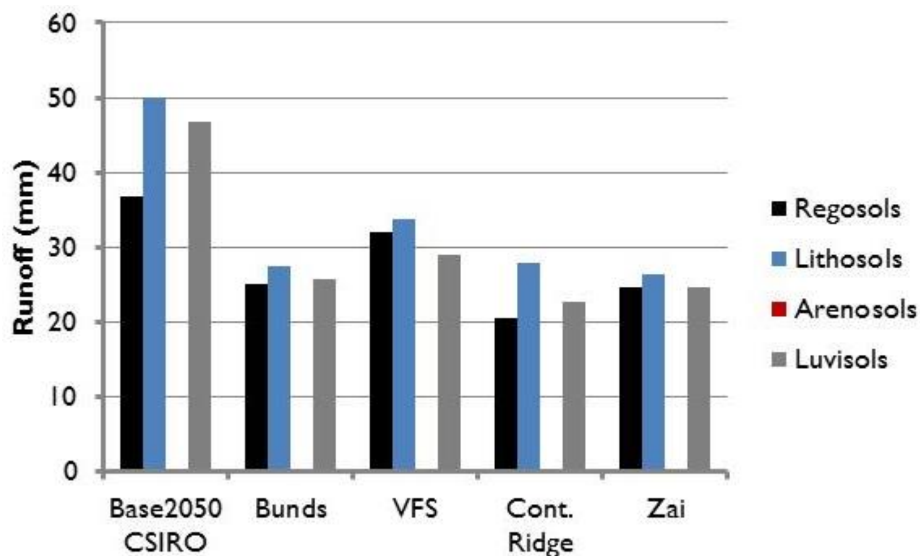


Runoff for sorghum without any conservation practices on finer textured soils with 2050 future climatic scenarios averaged from about 36 to 43 millimeters with the IPSL climatic model, and from about 40 to 44 millimeters with the CSIRO model (Figure A.62). In contrast, baseline runoff with 1991–2000 climatic data averaged from 61–70 millimeters (Figure A.28). These differences are largely driven by differences in annual temperatures and the frequency of heavy rain events rather than differences in annual precipitation, which averaged 527 millimeters using baseline data, versus 524 millimeters and 500 millimeters with the 2050 IPSL and CSIRO climate predictions, respectively. The decrease in runoff that occurred with the 2050 IPSL model are reasonable in view of the fact that annual precipitation with this scenario is very similar to precipitation under baseline conditions, but mean annual temperature was 1.5 °C warmer than baseline conditions. The decreases in runoff that occurred with the 2050 CSIRO model are largely driven by a decrease in annual precipitation relative to baseline conditions, as well as by a warming of 1.0 °C and a decrease in the frequency of heavy rain events relative to baseline climatic data. Runoff was extremely low on sandy arenosols with both 2050 ISPL and CSIRO climatic data (Figure A.62).

Rainwater harvesting practices caused changes in runoff with 2050 climatic data in comparison with conditions without water harvesting. For sorghum, surface runoff decreased relative to ru noff without water harvesting practices, particularly for finer textured soils (Figure A.62). Contour ridges, *zai* holes, and bunds were equally effective at reducing surface runoff with sorghum on finer textured soils, and all three were more effective than vegetative filter strips; this is the same order of effectiveness that was observed using 2030 climatic data. Contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 49–68 percent, 50–62 percent, 55–57 percent, and 28–53 percent respectively, on finer texture soils during the relatively wet climatic conditions generated by the 2050 IPSL model. In contrast, contour ridges, *zai*, bunds, and vegetated filter strips decreased surface runoff by 25–44 percent, 29–33 percent, 25–32 percent, and 9–21 percent respectively, on finer texture soils during the relatively drier climatic conditions generated by the 2050 CSIRO model. Thus, while the ranked order of effectiveness for water harvesting practices was the same using both 2050 climatic prediction scenarios, the effectiveness of a particular water harvesting practice was generally somewhat greater with the IPSL generated climate than the CSIRO climate.

FIGURE A.62: SURFACE RUNOFF FOR SORGHUM GROWN ON DIFFERENT SOILS FOR IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA WITH AND WITHOUT RAINWATER HARVESTING PRACTICES SUCH AS BUNDS, VEGETATIVE FILTER STRIPS (VFS), CONTOUR RIDGES AND *ZAI*





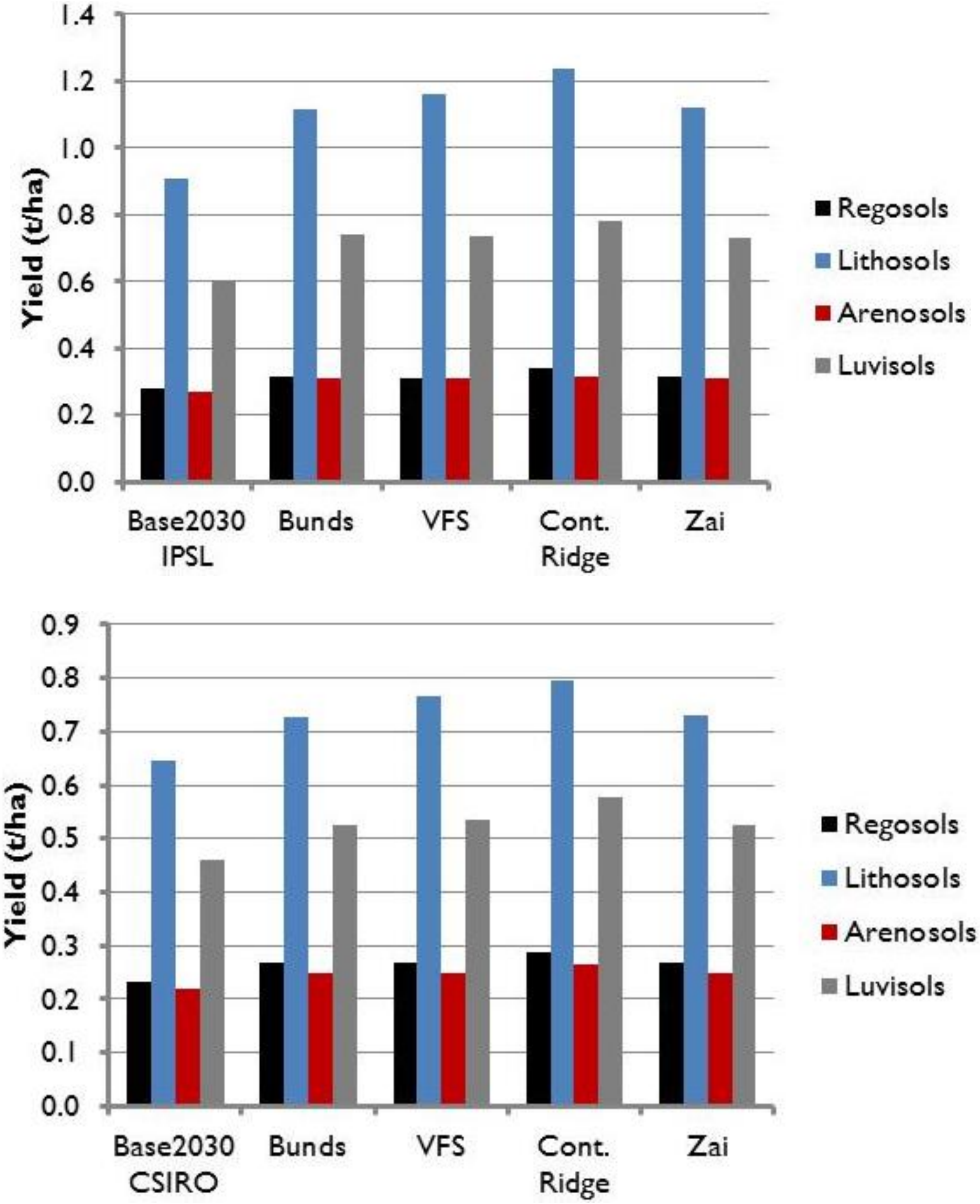
Sorghum yields

Sorghum yields under IPSL based 2030 climatic conditions (628 millimeters) without water harvesting practices (Figure A.63) were comparable on lithosols (0.91 tons/hectare) and luvisols (0.6 tons/hectare) to yields under measured 1991–2000 climatic conditions (527 millimeters) on the same soils (0.91 and 0.62 tons/hectare) without water harvesting practices. Similarly, sorghum yields under 2030 IPSL climatic conditions without water harvesting practices were relatively unchanged from yields on regosols and arenosols under 1991–2000 conditions without these practices. In contrast, sorghum yields under CSIRO based 2030 climatic conditions (563 millimeters) without water harvesting practices (Figure

A.63) on lithosols (0.65 tons/hectare) and luvisols (0.46 tons/hectare) were lower than yields under measured 1991–2000 climatic conditions (527 millimeters) on the same soils (0.91 and 0.62 tons/hectare) without water harvesting practices. Similarly, sorghum yields under 2030 CSIRO climatic conditions without water harvesting practices were lower than yields on regosols and arenosols under 1991–2000 conditions without these practices. These results show that sorghum yields do not respond to increased precipitation in the IPSL 2030 scenario, probably because of increased air temperatures. The reasons for a decrease in yield of sorghum with 2030 CSIRO climate data are unclear, because precipitation has increased somewhat, while air temperature is unchanged from baseline climatic conditions.

Rainwater harvesting practices were relatively effective at improving sorghum yields on all soils (Figure A.63) for both the relatively wet IPSL generated 2030 climatic data and the less wet CSIRO 2030 data relative to yields without these practices with the same climatic data. Sorghum yield on lithosols increased by 23–36 percent and by 13–23 percent with water harvesting practices relative to yields without these practices for IPSL and CSIRO 2030 climatic data, respectively. Sorghum yields on luvisols increased by 22–30 percent and by 14–25 percent with water harvesting practices relative to yields with IPSL or CSIRO 2030 climatic data, respectively. On less fertile regosols and arenosols, water harvesting practices increased sorghum yields by 12–23 percent and by 13–25 percent using IPSL and CSIRO 2030 climatic data, respectively, relative to yields on the same soils without these practices. To summarize, water harvesting practices were relatively effective at improving sorghum yields under IPSL and CSIRO 2030 climatic conditions.

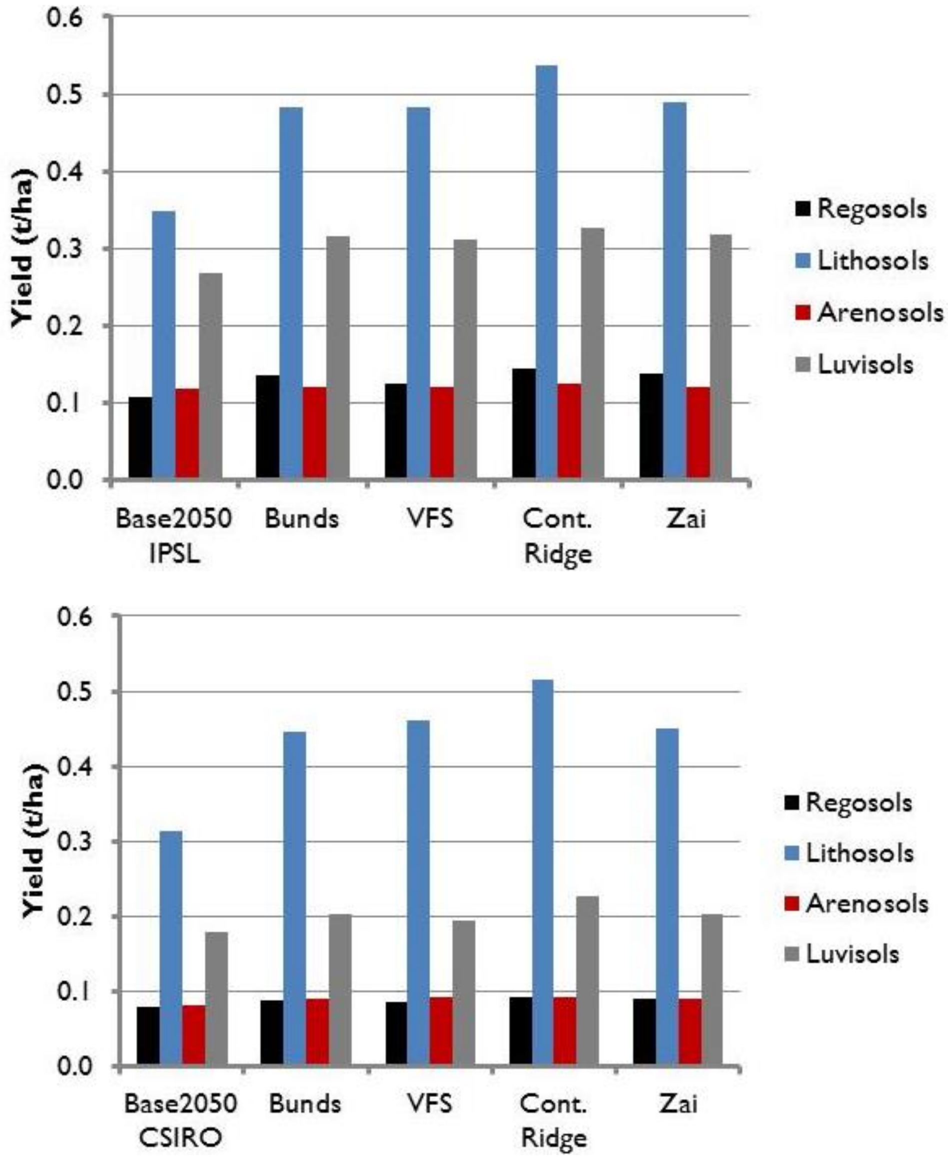
FIGURE A.63: SORGHUM YIELD FOR IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES



