June 2016

Ethiopia's Productive Safety Net Program (PSNP):

Soil carbon and fertility impact assessment

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November 2015

Please cite this work as follows:

Solomon D., Woolf, D., Jirka, S., De'Gloria, S., Belay, B., Ambaw, G., Getahun, K., Ahmed, M., Ahmed, Z., and Lehmann, L. 2015. "Ethiopia's Productive Safety Net Program (PSNP): Soil carbon and fertility impact assessment. A World Bank Climate Smart Initiative (CSI) Report. Cornell University. https://ecommons.cornell.edu/handle/1813/41301

The PSNP is implemented by the Government of Ethiopia with support from the following development partners: Canadian International Development Agency, Irish Aid, European Commission, Royal Netherlands Embassy, Swedish International Development Cooperation Agency, UK Department for International Development, United States Agency for International Development, World Food Program and World Bank.

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Important acronyms and abbreviations

ATR	Attenuated total reflectance
BD	Bulk density of the soil samples
CEC	Cation exchange capacity
CPWD	Community-based participatory watershed development
CSI	Climate smart initiative
GDP	Gross domestic product
DRM	Disaster risk management
FAO	Food and agriculture organization of the UN
FEWS NET	Famine early warning system network
FFW	Food-for-Work
FTIR	Fourier transform infrared
GT	Gigatonne
Ha	Hectare
HTS-XT	High throughput screening eXTension
ICRAF	International center for research in agroforestry
INDC	Intended nationally determined contribution
IPCC	Intergovernmental panel on climate change
ISFM	Integrated soil fertility management
ISWC	Integrated soil and water conservation
MERET	Managing environmental resources to enable transition
MIR	Mid infrared
MOA	Ethiopian ministry of agriculture
MODIS	Moderate-resolution imaging spectroradiometer
MSE	Mean square error
NPP	Net primary productivity
OCHA	Coordination of humanitarian affairs office of the UN
ORDA	Organization for rehabilitation and development in Amhara
PBS	Percentage base saturation
PSNP	Ethiopia's productive safety net program
RF	Random forest regression model
REST	Relief society of Tigray
SLM	Sustainable land management
SLMP	Sustainable land management project
SNNPRS	Southern nations and nationalities regional state
SSA	Sub-Saharan Africa
UN	United Nations
UNFCCC	United Nations framework convention on climate change
USAID	US agency for international development
UNCCD	United Nations convention to combat desertification
UNEP	United Nations Environment Programme
AfSIS	Africa Soil Information service
AFOLU	Agriculture, forestry and other land Use

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Bure), SNNPRS (Asore, Godaye, Gamot Terara, Sheshhecho and Usha) and Tigray (Serawat and Chearo) regional states. Land cover typology represent grassland, woodland, forestland, cultivated land or agroforestry. NPP represent moderate resolution imaging spectroradiometer (MODIS) net primary productivity (NPP). Bioclimatic zone represent Holdridge climatic zone simulated for each PSNP watershed using FAO's new local climate estimator (New_LocClim) program as described in section 2.1 of this report. For details about the independent variables see Solomon et al., 2015.

Figure 10 Relative parameter of importance from RF regression analysis of selected surface soil fertility co-benefits indicators (10a, total nitrogen; 10b, available phosphorus, 10c, available potassium; 10d, cation exchange capacity; 10e, bulk density and 10f, available water capacity) of the Ethiopia's PSNP watersheds. Parameter of importance is expressed as mean square error (MSE).

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Acknowledgements

This work was made possible through the generous financial support of The World Bank. We thank CARE-Ethiopia for coordinating and facilitating collaboration amongst Climate Smart Initiative (CSI) consortium partners. Field work to support findings in this paper was made possible through the assistance of CSI partners including Relief Society of Tigray (REST), Organization for Rehabilitation and Development in Amhara (ORDA), Farm Africa, SNV, Mercy Corps, and CARE-Ethiopia. Officials with the Ethiopian Ministry of Agriculture (MoA) natural resources management directorate, the six regional government (Tigray, Amhara, SNNPRS, Oromia, Afar, and Somali) MoA offices, and the CSI woreda-level MoA offices are acknowledged for their guidance and support during field operations—without them this work would not have been possible. We also thank Jimma University for its excellent organization and support as in-country research partner.

Abstract

Ethiopia's climate smart initiative (CSI) aims to integrate the implications of climate change into Productive Safety Net Programs (PSNP) activities, and systems to strengthen this important social safety net program, and enable Ethiopia to better manage climate risks and help its chronically food insecure population better cope with shocks, create assets and secure livelihoods, even as the climate changes. PSNP'CSI is also tasked with preparing the ground for PSNP's sustainable public work programs to access climate finance and possibly payments from ecosystem services and benefits to spur and enable the transition towards low-carbon, climate-resilient growth and development. More robust and cost effective analysis and information on soil carbon stock changes and associate soil fertility and productivity indicators over space and time is required at multiple stages of development and implementation of PSNP' participatory integrated watershed management projects to access climate finance and payments for ecosystem services and benefits generated as a result of the implementation of PSNP's landscape-level climate-smart restorative watershed management interventions in degraded watersheds and agricultural lands. Therefore, the main objectives of this study are to: (i) assemble georeferenced business as usual and project scenario baseline database on soil carbon and other soils fertility, health and productivity indicators for six chronical food insecure and vulnerable Ethiopian regional states (i.e., Afar, Amhara, Oromia, SNNPR, Somali and Tigray), where PSNP's sustainable agricultural and environmental rehabilitation public works have been implemented widely, ii) evaluate the impacts of Ethiopia's PSNP participatory integrated watershed intervention projects on soil carbon capture and sequestration, as well as on other climate smart environmental and agricultural co-benefits in light of climate change, food security and low-carbon livelihoods in these regions, (iii) assess low-cost soil carbon and soil fertility measurement techniques for Ethiopia's PSNP that possess the following important elements, and (iv) support Ethiopia's safety net climate smart initiative to take advantage of international carbon and climate finance opportunities to support sustaining the existing activities as well as scaling-up future implementations of PSNP participatory watershed public works projects in Ethiopia. Ethiopia's PSNP CSI soil carbon and fertility assessment developed a robust georeferenced and downscaled national business-as-usual and project scenario baseline database for Ethiopia's PSNP in selected CSI implementation Woredas of the six Ethiopian regional states using standardized soil analytical measurements. The integrated and multidisciplinary baseline data includes include information about the livelihoods, vegetation, climate, best management practices, time, geospatial aspects of the selected CSI Woredas, in addition to the basic soil carbon and other critical soil biological, physical and chemical characteristics that affect soil fertility and productivity and food security. By integrating this multidisciplinary baseline database with CSI's aboveground ground biomass resources assessment and geospatial modeling studies, it has been demonstrated that: (i) it is capable of enabling modelling and prediction of soil carbon capture and sequestration, as well as other climate smart environmental and agricultural co-benefits, and (ii) it allow current and future spatial and temporal geospatial mapping, monitoring and reporting, as well as scaling up opportunities. Ethiopia's PSNP CSI soil carbon and fertility assessment identified the key drivers of soil carbon sequestration and soil fertility in selected PSNP sites, and evaluate their impact on soil carbon capture and sequestration, as well as on other environmental and agricultural

co-benefits. The study demonstrated that implantation of PSNP's restorative landscape-level participatory integrated watershed management interventions in degraded watersheds could be considered as an important strategy for enhancing the soil's carbon sinking capacity of degraded ecosystems and agricultural lands, and for reducing the rate of enrichment of atmospheric CO_2 while having positive impacts on decreasing siltation of waterways and reservoirs, water availability and quality, food security, and on the sustainability environment. Ethiopia's PSNP CSI soil carbon and fertility assessment also explored MIR-spectroscopy based low-cost soil carbon and fertility co-benefits analytical techniques, as well as of plant growth bioassay-based approached to measure the productivity for Ethiopia's PSNP. This study demonstrated that MIR-spectroscopy is a non-destructive analytical tool that preserves the integrity of the soil system while analyzing several soil properties simultaneously. Compared to the conventional standardized laboratory techniques-based assessments, it clearly provide a rapid and cost-effective analysis of soil carbon, and other soil chemical and physical characteristics of large number of samples collected from various agricultural, forestry, pastureland and other land use systems. It is appropriate to region, scale and varying landscapes and land use types of Ethiopia's PSNP. The technique enable rapid but effective assessment, monitoring and reporting of carbon stock changes and other climate smart co-benefits as a result of the implementation of safety net public works projects in food-insecure regions of the country. This makes it very attractive complementary option to Ethiopia's PSNP to: (i) develop downscaled geospatially-referenced soil-based baseline database, (ii) to conduct fast and reliable broad spatial scale assessment, monitoring and reporting of soil carbon sequestration activities, and (iii) for assessing soil fertility and health, land degradation and other soil-related ecosystem services and co-benefits in PSNP watersheds to understand the soils' s ability to perform production, environmental and climate related functions, as well as to support the country's effort to secure climate finance and payments for ecosystem services and benefits generated as a result of the implementation of PSNP's participatory integrated watershed management projects.

1 Introduction

1.1 Country background and biophysical context

Ethiopia, with a total area of 1.2 million km^2, is the largest landlocked country in Africa. Its topographical features encompass high and rugged mountains, flat-topped plateaus, deep gorges, and rolling plains; with altitudes ranging from 110 m below sea level at the Danakil Depressions in the northeast to 4600 m above sea level at Ras Dashen Mountain in the northwest. Although there are roughly 12 different patterns of landforms present within this altitudinal range, the country is generally divided into three basic geographical units: the eastern plateau, the Rift Valley and the western plateau (Debele, 1985; Taddese, 2001; Yirdaw, 2002; Lemma, 2006; Abebe et al., 2012).

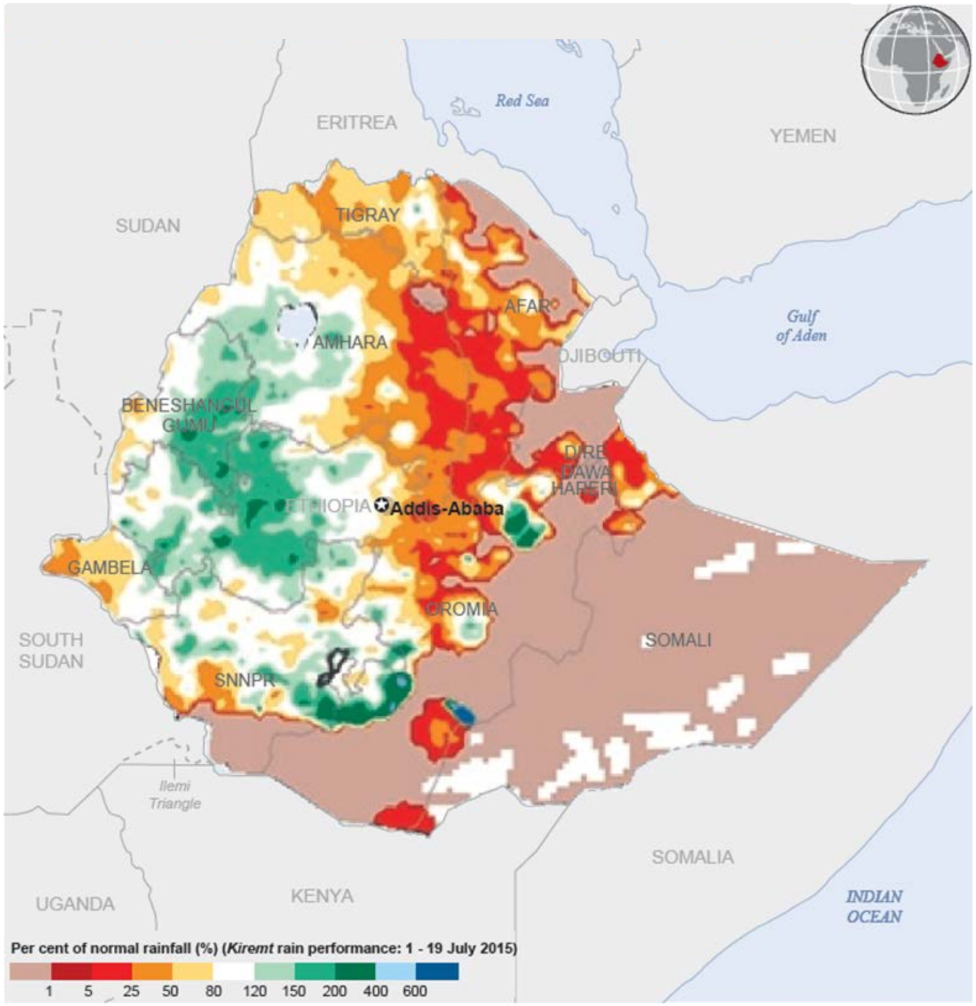

Figure 2. El Niño impacts on the 2015rainy season (June to September) precipitation distribution in Ethiopia (Sources: US Agency for International Development, USAID; Famine Early Warning System network, FEWS NET; UN Office for the Coordination of Humanitarian Affairs (OCHA). The predictions are that food insecurity will continue to deepen throughout the year, not least with the on-going El Niño phenomenon, which is expected to continue to affect (with 80% probability) the rainfall patterns through the first quarter of 2016.

Ethiopia has a tropical monsoon climate but with wide topography-induced variations including climatic conditions typical of tropical savanna and desert in the lowlands. However, the country's climate can be generally classified into three very broad climatic zones: (i) a cool zone consisting of the western and eastern sections of the high plateau with altitude over 2400 m above sea level, (ii) a temperate highland zone between 1500 and 2400 m above sea level and (iii) a hot lowland zone below 1500 m above sea level (Taddese, 2001; Abebe et al., 2012). The temperature of the country is significantly influenced by altitude among other factors, and varies from 35°C in the Danakil lowlands to less than 7.5°C at around the Ras Dashen Mountain. Precipitation amounts vary from over 2200 mm per annum in the southwestern highlands to less than 100 mm per annum in the extreme North, and in lowlands of the northeastern and southeastern parts of the country. The rainfall is highly erratic, and falls often as convective storms with very high intensity and extreme spatial and temporal variability. The result is that there is a high risk of erosion, intra-seasonal dry spells, drought, and deepening of food insecurity (see Figure 1; Debele, 1985; Abebe et al., 2012).

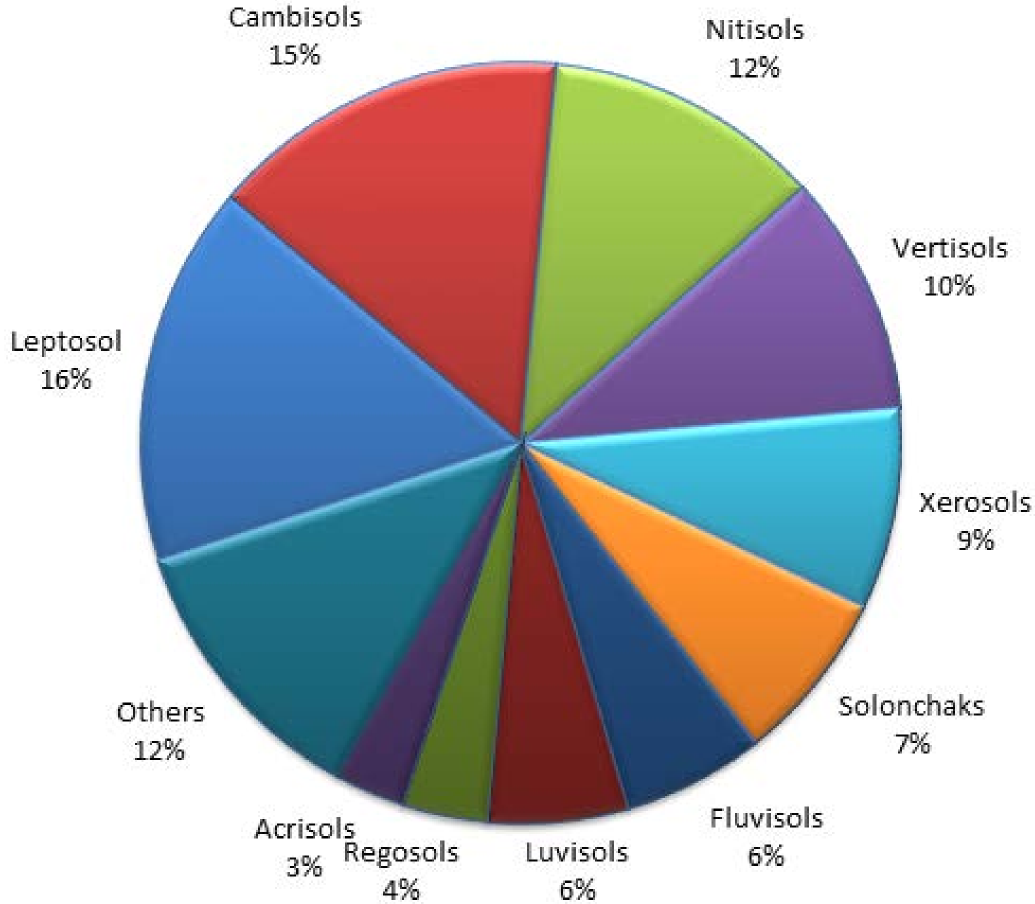

Figure 2. Soil types of Ethiopia and their distribution (Redrawn from Debele, 1985).

The great climatic variability, topographical diversity, and the various geological factors endowed Ethiopia with a variety of biophysical environments that include different soil and vegetation types, water resources, and multitudes of ecosystems and production zones with contrasting agricultural potentials. The Food and Agriculture Organization of the United Nations (FAO) revised soil map provides the description and regional distribution of soil types of the country (FAO, 1988; Hurni et al., 2007). Of the 28 soil orders described in FAO's revised legend (FAO, 1988), 17 soil orders are known to occur in Ethiopia (Debele, 1985; Haileslassie et al., 2005; Hurni et al., 2007; Shiferaw et al., 2013). In spite of the variability, six units in increasing order of importance (i.e., Leptosol, Cambisols, Nitisols, Vertisols, Xerosols, and Solonchaks) cover up to 62% of Ethiopia's land mass (see Figure 2). Nitisols and Cambisols are the dominating soil types over much of the highlands, while Vertisols and Regosols are prevalent mainly on the East and West along the edge of the arid lowlands. Regosols, Yermosols and Xerosols occupy much of the Somali plateau and the arid lowlands of Ethiopia (Hurni et al., 2007; Abebe et al., 2012).

Ethiopia's agroecological zones are traditionally classified mainly based on temperature, rainfall and altitude into: dry hot, dry warm, sub-moist warm, sub-moist cool, moist cool, cold, moist cold and very cold or alpine (Debele, 1985; MoA, 2000; Abebe et al., 2012). The natural vegetation in these agroecological zones ranges from Afro-alpine through dense high canopy montane forest and wetland to woodland savannah, grassland, scrubland, semi desert and desert vegetation.

1.2 Population context

With a 2014 population of approximately 96.6 million, Ethiopia is the second most populous country in Sub-Saharan Africa (SSA) (WB, 2012; CIA, 2015). Most of the world's population growth in the next 40 to 50 years is expected to come from Africa, and Ethiopia will be a large part of the anticipated growth. If Ethiopia maintains its current growth rate of ca. 2.9%, its population is expected to almost double in the next 20 years, and cross 300 million by 2050, projected to become among the world's top ten most populous countries (UN, 2012; CIA, 2015). This will induces increased demand for food, energy and other natural resources, and also greatly influence the manner in which these resources are utilized.

1.3 Sectoral context

Despite a recent economic upturn, Ethiopia is still one of the poorest countries in the world and faces a number of critical development challenges. It has a gross per capita income of US$ 505 and a low human development index of 173 out of 185 countries worldwide (WB, 2013; UNDP, 2014).

Smallholder agriculture is the main livelihood for an overwhelming majority of Ethiopia's population, and it is the basis of the country's national economy. It accounts for up to 80% of the employment, contributes up to 43% to of the gross domestic product (GDP), and makes up to 70% of the country's export revenue (Wondifraw et al., 2014). However, most Ethiopian smallholder farmers still practice subsistence level and less diversified rain fed agriculture with very low productivity. Thus, food insecurity and malnutrition still remain high in the country, and most rural smallholder farming households are live under a very fragile existence.

1.4 Environment and land degradation context

More recently a number of related factors have further heightened the fragility of the country's rural farming households. For example, Ethiopia's rapid population growth and lack of alternative employment opportunities in other economic sectors have increased pressure on the limited arable land under smallholder farming system and have led to further subdivision of the already small and fragmented family farms, making them too small to grow the required food for the household. Rapid population growth is also linked to expansion of cultivated land for meeting short-term survival needs at the expense of natural forests, wood and grasslands, leading to declining aboveground vegetation cover, increased farming on steep slopes, and to extensive land and other natural resources degradation. In fact, Ethiopia is now one of the countries in SSA most seriously affected by environmental and land degradation (Tilahun et al., 2001; Lambin et al., 2003; Shiferaw et al., 2013; Gashaw et al., 2014).

Land degradation is the reduction in the capacity of the land to provide ecosystem goods and services and assure its functions over a period of time for its beneficiaries (FAO, 2011).

The causes of Ethiopia's extensive environmental and land degradation are complex and diverse, and are not limited to the country's rapidly growing population. They include a number of factors such as the low level livelihood of the rapidly growing rural population, the heavy reliance on subsistence agriculture, the unsustainable farming practices, the very high dependence on wood and other biomass for household energy, and the poor livestock management including overgrazing and expansion of livestock population beyond carrying capacity of the land. The country's rugged topography, coupled with inadequate sustainable land management and agricultural knowledge and poor extension service, limited adoption of integrated soil conservation and soil fertility management practices, as well as the breakdown of traditional land productivity restoration measures (such as fallowing) also contribute to the current extensive degradation observed in the country (Hurni, 1988, 1993; Taddese, 2001; WB, 2008; Abebe et al., 2012; Shiferaw et al., 2013; Gashaw et al., 2014).

Among the many consequences of the environmental and land degradation in Ethiopia are: (i) loss of topsoil (the national soil loss rate is classified as 'moderate to high', which is estimated at 30-100 tonnes (t)/ hectare (ha) but could reach up to 300 t/ha per year depending on land use practices, Wright and Adamseged, 1986) , mass movement and terrain deformation through water and wind erosion, (ii) the country's low and declining agricultural land productivity and ability to provide food and feed for the ever increasing human and animal populations, (iii) the persistent food insecurity and the threat of losing the capacity for achieving national food security, (iv) the devaluation and eventual loss of the country's land for agricultural purposes, and the high cost of restoring and maintaining natural environments, (v) the loss of carbon stock and atmospheric carbon sink capacity of the land, and (vi) the increased severity of the impact of drought and risks of natural disasters. Indeed, Ethiopia's State of Environment Report (EPA, 2003) has now officially established that there is a close relationship between environmental and land degradation, drought, crop failure, malnutrition and increased level of rural poverty in the country. The report highlighted that land degradation especially accelerated soil erosion, soil organic carbon and plant nutrient depletion and the decline in water quality are critical environmental problems facing the country, and the major causes of the chronic food insecurity widely experienced by Ethiopia's largely rural population. All of these factors contribute to increasing vulnerability of Ethiopia's resource poor smallholder farming communities. Therefore, of all the challenges facing Ethiopia, ending chronic food shortages and rural poverty and achieving enhanced livelihood and long-term food security in an environmentally and socially sustainable manner is the most pressing agenda for the country.

1.5 Food security and productive safety net program context

Ethiopia has suffered recurrent food crises and famines for centuries (Pankhurst, 1989; Béné et al., 2012). Historically, responses to chronic food insecurity were dominated by emergency food aid (Devereux, 2010; Van Domelen and Coll-Black, 2012). Between 1994 and 2003, an average of 5 million Ethiopians were considered at risk and in need of emergency assistance every year, and from 1998 to 2005 the annual number of food aid beneficiaries fluctuated between 5 and 14 million (Devereux et al., 2006; Béné et al., 2012). Over time, however, concerns arose regarding several operational shortcomings in Ethiopia's emergency food aid appeal system's ability to maintain a reliable safety net and develop productive assets among the rural food insecure population. While food aid saved lives, it became apparent that it often failed to protect livelihoods, resulting in millions of people in Ethiopia sliding into poverty. By the early 2000s, there was a growing consensus between the Ethiopian Government and its development partners on the need to reform the emergency food aid system in favor of a more productive approach to providing a more solid safety net to vulnerable populations (Béné et al., 2012; Van Domelen and Coll-Black, 2012).

Recognizing this situation in 2005 Ethiopia launched an alternative system, the Productive Safety Net Program (PSNP), to help address the needs of the country's chronically food insecure households. As a result, Ethiopia's PSNP emerged as an internationally acknowledged social protection flagship program both in its scope and in its partnership approach, having reoriented conventional rural safety net programs to better respond to the needs of food insecure households and create productive investments to underpin rural economic growth and environmental rehabilitation (Béné et al., 2012; Van Domelen and Coll-Black, 2012; WB, 2013b).

This is achieved through: (i) enhancing the resilience of vulnerable households to food insecurity through timely and predictable food and cash transfers in a way that prevents asset depletion at household level and builds assets at community level (the program provides transfers through labor-intensive public works that focus on soil and water conservation and building social infrastructures such as construction of roads, schools, clinics etc., and through direct support to labor poor households with the elderly and the sick), (ii) increasing adoption of disaster risk management (DRM) systems through improved early warning, contingency planning and financing and risk mitigation to respond to shocks, and (iii) rehabilitation of degraded natural and managed ecosystems to enhance societal- and ecosystem- resilience, and to mitigate and adapt to climate change (Van Domelen and Coll-Black, 2012; WB, 2013b, 2014). With about 47,000 small community projects in Ethiopia, PSNP is now believed to be the largest social protection program in SSA outside of South Africa, and has reached around 12% of the population, covering over 40% of the country's administrative Woredas (Cooper et al., 2012; Van Domelen and Coll-Black, 2012).

PSNP is an internationally acknowledged social protection safety net program of the Government of Ethiopia that responds not only to chronic food insecurity among the rural poor, but also targets these highly climate-vulnerable population and create productive investments that improve access to natural resources and services, stimulates markets, and underpins participatory agroecosystem and environmental rehabilitation.

Ethiopia's PSNP public works aimed at restoring local environments degraded by years of overuse and unsustainable management include implementation of a package of sustainable integrated watershed management interventions in accordance with the Ethiopian Ministry of Agriculture's (MoA) procedures on community-based participatory watershed development (CPWD) (Desta et al., 2005; Berhane et al., 2011; Van Domelen and Coll-Black, 2012). These multiple sustainable watershed management interventions range from integrated soil and water conservation (ISWC) practices such as construction of stone and soil embankments, hillside terraces, deep water infiltration trenches, shallow wells and ponds and stream diversion for irrigation, digging drainage channels to reduce flood damage to farmlands to adopting suitable integrated soil fertility (ISFM) and crop management practices that involve the use of organic amendments, improved varieties, diversified cropping systems, and the use of multi-purpose leguminous cover cops and multi-strata agroforestry systems that can protect farmlands while providing additional food and fodder and improving the sustainability of agroecosystem attributes. They also include degraded land rehabilitation and marginal land reclamation measures such as area closures and natural regeneration of indigenous grass, shrub and tree species and/or the establishment of woodlots and forests etc. that can improve the qualities of both the natural environment and the neighboring agroecosystems.

Over the years, albeit with limited spatial and temporal quantitative data, Ethiopia's PSNP has been considered to be a successful sustainable environmental rehabilitation and resilience enhancing program largely credited with: (i) reducing sediment in streams in areas closed to grazing and cultivation, (ii) increasing woody biomass and forage production, (iii) increasing water availability and quality, (iv) increasing ground water recharge and improved downstream base flow of streams, (v) enhancing down-stream crop production through soil and water conservation interventions, (vi) increasing soil carbon storage (based on estimates from just two of several thousand watersheds), (vii) increasing biodiversity, and (viii) enhancing livelihoods and access to social services (Berhane et al., 2011; Béné et al., 2012; Van Domelen and Coll-Black, 2012; Tongul and Hobson, 2013; WB, 2013b).

Ethiopia's community-based participatory watershed development (CPWD) program is a national consolidated guideline including for the country's PSNP to promote and expand community watershed development in the country.

It aims at (i) conserving soil, water and vegetation for productive uses; (ii) harvesting surplus water to create water sources and to recharge ground water; (iii) promoting sustainable farming and stabilizing crop yields by adopting suitable soil, water, nutrient and crop management practices; (iv) rehabilitating and reclaiming marginal lands through appropriate conservation measures and mix of trees, shrubs and grasses based on land potential; and (v) enhancing income of individuals particularly the most vulnerable section of the rural poor, by diversifying agricultural production and developing enterprises linked to sustainable use of natural resources (Desta et al., 2005).

1.6 Climate change and climate smart initiative context

Despite the evidence that Ethiopia's PSNP is helping to rehabilitate both the agricultural and rural environment and contributing towards building rural households' food security and their ability to cope with disasters, there are further challenges ahead from climate change (WB, 2013b). The studies by Intergovernmental Panel on Climate Change (IPCC) show that global average surface temperatures are likely to increase because of radiative forcing of greenhouse gases (GHGs) in the atmosphere by 1.1 to 6.4°C in the 21st century, depending on the region (Vuuren et al., 2007; IPCC, 2013;). Projected increases in global temperatures are likely also to lead to increased frequency and severity of extreme weather events such as droughts and flooding across the globe.

Ethiopia, as part of the global community is feeling the impact of this change. Historical trends show that Ethiopia's temperature increased by up to 1.3°C from 1900 to 2006. Future projections show that the country is becoming even warmer, with average projected increases reaching up to 2.2 °C by the 2050's and over 3°C by 2100 (WB, 2013b; IPCC, 2013). This will be associated with heat waves and higher water losses from soil, plants and water sources. In some areas, this means a real risk of more droughts that will constrain crop growth and yield or could lead to catastrophic failure and chronic famine. Although the changes in rainfall are more difficult to predict and thus more uncertain, most models suggest that rainfall is likely to increase in general across Ethiopia by anywhere between 1 to 10% by 2050's, and by up to 20% by 2100 (WB, 2013b; IPCC, 2013). However, the same model predictions show significant regional variation, with more rain in some areas and less in others exposing them to regular severe flood and drought events, respectively. Ethiopian agriculture is typically rain-fed and relies on predictable rainy seasons. The increasing unpredictability of future rains is, therefore, a key barrier to successful food production and could become a significant threat to food security. However, it is also likely that climate change will not only bring new risks and shocks but also it will worsen existing problems (WB, 2013b). In such cases, the normal weather shocks affecting people's livelihoods will become more severe, more frequent, and will come with shorter warning times. Drier conditions will mean there are likely to be more frequent or widespread challenges for Ethiopia's pastoralist communities to find enough water and grazing for their livestock. It is also possible that climate change impacts will cause more land degradation, making it harder for Ethiopia's smallholder farmers to grow crops and make a living. Such repeated exposure to more acute weather shocks, with no time to avoid or prepare for them could seriously degrade the resilience built around rural smallholder farming and pastoral communities through PSNP, and could drive Ethiopia's rural poor deeper into food insecurity and exacerbate their vulnerability.

In order to respond to these climate change challenges, Ethiopia's PSNP incorporated in 2013 a climate smart initiative (CSI). This initiative aims to integrate the implications of climate change into PSNP to strengthen this important social protection safety net (SSN) program, and enable the country to better manage climate risks and help chronically food insecure people resist shocks, create assets and become food self-sufficient, even as the climate changes. CSI is expected to test out new activities and overall systems of support that focus on building livelihoods that are both sustainable and resilient to climate change. It has a strong focus on local needs and priorities, and seeks to get these lessons integrated into policy and practices.

Ethiopia's climate smart initiative (CSI) aims to integrate the implications of climate change into PSNP's activities, and systems to strengthen this important SSN program, and enable Ethiopia to better manage climate risks and help its chronically food insecure population better cope with shocks, create assets and secure livelihoods, even as the climate changes.

1.7 Significance of the study

Ethiopia's initial national communication to the United Nations Framework Convention on Climate Change (UNFCCC) and its Intended Nationally Determined Contribution (INDC) indicate that the sector wise carbon dioxide (CO_2) and non- CO_2 GHG emission profile of the country is dominated by emissions from agriculture and forestry (NMSA, 2001; Shiferaw et al., 2013; UNFCCC, 2015). The initial estimate also shows that the sink capacity of Ethiopia's forestry, other woody biomass and grassland sectors is decreasing rapidly due to deforestation mainly for agricultural and energy use and overgrazing.

Despite the fact that Ethiopia contribute only to 0.27% of the global emissions, the country has made an ambitious commitment to curb its greenhouse gas emissions between now and 2030. As one of Africa's most vulnerable nations to climate change, Ethiopia recently submitted its INDC to the UNFCCC, where the country intends to limit its net greenhouse gas (GHG) emissions in 2030 to 145 Mt CO_2e or lower. This would constitute a 255 Mt CO_2e reduction from the projected business-as-usual or the conventional economic growth emissions scenario in 2030. It represents a major shift, since the business-as-usual economic growth would more than double Ethiopia's greenhouse emissions by 2030 to 400 Mt CO_2e. Ethiopia's INDC shows that 86% of the expected abatement potential is anticipated to come from the agriculture, forestry and other land use (AFOLU) sector.

While responding to chronic food insecurity among the rural poor, PSNP's participatory integrated watershed management intervention activities are also focused on rehabilitating Ethiopia's rural environment and the AFOLU sector by enhancing productivity, above and belowground biomass and soil carbon storage. Therefore, there is a potential for PSNP to secure climate finance through demonstrating how these participatory integrated watershed management interventions are sequestering atmospheric carbon and reducing GHG emissions (mitigation) and helping people respond to the impacts of climate change (adaptation) (WB, 2013b; Woolf et al., 2015; Jirka et al., 2015). There are also numerous ecosystem services and co-benefits generated through Ethiopia's PSNP sustainable integrated watershed management intervention activities. Because resource poor and chronically food insecure households control much of the highly degraded and ecologically sensitive land, Ethiopia's PSNP potentially stand also to benefit from international market-based approaches involving payments for generating ecosystem services and co-benefits.

1.7.1 Significance of Ethiopia's PSNP participatory integrated watershed management interventions

Ethiopia's PSNP sustainable public works program involve participatory integrated watershed management interventions at the watershed level can be generally categorized into two broad groups: (i) degraded and marginal land rehabilitation and reclamation through the combination of ISWC, gully control and restoration, area enclosure with natural forestland, woodland and grassland regeneration, afforestation and reforestation, and (ii) promoting climate smart sustainable agriculture in smallholder mixed crop and livestock agroecosystems systems via ISWC and integrated soil fertility management (ISFM) and agroforestry systems.
Ethiopia's CSI is tasked with preparing the framework for PSNP sustainable public works program to access climate finance, which is broadly defined as financial support channeled by national, regional and international entities for climate change mitigation and adaptation projects and programs to spur and enable the transition towards low-carbon, climate-resilient growth and development (Buchner et al., 2011; WB, 2013b).

More robust and cost effective analysis and information on above and below ground carbon stocks and projections of future emissions reduction over space and time is required at multiple stages of development and implementation of PSNP's participatory integrated watershed management intervention projects to access climate finance. Specifically, it is critical for Ethiopia's PSNP's to establish rigorous baselines (Lubowski et al., 2006) and prioritize the location of emissions reduction or sequestration activities for the monitoring, reporting and verification (MRV) of such activities in order to secure climate finance (Naidoo et al., 2008; Petrokofsky et al., 2012), and for investors to see appreciable reductions in GHG emissions and a return on their investment. These systems must be appropriate in scale and to the region in question, and must have the required flexibility for application in varying land use types. However, accurate carbon accounting methodologies and appropriate local and regional measurement and monitoring techniques in almost all PSNP projects are largely lacking. There are questions as to how PSNP projects are going to demonstrate initial and baseline scenarios (also referred to as business-as-usual), permanence of the sequestered carbon in the project scenario, as well as other climate smart agricultural and environmental services and co-benefits (such as soil fertility and productivity enhancements) as a result of the implementation PSNP. There is also an overall need to promote the availability of information on socio-economic aspects of land degradation and climate change, and improve the integration of such information into impact and vulnerability assessments to have a comprehensive understanding of the many social and environmental co-benefits that this SSN program brings to resource poor smallholder farming household's in chronically food insecure regions of Ethiopia. These challenges mean for example carbon sequestration gains or prevented losses as a result of implementation of PSNP projects are at times difficult to quantify, and this lack of quantifiable data to some extent inhibits the country's ability to leverage and benefits from climate change adaptation and mitigation finance and payments for the ecosystem services and co-benefits created by the PSNP.

As part of the comprehensive CSI, the soil carbon and fertility impact assessment, along with Ethiopia's PSNP carbon benefits (Woolf at al., 2015) and climate finance (Jirka et al., 2015) investigations: (i) aim to address these constraints, (ii) explore in depth the role that food security interventions in the form of PSNP's participatory integrated watershed management interventions can play in rehabilitating of degraded ecosystems, enhancing agroecosystem productivity and mitigating climate change, and (iii) seek short- and long-term opportunities for accessing climate finance and payments for ecosystem services and co-benefits generated by these productive investments to support the scaling-up and sustainability of the Ethiopian government's current and future social protection safety net public works program in the country.

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1.7.2 Significance of soil carbon sequestration for climate change and food security

The rising atmospheric CO_2 concentration is a concern because of its climate-altering potential. Since the beginning of the Industrial Revolution in the 18th century, atmospheric CO_2 has increased by more than 30% (Post et al., 2004). The increase in fossil fuel burning and associated CO_2 emissions is expected to continue for the foreseeable future, and a doubling or even tripling of the preindustrial concentration of atmospheric CO_2 is possible by the end of the21st century (IPCC, 2001).

Carbon sequestration implies transferring atmospheric CO_2 into long-lived carbon pools and storing it securely so it is not immediately reemitted.

Soil carbon sequestration means increasing soil organic carbon stocks through judicious land use and recommended best management practices. The potential soil carbon sink capacity of managed ecosystems approximately equals the cumulative historic carbon loss estimated at 55 to 78 Gt.

Soils represent the largest reservoir of terrestrial carbon on the global scale, and plays a critical role in carbon cycling. Global soils contains about 4.3 times the size of the atmospheric carbon pool (760 gigatonne, Gt), 5.9 times the size of the biotic carbon pool (560 Gt); and current estimates of the global soil organic carbon pool are in the order of 3300 Gt in the top 3 meter (Solomon et al., 2007a; Tarnocai et al., 2009). Increasing carbon in soil by enhancing carbon sequestration and storing it as soil organic carbon is desirable for mitigating the global climate, since even a relatively small increase in the proportion of soil carbon could make a significant contribution to reducing CO_2 concentration from the atmosphere (Lal 2004; Post et al., 2004; Walcott et al., 2009; Shiferaw et al., 2013).

In undisturbed terrestrial ecosystems such as natural forests and grasslands, each soil has a carbon carrying capacity (i.e., equilibrium soil carbon content) depending on climate, vegetation, topography, parent material and time. In such ecosystems, the biogeochemical cycling of carbon is essentially in balance with minimal short-term losses or gains. However, soil carbon stocks are highly vulnerable to human activities, and the steady state attained in such undisturbed natural ecosystems, and thereby the amount and stability of soil organic carbon, can be dramatically reduced (often rapidly) in response to land use and land cover changes that reduce organic matter inputs and affect rates and processes underlying the equilibrium state until a new steady state is eventually established in the ecosystem (Guo and Gifford, 2002; Solomon et al., 2005, 2007a; Victoria et al., 2012).

The principal types of land use and land cover changes involve deforestation, clearing of natural forest and grassland ecosystems for agricultural purposes, as well as unsustainable agricultural

and soil management practices in agroecosystems. Some estimates indicate that these practices have led to a global increase in the total area of cultivated land by more than 425% since 1850, with the most rapid changes occurring in tropical and subtropical regions such as Ethiopia, especially after the 1950's (Houghton, 1999). Given that one third of the global soil carbon pool is in the tropics (Eswaran et al., 1993), these anthropogenic disturbances influence the global carbon cycle by increasing the CO_2 flux from the soil to the atmosphere, and are expected to have consequences on the Earth's climate, and on the associated soil organic matter dynamics and the biogeochemical cycling of plant nutrient elements therein.
Soils under undisturbed natural forests or grasslands tend to have higher soil organic carbon content than degraded soils or soils under cropland. Studies conducted in temperate and tropical ecosystems including Ethiopia indicate that the conversion of undisturbed natural ecosystems such as forests and grasslands to agricultural land causes depletion of the soil organic carbon pool by as much as 60% in soils of temperate regions and by 85% or more in cultivated soils of the tropics (Lal, 2004; Solomon et al., 2002, 2007a). The depletion is exacerbated when the output of carbon as a result of these conversions or unsustainable management practices exceeds the input, and when soil degradation becomes severe. The soil organic carbon pool up to one meter depth ranges from 30 t/ ha in arid climates to 800 t/ha in organic soils in cold regions, with a global range of 50 to 150 t/ha. Studies show that some of these soils have lost as much as 20 to 80 tonnes of carbon per ha, which is mostly emitted into the atmosphere as CO_2 (Lal, 2004). After conversion of natural ecosystems to crop land, appropriate management measures that reduce soil organic matter losses and/or increase its inputs can maintain or increase soil organic carbon content of agricultural soils (See Figure 2 for enhancement of carbon sequestration in soils).

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Organic carbon enters the soil system as a heterogeneous mixture of compounds released from living plants, animals and microbes, and their residues ranging in size and complexity from simple monomers to complex biopolymers (Solomon et al., 2007a). Most of this carbon is readily mineralized by soil microorganisms within a short timescale of one or two years (Jenkinson and Ladd, 1981). The remaining portion, however, can be stabilized as part of soil organic matter for longer timescales of up to thousands of years (Sollins et al., 1996). Besides serving as a sink for atmospheric CO_2, soil organic carbon is the main constituent of soil organic matter and it has major influence on the soil's ability to store water, supply essential plant nutrients such as nitrogen, phosphorus, sulfur, and to produce crops. Thus, it is a very important determinant for agroecosystem productivity and food security, and for the functioning of the ecosystem as a whole. In fact without soil organic carbon and soil organic matter, the Earth's surface would be a sterile mixture of weathering minerals (Craswell and Lefroy, 2001). Population growth and increased demand for food have necessitated the transformation of large areas of land for agriculture, particularly in countries such as Ethiopia. Since inorganic fertilizers and other inputs are expensive or beyond the reach of the majority of resource poor smallholder households, much of the increased agricultural output has relied on the exploitation of reserves of soil organic carbon and organic matter (Buringh and Dudal 1987). Loss of this soil organic carbon could lead to reduction in soil fertility, health and quality and biomass production. Severe depletion could enhance land degradation, reduce the soils ability to sequester carbon, adversely impact water quality, and in exceptional cases could induce desertification. In light of predicted climate change and a more unified approach to mitigate GHG emissions, the prospect of innovative food security-based climate smart safety net environmental rehabilitation and sustainable agricultural production approaches that can enhance the ability of highly degraded and carbon-poor soils to retain carbon and act as a sink for increasing CO_2 concentrations in the atmosphere and in the process become more healthy and productive in a socially and environmentally sustainable manner will have a profound impact for global climate change mitigation, as well as for the livelihoods and resilience of resource-poor and food-insecure regions of the world.

Soil carbon stocks in undisturbed terrestrial ecosystems such as natural forests and grasslands are usually highly vulnerable to human intervention. The steady state attained in such natural ecosystems, and the amount and stability of soil organic carbon can be dramatically (often rapidly) reduced in response to anthropogenic land use and land cover changes until a new steady state with a much lower soil carbon stock is eventually established in the degraded ecosystem.

1.8 Main objectives of the study

The main objectives of this study are to: (i) assemble business-as-usual baseline and project scenario database on soil carbon and other soil fertility, health and productivity indicators for six chronically food insecure and vulnerable Ethiopian regional states (i.e., Afar, Amhara, Oromia, SNNPR, Somali and Tigray), where PSNP's sustainable agricultural and environmental rehabilitation public works have been implemented widely, ii) assess the impacts of Ethiopia's PSNP participatory integrated watershed management interventions on soil carbon capture and sequestration, as well as on other climate smart environmental and agricultural co-benefits in light of climate change, food security and low-carbon livelihoods in these regions, and (iii) support Ethiopia's social protection safety net climate smart initiative to take advantage of international carbon and climate finance opportunities to support sustaining the existing activities as well as scaling-up future implementations of PSNP participatory watershed public works projects in Ethiopia.

1.8.1 Specific objectives of the study

The specific objectives of the present investigation involve:

(i) Develop a robust georeferenced and downscaled national business-as-usual and project scenario baseline database for Ethiopia's PSNP in selected CSI implementation Woredas of the six Ethiopian regional states using standardized soil analytical measurements with the following critical elements:
   a. The baseline database should be integrated and multidisciplinary rather than of a single disciplinary focus. The content of the database ought to include information about the livelihoods, vegetation, climate, best management practices, time, geospatial aspects of the selected CSI Woredas, in addition to the basic soil carbon and other critical soil biological, physical and chemical characteristics that affect soil fertility and productivity and food security.
   b. The baseline database ought to enable modelling and prediction of soil carbon capture and sequestration, as well as other climate smart environmental and agricultural co-benefits.
   c. It should permit current and future spatial and temporal geospatial mapping and scaling up opportunities.
   d. The soil carbon baseline and project scenario database should provide monitoring, verification and reporting opportunity on soil carbon capture and storage, and other climate smart environment co-benefits generated as a result the implementation of PSNP's sustainable public works to stakeholders and investors.

(ii) Identify key drivers of soil carbon sequestration and soil fertility in selected PSNP sites, and evaluate their impact on soil carbon capture and sequestration, as well as on other environmental and agricultural co-benefits.

(iii) Develop low-cost soil carbon and soil productivity measurement techniques for Ethiopia's PSNP that possess the following important elements:
   a. The cost-effective measurement technique should rely on scientifically rigorous and internationally accepted standard soil carbon and soil fertility analytical systems for calibration and prediction.
   b. It should enable rapid but effective assessment, monitoring and reporting of carbon stock changes and other climate smart co-benefits as a result of the implementation of safety net public works projects in food-insecure regions of the country to secure carbon and climate finance.
   c. The low-cost measurement technique ought to be also appropriate to region, scale and varying landscapes and land use types of Ethiopia's PSNP.

2 Methodology

2.1 Brief description of PSNP's CSI study sites

The reconnaissance survey for soil carbon and fertility impact assessment following the implementation of Ethiopia's PSNP participatory watershed interventions was conducted in 30 different watersheds (27 PSNP and 3 non-PSNP watersheds) distributed across 27 Woredas in the more chronically food insecure parts of Ethiopia's six regional states (Figure 3 and Table 1).