Sorghum yields under IPSL and CSIRO based 2050 climatic conditions (524 and 500 millimeters) without water harvesting practices (Figure A.64) on relatively fertile lithosols (0.35 and 0.31 tons/hectare) and luvisols (0.27 and 0.18 tons/hectare) were significantly less than yields under measured 1991–2000 climatic conditions (527 millimeters) on the same soils (0.91 and 0.62 tons/hectare) without water harvesting practices. Similarly, sorghum yields under 2050 climatic conditions without water harvesting practices were about one third as large as yields on regosols and arenosols under 1991–2000 conditions without these practices. Sorghum yields decrease in response to warmer annual temperatures, regardless of whether or not precipitation decreases.

Rainwater harvesting practices were very effective at improving sorghum yields on the more fertile lithosols (Figure A.64) for IPSL and CSIRO generated 2050 climatic data relative to yields without these practices with the same climatic data. Sorghum yield on lithosols increased by 39–55 percent under IPSL 2050 conditions and by 42–64 percent under CSIRO 2050 conditions with water harvesting practices relative to yields without these practices for the corresponding 2050 climatic data. Sorghum yields on luvisols increased by 17–22 percent and by 9–27 percent with water harvesting practices under IPSL or CSIRO 2050 climatic data, respectively. Water harvesting practices increased sorghum yields by 17–35 percent or 9–17 percent under IPSL or CSIRO 2050 data on less fertile regosols. Water harvesting practices were least effective at increasing sorghum yield on arenosols, where the effectiveness of these practices under IPSL and CSIRO 2050 climatic data was only 2–5 percent or 9–11 percent, respectively. To summarize, water harvesting practices were more effective at increasing sorghum yields on lithosols than luvisols or regosols, while they were somewhat ineffective at increasing sorghum yields on arenosols under IPSL or CSIRO 2050 climatic conditions.

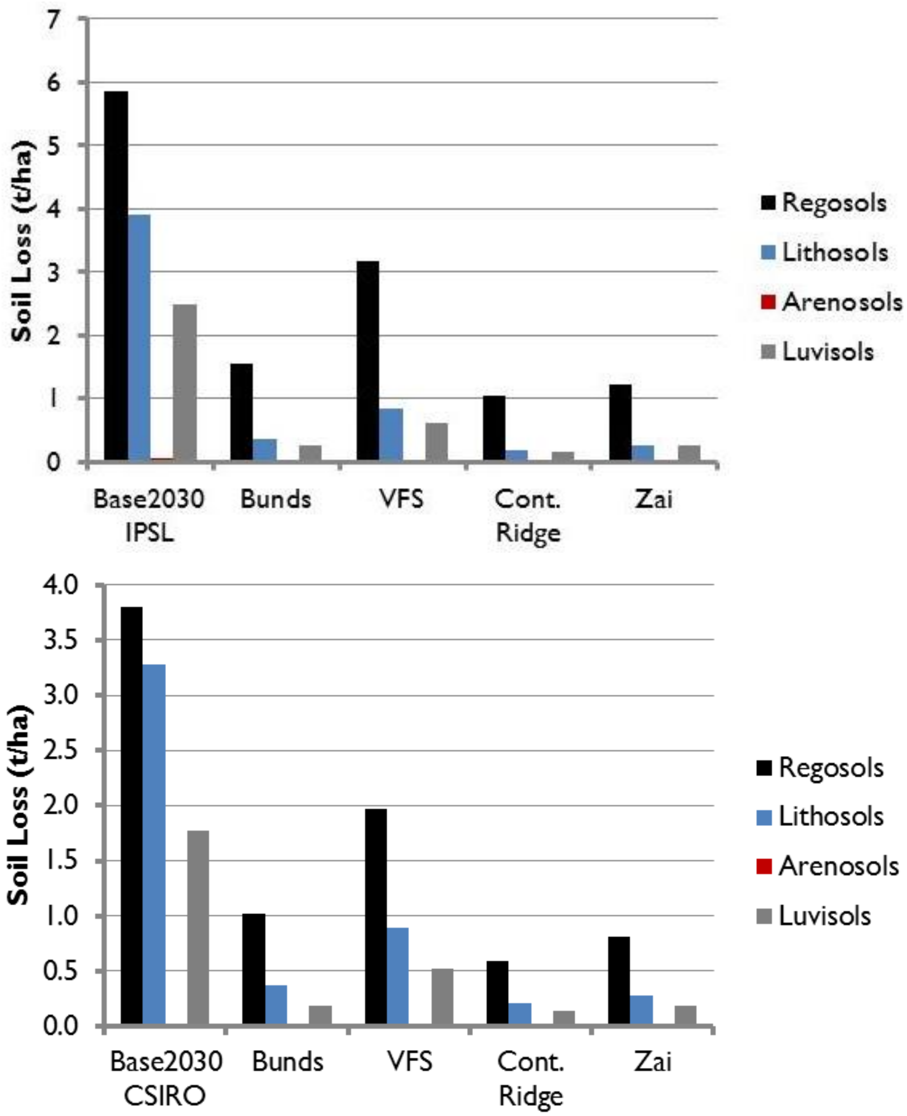
FIGURE A.64: SORGHUM YIELD FOR IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES



Soil loss on sorghum fields

Soil loss without water harvesting practices was larger on all soils for the wetter IPSL generated 2030 climatic conditions relative to soil loss under the drier CSIRO generated 2030 climatic conditions (Figure A.65). Patterns in soil loss were affected both by slope steepness and amounts of runoff from each soil (Figure A.61) as well as by changes in crop biomass (Figure A.63) and soil cover. Soil loss was smallest under arenosols, which had extremely high infiltration rates and little runoff. Water harvesting practices were very effective at reducing soil loss on all soils under both the IPSL (reductions ranged from 46–95 percent) and CSIRO (reductions ranged from 48–94 percent) generated 2030 climatic conditions (Figure A.65) relative to 2030 baseline climatic conditions. Reductions in soil loss are directly related to the effectiveness of these practices at reducing runoff (Figure A.61). Contour ridges and *zai* were equally effective at reducing soil loss, and both practices were more effective than bunds, which, in turn, were more effective than vegetated filter strips. The effectiveness of these practices was greater on lithosols and luvisols than on the steeper regosols.

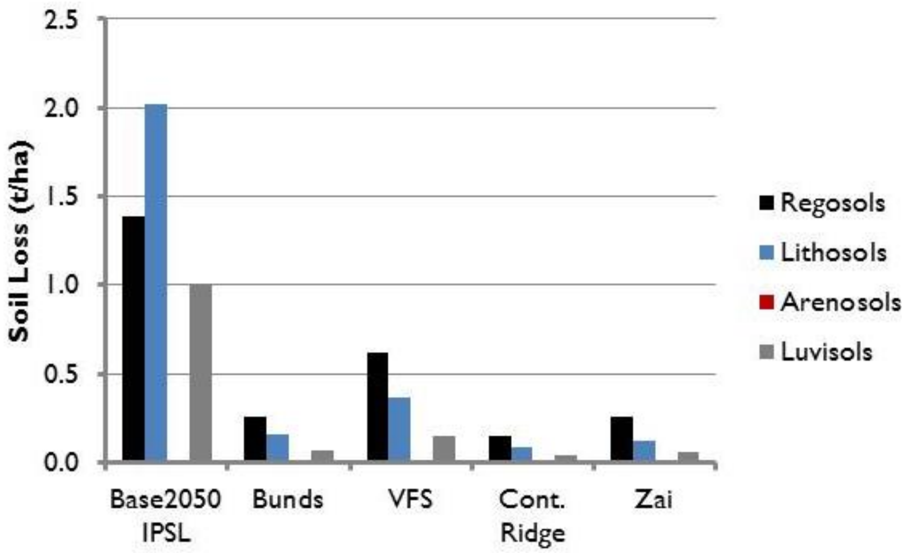
FIGURE A.65: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER SORGHUM FOR THE FOUR SOILS EVALUATED USING IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA

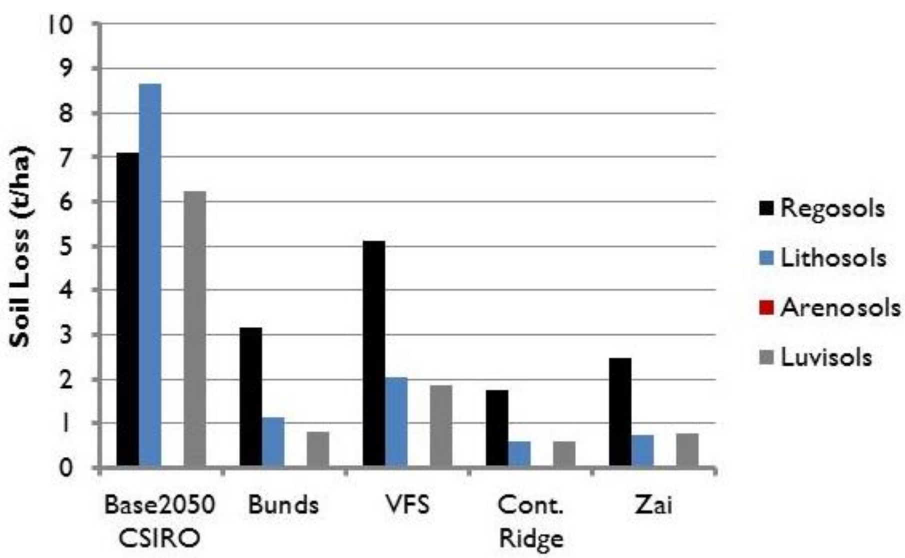


Soil loss without water harvesting practices was much larger for the CSIRO than the IPSL generated 2050 climatic conditions (Figure A.66), despite lower precipitation with the former. This result is due to decreases in crop biomass and soil cover (Figure A.64) under the drier CSIRO 2050 climate relative to the wetter ISPL 2050 climate. Soil loss was smallest under arenosols, which had extremely high infiltration rates and little runoff.

Water harvesting practices were very effective at reducing soil loss relative to 2050 baseline climatic conditions on all soils under both the IPSL (reductions ranged from 56–96 percent) and CSIRO (reductions ranged from 28–93 percent) generated 2050 climatic conditions (Figure A.66). Reductions in soil loss are directly related to the effectiveness of these practices at reducing runoff (Figure A.62). The effectiveness of water harvesting practices at reducing soil loss is as follows: contour ridges and *zai* were equally effective, and both were more effective than bunds, which, in turn, were more effective than vegetated filter strips. The effectiveness of these practices was greater on lithosols and luvisols than on the steeper regosols.

FIGURE A.66: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER SORGHUM FOR THE FOUR SOILS EVALUATED USING IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA

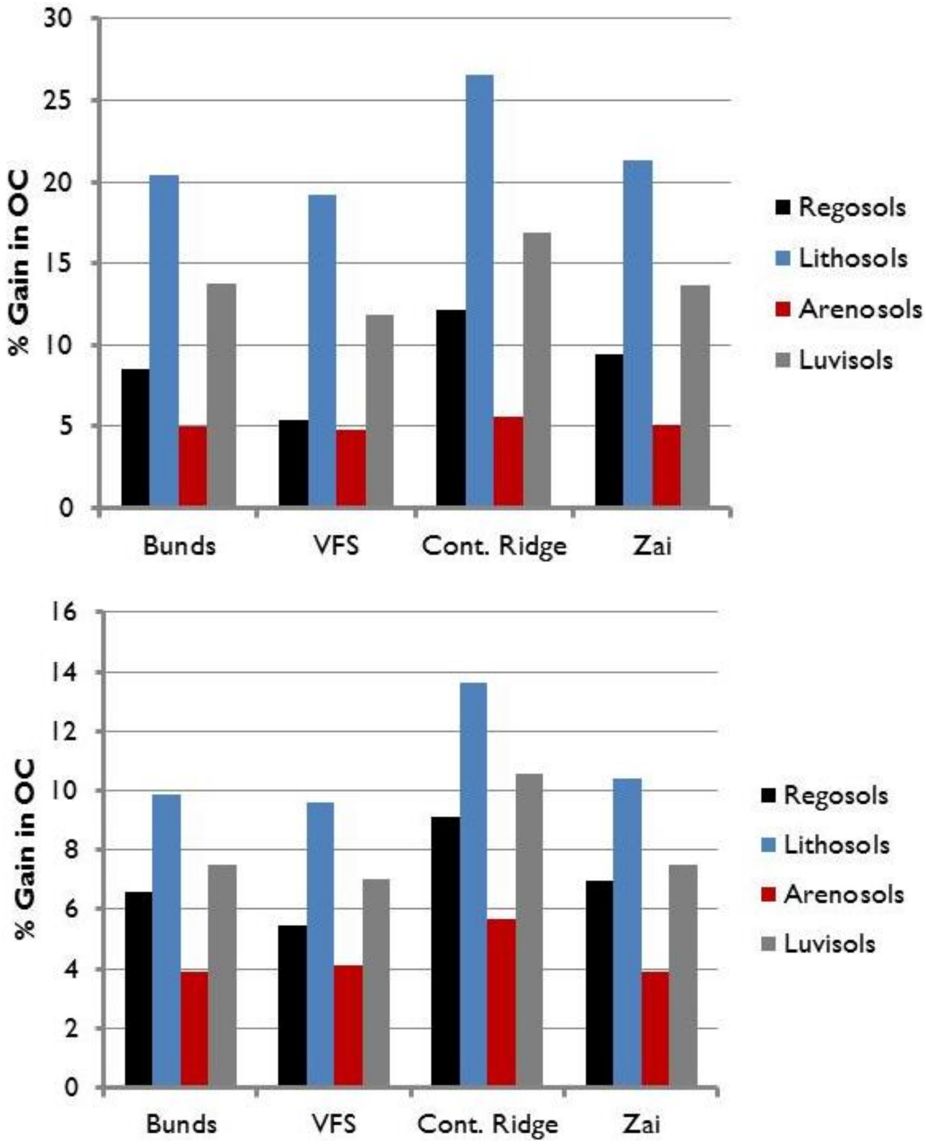




Soil organic carbon on sorghum fields

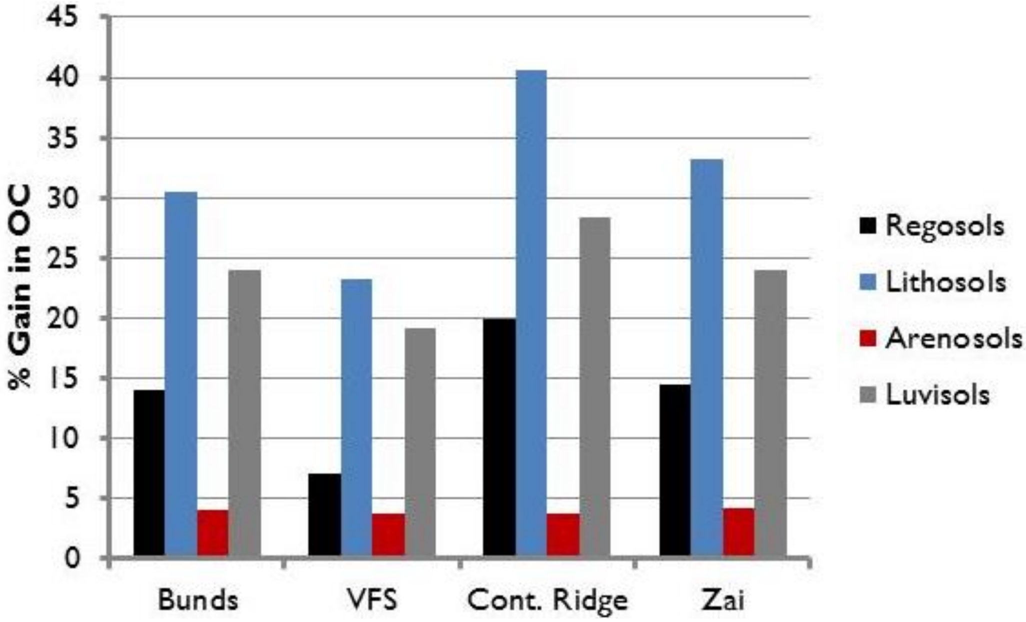
Water harvesting practices increased soil organic carbon by 5–27 percent for IPSL 2030 climatic conditions and by 4–14 percent for CSIRO 2030 climatic conditions (Figure A.67). These gains are in proportion to the level of reductions in erosion (Figure A.65) relative to reductions without these practices, and are also affected by recycling of harvested crop biomass. The biggest gains occurred with contour ridges, particularly on lithosols, with smaller gains on luvisols and regosols. The smallest gains occurred on arenosols. *Zai* and bunds were reasonably effective at increasing soil organic carbon, while vegetated filter strips were the least effective conservation practice.

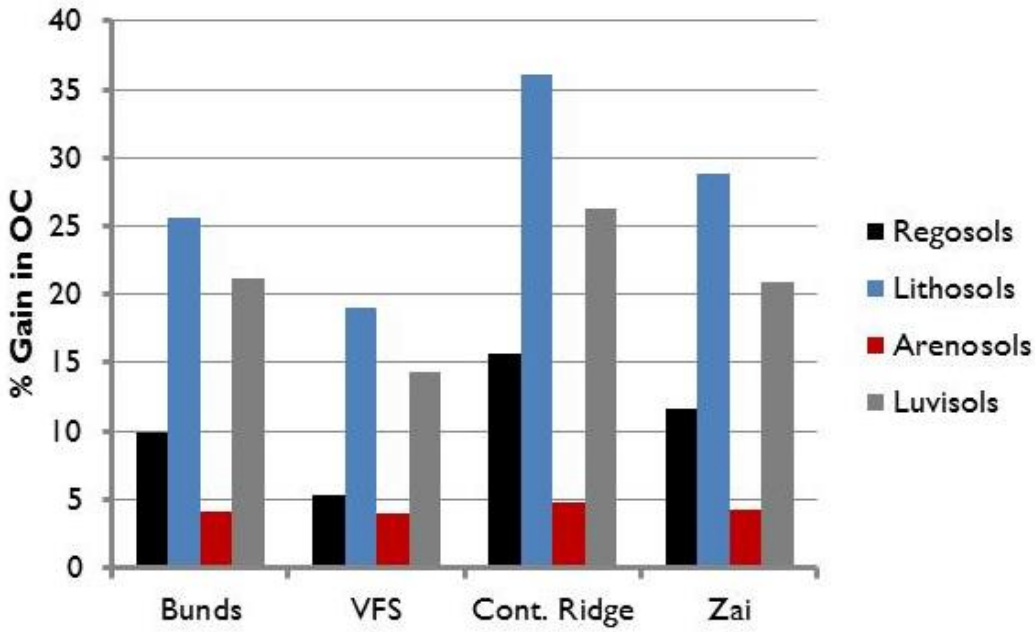
FIGURE A.67: INCREASE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM REDUCTIONS IN SOIL LOSS WITH SORGHUM USING IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA



Water harvesting practices increased soil organic carbon by from 4–41 percent for IPSL 2050 climatic conditions and by 4–36 percent for CSIRO 2050 climatic conditions (Figure A.68). These gains are in proportion to the level of reductions in erosion relative to reductions without these practices, as well as in proportion to increases in crop biomass returned to the soil after crop harvest. The biggest gains occurred with contour ridges, particularly on lithosols, and to a lesser extent on flatter luvisols and steeper regosols. *Zai* and bunds were also effective at increasing soil organic carbon, while vegetated filter strips were the least effective conservation practice. Gains in soil organic carbon with all water harvesting practices were smallest on steeper regosols that had higher erosion rates, and on low fertility arenosols.

FIGURE A.68: INCREASE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM REDUCTIONS IN SOIL LOSS WITH SORGHUM USING IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA





Impact of rainwater harvesting practices on irrigated rice under future climatic scenarios

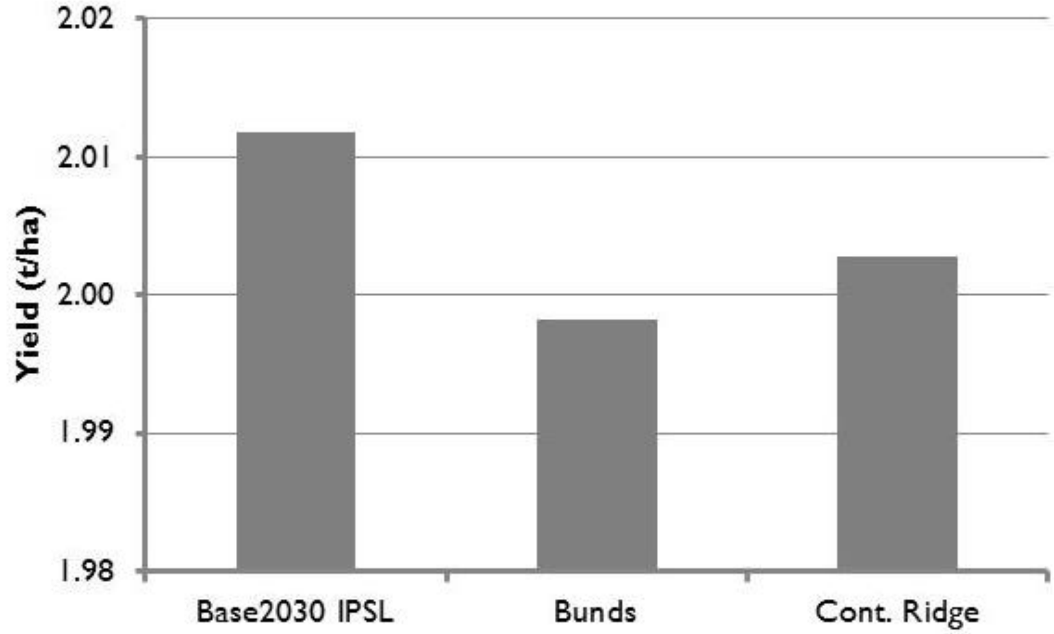
Yield of rice without water harvesting practices under IPSL and CSIRO 2030 climatic conditions was generally high, at about 2.01–2.16 tons/hectare on luvisols (Figure A.69), as a result of supplemental irrigation. Rice yields without water harvesting practices under IPSL and CSIRO 2050 climatic conditions were lower, at about 1.4 tons/hectare. (Figure A.70). The decrease in rice yields from 2030 to 2050 can be attributed primarily to a decrease in precipitation between the two time horizons. Under IPSL and CSIRO 2030 climatic conditions the installation of water harvesting practices had a slightly negative (-1 to -3 percent), but relatively insignificant impact on yield of rice (Figure A.69) relative to yields without these practices, because water supply was generally adequate even under baseline conditions due to supplemental irrigation. While IPSL and CSIRO 2050 climatic conditions, water harvesting practices had a slightly more positive, yet still relatively insignificant (-0.5 to 1 percent) impact on rice yield (Figure 70) relative to yields without these practices.

Water harvesting practices decreased surface runoff from rice on luvisols by from 21–30 percent under IPSL and CSIRO 2030 climatic conditions (Figure A.71). Both bunds and contour ridges were effective at reducing surface runoff. Under IPSL and CSIRO 2050 climatic conditions, water harvesting practices decreased surface runoff from rice by from 20-38 percent (Figure A.72), with bunds and contour ridges both being very effective at reducing surface runoff.