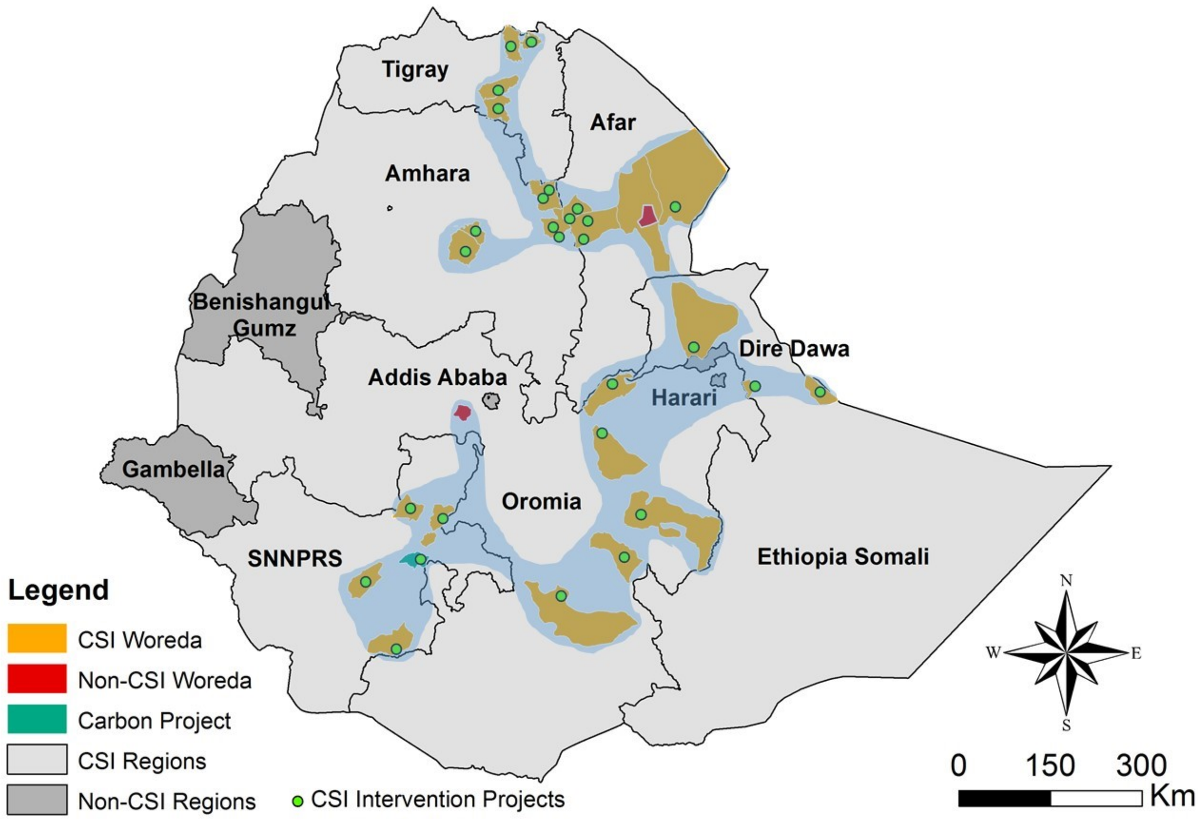

Figure 3. Geographical locations of Ethiopia's PSNP integrated watershed management intervention sites for soil carbon and soil fertility and productivity impact assessment.

These watersheds encompass eight livelihood zones (i.e., pastoral, agropastoral, cereal system Dega Zone, cereal system Woina Dega - dry zone, cereal system Vertisols: Woina Dega - wet/moist zone, cereal system non-Vertisols Woina Dega - wet/moist zone, systems dominated by cereals where enset and other root crops are minor and systems where enset is co-dominant crop along with cereals). The CSI watersheds in the Afar regional state are dominated by pastoral forms of livelihoods, while cereal dominated mixed crop-livestock agricultural systems are the predominant form of farming systems in the CSI sites of the Amhara regional state. Agropastoral livelihoods are prevalent in the CSI watersheds of the Somali and at the Bale zone of the Oromia regional state, whereas the remaining CSI sites of the Oromia regional state were mostly cereal-based Woina Dega and Dega zone crop-livestock faming systems practiced on non-Vertisol soils.

Table 1. Surveyed and sampled regional, Woreda, Kebele and CSI and non-CSI participatory watershed intervention sites, as well as selected location, topographical and climatic characteristics.

Region	Woreda	Kebele	Watershed	Location		Altitude[‡]	MAT[#]	MAP[±]
				Latitude (N)	Longitude (E)	m a.s.l.	°C	mm
Afar	Ewa	Bolotamo	Alada Sikuma	11°49'54"	39°53'38"	1125	22.10	952
	Ewa	Ewa	Duba	11°44'56"	39°59'00"	984	23.11	927
	Chifra	Chifra	Jara	11°40'18"	40° 00'27"	961	23.24	1045
	Gewane	Yangudi Rassa	Yangudi Rassa†	10°47'27"	40°39'32"	793	24.90	510
	Dubti	Ayrolaf and Gebelaytu	Gebelaytu	11°47'45"	41° 05'04"	370	24.49	277
	Elidar	Woha Limat	Woha Limat	11°57'00"	41°25'32"	381	28.90	349
Amhara	Kobo	05	Rhama Bokum	12°17'15"	39°42'44"	1498	24.61	994
	Kobo	Zobel	Zobel	12°11'33"	39°43'37"	2005	23.03	967
	Habru	Geradu 04	Sefed Amba	11°45'29"	39°37'41"	1860	17.82	961
	Habru	Geradu	Woira Amba	11°44'17"	39°37'48"	2013	17.82	1059
	Tach Gayent	012/Aduka	Alalo	11°32'48"	38°31'38"	2310	14.79	1685
	Simada	07/Aje	Ertib Wenz	11°18'45"	38°17'41"	2471	16.64	1512
Oromia	Delo Mena	Naniga Dhera	Shek kedir Karo	6°14'45"	39°53'58"	1134	21.14	845
	Daro Lebu	Odaleleba	Lege Hora	8°37'5.28"	40°20'35"	1710	18.65	1288
	Ejere	Tulu Korma	Tulu Korma†	9° 01'14"	38°21'30"	2136	16.39	1118
	Sewywna	Chopi	Bila	7°19'59"	40°59'18"	1582	25.11	581
	Goro	Keku	Wayu Bure	6°56'50"	40°40'51"	1680	24.79	490
	Meiso	Fayo	Fayo	9°13'60"	40°43'52"	1392	22.96	891
SNNPRS	Alaba	Asore	Asore	7°14'41"	38° 5'37"	1699	19.19	1018
	Damot Gale	Wondara Balose	Godaye	6°56'20"	37°48'35"	2170	18.86	1350
	Humbo	Longena	Gamot Terara†	6°44'10"	37°52'04"	1548	19.50	1100
	Soro	Shera	Sheshhecho	7°25'54"	37°34'06"	1944	19.60	1295
	Demba Gofa	Borda	Usha	6°20'38"	36°55'13"	1445	19.24	1712
	Konso	Lehaife	Boloshe	5°24'07"	37°20'49"	1473	20.82	832
Somali	Gursum	Fafan	Caracaska	9°14'08"	42°35'19"	1472	20.12	671
	Shinile	Baraq	Baraq	9°40'39"	41°57'40"	1074	26.83	484
Tigray	Gulo Mekeda	Shewit Lemlem	Serawat	14°25'20"	39°21'25"	2330	19.49	804
	Ahferom	Sero	Chearo	14°19'55"	39°13'35"	2048	19.48	803
	Kola Tembain	Dr. Atikilty	Dr. Atikilty	13°40'44"	38°57'29"	1926	22.41	771
	Tanqua Aberegele	Gera	Aba Tila	13°25'53"	38°59'28"	1487	27.40	820

**Harshin Woreda CSI site in Somali region was not accessible for sampling despite repeated attempts. Gidan Woreda CSI site in Amhara region was replaced by two other PSNP watersheds (Sefed Amba and Woira Amba) following the recommendation by MoA and CSI regional representatives. †Non-PSNP sites; ‡Altitude represents the central location of the most prominent land use practice in each CSI watershed intervention site; # MAT, mean annual temperature; ± MAP, mean annual precipitation. **Detailed site, sample type, management, vegetation, geographical and climate information for each watershed intervention sites is provided in another consortium output i.e., Ethiopia's PSNP CSI - Cornell group's georeferenced site, management, GIS, climate, carbon, soil fertility, yield and low-cost soil MIR analysis national baseline database (NBD) (see Solomon et al., 2015).*

Cereals or cereal and enset co-dominant systems with root crops as minor constituents were the major components of the crop-livestock mixed agricultural livelihoods of the CSI watersheds of the SNNPR regional state, while the CSI sites at the Dega and Woina Dega dry zones of the Tigray are dominated by cereal system crop-livestock farming systems (see details in national baseline database (NBD) Solomon et al., 2015 and Woolf et al., 2015).

The altitude of the Ethiopia's PSNP sites range from 370 m above sea level (a.s.l.) at the Gebelaytu CSI watershed of Dubti Woreda in Afar regional state to 2471 m a.s.l. at Ertib Wenz CSI watershed site at the Simada Woreda in the Amhara regional state (Table 1).

FAO's new local climate estimator (New_LocClim) program, which utilizes the extensive global agroclimatic database (FAOCLIM) maintained by the Agrometeorology group of FAO, was used to provide detailed average estimates of about 25 different climatic variables (temperature, precipitation, evapotranspiration, water vapor pressure, wind speed, day length runoff, runoff ratio aridity, aridity index, net primary productivity, agro-ecological zones, major growing seasons etc.) of the surveyed and sampled CSI watersheds (Table 1, with details in Solomon et al., 2015 and Woolf et al., 2015).

The mean annual temperature (MAT) of the CSI watersheds varies from 14.79˚C at the Alalo watershed of Tach Gayent Woreda in the Amhara regional state to as high as 28.90˚C at the Woha Limat watershed of the Elidar Woreda in the Afar regional state. The mean annual precipitation (MAP) range from as low as 277 mm at the Gebelaytu watershed of Dubti Woreda in Afar to 1712 mm at the Usha watershed of Demba Gofa Woreda in the SNNPR regional state.

FAO's local climate estimator and the survey show that agro-ecological zones of the PSNP watershed sites are very diverse and include the arid and semiarid zones of the Afar, Somalia and the Oromia lowlands, the mostly dry subhumid and subhumid highlands of the Amhara and Tigray highlands and the sub-humid and humid ecosystems of the Oromia and SNNPRS states.

The soils of the CSI watersheds are well-drained, light grey to dark red, friable sandy loam to clay in texture (Table 2). The depth of the control soils vary from highly eroded and extremely shallow soils (0.25 m depth) at the Serawat watershed of Gulo Mekeda Woreda in Tigray regional state to deep soils (>1 m) observed in Shek kedir Karo watershed at Delo Mena Woreda in Oromia and Godaye watershed in Damot Gale Woreda in SNNPR regional states (Figure 4).

Table 2. Ethiopia's PSNP watershed control sites, selected soil characteristics, and summary of PSNP's integrated watershed management interventions implemented at each sites.

Region	Woreda	Watershed condition*	Selected soil characteristics					PSNP integrated watershed management interventions††			
			Soil color	Soil texture	pH†	CEC‡	TC#	BAU±	Project scenario I	Project scenario II	Project scenario III
Afar	Ewa Alada Sikuma	Degraded grassland	Yellowish red	Sandy clay loam	7.44	9.91	0.39	NI	ISWC-PE-GL-3yr		
	Ewa Duba	Degraded grassland	Yellowish red	Sandy clay loam	7.57	9.27	0.33	NI	ISWC-PE-GL-3yr	NINR-PE-GL-3yr	
	Chifra	Degraded grassland	Yellowish red	Clay	7.87	8.63	0.68	NI	ISWC-PE-GL-3yr		
	Gewane	Undisturbed grassland	Greyish dark	Clay loam	7.23	18.04	2.29	NI	NINR-PE-GL-20yr		
	Dubti	Degraded woodland	Light grey	Loamy sand	8.40	7.04	0.80	NI	ISWC-PE-WL-3yr	ISWC-CL-3yr	
	Elidar	Degraded woodland	Light grey	Silty loam	8.05	8.93	0.78	NI	ISWC-PE-WL-3yr		
Amhara	Kobo Rhama Bokum	Degraded woodland	Light grey	Sandy loam	7.75	7.27	0.37	NI	ISWC-PE-WL-5yr		
	Kobo Zobel	Degraded woodland	Light grey	Sandy loam	7.09	7.98	0.39	NI	ISWC-PE-WL-5yr	ISWC-CL-3yr	
	Habru Sefed Amba	Degraded woodland	Light grey	Loam	7.06	8.21	0.71	NI	ISWC-PE-WL-5yr	ISWF-AF-5yr	ISWF-CL-5yr
	Habru Woira Amba	Degraded woodland	Light grey	Sandy loam	6.90	10.00	0.91	NI	ISWC-PE-FL-21yr	ISWC-PE-GL-21yr	ISWF-CL-21yr
	Tach Gayent	Degraded woodland	Greyish yellow	Loam	6.10	9.51	0.69	NI	ISWC-PE-WL-5yr	ISWC-PE-WL-1yr	ISWF-CL-5yr
	Simada	Degraded woodland	Dark grey	Clay	6.18	8.59	0.69	NI	ISWC-PE-WL-5yr	ISWF-CL-5yr	ISWC-CL-5yr
Oromia	Delo Mena	Degraded woodland	Red	Sandy clay	4.97	8.76	0.73	NI	ISWC-PE-WL-3yr	NINR-PE-WL-20yr	
	Daro Lebu	Degraded woodland	Light grey	Clay	4.69	6.33	0.29	NI	ISWF-AF-17yr	ISWC-GM-5yr	
	Ejere	Degraded woodland	Reddish grey	Silty clay	5.39	8.24	1.04	NI	ISWC-PE-WL-13yr	NINR-PE-WL-13yr	ISWF-AF-13yr
	Sewywna	Degraded woodland	Reddish yellow	Sandy clay loam	7.59	9.01	0.71	NI	ISWC-PE-WL-3yr	ISWF-CL-3yr	
	Goro	Degraded forestland	Reddish brown	Silty clay loam	7.01	7.28	0.84	NI	ISWC-PE-FL-3yr	ISWC-CL-3yr	
	Meiso	Degraded woodland	Yellowish brown	Sandy loam	7.37	6.06	0.85	NI	ISWC-PE-FL-2yr	ISWC-CL-2yr	
SNNPRS	Alaba	Degraded woodland	Reddish yellow	Sandy loam	6.76	9.72	1.03	NI	ISWC-PE-WL-20yr		
	Damot Gale	Degraded cropland	Red	Clay	5.73	10.39	0.78	NI	ISWF-AF-20yr	ISWF-CL-20yr	
	Humbo	Degraded woodland	Red	Clay loam	5.58	12.54	1.17	NI	ISWC-PE-WL-8yr		
	Soro	Degraded woodland	Dark red	Clay	5.58	11.23	1.20	NI	ISWC-PE-WL-13yr	ISWF-PE-GL-13yr	ISWF-CL-20yr
	Demba Gofa	Degraded woodland	Yellowish red	Sandy loam	6.29	8.11	0.81	NI	ISWC-PE-WL-17yr	ISWC-PE-WL-4yr	ISWF-CL-17yr
	Konso	Degraded woodland	Yellowish red	Clay	5.89	7.35	0.55	NI	ISWC-PE-WL-17yr	ISWC-PE-FL-17yr	
Somali	Gursum	Degraded grassland	Yellowish red	Sandy clay loam	7.62	9.41	0.44	NI	ISWC-CL-3yr		
	Shinile	Degraded grassland	Yellowish red	Sandy clay loam	7.78	9.60	0.40	NI	ISWC-PE-GL-3yr		
Tigray	Gulo Mekeda	Degraded woodland	Pale yellow	Sandy loam	6.65	9.00	0.73	NI	ISWC-PE-WL-5yr	ISWC-PE-WL-1yr	
	Ahferom	Degraded woodland	Yellowish red	Loamy sand	7.06	8.19	0.38	NI	ISWC-CL-15yr		
	Kola Tembain	Degraded woodland	Yellowish brown	Loam	7.00	7.61	0.57	NI	ISWC-PE-WL-5yr	ISWC-PE-GL-5yr	ISWC-CL-5yr
	Tanqua Aberegele	Degraded woodland	Yellowish brown	Sandy loam	7.32	6.61	0.50	NI	ISWC-PE-WL-2yr	ISWC-CL-2yr	

PSNP watershed control site condition; †pH, pH water; ‡CEC, cation exchange capacity in $cmol_c$/kg soil; #TC, total soil carbon percent; ±BAU, business-as-usual scenario; NI, business-as-usual scenarios with no intervention; ††PSNP project interventions, PSNP participatory watershed public works project interventions; PE, permanent (area) enclosure; NR, natural regeneration; WL, woodland; FL, forestland; GL, grassland; AF, agroforestry; CL, cropland; GM, gully management; ISWC, integrated soil and water conservation; ISWF, integrated soil and water conservation and integrated soil fertility management;* ***Examples of management types**:* ***ISWC-PE-GL-3yr****, grassland permanent enclosure site with ISWC measures implemented for 3 years;* ***NINR-PE-GL-3yr****, grassland unassisted natural regeneration permanent enclosure site managed for 3 years without ISWC;* ***ISWC-PE-WL-3yr****, woodland permanent enclosure site under ISWC for 3 years;* ***ISWC-CL-3yr****, cropland managed for 3 years with ISWC measures;* ***ISWF-CL-5yr****, cropland under ISWC and integrated soil fertility management for 5 years;* ***ISWF-AF-5yr****, agroforestry site managed using ISWC and ISFM measures for5 years;* ***ISWC-GM-5yr****,* severely *degraded gully managed for 5 years with ISWC measures (details provided in Table 3 and in the NBD Solomon 2015).*

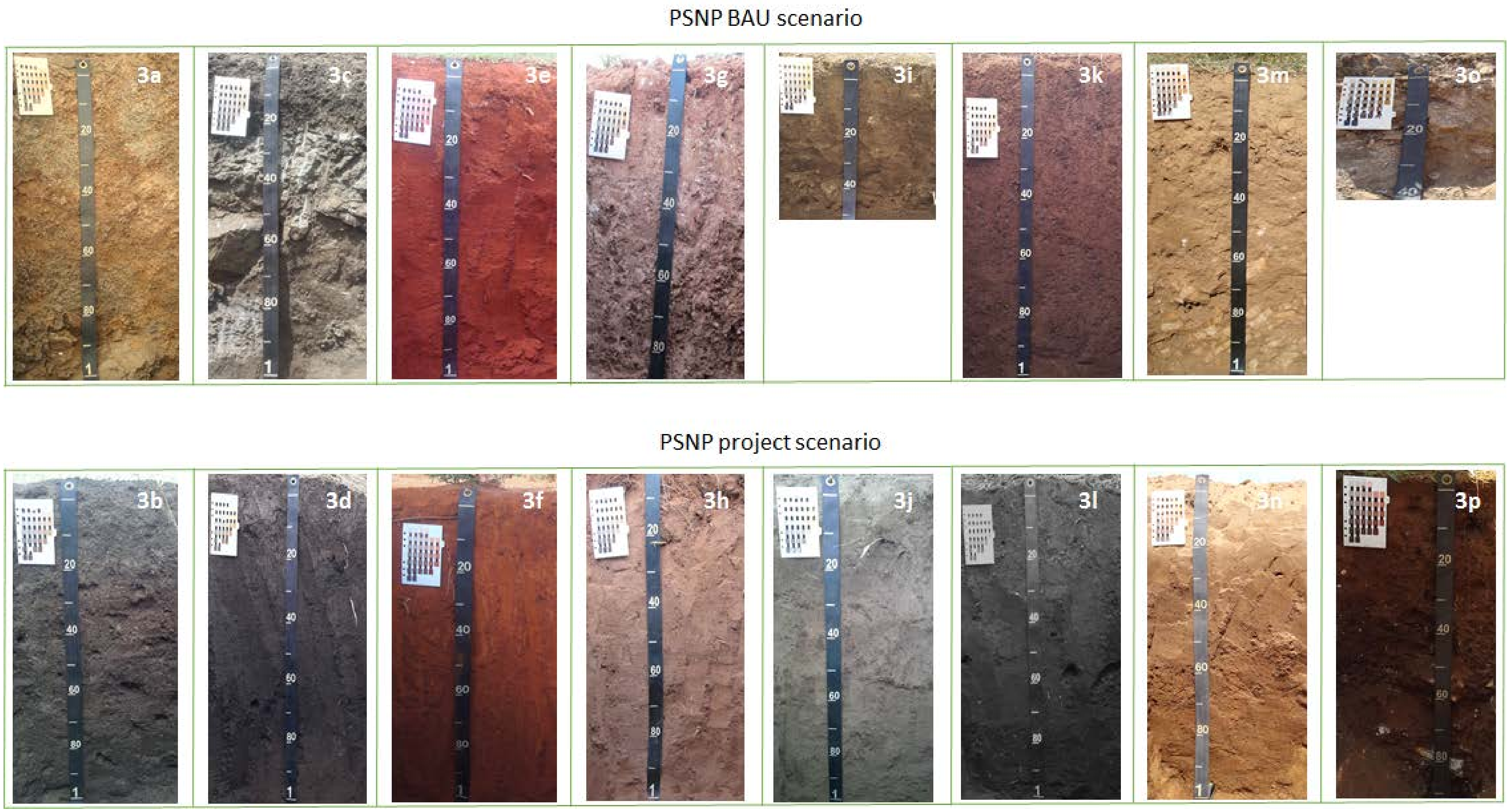

Figure 4. Selected soil profiles showing land under the business-as-usual and corresponding project scenario from Habru Woira Amba (3a and 3b) and Habru Sefed Amba (3c and 3d) Woreda in the Amhara regional state, Delo Mena (3e and 3f) and Sewywna Woreda in Oromia regional state (3g and 3h), Alaba (3i and 3j) and Damot Gale (3k and 3l) Woreda in the SNNPR state and from Ahferom (3m and 3n) and Gulo Mekeda (3o and 3p) Woreda in the Tigray regional state, respectively.

2.2 PSNP's site conditions and watershed management interventions

Three rounds of field survey and data collection of Ethiopia's PSNP watersheds were conducted between November, 2013 and July, 2014. Qualitative data about site conditions, local farming systems, PSNP participatory integrated watershed management interventions, as well as opinions of farmers on trends, status, challenges and constraints of PSNP's sustainable public works programs were collected through formal and informal group discussions involving key informant interviews. The informants include regional- and Woreda-level CSI project coordinators and MoA natural resources management experts, farmers and local community leaders. Moreover, additional information about socio-economic and environmental indicators such as crop yield, crop choice, forage availability, tree species type, forest and vegetation cover, water availability and farming systems was also recorded. Table 3 provides a brief summary of the representative PSNP's site conditions observed under business-as-usual and project scenarios in the six regional states of Ethiopia (see detailed descriptions of each watershed site conditions and geospatial maps of watershed management interventions in the national baseline database (NBD), Solomon et al., 2015 and Woolf et al., 2015).

In almost all PSNP watersheds, the presence of highly degraded grasslands, woodlands, and forestlands with signs of extensive surface (sheet and rill) erosion and formation of deep gullies as shown in Figure 4 were evident across the landscape. There were also clear signs of anthropogenic degradations in the form of overgrazing of grasslands, and the deforestation, clearing and overexploitation of vegetation incuding excessive removal dead leaves and other biomass residues from grasslands, woodlands and forestlands. These anthropogenic forces seem to be playing increasingly important roles in changing the environment and exposing the landscape to unprecedented wind (wind erosion seems to be more prevalent in the Rift Valley and the peripheral lowlands) and water erosion, soil and carbon losses, land degradation and depletion of natural resources such as water and biodiversity (Figure 5).