Soil loss from irrigated rice on relatively flat luvisols was relatively small (0.36 or 0.06 tons/hectare) without water harvesting practices under IPSL and CSIRO 2030 climatic data, respectively (Figure A.73). Soil loss was reduced very effectively (by from 77–83 percent for IPSL 2030 data and by from 82–85 percent for CSIRO 2030 data) using contour ridges and bunds on the relatively flat luvisols (Figure A.73). Erosion on irrigated rice under IPSL and CSIRO 2050 climatic data was also very small, ranging from 0.05 to 0.08 tons/hectare (Figure A.74). Bunds and contour ridges decreased these small erosion losses even further, by from 36–74 percent.

Reductions in erosion caused very small gains in soil organic carbon (Figure A.75), ranging from 1.6–1.9 percent under IPSL 2030 climatic data, and negligible gains or losses under the CSIRO 2030 climatic data, because of the inherently low rates of soil erosion and low soil organic carbon content on irrigated luvisols. Gains in soil organic carbon with bunds and contour ridges under IPSL and CSIRO 2050 climatic data were somewhat larger, ranging from 4–5 percent.

FIGURE A.69: IRRIGATED RICE YIELD FOR IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES



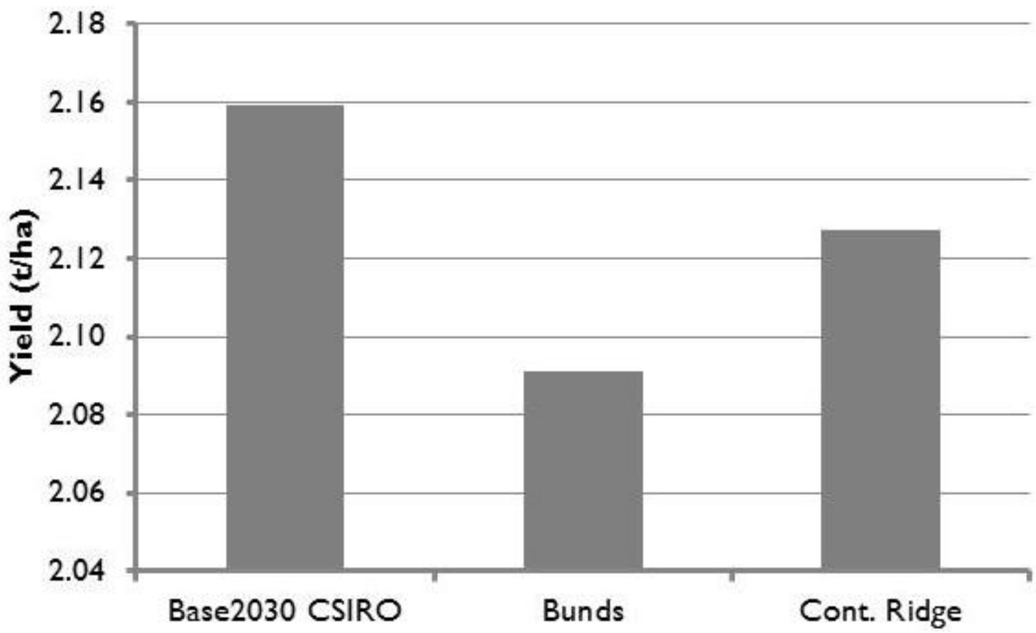


FIGURE A.70: IRRIGATED RICE YIELD FOR IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA WITH AND WITHOUT VARIOUS RAINWATER HARVESTING PRACTICES

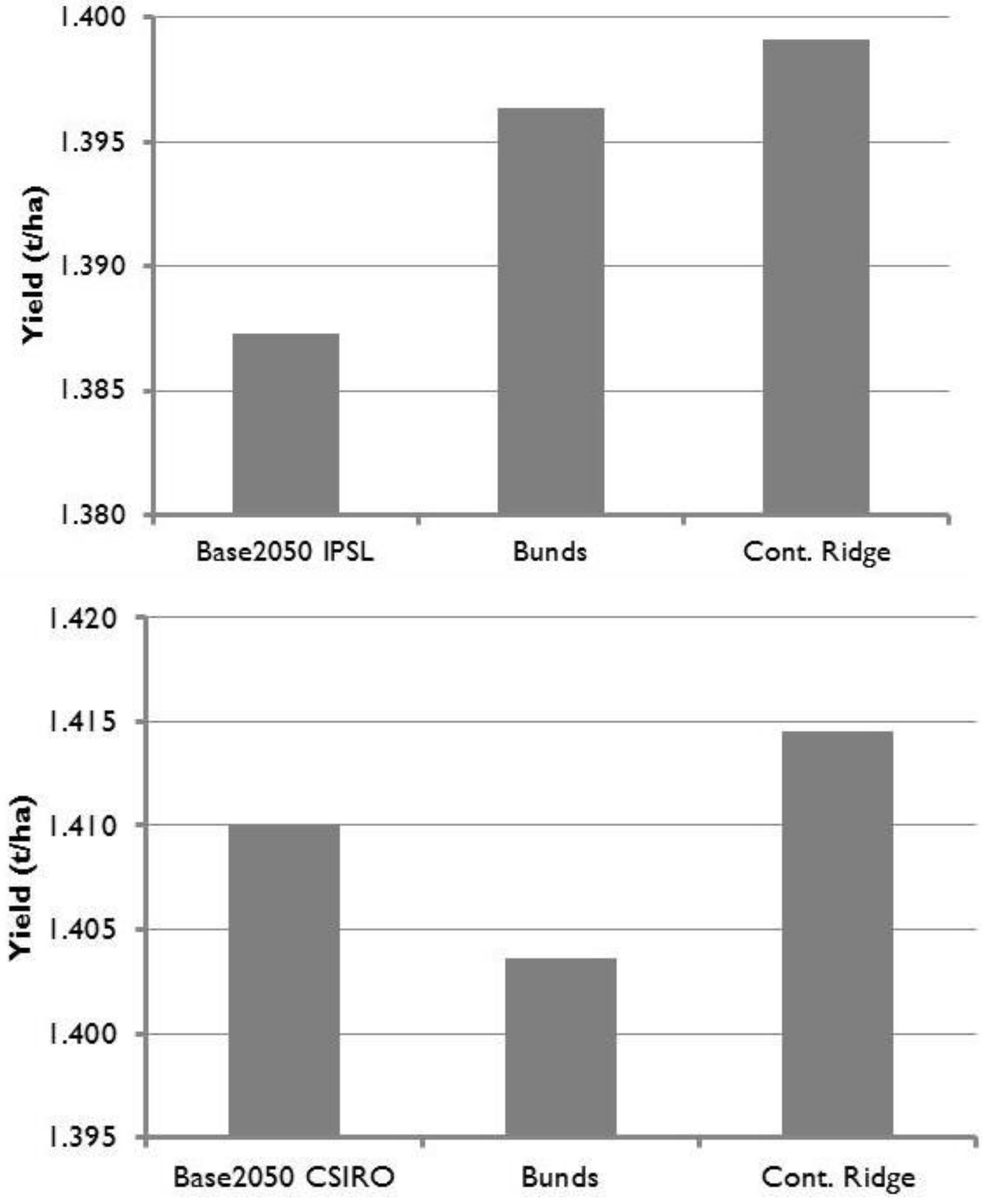
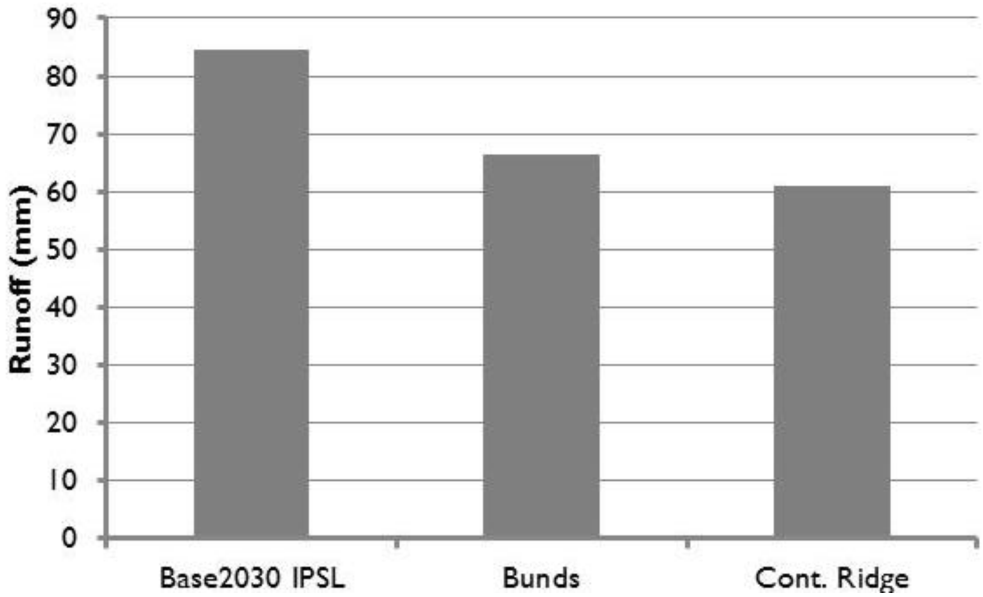


FIGURE A.71: SURFACE RUNOFF FOR RICE GROWN ON LUVISOLS FOR IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA WITH AND WITHOUT RAINWATER HARVESTING PRACTICES SUCH AS BUNDS AND CONTOUR RIDGES



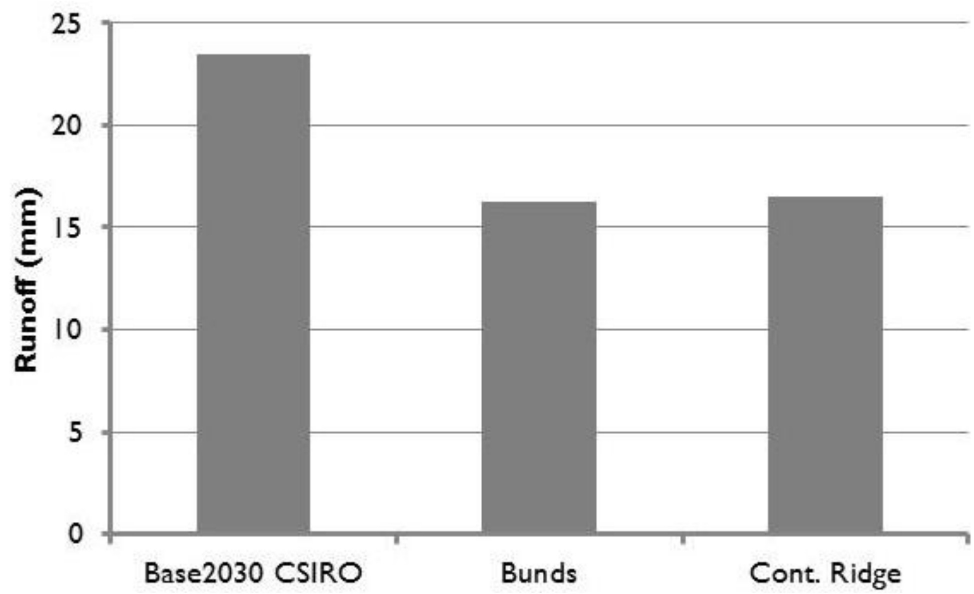


FIGURE A.72: SURFACE RUNOFF FOR RICE GROWN ON LUVISOLS FOR IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA WITH AND WITHOUT RAINWATER HARVESTING PRACTICES SUCH AS BUNDS AND CONTOUR RIDGES