Agricultural land degradation is one of the major causes of the chronic food insecurity widely experienced by the country's largely rural population and has been a concern for many years in the chronically food insecure PSNP woredas of Ethiopia. Observations of croplands during the joint survey of the CSI watersheds indicate that there are clear signs of high-population pressure, including excessive removal of crop residues for other competing needs, subdivision and reduction of farm size, expansion of cultivation to steep slopes, as well as indications of loss of arable land due to extensive soil erosion (Table 3). The excessive removal of crop residues from agricultural fields in the PSNP watersheds left most croplands devoid of surface mulch and the numerous positive ecosystem services and benefits of organic residue retention such as increased infiltration and reduced evaporation of rain water, reduced surface runoff and soil loss, addtion of organic carbon and organic matter, higher waterholding capacity and increased availability of essential plant nutrients leading to poor crop performance and yield. Field observations of the highly degraded agricultural lands of the CSI watersheds in many instances also revealed the presence of deeper gully formations suggeting the possibility that water is draining out from the depper layers of the agricultural landscapes, and potentially lowering the ground water table.

Table 3. Brief description of site conditions observed under business-as-usual and project scenarios, causes of degradation, and summary of PSNP integrated watershed management interventions implemented at the PSNP watersheds in six food insecure Ethiopian regions

BAU scenario*	PSNP participatory integrated watershed management interventions			
Land use	**Cause of degradation**	**PSNP project objective**	**Agronomic (ISFM‡) and biological measures**	**Physical (ISWC#) measures**
Degraded grassland	Overgrazing	**Grassland ecosystem rehabilitation**	Permanente enclosure†	**Soil conservation**
	Wind & water erosion	Restoration of degraded grassland	Live fencing	Stone fences
	Gully formation	Increasing grass and feed productivity	Natural regeneration	Stone & soil faced bunds
	Low soil carbon & organic matter	Increasing soil carbon & organic matter	Natural regeneration	Stone & soil faced hillside terraces
	Low soil fertility	Increasing soil fertility		**Water harvesting & utilization**
		Moisture a water harvesting		Stone & soil faced trenches
Degraded forestland	Over-exploitation of vegetation	**Forest & woodland ecosystem rehabilitation**	Permanente enclosure*	Soil conservation
	Over-exploitation of residues	Restoration of degraded forest and woodlands	Live fencing	Graded stone & soil faced bunds
	Wind & water erosion	Increasing soil carbon & organic matter	Natural regeneration	Stone & soil bund hillside terraces
	Gully formation	Increasing soil fertility	Woodlot establishment	Bench terraces
	Loss of soil carbon & organic matter	Gully rehabilitation	Afforestation & reforestation	Gully control & rehabilitation
	Low soil fertility & productivity	Moisture & water harvesting	Leguminous shrubs & trees hedge rows	Gabion, lose stone & brushwood checkdams
		Increasing fodder & wood production	Contour grass strips	Cutoff drains & discharge waterways
			Vegetative waterways	Gully cut reshaping & filling
			Vegetative gully stabilization	**Water harvesting & utilization**
				Stone & soil faced trenches
				Small pond, micro & eyebrow basins
Degraded cropland	Unsustainable agricultural practices	**Agroecosystem rehabilitation**	ISFM & building agroecosystem productivity	**Soil conservation**
	Cultivation of steep slopes	Restoration of degraded farmland	Cultivation on protected l& & slope	Stone & soil bunds
	Wind & water erosion	Gully rehabilitation	Cultivation on protected gullies	Stone & soil bund hillside terraces
	Gully formation	Moisture & water harvesting	Multi-strata agroforestry	Bench terraces
	Loss of carbon & organic matter	Increasing farmland& productivity	Intercropping & contour planting	Contour ploughing & ridge cultivation
	Low soil fertility & productivity	Increasing soil carbon & organic matter	Diversified cropping systems	Gully control & rehabilitation
		Increasing soil fertility	Multi-purpose leguminous crops	Gabion, lose stone & brushwood checkdams
		Moisture & water harvesting	Integrated crop-livestock systems	Cutoff drains & discharge waterways
			Compost, manure & crop residue application	Gully cut reshaping & filling
			Limited inorganic fertilizer application	**Water harvesting & utilization**
			Leguminous shrubs & trees	Stone & soil faced trenches
			Contour grass strips & hedge rows	Pond, geomembrane, micro & eyebrow basin water harvest
				Stream diversion & irrigation

** BAU, business-as-usual scenario; † Permanent enclosures are also alternatively referred to as area closures; ‡ ISFM, integrated soil fertility management; # ISWC, integrated soil and water conservation*.

Figure 5. Highly degraded woodland with clear signs of sheet and rill erosions and gully formations at the Asore watershed in Alaba CSI Woreda in SNNPR regional state of Ethiopia and corresponding woodland where livestock exclusion through permanent area enclosures and ISWC measures were implemented as part of PSNP's participatory watershed management interventions.

Better land and water management is critical to improvement of human well-being in the surveyed drought-prone and food insecure regions of the world. Understanding the current status and causes of environmental degradation in Ethiopia's PSNP watersheds is an important component of this approach, since such rapid deterioration in land and (agro)ecosystem quality is a great threat for agricultural productivity, food security and livelihoods of the population both at the local and national levels and also for the sustainability and the future of the country's ecosystem as a whole. Similarly, timely integrated watershed management interventions are crucial since rehabilitation of highly degraded ecosystems require a much greater resources and effort. Table 3 provides a brief summary of the various sustainable land management (SLM) practices implemented as part of Ethiopia's PSNP participatory watershed management interventions to restore local environments degraded by decades of unsustainable management and overuse.

The survey of the CSI Woredas in Ethiopia's six regional states show that the participatory integrated watershed management interventions in the grassland, woodland, forestland and agricultural ecosystem were focused on adoption of integrated physical and biological sustainable natural resource management and production practices involving: (i) integrated soil and water conservation (ISWC), (ii) improved water harvesting (iii) integrated soil fertility management (ISFM), and (iv) building productive and resilient (agro)ecosystems (Table 3).

The integrated watershed management activities in pastoral and agropastoral zones located primarily in the Afar and Somali regional states involve restoration of degraded grassland ecosystems and enhancing their productivity using live and stone fence permanent enclosures with mostly unassisted natural regeneration coupled with ISWC and improved moisture and water harvesting practices (Table 3).

Figure 6. PSNP's participatory watershed management intervention site at the Sefed Amba watershed of the Habru Woreda in the Amhara regional state of Ethiopia where improved water harvesting, retention and utilization approaches were implemented in cereal production and agroforestry fields.

Many past and to an increasing extent the current PSNP activities in the woodland and forestland ecosystems situated in CSI Woredas of the Amhara, Oromia, SNNPR and Tigray regional states were designed towards building productive and resilient ecosystems and increase availability of animal feed and wood for the smallholder community using live and stone fence permanent enclosures with assisted natural regeneration, reforestation and afforestation and comuntity and homestead woodlot establishements (see the forested section of Figure 5). These practices are supported by ISWC measures involving graded stone and soil faced bunds, bench terraces, contour grass strips and gully control and rehabilitation activities such as gabion, lose stone and brushwood checkdams, cutoff drains and discharge waterways, gully cut reshaping and filling, vegetative gully stabilization and vegetative waterways. Water harvesting and utilization approaches in these (agro)ecosystems were mostly geared towards capturing more surface water in the soil using small ponds and micro and eyebrow basins (Table 3).

Overall, the survey show that Ethiopia's PSNP participatory watershed management activities in degraded agricultural lands are generally designed to reduce soil erosion and build productive and resilient agroecosystems through a combination of approches involving soil conservation (e.g., stone and soil bunds, bench and hillside terraces, contour ploughing and ridge cultivation, leguminous shrub and tree hedge rows, contour grass strips etc. see Figure 6), gully control and rehabilitation (e.g., building gabions, loose stone and brushwood checkdams, cutoff drains and discharge waterways and gully cut reshaping and filling etc.) techniques. PSNP's improved water harvesting, retention and utilization approches implemented in the various agroecological zones genarlly encompass stone and soil faced trenches, small ponds, geomembrane (see Figure 6), micro and eyebrow basins, stream diversion and in some cases the use of irrigation systems.

Figure 7. PSNP's CSI participatory watershed management intervention site at the Godaye watershed of the Damot Gale CSI Woreda in SNNPR state of Ethiopia where both ISWC and ISFM practices where used to rehabilitate agricultural land.

Soil fertility, organic carbon and thus organic matter decline remains among the major biophysical causes of declining per capita food production in many of the subsistence smallholder farms in the surveyed PSNP Woredas of Ethiopia. Use of inorganic fertilizers to replenish soil nutrient decline is one of the ways of counterbalancing the low soil fertility. However, nutrients applied through mineral fertilizers by the smallholder farmers in the Ethiopia's PSNP watersheds remain extremely low due to application of insufficient amounts well below the recommended levels (Details available in Woolf et al., 2015). High costs of commercial fertilizers, lack of credit, delays in delivery, poor transport and marketing infrastructure, poor knowledge of best management practices and extension services individually or jointly also constrained the optimal use of inorganic fertilizers.

The survey indicate that Ethiopia's PSNP participatory watershed management activities in degraded agricultural lands also aim to overcome the persistent low soil fertility and enhance soil organic carbon and organic matter through ISFM interventions. At the core of the PSNP's ISFM paradigm is the recognition that no single component of the integrated sustainable management system can stand on its own in meeting the soil fertility and soil health requirements of Ethiopia's PSNP watersheds to build productive and resilient agroecosystems. Thus, PSNP's watershed management activities employ a judicious manipulation of a variety of approaches ranging from the use of intercropping and contour planting, diversified cropping systems involving multi-purpose leguminous crops, leguminous shrub and tree hedge rows to multi-strata agroforestry schemes (Figure 7). The survey also revealed the use of sustainable soil management practices that increases nutrient inputs through composting, manure and crop residue application and the use of legumes for natural nitrogen fixation. In addition to enhanced fertility, the use of organic resources in the agroecosystem help to enhance aggregate stability, resistance to soil compaction and soil erosion, reduce soil bulk density, nutrient leaching and greenhouse gas emissions.

2.3 Soil carbon and fertility impact assessment sampling strategy

Changes in land use and management practices to store and sequester carbon are becoming integral to global efforts that both address climate change and alleviate poverty. Stringer et al. (2012) indicated that community-based participatory land management projects within the voluntary carbon market sector increasingly apply standards and protocols designed to reduce trade-offs and deliver multiple benefits across above and below carbon storage, poverty alleviation, community empowerment, and biodiversity conservation dimensions. However, accurate accounting methodologies underpinning the carbon components of such assessments are lacking due to an absence of scientific approaches, data, models, appropriate local monitoring methods and regional measurement protocols, particularly in the semi-arid and dry sub-humid systems of sub-Saharan Africa, where methods need to address inherent spatial and temporal dynamism (Schmidt et al., 2011; Reynolds et al., 2011). Appropriate soil sampling methods are vital to derive sound understanding of soil carbon, organic matter and soil fertility co-benefits changes following the project scenarios or the implementation of participatory integrated watershed management interventions in a scientific way (Powlson et al 2011; Fileccia et al., 2014). These challenges mean carbon sequestration gains (or prevented losses), as well as other co-benefits are difficult to quantify, and need to be integrated with assessments of livelihood costs, benefits and trade-offs. The lack of coherent and credible science accessible to practitioners remains a significant obstacle to the development of integrated practice.

Fileccia et al. (2014) highlighted that there are two common sampling (diachronic and synchronic) approaches to calculate soil carbon stocks of a newly introduced best management practice (project scenario) in comparison to a conventional management or business-as-usual scenario. The diachronic approach consists of measuring soil carbon stock (t) in years on the same field plot or landscape of the new best management practice and the conventional or control management. For example, in the case of the project scenario, soil carbon stock measurements should be recorded at time - *0* (at the beginning of the implementation of the new best management practice in both the project and control sites where no new management practices implemented) and time - *x* in both the control and the project sites following the implementation of the new best management practice in the project site. The major disadvantage of the diachronic approach is that one must start the measurements at the time of implementation and continue to measure over long periods of time before being able to evaluate the quantity of soil carbon stock changes or carbon sequestered as a result of the implementation of the new best management practice or the project scenario compared to the control conventional management or business-as-usual scenario. Such approaches are applicable only to new projects and are not relevant in projects where the activities are already implemented in the landscape. For these reasons most landscape level estimates of soil carbon stocks and co-benefits such as soil fertility changes in sustainable land management projects are generally based on a synchronic approach. The synchronic approach consists of comparing the soil carbon stock of a field plot or a certain land scape, at a given time - *tn* (e.g., soil carbon stock in agricultural field or in the landscape under the best management practice tested during *x* number of years) with that of a field under traditional management or control scenario during this time which represents *t0* state or the reference point. Although this method is usually preferred or in some cases the only approach for already established and ongoing projects, the uncertainty in this approach remains the absolute comparability of the field plots or the landscapes which must be similar in terms of other soil properties such as soil chemical, biological and physical characteristics and other hydrological variables.

Soil sampling for assessing the impacts of Ethiopia's PSNP's CSI interventions on soil carbon capture and other soils fertility indicators was conducted using the synchronic approach. The samples were collected between November, 2013 and July 2014 from 30 different (i.e., 27 PSNP and 3 non-PSNP) watersheds distributed across 27 Woredas in Ethiopia's six regional states (Figure 3 and Table 1). Sampling units representing different land use practices across the landscape as shown in Figure 8 (Figure 8a for control, Figure 8b for woodland, 8c for grassland, and 8d for agriculture land) representing business-as-usual or control scenarios and best management practices (project scenarios) within Ethiopia's PSNP were identified both spatially and temporally in each watershed following three rounds of reconnaissance survey. Georeferenced soil sampling sites (shown by yellow pins in Figure 8) were selected for each soil sampling unit (145 sampling sites in total) considering representativeness and uniformity of the sampling units (Figure 8).

The soil sampling strategy in watersheds where ISWC activities were implemented includes collection of the main soil sample close to the lower section of the terrace near the wall (usually called deposition zone) of the various types of terraces or ISWC structures. This is followed by collection of additional replicate soil samples every 5 to 25 m away from the deposition zone distributed across the middle and the upper section of the terrace (loss zones) depending on the size of the watershed and the objective of the sample collection.

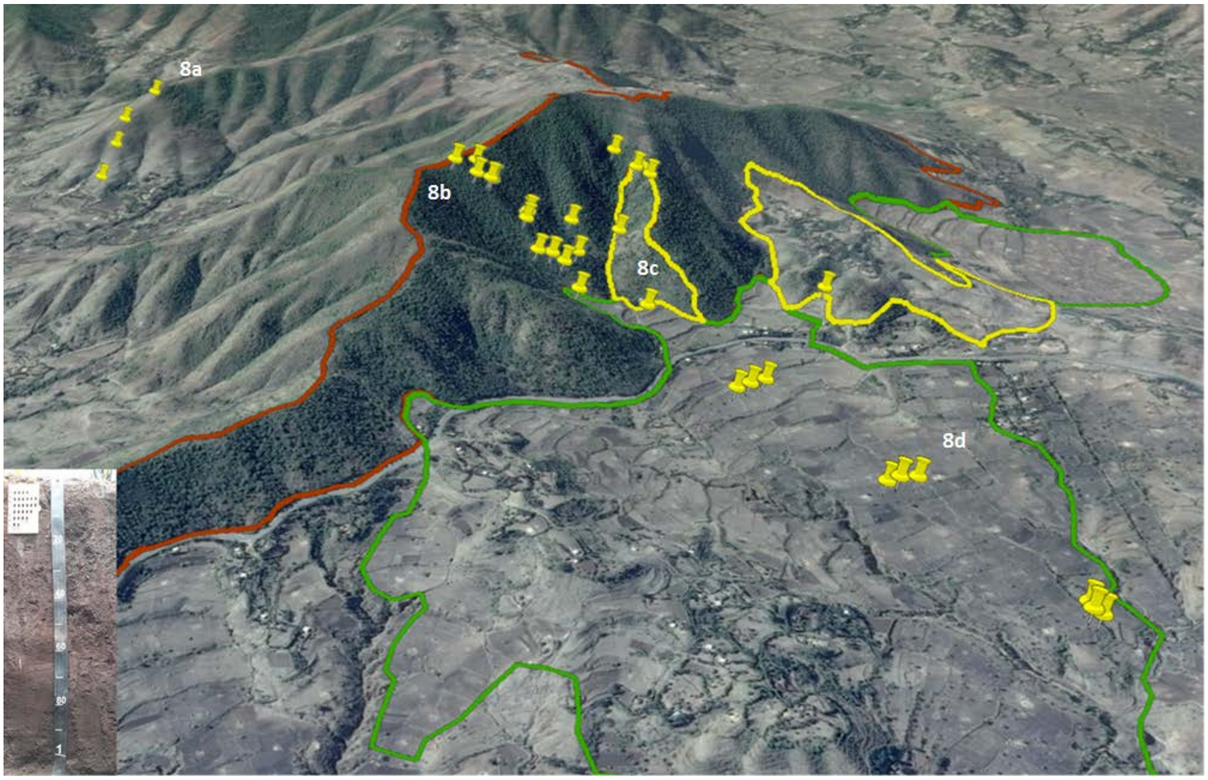

Figure 8. Geospatial image of PSNP's CSI participatory watershed management intervention sampling units (8a show the business-as-usual or control sites, 8b show woodland sites, 8c show grassland sites and 8d show agricultural fields) at the Woira Amba watershed of the Habru Woreda in the Amhara regional state of Ethiopia. Each yellow pin indicates the spatially georeferenced position of profile sample collected (see inset for example) from the individual sampling integrated watershed management intervention units.

Using this approach, the survey and sampling team collected a total of 627 approximately one kilogram soil samples (i.e., 395 surface soil samples from 0-15 cm depth and 232 soil profile samples collected from 0-15 cm, 15-45 cm and 45-100 cm depth). The soil profile samples were collected to quantify soil carbon stocks changes in up to 1 m depth from selected matured PSNP watersheds in the Amhara (Sefed Amba and Woira Amba), Oromia (Billa, Shek Kedir Karo and Wayu Bure), SNNPRS (Asore, Godaye, Gamot Terara, Sheshhecho and Usha) and Tigray (Serawat and Chearo) regional states. When quantifying changes in soil carbon stocks by comparing two or more land use types or integrated watershed management interventions implemented in the PSNP sites, it is essential to take into account soil bulk density. Hence, 145 core samples were collected using 100 cm^3 volumetric steel cylinders for bulk density measurement from the surface (0-15 cm) and deeper soil layers (15-45 cm and 45-100 cm) of the sampling sites distributed across the 30 different PSNP watersheds of Ethiopia's six regional states. In addition 27 surface soil samples (0-15 cm) were collected from the business-as-usual and various PSNP integrated watershed intervention sites in the Amhara (Alalo-Tach Gayent, Sefed Amba and Ertib Wonz-Simada), Oromia (Shek Kedir Karo-Oromia), SNNPRS (Godaye-Damot Gale), and Tigray (Chearo-Ahferom) regional states for the purpose of conducting plant growth bioassay greenhouse trials to assess the productivity of soils under the control and project scenarios.

2.4 PSNP soil carbon and soil fertility analysis

After visible remnants of roots and other large plant residues were removed, the surface and subsurface soil samples collected from the various PSNP watersheds were air-dried, thoroughly mixed and sieved to pass 2 mm sieve (exceptions are samples collected for the bulk density analysis), prior to standard and low-cost soil chemical and physical analysis.

2.4.1 Analytical approaches for standard soil physical properties analysis

Soil bulk density: - Bulk density of the soil samples (BD in g/cm^3 = dry soil weight (g) / soil volume (cm^3) was quantified directly from the core samples collected from the field and dried at 105 °C in a drying oven, and subsequently weighed on a digital electronic balance.

Soil texture: - Soil particle size distribution into sand, silt and clay; which is a key component of any minimum dataset used for assessing soil quality, was analyzed using the rapid soil texture method designed for processing large volumes of soil samples (Kettler et al. (2001) with accuracy comparable to more conventional tests involving standard hydrometer and pipette techniques.

Soil water: - Water may be preset in soils on particle surfaces, with organic chemical compounds, and in macro- and micro-pores. However, there are three general forms of soil water contents more relevant for evaluating landscape level soil quality changes following the implementation of integrated watershed management interventions in (agro)ecosystems: (i) water retained in the soil at field capacity (-0.10 bar) which is the upper limit of plant available water in the soil, (ii) water retained in the soil at the point where plants start to wilt, which is the lower limit of plant available water - also called permanent wilting point (-15 bar), and (iii) plant available water content, which is the amount of water held in the soil between the field capacity at -0.10 bar and permanent wilting point at -15 bar of that particular soil (Osman, 2013). These values (i.e., soil water held at field capacity, soil water retained at permanent wilting point and plant available water) were measured in the present investigation using the pressure plate extractor method according to Dane and Hopmans (2002).

2.4.2 Analytical approaches for standard soil carbon and other soil chemical property analysis

Soil carbon and nitrogen: - Total carbon and nitrogen concentrations in the soil samples were analyzed by dry combustion according to the specifications of Nelson and Sommers (1996) using a Temperature Conversion Elemental Analyzer (TC/EA)***.***

Soil organic matter: - The organic matter content of the soil samples was independently analyzed using a simple high sample volume ashing procedure for routine determination of soil organic matter as described by Storer et al. (1984). This method is consistent with traditional procedures, but eliminates the use of hexavalent chromium as an environmental pollutant which is commonly used in traditional colorimetric techniques.

Plant available nutrients, cation exchange capacity (CEC) and percentage base saturation (PBS): - Plant available nutrients and other elements were extracted using Mehlich III extractant (Mehlich 1984), and quantified by Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES). Potential cation exchange capacity (CEC) was calculated by summing the amount of charge per unit soil from the cations extracted by Mehlich III. Wang et al. (2004) found a good correlation between cations extracted using Mehlich III solution and ammonium acetate at pH 7, and demonstrated that this analytical approach is cost-effective and scientifically valued technique to get a measure of the potential CEC in soils. Percentage base saturation (PBS) was obtained by dividing the total amount of charge per unit soil of Ca, K, Mg and Na by the potential CEC.

Soil pH: - Soil pH was determined in deionized water at a soil to solution ratio of 1:2 (w/v) using a combination electronic pH meter according to Hendershot et al. (1993). Suspensions were shaken for 30 min, and allowed to settle for 1 h before the supernatant pH measurement was recorded. Buffer pH was measured from each soil sample in similar manner using modified Mehlich III solution at a soil to solution ratio of 1:2 soil to solution ratio (w/v).

2.4.3 Analytical approaches for cost-effective mid infrared (MIR) spectroscopy-based soil analysis

Soil mid infrared (MIR) spectroscopy: - The mid-infrared spectra from the soil samples were acquired from 4000-602 cm^{-1} at a resolution of 4 cm^{-1} using High Throughput Screening eXTension (HTS-XT) Bruker Tensor Fourier transform infrared (FTIR) attenuated total reflectance (ATR) spectroscopy following procedures outlined in Terhoven-Urselmans et al. (2010) at the International Centre for Research in Agroforestry (ICRAF) in Nairobi, Kenya. Soil samples were finely ground to 0.05 µm using an agate mortar and pestle and loaded into aluminum micro titer plates. The samples were filled into four replicate wells, and each well was scanned 32 times and aggregated spectra was collected from each replicate. The four spectra were averaged to account for within sample variability and for differences in particle size and packing density. Reference readings were conducted with no sample loaded onto the ATR crystal. The soil carbon and nutrient contents, and other soil physical and chemical characteristics were determined for all samples using predictions via mid-infrared Random Forest (RF) regression model-based analysis calibrated to the data collected directly from analysis of soil carbon using dry combustion and other standard soil wet-chemical and physical measurements. The MIR RF predictions were generated from direct analyses of 436 samples (69%) of the total 628 samples. The application of RF ensemble models in soil science is a relatively recent phenomenon (Grimm et al., 2008; Vågen et al., 2016), but has been effectively demonstrated to have potential to be a powerful approach that can significantly improve the prediction of soil functional properties and mapping of land degradation prevalence in Ethiopia (Vågen et al., 2013) and in general in Africa (Hengl et al., 2015)

3 Results and discussions

3.1 PSNP's CSI national baseline database (NBD)

One of the major challenges of Ethiopian's PSNP to benefits from climate change adaptation and mitigation finance and payments for ecosystem services and benefits is the lack spatially explicit, downscaled quantitative empirical datasets demonstrating soil carbon sequestration gains, prevented GHG losses, and co-benefits generated as a result of implementation of PSNP integrated watershed management interventions in the relatively food insecure regions of the country.