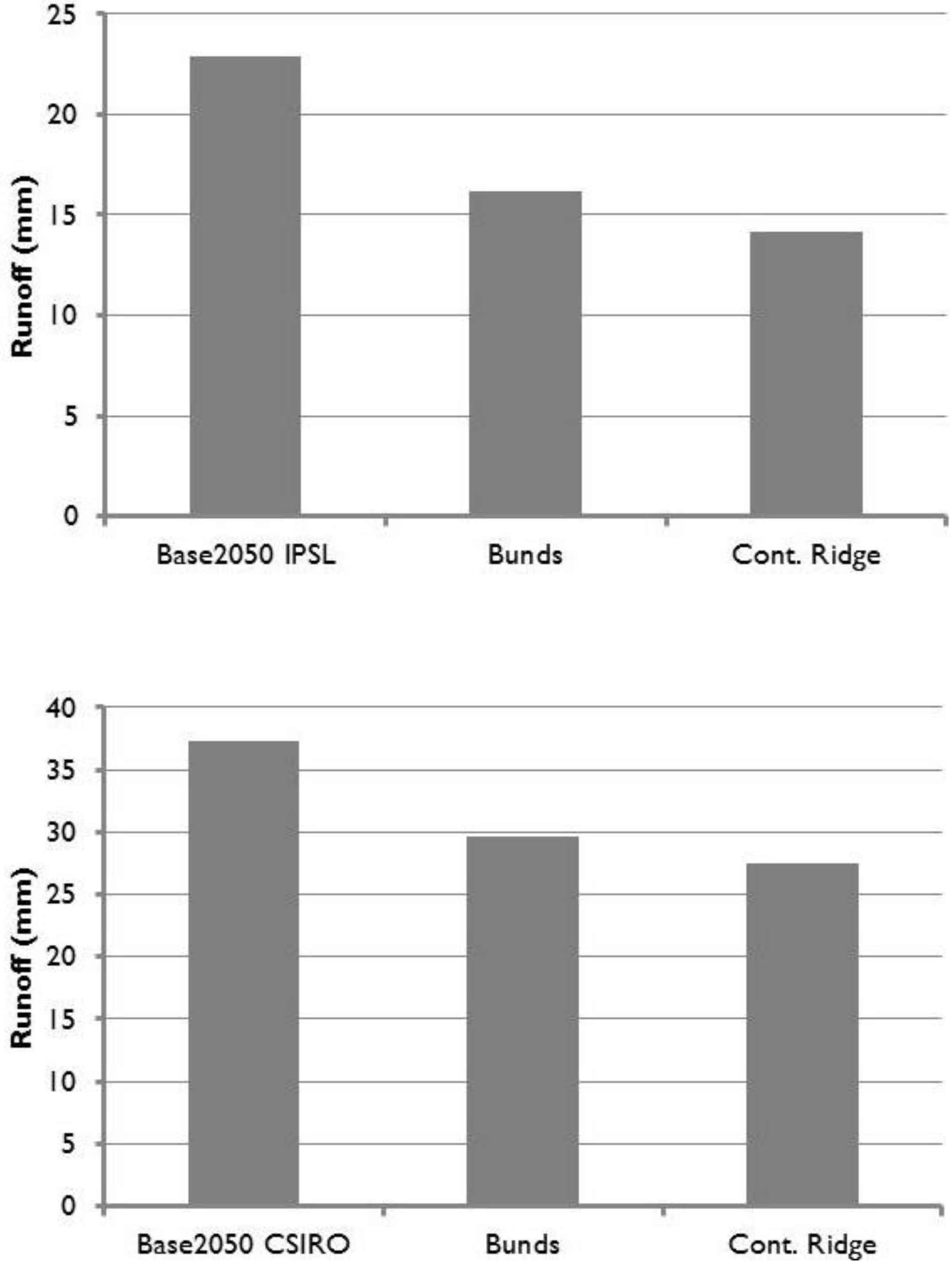


FIGURE A.73: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER IRRIGATED RICE FOR LUVISOLS USING IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA

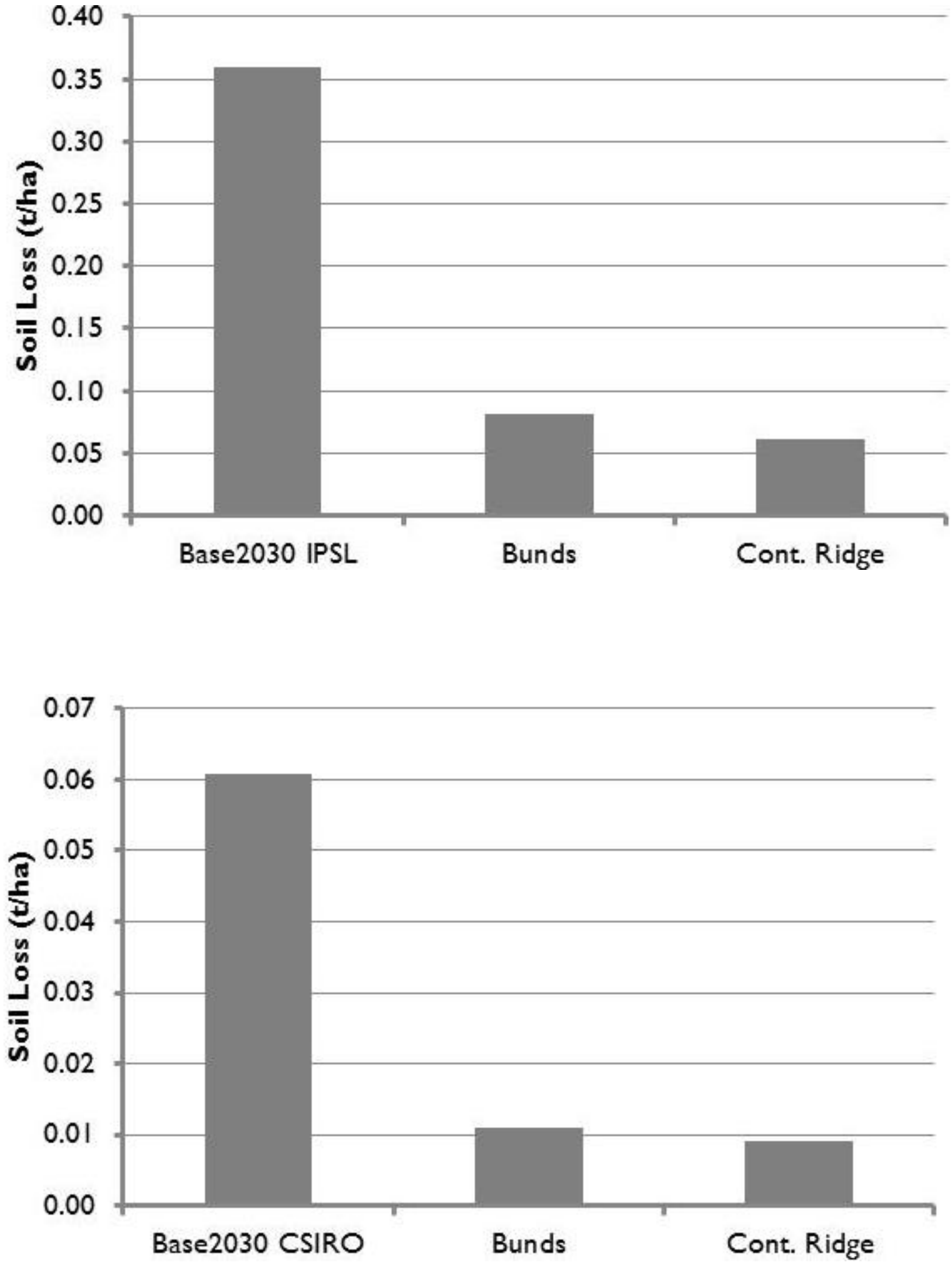
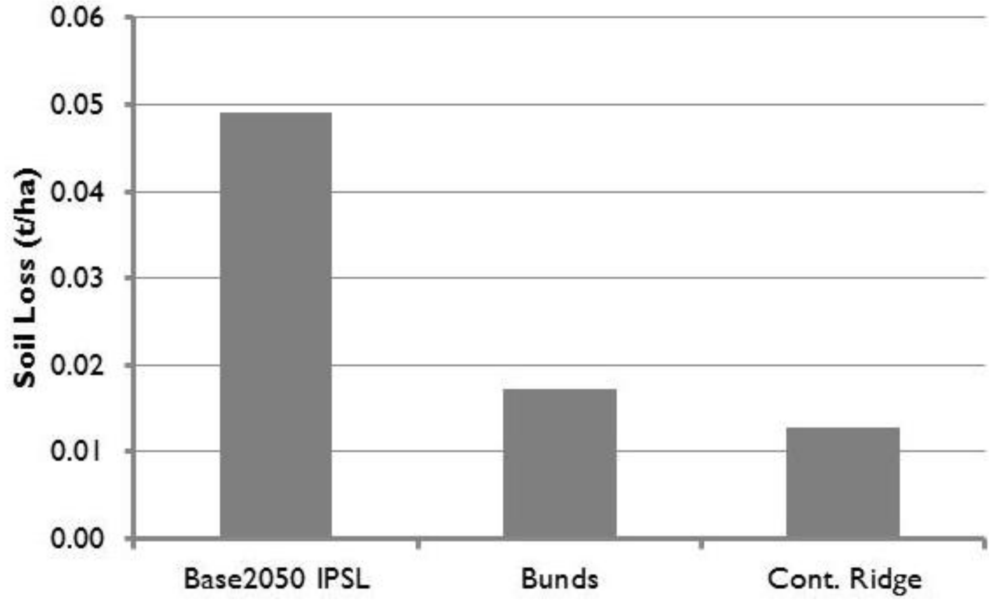


FIGURE A.74: EFFECT OF VARIOUS RAINWATER HARVESTING PRACTICES ON SOIL LOSS UNDER IRRIGATED RICE FOR LUVISOLS USING IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA



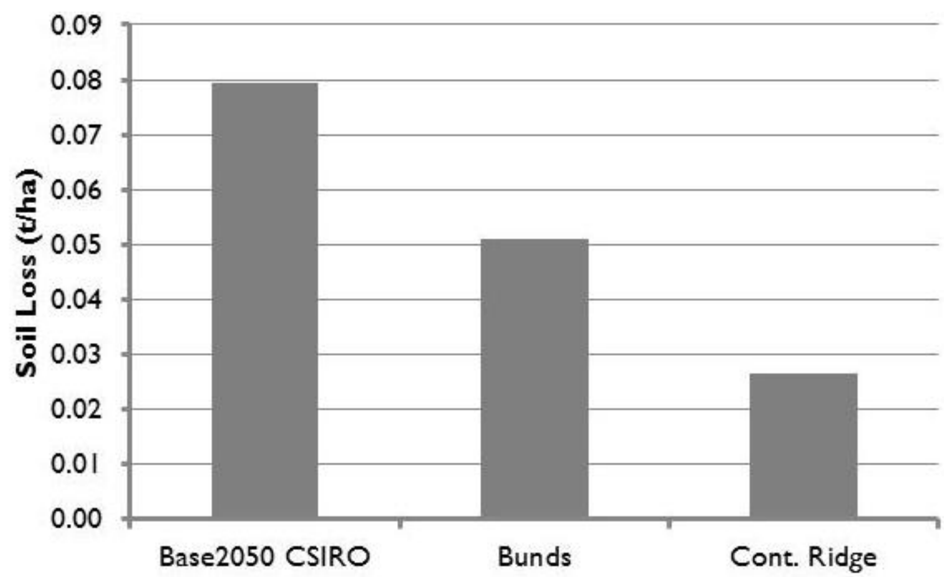


FIGURE A.75: CHANGE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM CHANGES IN SOIL LOSS WITH IRRIGATED RICE USING IPSL (TOP) AND CSIRO (BOTTOM) 2030 CLIMATIC DATA

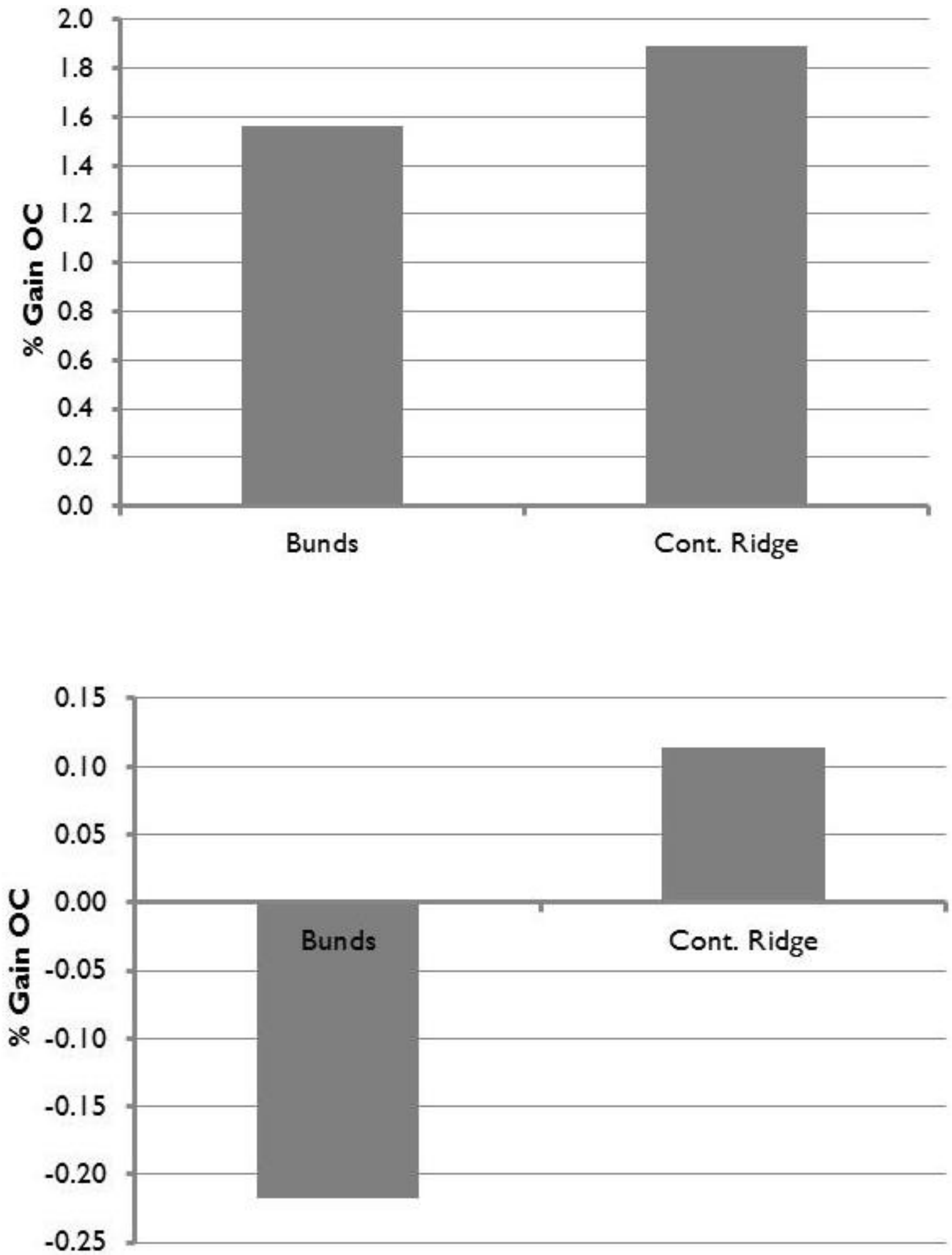
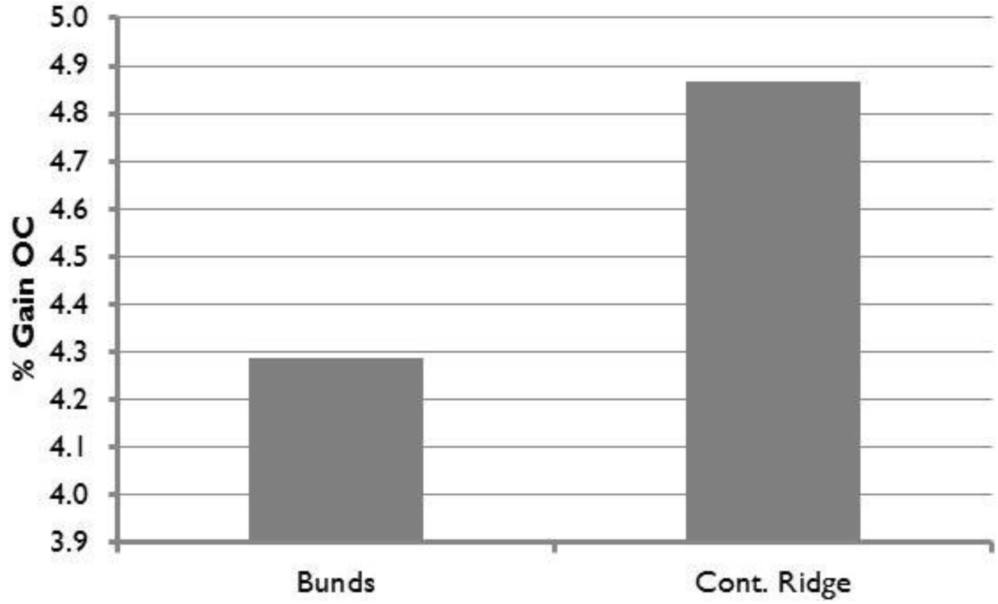
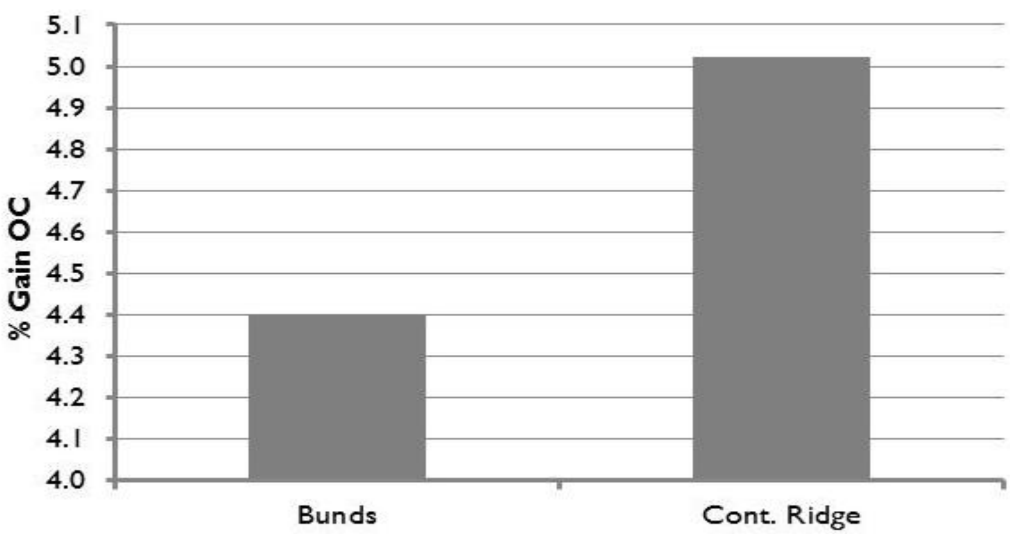


FIGURE A.76: INCREASE IN SOIL ORGANIC CARBON (OC) CONTENT RESULTING FROM DECREASES IN SOIL LOSS WITH IRRIGATED RICE USING IPSL (TOP) AND CSIRO (BOTTOM) 2050 CLIMATIC DATA





ANNEX B. IMPACT OF PRACTICES ON YIELDS (% CHANGE)

TABLE B.1: BASELINE CLIMATIC CONDITIONS (MOPTI MEASURED 1991-2000)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	13.0	-2.4	13.4	
	Lithosols	44.2	21.1	10.9	
	Arenosols	2.4	-5.6	9.4	
	Luvisols	40.6	61.7	17.1	2.2
VFS	Regosols	14.4	-5.8	11.7	
	Lithosols	45.8	14.0	9.6	
	Arenosols	4.4	-5.6	10.2	
	Luvisols	36.5	55.3	17.1	
Contour Ridges	Regosols	15.7	4.7	16.5	
	Lithosols	47.0	35.4	24.4	
	Arenosols	4.6	-1.2	14.8	
	Luvisols	36.6	76.1	23.3	2.6
Zai	Regosols	14.0	1.0	13.4	
	Lithosols	51.7	28.0	10.0	
	Arenosols	2.4	-5.2	10.9	
	Luvisols	45.8	66.3	17.1	

TABLE B.2: PERCENT CHANGE IN YIELDS RELATIVE TO BASELINE CLIMATE (1991-2000) WITHOUT CONSERVATION PRACTICES

		Maize	Millet	Sorghum	Rice
ISPL 2030	Regosols	-2.9	111.9	-14.0	
	Lithosols	152.7	109.7	0.0	
	Arenosols	3.4	109.0	-4.8	
	Luvisols	66.2	224.8	-3.5	4.1
CSIRO 2030	Regosols	-22.2	32.6	-28.6	
	Lithosols	170.2	123.5	-29.0	
	Arenosols	-25.5	15.3	-22.7	
	Luvisols	121.5	234.1	-26.3	11.9
ISPL 2050	Regosols	-44.3	-17.3	-67.1	
	Lithosols	10.2	2.2	-61.8	
	Arenosols	-50.0	-18.5	-58.5	
	Luvisols	-5.8	47.5	-57.2	-28.1
CSIRO 2050	Regosols	-76.6	-48.4	-75.8	
	Lithosols	-28.8	3.9	-65.5	
	Arenosols	-74.3	-47.8	-71.2	
	Luvisols	-23.8	44.4	-71.5	-26.9

TABLE B.3: SLIGHT WARMING, SIGNIFICANT INCREASE IN RAINFALL (IPSL 2030)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	1.0	-1.0	13.1	
	Lithosols	-12.0	7.7	22.9	
	Arenosols	1.0	-2.7	15.4	
	Luvisols	1.0	-2.2	23.1	-0.6
VFS	Regosols	1.0	-3.1	12.1	
	Lithosols	4.0	6.0	27.8	
	Arenosols	1.0	-6.1	15.4	
	Luvisols	3.0	-5.6	22.5	
Contour Ridges	Regosols	2.0	-1.0	22.9	
	Lithosols	3.0	11.6	36.2	
	Arenosols	3.0	-1.7	16.4	
	Luvisols	5.0	-0.7	30.0	-0.4
Zai	Regosols	1.0	-1.8	13.1	
	Lithosols	-11.0	7.3	23.2	
	Arenosols	1.0	-2.5	15.4	
	Luvisols	1.0	-2.7	21.1	

TABLE B.4: SIGNIFICANT WARMING, NO CHANGE IN RAINFALL (IPSL 2050)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	2.8	1.0	27.4	
	Lithosols	8.0	1.3	39.0	
	Arenosols	-1.5	-4.4	1.5	
	Luvisols	2.1	-1.5	18.4	0.7
VFS	Regosols	2.3	-2.3	17.1	
	Lithosols	8.4	-0.5	39.0	
	Arenosols	-0.6	-5.2	1.5	
	Luvisols	4.1	-4.0	16.7	
Contour Ridges	Regosols	6.5	-0.7	35.0	
	Lithosols	11.5	2.0	54.7	
	Arenosols	1.5	-6.5	4.6	
	Luvisols	7.7	-1.1	21.8	0.9
Zai	Regosols	4.1	-2.0	28.2	
	Lithosols	7.4	0.8	40.6	
	Arenosols	-1.2	-6.5	1.5	
	Luvisols	2.5	-1.5	18.7	

TABLE B.5: NO WARMING, INCREASE IN RAINFALL (CSIRO 2030)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-2.0	-4.2	16.5	
	Lithosols	0.0	11.1	12.5	
	Arenosols	-0.2	-4.3	13.6	
	Luvisols	-0.4	-0.9	14.4	-3.2
VFS	Regosols	20.6	0.6	16.5	
	Lithosols	1.3	9.0	18.6	
	Arenosols	3.8	-5.1	13.2	
	Luvisols	13.4	-3.0	16.6	
Contour Ridges	Regosols	22.4	-19.5	24.8	
	Lithosols	1.1	12.7	23.1	
	Arenosols	4.6	-6.8	19.8	
	Luvisols	16.0	-5.6	25.3	-1.5
Zai	Regosols	-1.7	-19.2	16.5	
	Lithosols	0.3	13.4	12.9	
	Arenosols	-0.2	-7.4	13.6	
	Luvisols	-0.9	-7.3	14.4	

TABLE B.6: SIGNIFICANT WARMING, SIGNIFICANT DECREASE IN RAINFALL (CSIRO 2050)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	8.8	5.9	12.8	
	Lithosols	33.1	3.6	42.3	
	Arenosols	1.7	1.3	8.9	
	Luvisols	13.5	-1.5	13.3	-0.5
VFS	Regosols	10.4	7.0	9.3	
	Lithosols	28.6	1.0	47.0	
	Arenosols	3.5	1.3	11.1	
	Luvisols	16.1	-1.7	9.2	
Contour Ridges	Regosols	17.0	2.2	17.4	
	Lithosols	33.5	2.3	64.3	
	Arenosols	3.5	-1.9	11.1	
	Luvisols	22.0	-5.4	26.5	0.3
Zai	Regosols	9.9	2.2	14.0	
	Lithosols	34.3	2.0	43.2	
	Arenosols	1.2	-1.9	8.9	
	Luvisols	11.5	-5.8	13.3	

ANNEX C. IMPACT OF PRACTICES ON RUNOFF (% CHANGE)