PSNP's CSI National Baseline Database (NBD) is the first georeferenced multidisciplinary database which include information about livelihoods, type and duration of best management practices, vegetation, geographical and climatic data collected from the comprehensive survey of Ethiopia's PSNP watersheds spread across six regional states, as well as the soil carbon and other critical soil biological, physical and chemical characteristics generated by the standard and cost-effective analytical approaches.

PSNP's CSI NBD is expected to provide sustainable public works policymakers, practitioners, investors and other stakeholders the possibility to: (i) enable conduct rapid and effective watershed-level assessment and reporting of carbon stock changes and other co-benefit as a result of the implementation current PSNP's integrated watershed interventions, (ii) enable to model and predict future soil carbon capture and sequestration potentials, as well as other environmental and agricultural co-benefits, and (iii) permit spatial and temporal geospatial mapping and scaling up opportunities.

The current study developed the first robust downscaled national business-as-usual and project scenario baseline database for Ethiopia's PSNP. The multidisciplinary georeferenced dataset which is now organized into a single national baseline database (NBD, Solomon et al., 2015[1])

[1]*Solomon, D., Woolf, D., Jirka, S., De'Gloria, S., Belay, B., Ambaw, G., Getahun, K., Ahmed, M., Ahmed, Z., and Lehmann, L. 2015. "Ethiopia's Productive Safety Net Program (PSNP) national baseline database (NBD): Georeferenced site, management, topography, climate, soil carbon, soil fertility indicators, yield and low-cost soil mid-infrared (MIR) analysis results". A World Bank Climate Smart Initiative (CSI) Report. Cornell University. https://ecommons.cornell.edu/handle/1813/41299.*

includes information about livelihoods, type and duration of best management practices, vegetation, geographical and climatic data collected from the comprehensive reconnaissance survey of Ethiopia's PSNP watersheds spread across the CSI Woredas in six regional states, as well as the soil carbon and other critical soil biological, physical and chemical characteristics generated by the standard and cost-effective soil analytical approaches from these sites.

The downscaled CSI national baseline dataset is expected to enable Ethiopia's PSNP public works practitioners, Ethiopia's MoA natural resource and land managers, policy makers, researchers, investors and other stakeholders with the possibility to: (i) conduct rapid and effective watershed-level assessment and reporting of carbon stock changes and other co-benefit as a result of the implementation of current PSNP's integrated watershed interventions, (ii) model and predict future soil carbon capture and sequestration potentials, as well as other environmental and agricultural co-benefits, and (iii) permit spatial and temporal geospatial mapping and scaling up opportunities.

3.2 Key drivers of soil carbon stocks and fertility indicators in PSNP watersheds

It is widely accepted that the effects of global warming could be offset by the reduction of carbon emissions and the protection and increase of carbon stocks worldwide (Lal, 2004; Solomon et al., 2007b). Soil carbon and soil organic matter are also fundamental properties of soils, and have been directly and positively related to soil fertility and agricultural productivity potential (McDowell et al., 2012). There are many advantages to increasing soil carbon sequestration and maintaining high level of soil organic matter in (agro)ecosystems ranging from reduced soil bulk density, increased soil aggregate stability, and enhanced resistance to soil compaction and resistance to soil erosion to enhanced essential plant nutrient content, reduced nutrient leaching and loss, to increased soil biological activity. Therefore, accurate assessment of soil carbon stocks is critical, and concerned nations need to assess their stocks and fluxes of carbon (Bell and Worrall, 2009).

The carbon storage capacity of soils is, however, dynamic and depends on various management and environmental changes (Schlesinger, 1995). Drivers of soil carbon storage are likely also highly localized in some cases, and vary in importance in different regions due to local anthropogenic and biophysical factors influencing soil carbon dynamics. Therefore, globally significant body of research have focused on identifying localized drives for soil carbon sequestration, as well as on quantifying changes in contrasting management, biophysical and environmental conditions (West and Post 2002; Dawson and Smith, 2007; Hobley et al., 2015). While detecting and quantifying differences in soil carbon stocks is an important undertaking, identifying the most relevant factors driving these changes in landscape-level projects involving multiple ecosystems, livelihood zones, and biophysical and socio-economic conditions - especially within the necessary timeframe required for carbon accounting purposes can be very challenging (Richards, 2001).

Ethiopia's PSNP CSI utilized Random Forest (RF) statistical classification algorithms (as contained within the R package ''Random Forest''), which is widely credited to classify large amounts of data with accuracy in large-scale spatial explicit soil carbon stock investigations (Breiman, 2001; Mascaro et al., 2014; Hobley et al., 2015) to identify the most relevant factors influencing soil carbon storage and soil fertility indicators in the investigated watersheds.

Using this approach, the large number of independent parameters listed Ethiopia's PSNP CSI national baseline dataset (>100) were narrowed down into 22 most relevant independent variable (Figure 9) that affect soil carbon stocks and soil fertility co-benefits in the investigated watersheds (see for details about NBD in Solomon et al., 2015).

The most relevant independent variable encompass:

(i) *Management*
  a. Livestock exclusion
  b. Biological ISWC measure,
  c. Physical ISWC measures,
  d. Area closures
  e. Organic amendments

(ii) *Vegetation*
  a. Availability of vegetation cover
  b. Land cover typology
  c. Net primary productivity (Moderate-resolution imaging spectroradiometer (MODIS) net primary productivity (NPP)

(iii) *Geographical*
  a. Topographic index
  b. Aspect
  c. Slope
  d. Elevation

(iv) *Climatic*
  a. Temperature
  b. Precipitation
  c. Aridity
  d. Bioclimatic zone
  e. Evapotranspiration

(v) Edaphic factors
  a. Sand
  b. Silt
  c. Clay
  d. Soil depth (selectively applied to samples collected from soil profiles)

(vi) *Time* (the duration that PSNP's integrated watershed management interventions were implemented at the watersheds).

The relative parameter of importance expressed as the mean square error (MSE) value in Figure 9 show that among the 22 most relevant variables, management (livestock exclusion and physical and biological ISWC measures) implemented as part of Ethiopia's PSNP integrated watershed management interventions seem to be the most important driving factor for the surface (Figure 9a) and deep soil profile (Figure 9b) carbon socks of the investigated CSI sites. The RF regression analysis also show that, in addition to management, other independent variables including vegetation (i.e., vegetation cover and land cover typology), time, edaphic (i.e., clay and sand content), topography, and climate (i.e., temperature) appeared to have an important influence on surface and deep soil profile soil carbon stocks of the PSNP watersheds. These results suggest that the impact of sustainable watershed on soil carbon stocks could be much stronger than the influence of the bio-physical and environmental factors in Ethiopia's highly degraded PSNP watersheds. The outcome of these study is in line with the results of Lugo and Brown (1993) who suggested that soil carbon recovery in highly degraded sites requires a wide range of management measures ranging from closure and conversion of the degraded sites into grasslands or forests through unassisted natural regeneration to a more pro-active management of the degraded sites for greater soil carbon storage. Our results are also comparable to the results reported for variety of (agro)ecosystems by Powers and Schlesinger (2002) from Costa Rica, by Krishnan et al. (2007) from India, and by Schulp and Veldkamp (2008) from in The Netherlands.

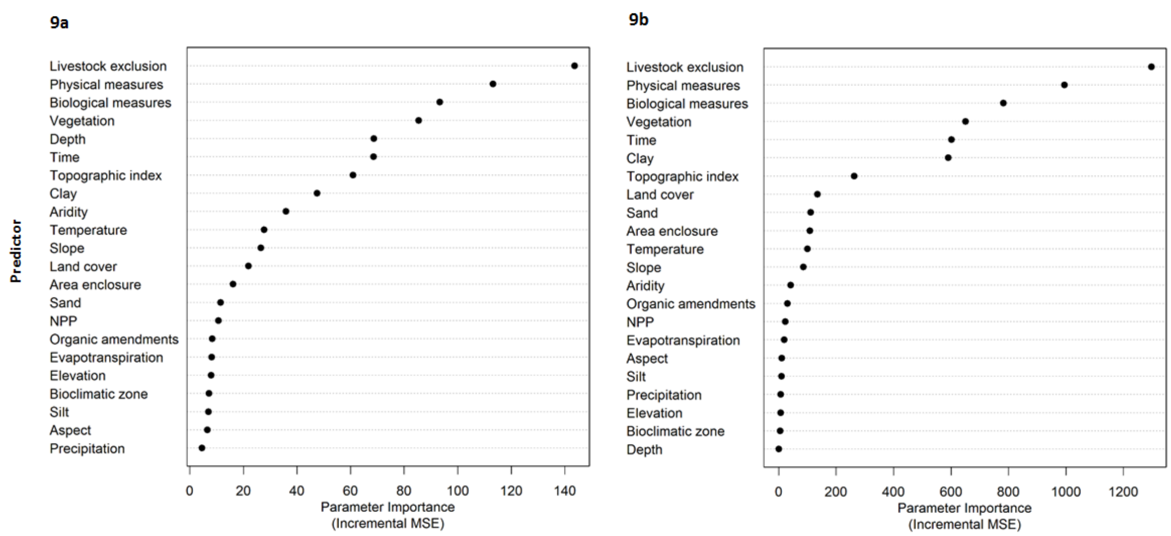

Figure 9. Relative parameter of importance from Random Forest (RF) regression analysis of surface layer (0-15 cm, 9a) and soil profile (up to 100 cm depth, 9b) soil carbon stocks of Ethiopia's PSNP watersheds. Parameter of importance is expressed as mean square error (MSE). Soil profile samples were collected from 12 watersheds in Amhara (Sefed Amba and Woira Amba), Oromia (Billa, Shek Kedir Karo and Wayu Bure), SNNPRS (Asore, Godaye, Gamot Terara, Sheshhecho and Usha) and Tigray (Serawat and Chearo) regional states. Land cover typology represent grassland, woodland, forestland, cultivated land or agroforestry. NPP represent moderate resolution imaging spectroradiometer (MODIS) net primary productivity (NPP). Bioclimatic zone represent Holdridge climatic zone simulated for each PSNP watershed using FAO's new local climate estimator (New_LocClim) program as described in section 2.1 of this report. For details about the independent variables see Solomon et al., 2015.

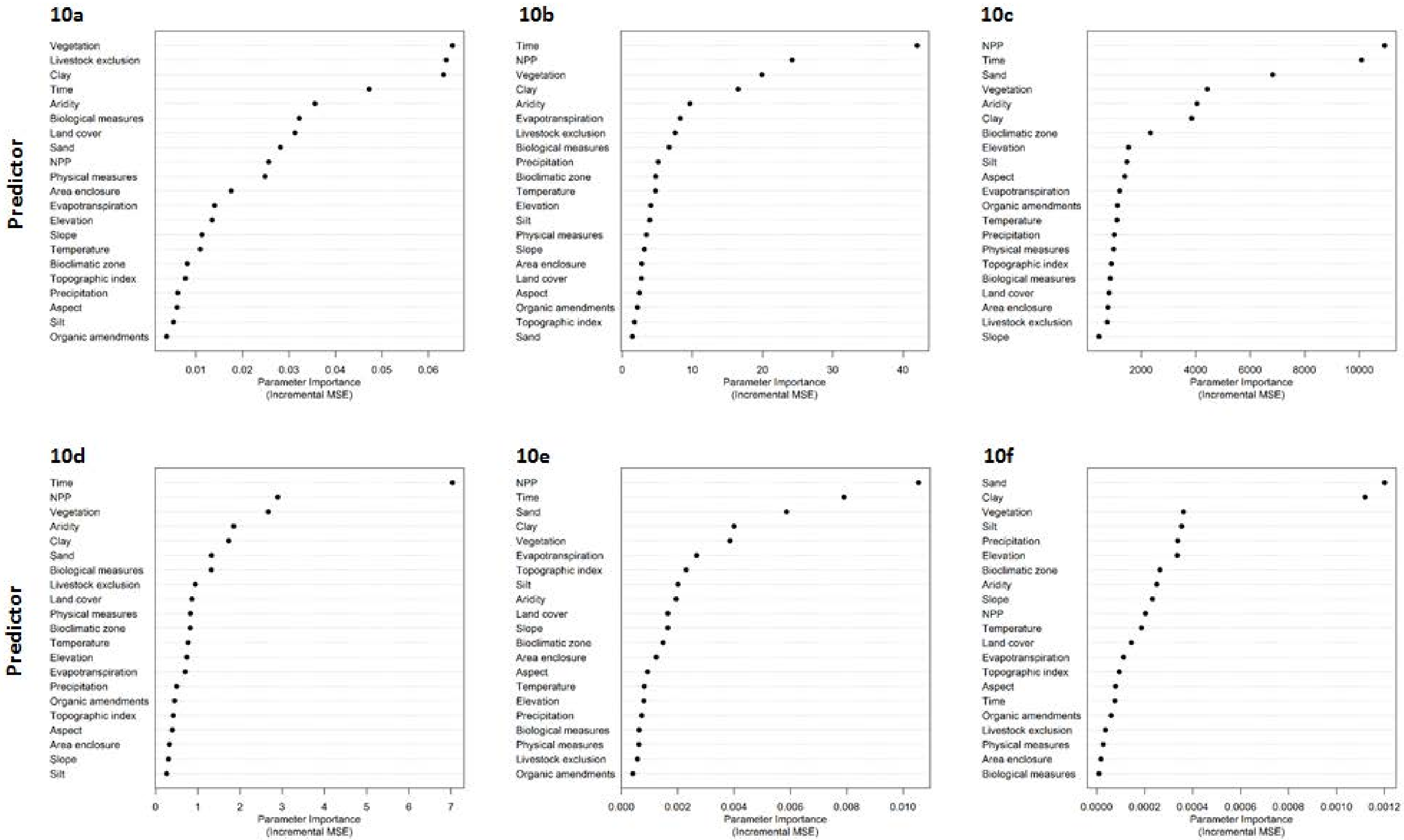

Figure 10 Relative parameter of importance from RF regression analysis of selected surface soil fertility co-benefits indicators (10a, total nitrogen; 10b, available phosphorus, 10c, available potassium; 10d, cation exchange capacity; 10e, bulk density and 10f, available water capacity) of the Ethiopia's PSNP watersheds. Parameter of importance is expressed as mean square error (MSE).

The relative importance of the 22 selected parameters on chemical (total nitrogen, Figure 10a; available phosphorus, Figure 10b; available potassium, Figure 10c; and cation exchange capacity, Figure 10d), and physical (bulk density, Figure 10e and available water capacity, Figure 10f) soil fertility co-benefits of surface soil samples collected from PSNP watersheds are shown in Figure 10. According to Figure 10a, the total nitrogen content in the surface layers of Ethiopia's PSNP watersheds seem to be strongly influenced by vegetation (vegetation cover, land cover typology and NPP), management (livestock exclusion and biological and physical ISWC measures), edaphic (soil clay and sand content), time and climatic (temperature) variables in decreasing order of importance.

Available soil phosphorus (Figure 10b) and potassium (Figure 10c), cation exchange capacity (Figure 10d) and bulk density (Figure 10e) of the surface soils of Ethiopia's PSNP watersheds appeared to be considerably affected in decreasing order of importance by time (duration of time that PSNP's integrated watershed management interventions have been implemented), vegetation (NPP, availability of vegetation cover, land cover type), edaphic (clay and sand contents), climate (aridity, precipitation, bioclimatic zone and evapotranspiration) and management (biological ISWC and livestock exclusion measures). However, although management still have an important role to play, edaphic (sand, clay and silt), vegetation (vegetation cover and NPP) climate (precipitation, bioclimatic one and aridity) and geographical parameters (elevation, and aspect) seem to be among the top ten most relevant factors driving available soil water content in the investigated PSNP watersheds (Figure 10f).

Management - implemented as part of PSNP's integrated watershed interventions– has a much stronger influence on the surface and deep soil carbon stocks recovery and carbon storage than the other independent (time, vegetation, climatic, geographic, and edaphic) variables in the investigated highly degraded CSI watersheds and (agro-) ecosystems of Ethiopia.

3.3 Influence of management on soil carbon stocks and soil fertility co-benefits

3.3.1 Business-as-usual vs PSNP project scenarios

The relative parameter of importance from the RF analysis show that productive and resilient ecosystem building management measures implemented as part of PSNP's integrated watershed management interventions greatly impacted soil carbon stock and soil fertility co-benefits in the various CSI watersheds in Ethiopia (Figure 9 and 10). The RF analysis also provided an indication that among other things vegetation and land cover typology, and possibly the accompanying protection from erosive forces and addition of organic residues into the soil from the prevailing vegetation can influence the recovery of soil carbon in various ecosystems. Soil fertility is closely related to soil organic carbon and thus organic matter content of soils. Therefore it is plausible to assume that positive vegetation and land cover typology changes that are mainly the results of PSNP's watershed management interventions could play an important role in influencing additional ecosystems services and co-benefits since they are fundamental components of the overall ecosystem productivity and functioning.

Soils under the project scenario stored up to three times more carbon compared to soils under the corresponding business-as-usual scenario.

Soils under the project scenario contain larger concentrations of plant nutrients such as nitrogen, phosphorus and potassium, and higher nutrient retention capacity than the corresponding soils business-as-usual scenario.

Soils under the project scenario contain higher available water content and lower bulk density than the corresponding soils under the business-as-usual scenario.

Understanding the overall ecosystem functioning and changes in ecosystem services and co-benefits in PSNP watersheds is important to estimate the incremental or additional soil carbon gains as a result of the implementation public works project activities, as these are the main goals of the carbon inventory for carbon climate change mitigation projects in Ethiopia. Estimation of these incremental or additional carbon benefits or carbon stock gains require monitoring of carbon stocks of a given area over a given period of time under business-as usual scenario as well as changes in carbon stocks for the project area over the same period of time as a result of implementation of project activities under "project scenario". Hence, the influence of management in PSNP watersheds was further investigated by broadly aggregating the surface and soil profile carbon stocks and soil fertility data collected from Ethiopia's six regional states into business-as-usual and project scenarios (Figure 11, Figure 12 and Figure 13).

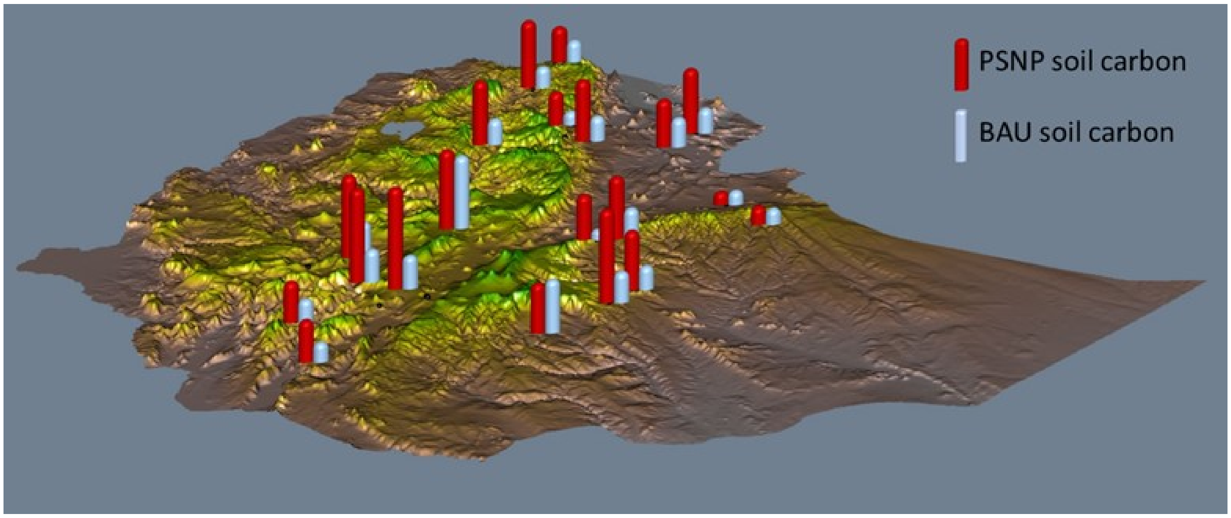

Figure 11. Topographic map of Ethiopia depicting an overview of the surface soil carbon stock changes under business-as-usual (BAU) and project (PSNP) scenarios at the PSNP watersheds.

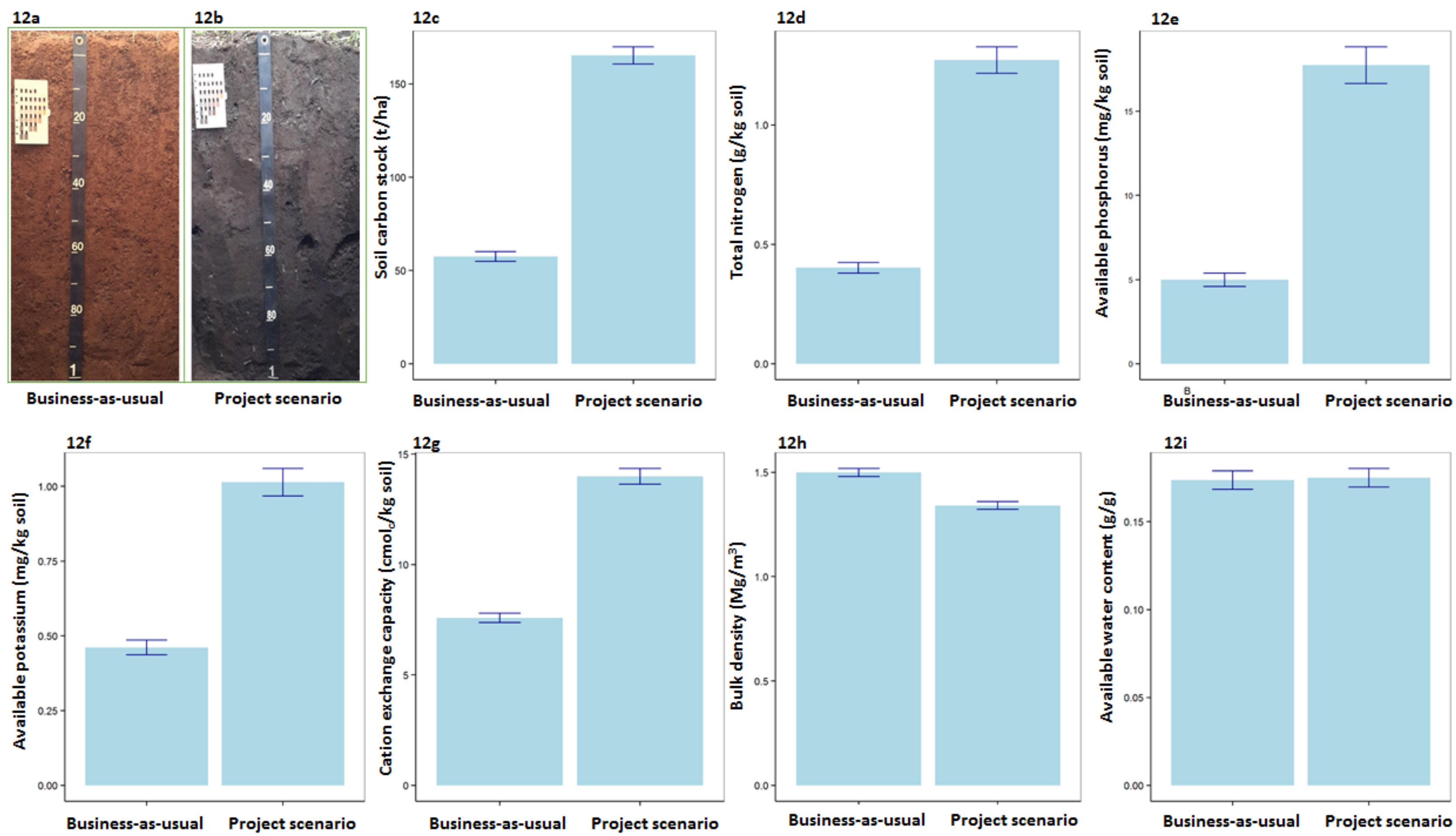

Figure 12. An overview of representative red and dark colored deep soil profiles (up to 100cm) from business-as-usual (red colored soil profile, 12a) and project (dark colored soil profile, 12b) scenarios, changes in deep soil carbon stock (12c), and selected fertility and productivity indicators (12d, total nitrogen; 12e, available phosphorus, 12f, available potassium; 12g, cation exchange capacity; 12h, bulk density and 12i, available water capacity) of deep soil profile samples under business-as-usual and project scenarios in Ethiopia's PSNP watersheds. The darker color observed in soil profiles under project scenario is usually an indication for larger soil carbon accumulation compared to the more reddish color observed in soil profiles under business-as-usual scenario.