TABLE C.1: BASELINE CONDITIONS (MOPTI MEASURED 1991-2000)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-11.9	-8.9	-17.7	
	Lithosols	-23.1	-15.7	-20.9	
	Arenosols	-18.2	-11.7	6.0	
	Luvisols	-23.4	-17.3	-20.2	-11.4
VFS	Regosols	-2.4	-6.9	-4.4	
	Lithosols	-14.7	-13.4	-14.0	
	Arenosols	-6.8	-9.6	-7.6	
	Luvisols	-19.8	-18.9	-17.1	
Contour Ridges	Regosols	-22.9	-19.4	-22.3	
	Lithosols	-26.3	-23.0	-19.7	
	Arenosols	-2.1	-12.0	-2.6	
	Luvisols	-32.7	-27.8	-25.7	-12.0
Zai	Regosols	-20.0	-21.0	-17.8	
	Lithosols	-27.9	-23.4	-21.6	
	Arenosols	-2.2	-12.1	-10.3	
	Luvisols	-26.5	-26.5	-21.5	

TABLE C.2: SLIGHT WARMING, SIGNIFICANT INCREASE IN RAINFALL (IPSL 2030)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-28.0	-21.0	-30.8	
	Lithosols	-29.0	-14.6	-22.9	
	Arenosols	-97.0	-98.0	-98.3	
	Luvisols	-32.0	-19.9	-27.7	-21.5
VFS	Regosols	-9.0	-14.5	-9.5	
	Lithosols	-17.0	-8.8	-3.2	
	Arenosols	-97.0	-98.1	-97.9	
	Luvisols	-25.0	-25.9	-21.9	
Contour Ridges	Regosols	-51.0	-42.2	-39.1	
	Lithosols	-41.0	-27.9	-18.1	
	Arenosols	-99.0	-98.7	-99.0	
	Luvisols	-47.0	-41.9	-33.4	-27.8
Zai	Regosols	-42.0	-41.0	-31.0	
	Lithosols	-39.0	-28.5	-22.1	
	Arenosols	-99.0	-99.0	-98.4	
	Luvisols	-41.0	-40.2	-28.3	

TABLE C.3: SIGNIFICANT WARMING, NO CHANGE IN RAINFALL (IPSL 2050)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-43.0	-32.6	-57.1	
	Lithosols	-42.2	-26.8	-54.8	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-42.6	-33.7	-57.1	-29.2
VFS	Regosols	-11.8	-26.4	-43.0	
	Lithosols	-14.8	-18.2	-28.4	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-34.4	-40.5	-52.8	
Contour Ridges	Regosols	-72.4	-66.5	-68.1	
	Lithosols	-61.3	-45.5	-48.6	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-71.1	-65.9	-67.7	-38.1
Zai	Regosols	-63.3	-64.8	-62.5	
	Lithosols	-59.6	-43.7	-50.3	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-63.5	-63.7	-57.9	

TABLE C.4: NO WARMING, INCREASE IN RAINFALL (CSIRO 2030)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-38.6	-16.8	-41.5	
	Lithosols	-38.7	-28.2	-36.8	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-40.8	-25.6	-40.2	-30.6
VFS	Regosols	-12.8	-15.4	-20.4	
	Lithosols	-19.2	-20.3	-13.4	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-31.6	-31.4	-31.3	
Contour Ridges	Regosols	-53.9	-51.2	-52.1	
	Lithosols	-49.5	-36.6	-35.8	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-57.0	-55.7	-48.2	-29.8
Zai	Regosols	-53.7	-48.5	-41.5	
	Lithosols	-50.5	-37.2	-36.8	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-51.3	-54.0	-40.2	

TABLE C.5: SIGNIFICANT WARMING, SIGNIFICANT DECREASE IN RAINFALL (CSIRO 2050)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-33.9	-21.7	-32.1	
	Lithosols	-36.8	-16.4	-25.3	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-36.5	-16.3	-30.3	-20.4
VFS	Regosols	-12.9	-9.2	-12.8	
	Lithosols	-20.9	-18.0	-8.7	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-30.7	-31.5	-21.5	
Contour Ridges	Regosols	-50.4	-41.8	-44.5	
	Lithosols	-45.9	-37.1	-24.5	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-49.5	-44.9	-38.5	-26.3
Zai	Regosols	-44.6	-41.8	-33.4	
	Lithosols	-44.7	-37.1	-28.6	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-45.0	-44.9	-33.0	

ANNEX D. IMPACT OF PRACTICES ON SOIL LOSS (% CHANGE)

TABLE D.1: BASELINE CONDITIONS (MOPTI MEASURED 1991-2000)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-70.1	-62.1	-69.0	
	Lithosols	-86.0	-76.5	-74.3	
	Arenosols	-83.6	-77.3	-69.3	
	Luvisols	-87.7	-79.9	-84.4	-75.1
VFS	Regosols	-53.7	-41.8	-48.9	
	Lithosols	-76.4	-63.8	-66.1	
	Arenosols	-61.6	-54.1	-55.0	
	Luvisols	-73.6	-61.1	-61.4	
Contour Ridges	Regosols	-83.1	-78.3	-80.8	
	Lithosols	-92.6	-87.5	-91.1	
	Arenosols	-89.0	-89.2	-83.2	
	Luvisols	-92.1	-86.7	-89.8	-80.4
Zai	Regosols	-80.2	-77.4	-76.3	
	Lithosols	-91.7	-86.9	-89.0	
	Arenosols	-87.7	-86.6	-80.5	
	Luvisols	-90.5	-85.8	-87.8	

TABLE D.2: SLIGHT WARMING, SIGNIFICANT INCREASE IN RAINFALL (IPSL 2030)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-75.9	-72.1	-73.4	
	Lithosols	-86.3	-82.8	-90.7	
	Arenosols	-89.2	-80.0	-84.3	
	Luvisols	-89.6	-84.6	-90.0	-77.3
VFS	Regosols	-55.2	-40.0	-45.8	
	Lithosols	-68.9	-59.6	-78.1	
	Arenosols	-67.6	-80.0	-72.5	
	Luvisols	-74.1	-58.5	-75.6	
Contour Ridges	Regosols	-89.8	-82.6	-82.3	
	Lithosols	-95.8	-89.1	-95.3	
	Arenosols	-100.0	-90.0	-94.1	
	Luvisols	-95.2	-89.7	-93.6	-83.1
Zai	Regosols	-85.4	-82.7	-78.9	
	Lithosols	-93.5	-88.3	-93.0	
	Arenosols	-97.3	-100.0	-88.2	
	Luvisols	-92.8	-88.6	-90.0	

TABLE D.3: SIGNIFICANT WARMING, NO CHANGE IN RAINFALL (IPSL 2050)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-80.1	-76.7	-81.3	
	Lithosols	-91.7	-86.7	-92.3	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-91.5	-89.8	-93.2	-64.8
VFS	Regosols	-50.9	-56.1	-55.6	
	Lithosols	-74.6	-67.6	-81.9	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-71.6	-73.4	-85.1	
Contour Ridges	Regosols	-93.7	-91.8	-89.4	
	Lithosols	-97.0	-92.8	-95.6	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-96.9	-95.9	-96.5	-74.1
Zai	Regosols	-90.7	-90.7	-81.4	
	Lithosols	-96.7	-92.9	-94.2	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-95.7	-95.1	-94.2	

TABLE D.4: NO WARMING, INCREASE IN RAINFALL (CSIRO 2030)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-82.7	-63.1	-73.3	
	Lithosols	-88.6	-85.6	-88.5	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-90.5	-85.6	-89.5	-82.1
VFS	Regosols	-55.8	-44.4	-48.3	
	Lithosols	-71.9	-60.8	-72.7	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-76.3	-59.2	-70.4	
Contour Ridges	Regosols	-90.9	-81.5	-84.3	
	Lithosols	-95.8	-89.2	-93.5	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-96.3	-87.2	-92.1	-85.1
Zai	Regosols	-91.2	-80.8	-78.7	
	Lithosols	-94.6	-88.8	-91.4	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-93.7	-87.2	-89.5	

TABLE D.5: SIGNIFICANT WARMING, SIGNIFICANT DECREASE IN RAINFALL (CSIRO 2050)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	-76.1	-69.3	-55.7	
	Lithosols	-91.8	-79.8	-87.0	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-89.8	-83.6	-86.9	-36.0
VFS	Regosols	-53.0	-47.3	-28.4	
	Lithosols	-79.1	-59.5	-76.5	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-73.5	-67.1	-70.3	
Contour Ridges	Regosols	-88.1	-83.4	-75.2	
	Lithosols	-96.1	-88.7	-93.0	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-94.6	-90.2	-90.8	-66.9
Zai	Regosols	-85.5	-83.4	-65.4	
	Lithosols	-95.6	-88.7	-91.6	
	Arenosols	-100.0	-100.0	-100.0	
	Luvisols	-92.0	-90.2	-87.4	

ANNEX E. IMPACT OF PRACTICES ON ORGANIC CARBON (% CHANGE)

TABLE E.1: BASELINE CONDITIONS (MOPTI MEASURED 1991-2000)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	13.2	4.3	7.3	
	Lithosols	25.6	10.8	9.6	
	Arenosols	3.7	0.7	13.0	
	Luvisols	18.7	5.5	17.1	1.6
VFS	Regosols	12.8	0.8	3.3	
	Lithosols	25.0	7.0	6.3	
	Arenosols	2.9	-0.5	6.8	
	Luvisols	28.2	2.8	11.0	
Contour Ridges	Regosols	15.6	7.3	9.0	
	Lithosols	29.3	13.4	19.2	
	Arenosols	5.4	3.3	12.2	
	Luvisols	19.3	7.5	18.4	2.1
Zai	Regosols	14.6	5.0	6.9	
	Lithosols	30.0	10.9	12.4	
	Arenosols	3.8	0.6	10.3	
	Luvisols	21.2	5.0	15.7	

TABLE E.2: SLIGHT WARMING, SIGNIFICANT INCREASE IN RAINFALL (IPSL 2030)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	9.1	1.3	8.5	
	Lithosols	0.1	6.3	20.4	
	Arenosols	1.0	-2.1	5.0	
	Luvisols	6.2	0.0	13.8	1.6
VFS	Regosols	10.3	-1.5	5.4	
	Lithosols	9.0	3.4	19.2	
	Arenosols	1.2	-3.9	4.8	
	Luvisols	11.4	-2.7	11.9	
Contour Ridges	Regosols	15.8	-0.6	12.2	
	Lithosols	12.0	5.8	26.6	
	Arenosols	2.5	-4.7	5.6	
	Luvisols	14.8	-1.6	16.9	1.9
Zai	Regosols	10.9	-1.4	9.5	
	Lithosols	1.5	3.8	21.4	
	Arenosols	1.2	-5.6	5.1	
	Luvisols	7.0	-2.9	13.7	

TABLE E.3: SIGNIFICANT WARMING, NO CHANGE IN RAINFALL (IPSL 2050)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	16.0	13.4	14.0	
	Lithosols	17.5	14.6	30.4	
	Arenosols	0.6	-1.3	4.0	
	Luvisols	12.9	8.4	24.0	4.3
VFS	Regosols	10.8	6.6	7.1	
	Lithosols	17.4	9.2	23.2	
	Arenosols	0.5	-2.2	3.8	
	Luvisols	12.5	4.0	19.1	
Contour Ridges	Regosols	26.9	16.9	19.8	
	Lithosols	28.9	14.3	40.6	
	Arenosols	2.0	-3.0	3.7	
	Luvisols	20.1	6.7	28.3	4.9
Zai	Regosols	21.6	14.5	14.4	
	Lithosols	21.6	13.5	33.2	
	Arenosols	0.7	-3.6	4.1	
	Luvisols	14.1	6.0	24.0	

TABLE E.4: NO WARMING, INCREASE IN RAINFALL (CSIRO 2030)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	2.1	-5.0	6.6	
	Lithosols	3.5	5.0	9.9	
	Arenosols	0.2	-2.3	3.9	
	Luvisols	1.8	-1.2	7.5	-0.2
VFS	Regosols	8.9	-3.4	5.4	
	Lithosols	5.7	3.2	9.6	
	Arenosols	2.2	-2.4	4.1	
	Luvisols	8.7	-2.4	7.0	
Contour Ridges	Regosols	11.1	-12.0	9.1	
	Lithosols	7.5	3.6	13.6	
	Arenosols	2.6	-4.1	5.7	
	Luvisols	10.7	-4.1	10.6	0.1
Zai	Regosols	2.7	-12.0	7.0	
	Lithosols	3.9	3.6	10.4	
	Arenosols	0.2	-4.2	3.9	
	Luvisols	1.6	-5.2	7.5	

TABLE E.5: SIGNIFICANT WARMING, SIGNIFICANT DECREASE IN RAINFALL (CSIRO 2050)

		Maize	Millet	Sorghum	Rice
Bunds	Regosols	16.1	10.1	9.9	
	Lithosols	32.9	15.1	25.7	
	Arenosols	1.0	-1.0	4.1	
	Luvisols	16.9	8.3	21.1	4.4
VFS	Regosols	13.9	7.6	5.4	
	Lithosols	28.8	8.8	19.0	
	Arenosols	1.5	-1.1	4.0	
	Luvisols	17.8	4.6	14.4	
Contour Ridges	Regosols	28.4	11.5	15.7	
	Lithosols	42.5	14.5	36.2	
	Arenosols	2.4	-2.8	4.8	
	Luvisols	26.9	4.4	26.3	5.0
Zai	Regosols	21.6	11.5	11.7	
	Lithosols	37.1	14.4	28.9	
	Arenosols	0.3	-2.8	4.2	
	Luvisols	17.0	3.8	21.0	

SOURCES

Akinbile, C. O. 2010. Behavioural pattern of upland rice agronomic parameters to variable water supply in Nigeria. *J. Plant Breed. Crop Sci 2*:73-80.

Akinbile, C. O. 2013. Assessment of the CERES-Rice model for rice production in Ibadan, Nigeria. Agricultural Engineering International: *CIGR Journal, 15*(1):19-26.

Andre, B., Alfred, H., Obed, L., Mustapha, N., Peter, O., Eric, S., and Lamourdia, T. 2006. African soils: Their productivity and profitability for fertilizer use. Documento presentado para la Cumbre Africana de Fertilizantes 9-13.

Bacci, L., Cantini, C., Pierini, F., Maracchi, G., and Reyniers, F.N. 1999. Effects of sowing date and nitrogen fertilization on growth, development and yield of a short day cultivar of millet (Pennisetum glaucum L.) in Mali. *European Journal of Agronomy 10*:9-21.

Baptista, S., Brottem, L. and de Sherbinin, A. et al. 2013. Background Paper on Regional Climate Change Vulnerability Assessment of West Africa. ARCC.

Belemvire, A., Maiga, A., Sawadogo, H., Savadogo, M., and Ouedraogo, S. 2008. Evaluation des valuation des impacts biophysiques et socioeconomiques des investissements dans les actions de gestion des ressources naturelles au nord du plateau central du Burkina Faso. Rapport de synthese Etude Sahel Burkina Faso. Ouagadougou 94 pp.

Botoni, E., and Reij, C. 2009. La transformation silencieuse de l'environnement et des systèmes de production au Sahel : Impacts des investissements publics et privés dans la gestion des ressources naturelles. Centre for International Cooperation (CIS). Vrije University, Amsterdam, The Netherlands.

Butt, T.A., McCarl, B.A., Angerer, J., Dyke, P.T., and Stuth, J.W. 2005. The economic and food security implications of climate change in Mali. *Climatic Change 68*: 355-378.

DAI. 2009. Global Food Security Response Case Study: Mali. DAI under subcontract to ACDI/VOCA produced for review by United States Agency for International Development. Location: not given. Draft 8/17/09.

Diarra, B., Diakite, H., and Macina, M. 2007. Elaboration de strategie d'adaption des ressources en eau aux changements climatiques. P:\Energy\2-Common\Projects ongoing\032135 NCAP2\From January 2007\NCAP Countries Activities\Outputs\Countries\Mali\032135.060821.MAL.Phase1.Output3.v1.doc

Doraiswamy, P.C., McCarty, G.W., Hunt, Jr, E.R., Yost, R.S., Doumbia, M., and Franzluebbers A.J. 2007. Modeling soil carbon sequestration in agricultural lands of Mali. *Agricultural Systems 94*:63-74.

FAO. 1993. Soil Tillage in Africa. Needs and Challenges. Food and Agriculture Organization of the United Nations. Land and Water Development Division No. 69. FAO

FAO. 2001. Water harvesting in western and central Africa. RAF Publication. Accra, Ghana.

FAO. 2014. Historical crop yield data for Mali. http://www.fao.org/agriculture/seed/cropcalendar/searchbycountry.do

FAOSTAT. 2014. Agricultural Organization of the United Nations. Available at: http://faostat.fao.org. Accessed May, 2/2014.

Fatondji, D., Bationo, A., Tabo, R., Jones, J.W., Adamou, A., and Hassane, O. 2012. Water use and yield of millet under the *zai* system: understanding the processes using simulation. In: Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT) (pp. 77-100). Springer Netherlands.

Folberth, C., Gaiser, T., Abbaspour, K.C., Schulin, R., and Yang, H.. 2012. Regionalization of a large-scale crop growth model for sub-Saharan Africa: Model setup, evaluation, and estimation of maize yields. *Agriculture, Ecosystems & Environment 151*:21-33.

Foltz, J.D., Aldana, U.T., and Laris, P. 2012. The Sahel's silent maize revolution: Analyzing maize productivity in Mali at the Farm-level (No. w17801). National Bureau of Economic Research.

Gassman, Philip W., et al. 2009. The Agricultural Policy Environmental Extender (APEX) model: An emerging tool for landscape and watershed environmental analyses." Center for Agricultural and Rural Development (CARD) Publications, Ames, IA.

ICRISAT. 1999. Efficient Soil Water Use: The key sustainable crop production in the dry areas of west Asia, and north and sub-Saharan Africa. International Crops Research Institute for the Semi-Arid Tropics.

Jalloh, A., Nelson, G.C., Thomas, T.S., Zoubmoré, R., and Roy-Macauley, H. 2013. West African Agriculture and Climate Change: A comprehensive analysis. Research Monograph. International Food Policy Research Institute. Washington: IFPRI.

Jones, P.G. and Thornton, P.K. 1993. A rainfall generator for agricultural applications in the tropics. *Agric. For. Meteorol. 63*: 1- 19.

Kablan, R., Yost, R., Brannan, K., and the Institute d'Economie Rural Mali. 2008. Aménagement en courbes de niveau (ACN): a water harvesting technology to increase rainfall capture, water storage and deep drainage in soils of the Sahel. Univ. Hawaii SM CRSP Bulletin.

Kihara, J., Fatondji, D., Jones, J. W., Hoogenboom, G., Tabo, R., and Bationo, A. 2012. Improving soil fertility recommendations in Africa using the decision support system for agrotechnology transfer (DSSAT). P. 187.

Kouyaté, Z., Franzluebbers, K., Juo, A.S.R., Hossner, L.R. 2000. Tillage, crop residue, legume rotation, and green manure effects on sorghum and millet yields in the semiarid tropics of Mali. *Plant and Soil 225*: 141-151.

Lacy, S. M., Cleveland, D. A., and Soleri, D. 2006. Farmer choice of sorghum varieties in southern Mali. Human Ecology *34*:331-353.

Lee, R. D., Hanna, W. W., Buntin, G. D., Dozier, W., Timper, P., and Wilson, J. P. 2004. Pearl millet for grain. Georgia Extension Bulletin 1216: 12.

Maredia, M. K., Byerlee, D., and Pee, P. 2000. Impacts of food crop improvement research: evidence from sub-Saharan Africa. *Food Policy 25*(5): 531-559.

Michigan State University. 2011. Mali agricultural sector analysis. USAID Food Security III Report. USAID, Washington, DC.

MMA: Mali Minstère de l Agriculture. 2007-2008. Données de bas de la CPS du Ministère de l'Agriculture,Campagne agricole, Bamako, Mali.

Moustapha, A. M. 2010. Rapport sur les techniques de captage de l'eau des pluies au Niger. Report from the Stockholm Environment Institute.

Ndjeunga, J.N. 2002. Local village seed systems and pearl millet seed quality in Niger. *Experimental Agriculture 38*:149–162.

Oguntunde, P. G., and van de Giesen, N. 2004. Crop growth and development effects on surface albedo for maize and cowpea fields in Ghana, West Africa. Intl. J. *Biometeorology 49*:106-112.

Omanya, G. O., Weltzien-Rattunde, E., Sogodogo, D., Sanogo, M., Hanssens, N., Guero, Y., and Zangre, R. 2007. Participatory varietal selection with improved pearl millet in West Africa. *Experimental Agriculture 43*:5-19.

ODI: The Overseas Development Institute. 2000. Rice production in Mali: country profile and case studies (January, 2000).

Payne, W.A., Wendt, C.W., and Lascano R.J. 1990. Root zone water balances of three low-input millet fields in Niger, *West Africa. Agronomy J. 82*:813-819.

Samaké, O., Smaling, E.M.A., Kropff, M.J., Stomph, T.J., and Kodio, A. 2005. Effects of cultivation practices on spatial variation of soil fertility and millet yields in the Sahel of Mali. *Agriculture, Ecosystems Environment 109*: 335-345.

Schlenker, W., and Lobell, D.B. 2010. Robust negative impacts of climate change on African agriculture. *Environmental Res. Letters 5*: 014010.

Senay, G. B., and Verdin, J.P. 2004. Developing index maps of water-harvest potential in Africa. *Applied Engineering Agric. 20*:789-799.

Spaan, W. P., Sikking, A.F.S., and Hoogmoed, W.B. 2005. Vegetation barrier and tillage effects on runoff and sediment in an alley crop system on a Luvisol in Burkina Faso. *Soil and Tillage Research 83*: 194-203.

Steglich, E. M., and Williams, J.R. 2008. Agricultural Policy/Environmental Extender Model: User's Manual. Version 604: 2008-16.

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciais, P., Guimberteau, M., Traore, S., and Baron, C. 2013. Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. Environmental Research Letters 8: 014040.

Tu Tiempo Climate Data. 2014. Available at: http://www.tutiempo.net/en/Climate/Segou/10-1999/612720.htm. Accessed April 25/2014.

Vadez, V., Hash, T., Bidinger, F.R., and Kholova, J. 2012. II. Phenotyping pearl millet for adaptation to drought. *Frontiers Physiology* 3.

Waidler D., White, M. J., Steglich, E.M., Wang, J. S., Williams, J.C.A., and Srinivasan, R. 2011. Conservation Practice Modeling Guide for SWAT and APEX. Texas Water Resources Institute Technical Report No. 399, College Station, Texas, p. 71.

Wang, X., Gassman, P.W., Williams, J. R., Potter, S., and Kemanian, A.R. 2008. Modeling the impacts of soil management practices on runoff, sediment yield, maize productivity, and soil organic carbon using APEX. *Soil Tillage Res. 101* (1-2): 78-88.

WARDA. 2006. Africa Rice Center Annual Report 2005-2006: Providing what's needed. Cotonou, Benin p. 52.

WARDA, 2008. Africa Rice Center. Africa Rice Trends 2007. Africa Rice Center, Cotonou, Benin: 84 pp.

Williams, J.W., Izaurralde, R.C., and Steglich, E.M.. 2008. Agricultural policy/environmental eXtender (APEX) model: theoretical documentation. BREC Rep 2008-17.

Worou, O.N., Gaiser, T., Saito, K., Goldbach, H., and Ewert, F. 2012. Simulation of soil water dynamics and rice crop growth as affected by bunding and fertilizer application in inland valley systems of West Africa. *Agriculture, Ecosystems Environment* 162: 24-35.

Xie, H., Nkonya, E., and Wielgosz, B. 2011. Assessing the risks of soil erosion and small reservoir siltation in a tropical river basin in Mali using the SWAT model under limited data condition. *Applied Engineering Agric. 27*: 895-904.

Yapi, A.M., Kergna, A.O., Debrah, S.K., Sidibe, A. and Sanogo, O. 2000. Analysis of the economic impact of sorghum and millet in Mali. ICRISAT Patancheru, India.

Zaongo, C.G.L., Hossner, L.R., and Wendt C.W. 1994. Root distribution, water use, and nutrient uptake of millet and grain sorghum on West African soils. *Soil Science 157*: 379-388.

Zaongo, C.G.L., Wendt, C.W., Lascano, R.J., and Juo, A.S.R. 1997. Interactions of water, mulch and nitrogen on sorghum in Niger. *Plant Soil 197*:119-126.

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