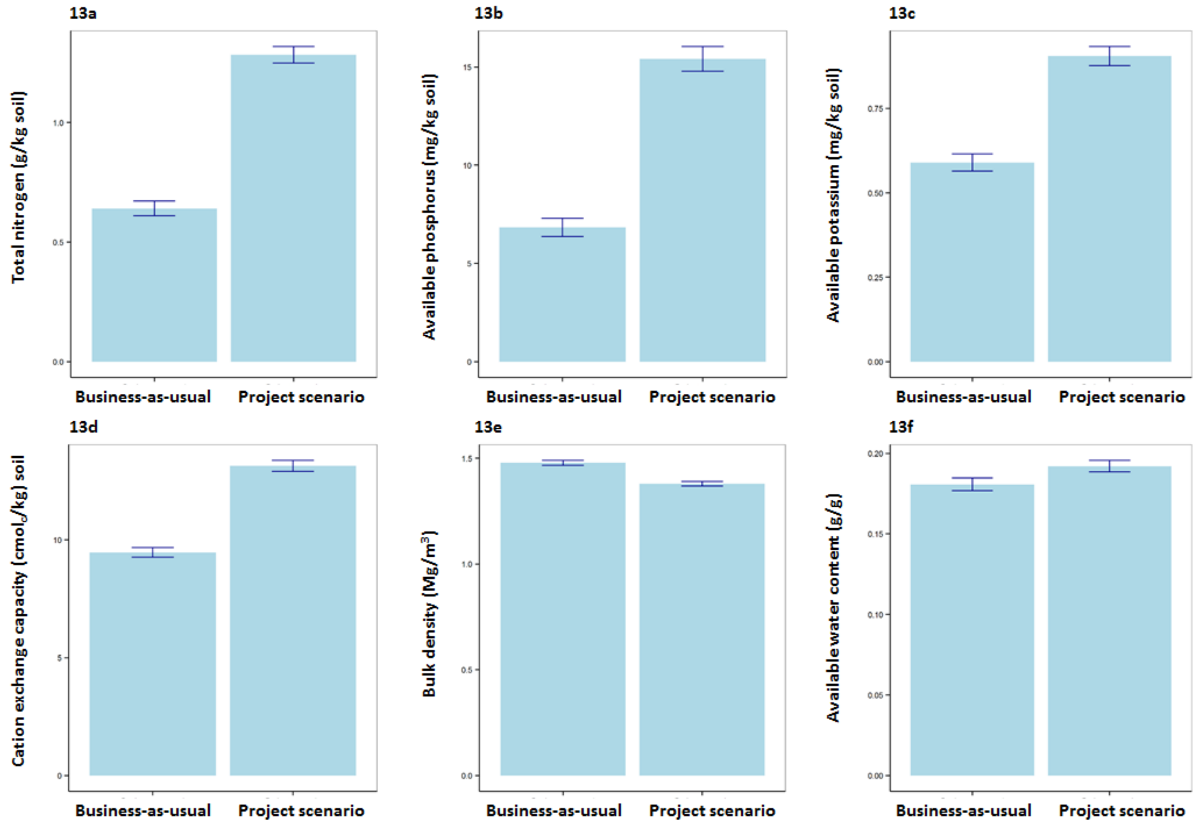

Figure 13. An overview of changes in selected fertility and productivity indicators (13a, total nitrogen; 13b, available phosphorus, 13c, available potassium; 13d, cation exchange capacity; 13e, bulk density and 13f, available water capacity) of surface soil samples under business-as-usual and project scenarios in Ethiopia's PSNP watersheds.

An overview of the surface soil carbon stock changes under business-as-usual and project (PSNP) scenarios show that up to three times more soil carbon is stored in the surface and deep soil profiles under project scenario compared to corresponding sites under business-as-usual scenario in Ethiopia's PSNP watersheds Representative pictures of yellowish red business-as-usual scenario (Figure 12a) and dark colored PSNP project scenario (Figure 12b) soil profiles obtained by digging 3×2×1 m (length, width and depth) soil pits are shown in Figure 12a and Figure 12b, respectively. Although not always in a one-to-one correspondence, uniform dark colors in well-drained soil profiles are usually associated with the presence of higher soil organic carbon and organic matter contents. Therefore, the color change from yellowish red to a much darker color observed in the soil profiles excavated from Ethiopia's PSNP watersheds (Figure 12b) could be considered as a further evidence for the higher soil organic carbon and thus organic matter content of soil profiles under the project than under business-as-usual (Figure 12a) scenarios. The results of selected surface (Figure 12) and profile (Figure 13) soil chemical characteristics indicate that considerably higher values of total nitrogen (Figure 12d and Figure 13a), available phosphorus (Figure 12e and Figure 13b) and potassium (Fig 12f and Figure 13c), and cation exchange capacity (which translates to plant nutrient retention capacity, Figure 12g and Figure 13d) were observed in soils under project scenario compared to soils under business-as-usual scenario. Similarly, some soil physical characteristics such as available surface soil water content were slightly higher (Figure 12i and Figure 13f) in soils under project than business-as-usual scenario, while the values for bulk density (Figure 12h and Figure 13e) appear to be lower in the surface soils and profiles under project scenario than the corresponding soils under business-as-usual scenario. Bulk density is an important soil health parameter closely linked with organic carbon and organic matter content, water infiltration, solute movement, aeration and plant root health. Higher bulk density, as in the case of soils under business-as-usual scenario, is usually an indication for impaired soil function and health.

3.3.2 Soil carbon stock and soil fertility co-benefits across various land cover typology

Figure 14 provide surface and deep soil profile carbon stocks by land cover typology without discerning for management (i.e., data includes soil carbon stocks from both business-as-usual and project scenarios) in Ethiopia's PSNP watersheds. The results show considerable variation in soil carbon stocks both across and within the various land cover typologies, and the role that land cover types play in soil carbon sequestration. Despite such variations, however, the median and mean values of the surface layers (Figure 14a) show agroforestry and forested ecosystems have the largest surface soil carbon stocks, followed by grasslands, woodlands and croplands. The least surface soil carbon stock was found under recently restored gullies with mixed vegetation (Fig 14a).

Agroforestry and forest land cover typologies contain the largest soil carbon stocks and the highest soil fertility co-benefits in Ethiopia's PSNP watersheds, followed by soils under grassland, woodland and cropland land cover types in order of importance. The smallest carbon stocks and co-benefits were found in recently improved gullies with mixed vegetation types.

The soil profile carbon stocks, however, show that the highest carbon stocks were found in Ethiopia's PSNP watersheds under agroforestry, forest and grassland land cover types, followed by soils under woodland and cropland (Figure 14b). It is widely accepted that continuous excessive grazing of grasslands - as in most degraded PSNP business-as-usual or control sites is detrimental to the growth of plant communities (Milchunas and Lauenroth, 1993), and results in low surface soil carbon stock as shown in the present study. The higher deep profile carbon observed in the grasslands (Figure 14b), however, suggest that belowground carbon, mainly in roots and soil organic matter, likely plays an important role in building deep soil carbon stocks in grassland land cover types and ecosystems.

The results in Figure 14 also show that in almost all cases, soil carbon stocks of the older or the more matured land cover typologies represented by the darker circles seem to be mostly in the middle and upper quartile groups of the boxplots. It is important to recognize that the basic process governing carbon balance in these land cover types is similar. The plants in all land cover types – agroforestry, forest, grassland, woodland and cultivated land take up CO_2 from the atmospheric and mineral nutrients and water from the soil, and transform them into organic products. Ecosystem disturbances in the form of unsustainable human interventions such as the ones that lead to extensive degradation of Ethiopia's PSNP watersheds, are among the most defining element for soil carbon accumulation in these land cover types. They often promote increased carbon loss from the soil through net CO_2 release to the atmosphere via enhanced oxidative decomposition and continue to influence the overall carbon uptake and losses that determine long-term ecosystem carbon balance of these land cover types (Randerson et al., 2002). However, these results provide further indication that the duration of integrated watershed management interventions that enabled rehabilitation of the ecosystem from its bare and degraded state into the current vegetation and land cover typology play an important role for ecosystem carbon uptake and balance, and for surface and deep soil carbon stock recovery and sequestration in the investigated land cover types.

Figure 15 and Figure 16 offer an overview of selected soil fertility co-benefit indicators by land cover types for the surface soil and profile samples collected from Ethiopia's PSNP watersheds, respectively. The results from the surface soil show that, with the exception of nitrogen where greater total concentrations were observed in both agroforestry and forestland cover types (Figure 15a), higher values for available phosphorus (Figure 15b), available potassium (Figure 15c) and cation exchange capacity (Figure 15d) were found in soils under agroforestry, followed by forest, and woodland, grassland and cropland land cover typologies. The lowest values were in all cases were fund in the recently restored gullies with mixed vegetation cover types. Agroforestry and forest land cover types exhibited the lowest surface soil bulk density values followed by cropland, grassland and woodland. The highest surface soil bulk density values were recorded in recently recovered gullies with mixed land cover typology (grass, shrubs and trees, Figure 15).

Similar to the soil profile carbon stocks values, the highest total nitrogen (Figure 15a), available phosphorus (Figure 15b), available potassium (Figure 15c), cation exchange capacity (Figure 15d) and available water contents (Figure 15f), as well as the lowest bulk density (Figure 15e) values were found under agroforestry lad cover type. Although lower than agroforestry, forest and grassland land cover types seem to have the second highest nitrogen, phosphorus and cation exchange capacity compared to cropland and woodland. There seems to be not much difference in available potassium (Figure 15c) and available water content (Figure 15f) of the remaining investigated land cover types. However, soil profiles form forest followed by grassland and woodland seems to have lower bulk density (Figure 15d) compared to soil profiles form cropland in PSNP watersheds. These results are in line with the results of the study by Nair et al. (2009) that gathered information on agroforestry systems - a collective name for land use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence - from sites around the world. These authors found soil carbon stock values for ranging from 6.9 to 302 t/ha. The average surface and deep soil profile soil carbon stocks in Ethiopia's PSNP watersheds are about 40 t/ha and 200 t/ha, respectively (see inset for Figure 14a and Figure 14b).

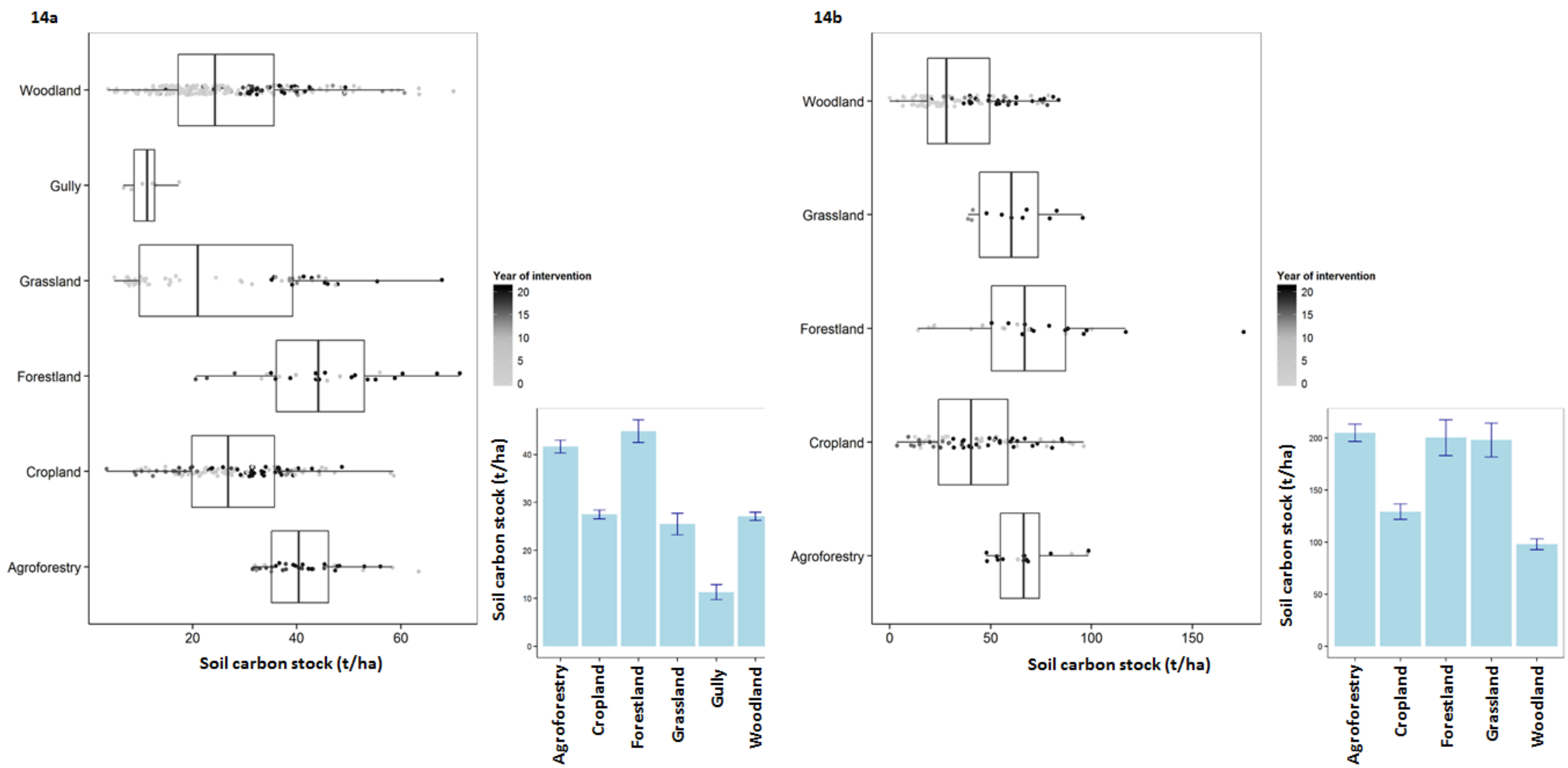

Figure 14. Surface (0-15 cm, 14a) and deep soil profile (up to 100cm, 14b) carbon stock variations by land cover typology in Ethiopia's PSNP watersheds. Surface soil carbon stocks in restored gullies (14a) with mixed vegetation (grass, shrubs and trees) were classified as separate land cover types under gully. The light to dark grey shades show carbon stock variations in each land cover types according to duration of integrated watershed management implemented. The insets in Figure 14a and 14b show the average values of surface and deep soil profile soil carbon stocks for each land cover type, respectively. Soil profile samples were collected from 12 watersheds in Amhara (Sefed Amba and Woira Amba), Oromia (Billa, Shek Kedir Karo and Wayu Bure), SNNPRS (Asore, Godaye, Gamot Terara, Sheshhecho and Usha) and Tigray (Serawat and Chearo) regional states.

Despite the great amplitude of the soil carbon stock values obtained by Nair et al. (2009), where the authors attributed it to the variation between systems, ecological regions and soil types across the investigated sites, the study by Nair et al. (2009) revealed a general trend where in almost all cases an increasing soil carbon sequestration was observed in agroforestry systems when compared to other land use and land cover types, rivalled only by forest land cover types. Trees in forest land cover types add large amount of organic carbon into the soil in various manners - in the form of litter fall and root biomass or as root exudates in the rhizosphere. These additions are the chief substrates for a vast range of organisms involved in soil biological activity and interactions, with important effects on soil nutrient cycling in (agro)ecosytems and soil fertility co-benefits. Trees, by participating in these complex biogeochemical processes, in forest land cover types contribute to soil carbon sequestration and to mitigation of greenhouse gases associated with global warming and climate change. The inclusion of trees in agricultural systems via agroforestry land cover types can also optimize nutrient cycling and could have positive effects on soil chemical and physical properties as shown in the present investigation.

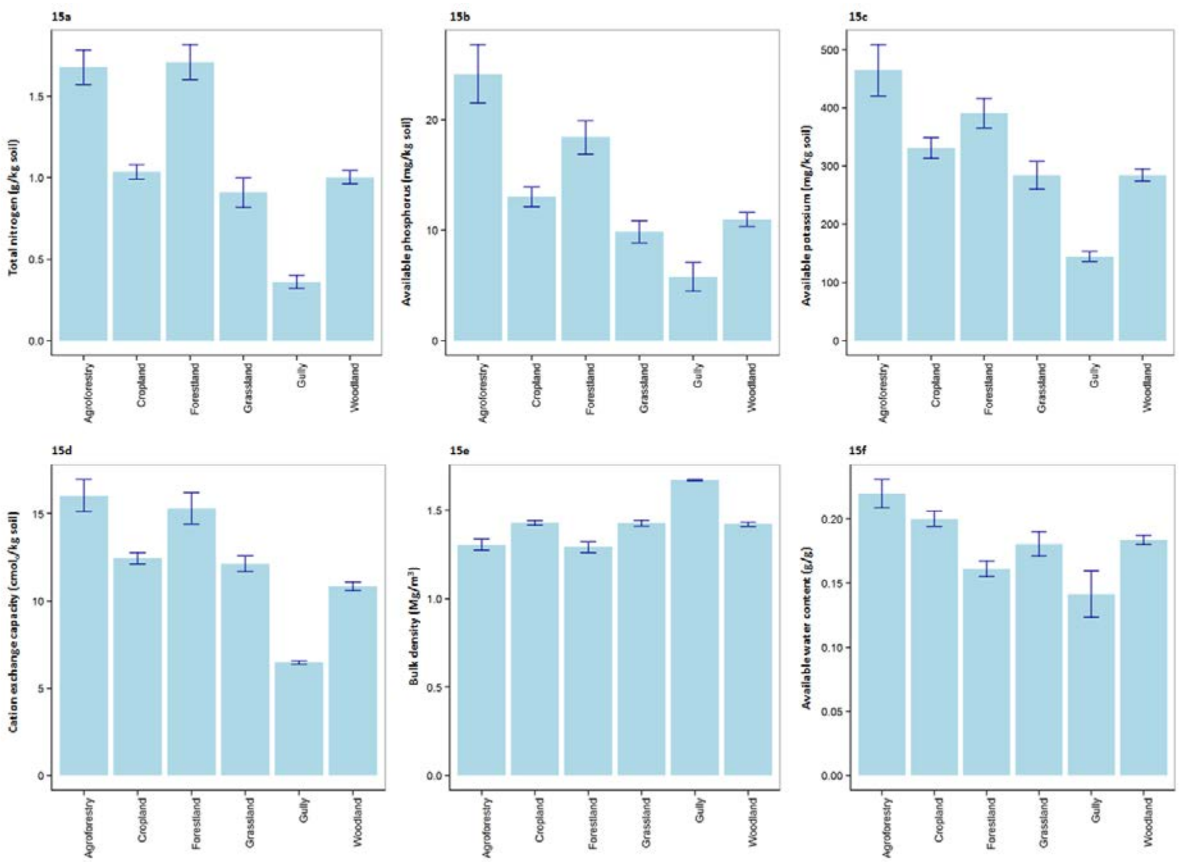

Figure 15. An overview of changes in selected soil fertility co-benefit indicators (15a, total nitrogen; 15b, available phosphorus, 15c, available potassium; 15d, cation exchange capacity; 15e, bulk density and 15f, available water capacity) of surface soil samples following land cover typology changes in Ethiopia's PSNP watersheds.

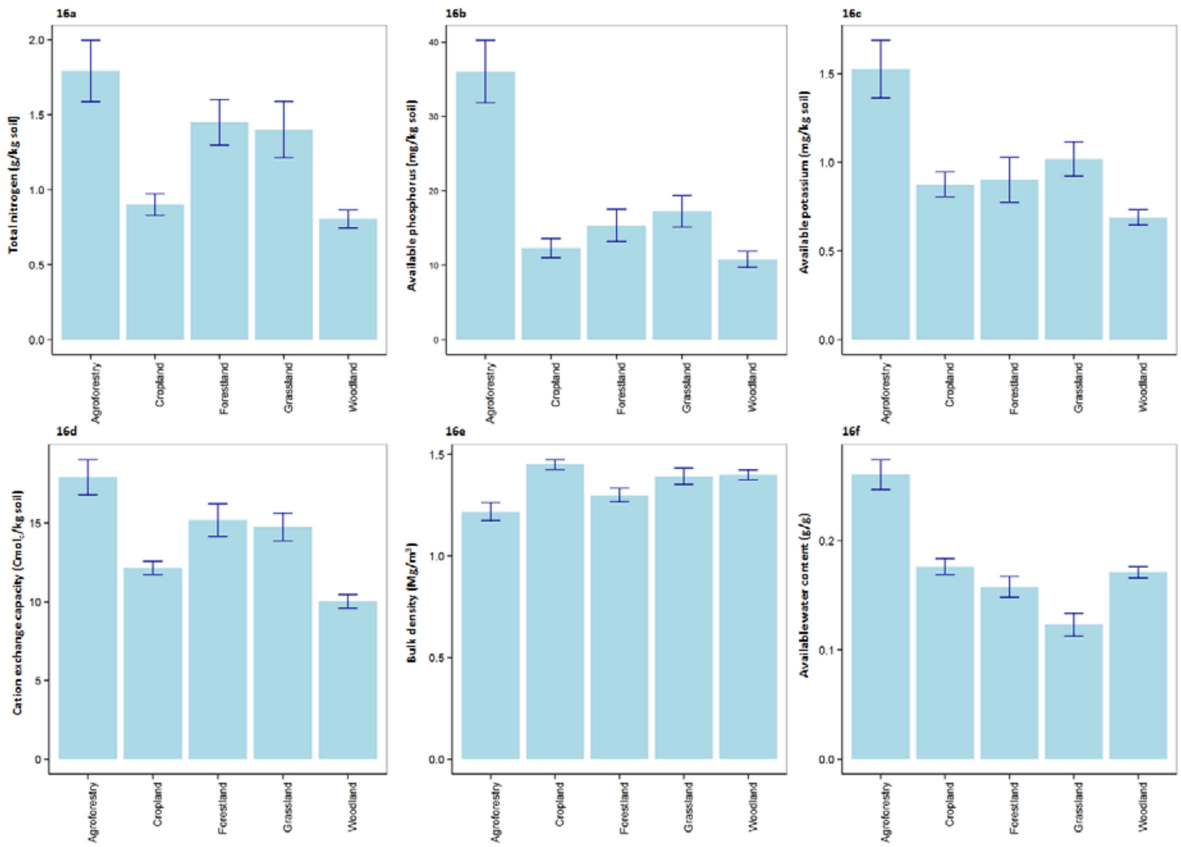

Figure 16. An overview of changes in selected fertility co-benefits (16a, total nitrogen; 16b, available phosphorus, 16c, available potassium; 165d, cation exchange capacity; 16e, bulk density and 16f, available water capacity) of soil profile samples following land cover typology changes in Ethiopia's PSNP watersheds.

3.3.3 Soil carbon stock and fertility co-benefits across degraded and improved (agro)ecosystems

Past long-term experimental studies have shown that soil carbon stocks in (agro)ecosystems are highly sensitive to changes in land use and land cover changes, with conversions such as from native forest and grassland ecosystems to agricultural systems almost always resulting in loss of soil carbon stocks (Paul et al., 1997; Solomon et al., 2002, 2007a). Deforestation and forest degradation is the second leading cause of global warming, responsible for up to 25% of global GHG emissions, which makes the depletion and loss of forests an important driver of climate change (IPCC, 2007). Likewise, the way in which land is managed following land use and land cover change have been also shown to affect soil carbon stocks. Therefore, there is an opportunity in the future to develop socio-economically sustainable climate smart land management strategies and land use and land cover types for various (agro)ecosystems across the globe that can lead to soil carbon storage and thereby help mitigate GHG effects and provide additional environmental co-benefits for example in the form of improving soil fertility.

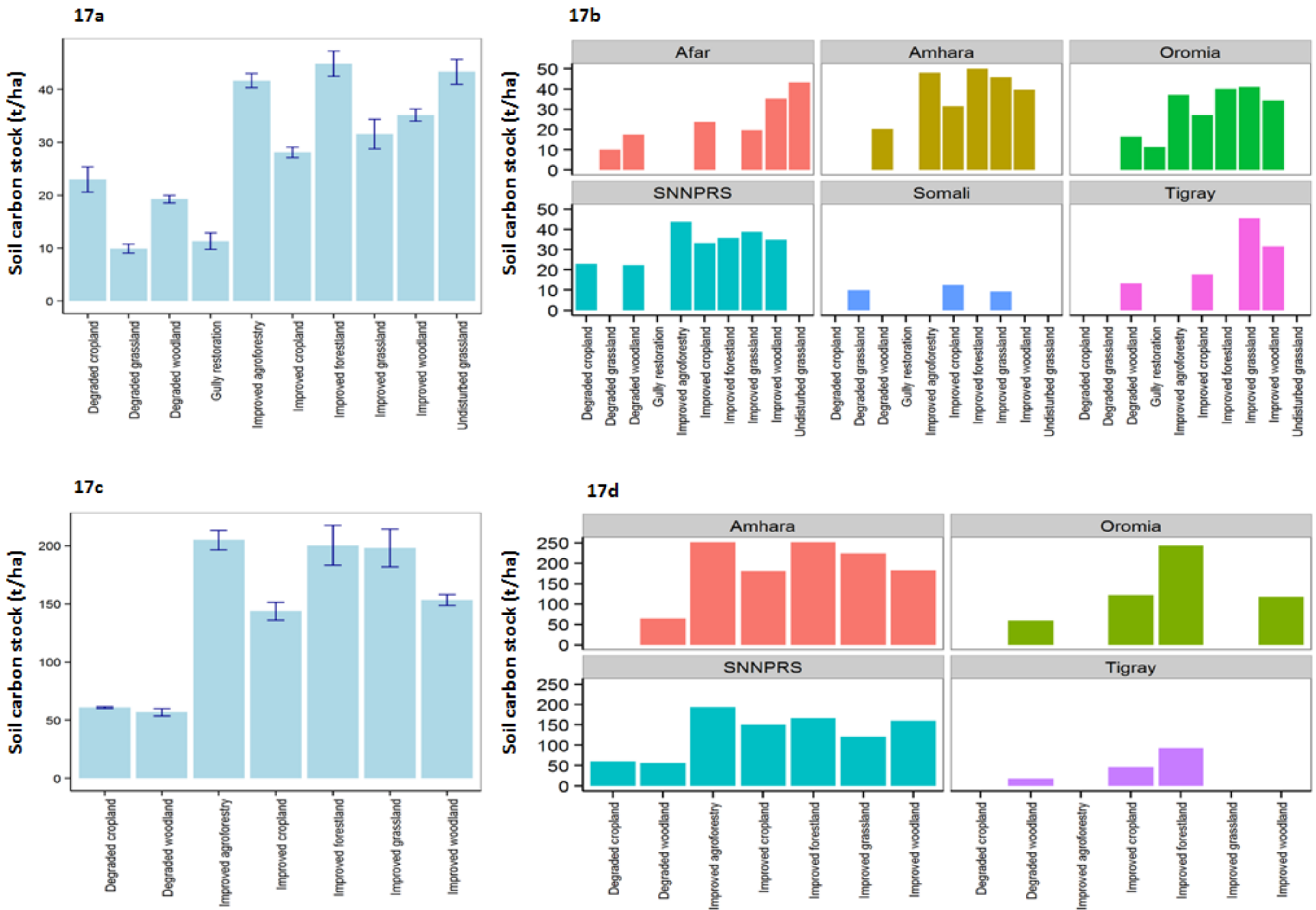

Figure 17. Surface soil (Figure 17a and Figure 17b) and deep soil profile (Figure 17c and Figure 17d) carbon stock changes in samples collected from degraded and improved land cover types in PSNP watersheds. Figure 17a and Figure 17c show aggregated surface soil carbon stock data, while Figure 17b and Figure 17d demonstrate regional state breakdown for surface soil and profile carbon stocks from degraded and improved land cover types in PSNP watersheds of the Ethiopia's six regional states.

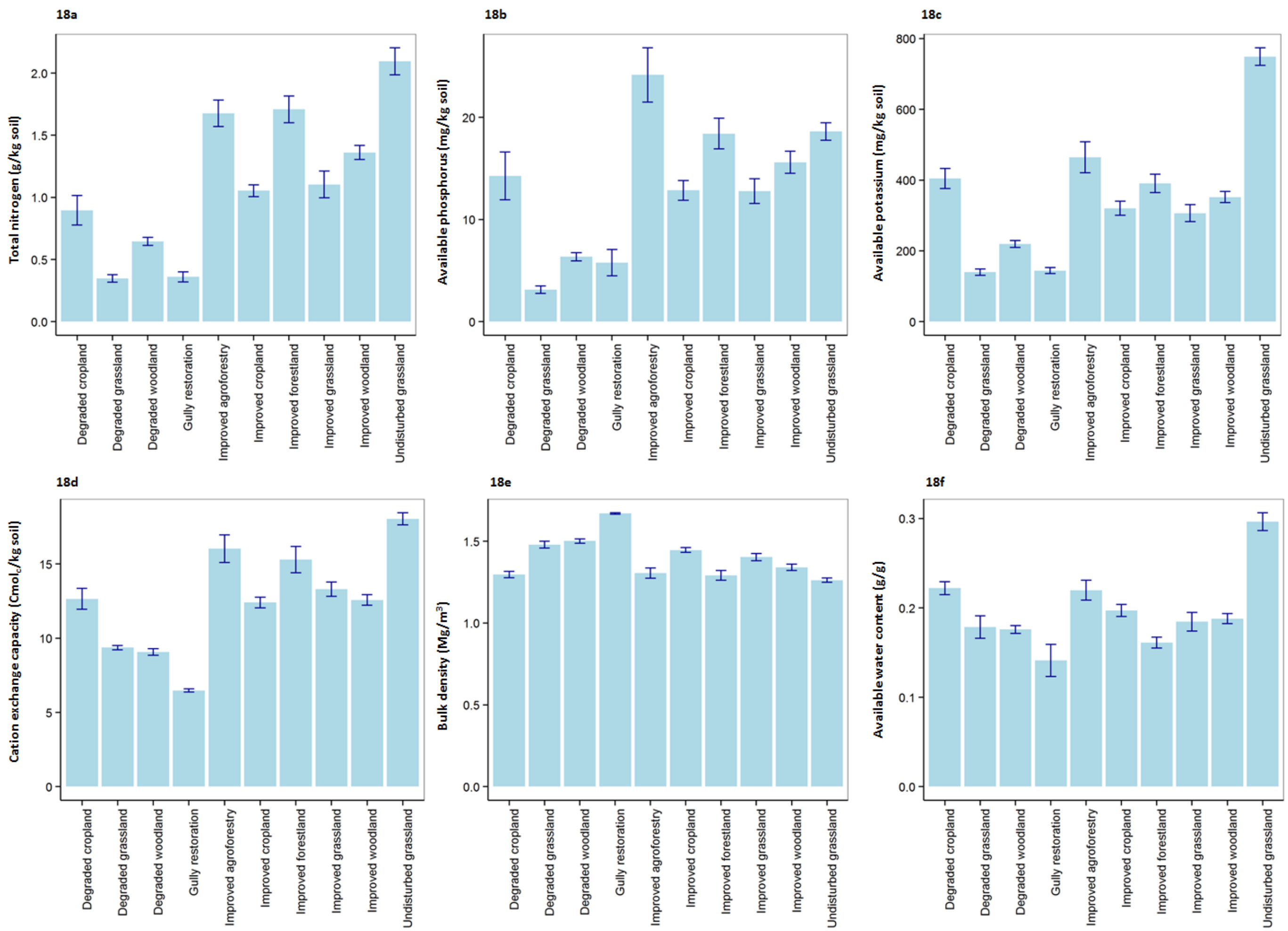

Figure 18. Surface soil (0-15 cm) fertility co-benefits (18a, total nitrogen; 18b, available phosphorus, 18c, available potassium; 18d, cation exchange capacity; 18e, bulk density and 18f, available water capacity) of samples collected from degraded and improved land cover types in Ethiopia's PSNP watersheds.

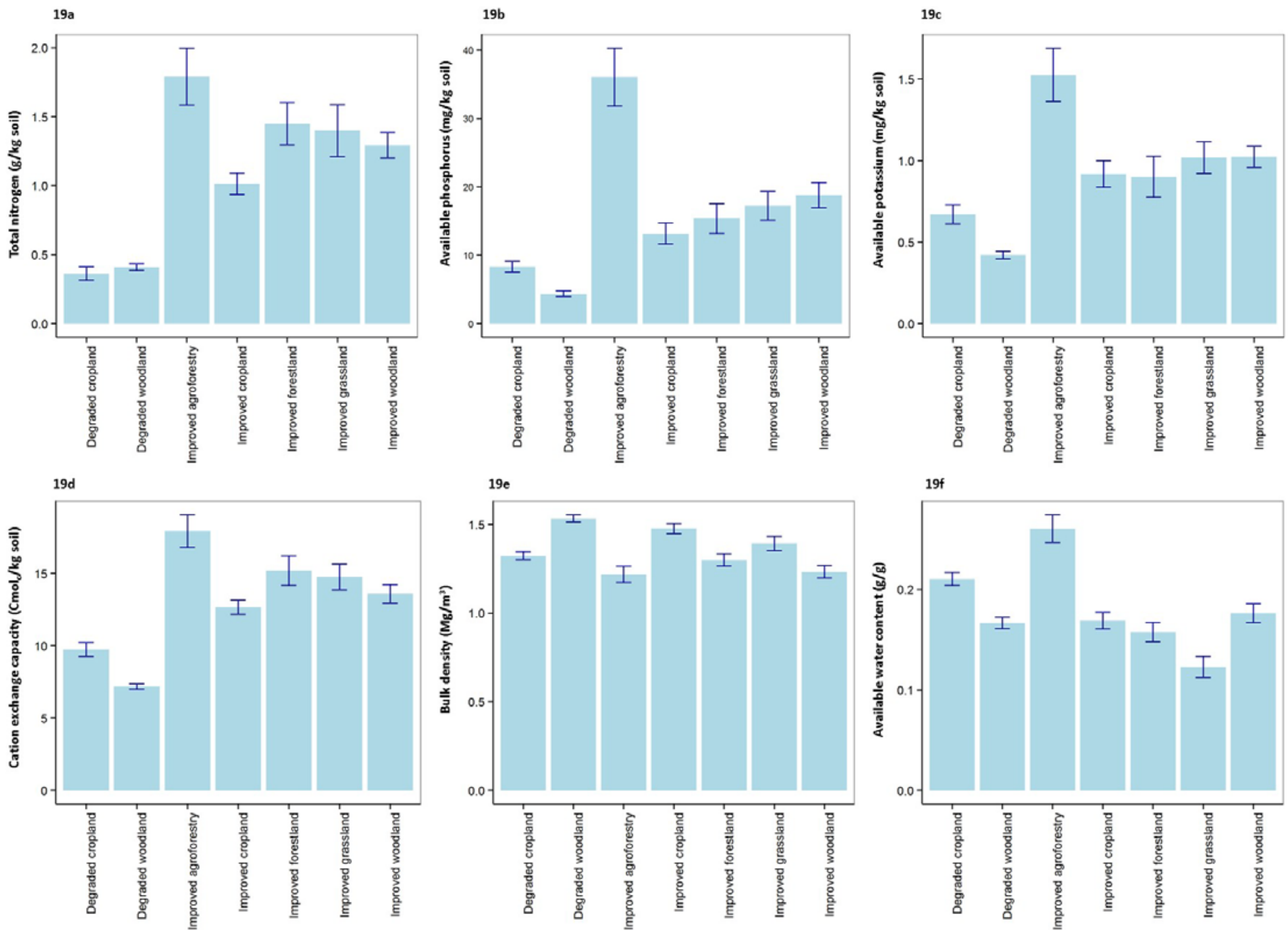

Figure 19. Deep soil profile (up to 100 cm) soil fertility co-benefits (19a, total nitrogen; 19b, available phosphorus, 19c, available potassium; 19d, cation exchange capacity; 19e, bulk density and 18f, available water capacity) of samples collected from degraded and improved land cover types in Ethiopia's PSNP watersheds.

The soil carbon stocks in the surface layers and deep soil profiles of improved agroforestry, forestland, grassland woodland, cropland and undisturbed grassland land cover types were 1 to 5 times more than the soil carbon stock of in the corresponding surface and deep soil profiles of degraded cropland, grassland and woodland land cover types.

The increasing soil carbon stocks as a result of the implementation PSNP's integrated watershed management interventions not only draw down CO_2 from the atmosphere but also provide soil fertility co-benefits to the (agro)ecosystems in question as effectively demonstrated by the increase in soil organic matter and by up to 3.5 times higher critical macronutrient concentrations such as nitrogen, phosphorous and potassium in the surface and deep soil profiles of improved land cover types in Ethiopia's PSNP watersheds.

Figure 17, 18 and 19 show soil carbon stock and soil fertility co-benefits as a result of rehabilitation of a broad class of degraded land cover types distributed across PSNP's watersheds in Ethiopia six food insecure regional states. The results clearly demonstrate that integrated watershed management intervention implemented as part of Ethiopia's PSNP to rehabilitate degraded (agro)ecosystems brought considerable improvement both in surface (Figure 17a, aggregated national surface soil carbon stock data, and Figure 17b disaggregated surface soil carbon stock data by regional state) and deep soil profile (Figure 17c, aggregated national surface soil carbon stock data, and Figure 17d disaggregated soil profile carbon stock data by region) carbon stocks. Results of the soil analysis show that for the most part aggregated national soil carbon stock values in the surface layers and deep soil profiles of improved agroforestry, forestland, grassland woodland, cropland and undisturbed grassland land cover types are 1 to 3 times more than the soil carbon stock of in the corresponding surface and deep soil profiles of degraded cropland, grassland and woodland land cover types (Figure 17a and Figure 17c). With the exception of the surface soil carbon stock values of the Somali region where almost no difference was observed between the degraded and relatively young (1 to 3 years old) improved land cover types most likely due to the less intense nature of the implemented interventions, the disaggregated surface soil and deep soil profile carbon data show that the carbon stock in the improved land cover types could reach up to 5 times more than the carbon stock in degraded land cover types (Figure 17b and Figure 17d). The highest surface soil and deep soil profile carbon stocks were obtained in the improved agroforestry, forest, grassland, and undisturbed grassland land cover types (Figure 17b and Figure 17d).

It is clear by now that organic carbon is an essential component of soil organic matter and confers numerous positive soil health related befits to the soil system such as increased aggregation and structure, water holding capacity, buffering, supply essential plant nutrients, and enhanced nutrient retention capacity and fertilizer use efficiency. Therefore, it is possible to conclude that increasing soil carbon stocks, not only draw down CO_2 from the atmosphere but also provide soil fertility co-benefits to the (agro)ecosystems. These have been effectively demonstrated by the results of the current study where analysis of samples collected from the surface and deep soil profiles of improved land cover types in Ethiopia's PSNP watersheds showed up to 3.5 times higher critical macronutrient concentrations such as nitrogen (Figure 18a and Figure 19a), phosphorous (Figure 18b and Figure 19b) and potassium (Figure 18c and Figure 19c). Compared to the values from the degraded land cover types, slightly higher available water content and lower bulk density values were also observed from the corresponding surface and profile samples of land cover types where integrated watershed management intervention as part of Ethiopia's PSNP was implemented to rehabilitate these degraded land cover types Surface soil (Figure 18d) and deep profiles (Figure 19d) samples under improved agroforestry, forestlands, grasslands, woodlands, croplands and under undisturbed grasslands also exhibited higher cation exchange capacity or ability to retain and exchange important plant nutrients elements present as cations such as calcium, potassium and magnesium compared to samples degraded cropland, grassland and woodlands.

PSNP's integrated watershed management interventions rehabilitated degraded cropland, grassland, woodland, and forest land cover types across the various watersheds in Ethiopia's six food insecure regional states delivered climate change mitigation and resilience-building benefits, as well as provided opportunity to restore the ecosystem and enhance key ecosystem services and co-benefits including increasing fertility and productivity of degraded soils.

Overall, these results suggest that integrated watershed management intervention designed and implemented as part of PSNP to rehabilitate degraded cropland, grassland, woodland and forestland land cover types across various watersheds in Ethiopia six food insecure regional states could deliver both climate change mitigation and resilience-building benefits, as well as provide opportunity to enhance key ecosystem services and co-benefits including increasing the fertility and productivity of degraded soils. Chazdon (2008) indicated that although restoring land cover types (e.g., rehabilitating and converting highly degraded cultivated land on steep slopes to improved forestland via assisted or natural regeneration) can contribute towards climate change mitigation and improve ecosystem services and co-benefits including enhancing biodiversity and conservation, there is a probability that the restored land cover type may not always match the composition and structure of the original land cover type of that particular ecosystem or ecoregion. Therefore, at times rehabilitated land cover types may require the introduction of new or adaptive management practices to make the rehabilitated and improved land cover type a more dynamic and resilient system that can withstand climate change related stresses, habitat fragmentation, and other anthropogenic effects (Chazdon, 2008). Thus, ecosystem rehabilitation programs such as Ethiopia's PSNP integrated watershed intervention programs should be aware of such possibilities and be flexible and robust enough to accommodate the changes and the possible new management needs into their planning, design and implementation steps, as well as show the readiness to take advantage of such changes.

3.3.4 Soil carbon stock and soil fertility co-benefits of PSNP's integrated watershed management interventions in agriculture, forestry and other land use sectors

Agricultural land: - Land degradation, which is alternatively defied as the decline of biological and economic productivity of land resources represented by soil carbon stock and nutrient depletions, loss of soil fertility, vegetation cover, and ecosystems and the services that they provide to the society, is a major ecological and socio-economic problem in Ethiopia's six (Afar, Amhara, Oromia, SNNPR, Somali and Tigray) chronically food insecure and vulnerable regions (UNCCD, 1994; Haileslassie et al., 2005; Mekuria et al., 2007; Mekuria et al., 20011). Several factors ranging from the country's rugged topography, rapid increase in human and livestock population pressure and consequent human activities such as intensive cultivation, overgrazing by livestock, deforestation and unsustainable land use practices to satisfy the country's food and livestock feed needs to climate change impacts that continued to expose the land to erosive forces such as wind and water have been cited as among the main facilitators for the extensive land degradation observed in Ethiopia's chronically food insecure regions (Hurni, 1993; Shiferaw and Holden, 1998; Dubale, 2001, for details see also section 1.4). For example, Osman and Sauerborn (2001) in a comprehensive review of the experiences and lessons learned from Ethiopia's soil and water conservation activities suggested that progressive deforestation and lack of effective catchment management on the highlands of Ethiopia have resulted in high water yield due to increased runoff caused by reduced water retention capacity of the soil. These authors indicated that consequently, in addition to onsite impacts, the problem of water erosion has expanded to low-lying areas in a form of reservoirs, lakes and marsh sedimentation, damage to agricultural land and settlements, as well as other infrastructures.

Several studies in the past stressed the importance of a coordinated multidisciplinary participatory sustainable land management strategies compatible with both the social and physical environment to combat land degradation in Ethiopia (GoE, 2007; Haregeweyn et al., 2015; Nyssen et al., 2004b; UNEP, 2013). In light of the severity of land degradation and its associated impacts, the Ethiopian government, and its development partners have implemented various soil and water conservation measures and participatory integrated watershed management interventions (Dubale, 2001; Herweg and Ludi, 1999). These initiatives include Food-for-Work (FFW, 1973-2002), Managing Environmental Resources to Enable Transition to more sustainable livelihoods (MERET, 2003–2015), Productive Safety Net Programs (PSNP, 2005-present), Community Mobilization through free-labor days (1998–present), and the National Sustainable Land Management Project (SLMP, 2008–2018; for details see also section 1.5). These efforts include the use of multi-institutional multiple sustainable environmental rehabilitation and resilience-enhancing approach involving indigenous soil and water conservation technology and participatory watershed management interventions that integrate physical and biological soil and water conservation practices, intensified natural resource use, and livelihood objectives (MoARD, 2006; Berhane et al., 2011; Béné et al., 2012; Van Domelen and Coll-Black, 2012; SLMP, 2013; Tongul and Hobson, 2013; WB, 2013b; Haregeweyn et al., 2015).

Osman and Sauerborn (2001) and Haregeweyn et al. (2015) indicated that studies that aim at a better understanding of the extent, causes, and impacts of soil erosion and land degradation, as well as the role of integrated soil and water conservation and watershed management practices implemented through the above initiatives in Ethiopia, are highly fragmented. Possible impacts, of soil and water conservation and watershed management such as improvement in land productivity (vegetation improvement and nutrient cycling), flood and sedimentation control, and climate regulation, remain under-researched. Furthermore, comprehensive multi-region and multi-(agro)ecosystem quantitative data-based investigations that evaluate past activities and draw lessons from experiences with the aim of aiding future development both at the regional and national levels are either largely absent, and the full extent and total areal coverage of integrated soil and water conservation and watershed management practices implemented through these initiatives in Ethiopia remain unknown (Haregeweyn et al., 2015).

Ethiopia’s CSI is the first comprehensive multiregional and multidisciplinary quantitative data-based investigation which aims to achieve these by evaluating the impact of PSNP’s integrated watershed management interventions on soil carbon capture and environmental and agricultural co-benefits both at the regional and national levels and aim to inform future PSNP social protection public works activities (i.e., PSNP 4). The type and extent of the control and integrated watershed management measures implemented at each PSNP watershed are listed in Table 2. In addition, Figure 20, 21, 22, 23 and 24 demonstrates both surface (Fig 20a and Figure 20b) and deep profile (Figure 20c and Figure 20d) soil carbon stocks and soil fertility co-benefits under no intervention (NI) and PSNP’s integrated watershed management interventions implemented in croplands and agroforestry systems, as well as in grasslands, woodlands and forestlands in six food insecure Ethiopian regional states.

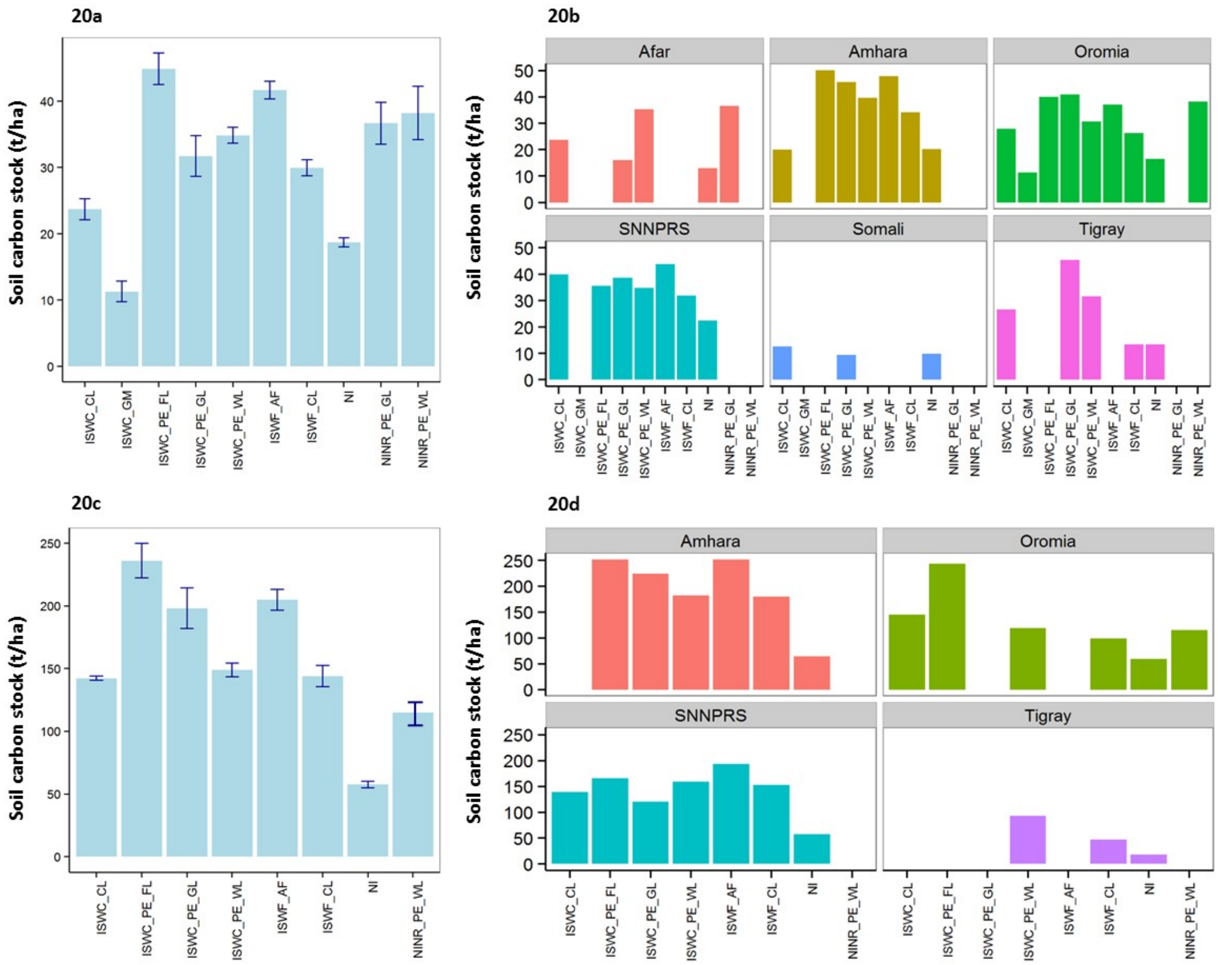

Figure 20. Surface (20a and 20b) and deep profile (20c and 20d) soil carbon stocks under no intervention (NI) and under PSNP's integrated watershed management interventions in six food insecure regional states of Ethiopia. ISWC_GM, integrated soil and water conservation implemented for gully management (samples were collected from rehabilitated gullies); ISWC-CL, integrated soil and water conservation implemented in croplands; ISWC-PE-FL, integrated soil and water conservation and permanent enclosure implemented in forestlands; ISWC-PE-GL, integrated soil and water conservation and permanent enclosure implemented in grasslands; ISWC-PE-WL, integrated soil and water conservation and permanent enclosure implemented in woodlands; ISWF-AF, integrated soil and water conservation and integrated soil fertility management implemented along with agroforestry systems; ISWF-CL, integrated soil and water conservation and integrated soil fertility management implemented in croplands; NINR-PE-EL. Figure 20a and Figure 20c show aggregate data, while Figure20b and Figure 20d – show breakdown by regional states.

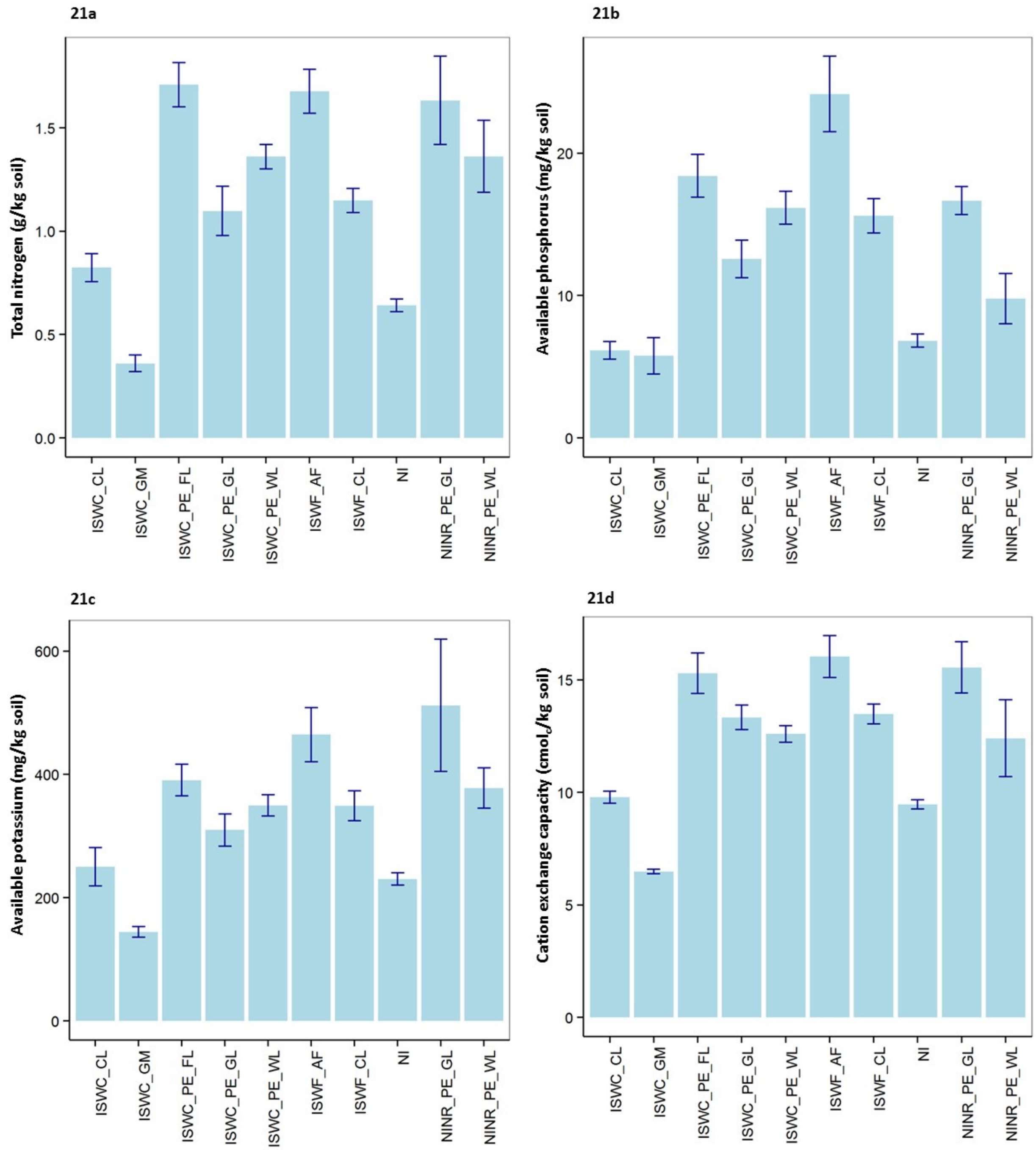

Figure 21. Aggregated surface soil fertility co-benefits (21a, total nitrogen; 21b, available phosphorus, 21c, available potassium; and 21d, cation exchange capacity) under no intervention (NI) and PSNP's integrated watershed management interventions in PSNP watersheds in Ethiopia.

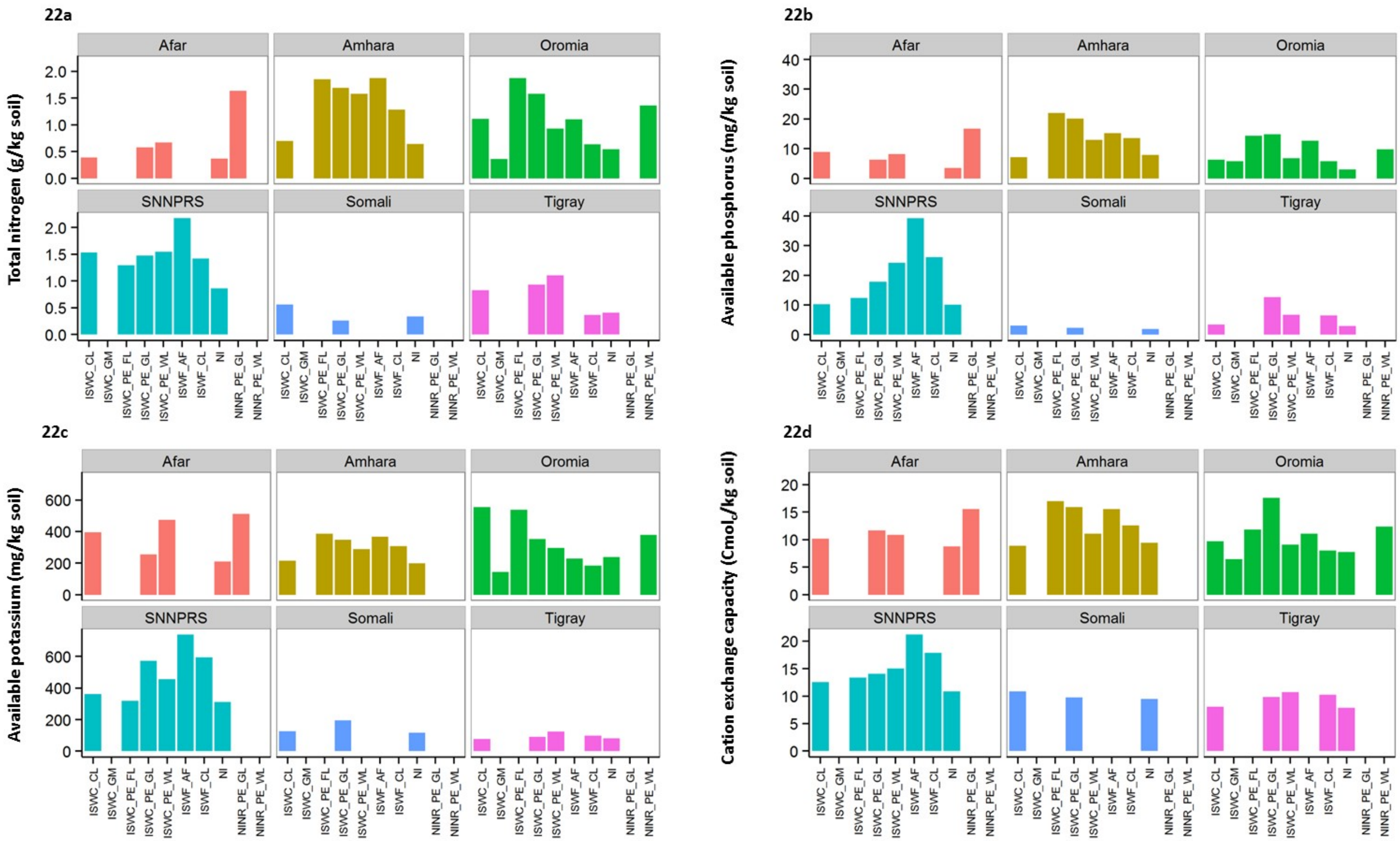

Figure 22. Breakdown by region of surface soil fertility co-benefits (22a, total nitrogen; 22b, available phosphorus, 22c, available potassium; and 22d, cation exchange capacity) under no intervention (NI) and under PSNP's integrated watershed management interventions in six food insecure regional states of Ethiopia.

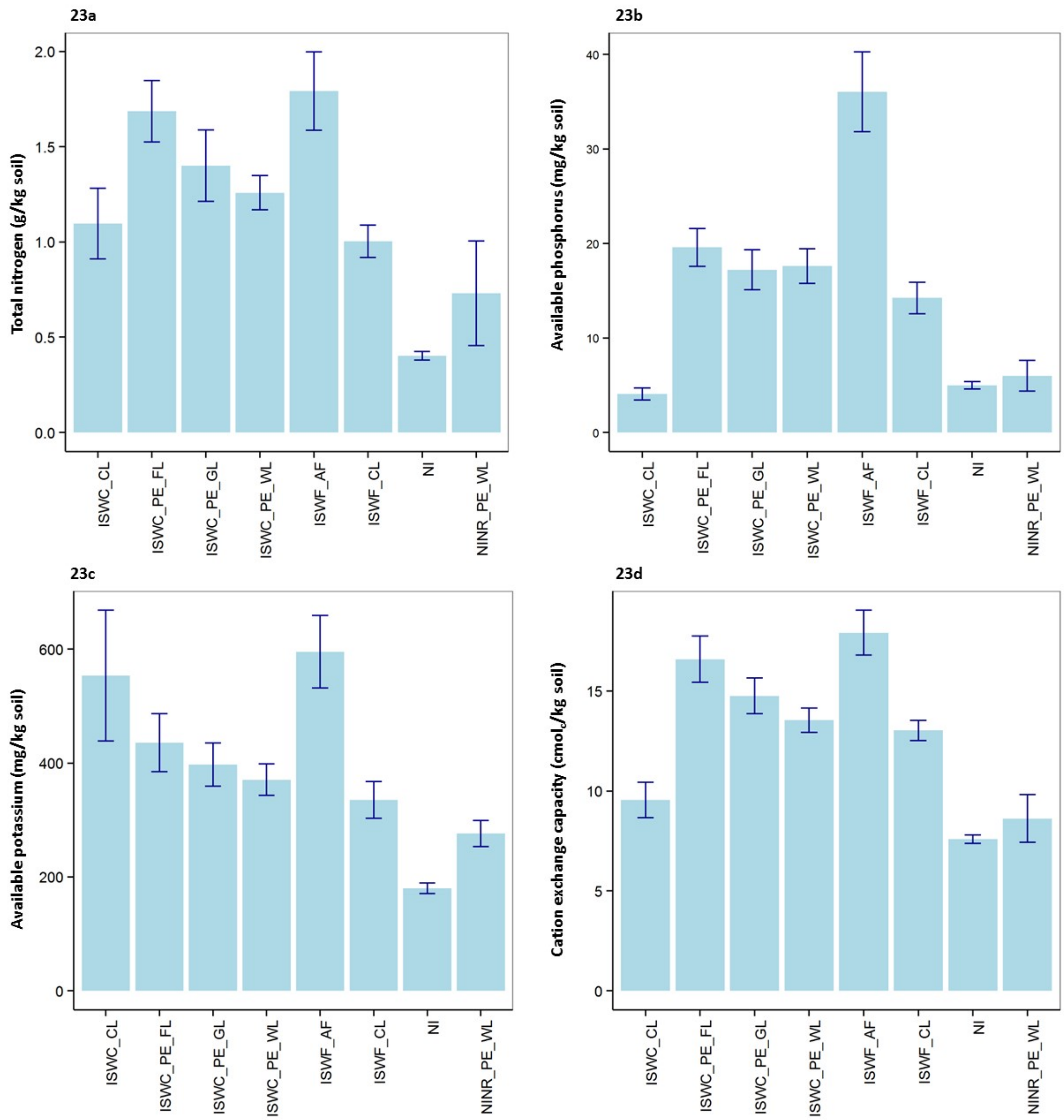

Figure 23. Aggregated deep profile (up to 100 cm) soil fertility co-benefits (23a, total nitrogen; 23b, available phosphorus, 23c, available potassium; and 23d, cation exchange capacity) under no intervention (NI) and PSNP's integrated watershed management interventions in PSNP watersheds in Ethiopia.

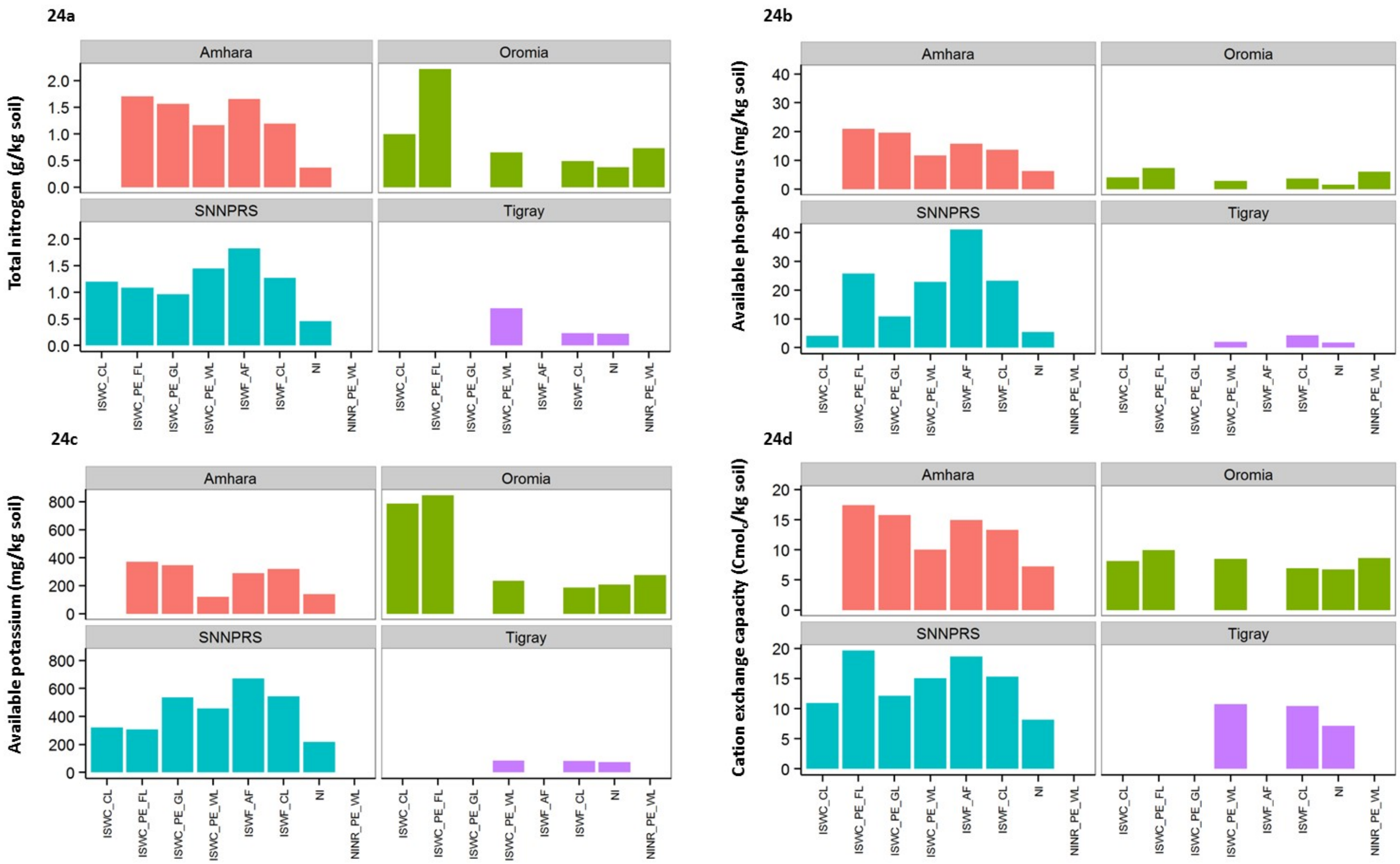

Figure 24. Breakdown of deep profile (up to 100 cm) soil fertility co-benefits (24a, total nitrogen; 24b, available phosphorus, 24c, available potassium; and 24d, cation exchange capacity) under no intervention (NI) and under PSNP's integrated watershed management interventions in six food insecure regional states of Ethiopia.

Aggregated results for croplands and agroforestry systems show that considerably higher surface (Figure 20a) and deep soil profile (Figure 20c) carbon stocks were observed in integrated soil and water conservation and soil fertility management interventions implemented in agroforestry (ISWF-AF, up to 1.3 times in surface soils and up to 3.8 times in deep soil profiles) followed by ISWF implemented in croplands (ISWF-CL, up to 0.7 times in the 0-15 cm surface soils and up to 2 times in 100 cm soil profiles), and integrated soil and water conservation measures implemented alone in croplands (ISWC-CL, up to 0.3 times in the surface soils and up to 1.8 times in soil profiles) compared to the corresponding amounts in the surface soil and deep soil profiles with no interventions (NI). With the exception of the Somalia region, the detailed surface (Figure 20b) and deep soil profile (Figure 20d) soil carbon data from Ethiopia's regional states support the above trend. Similarly, with the exception of available surface and soil profile phosphorus contents where there was no difference were found between the aggregated and regional breakdown data for the sites with no interventions (NI) and the cropland that received only integrated soil and water conservation measures (ISWF-CL), the overall trend in total nitrogen, available phosphorus, available potassium concentrations and the cation exchange capacity of the surface soil (Figure 21 and Figure 22) and the deep soil profiles (Figure 23 and Figure 24) also increased in the order: no interventions (NI) < integrated soil and water conservation measures implemented alone in croplands (ISWF-CL), ISWF implemented in croplands (ISWF-CL) > integrated soil and water conservation and soil fertility management interventions implemented in agroforestry (ISWF-AF).

Ethiopia's PSNP's soil carbon and fertility impact assessment show that integrated soil and water conservation (ISWC) measures implemented along with integrated soil fertility management (ISFM) interventions in agroforestry systems provided the highest surface and deep soil carbon sequestration and soil fertility co-benefits (e.g., larger total nitrogen, available phosphorus and available potassium concentrations and higher cation exchange capacity), followed by croplands managed by the combination of ISWC and ISFM and farm fields managed only by ISWC compared to the corresponding agricultural surface soils and deep soil profiles with no interventions (NI).

Our observation of the PSNP's CSI watersheds (Solomon et al., 2005) show that the agroforestry systems where integrated soil water conservation and soil fertility managements were implemented incorporate a number of nitrogen fixing leguminous crop plant species such as beans and peas etc. Similarly, the physical soil and water conservation measures in the agroforestry and croplands and were mostly stabilized with leguminous tree species. The main agricultural systems in most of the study areas is also dominated by smallholder farms practicing mixed crop and livestock production, and extensive amount of household and kitchen wastes along with semi-liquid livestock manure (the more solid part is usually used for fuel as manure cake) which mixed with cattle urine and bedding materials. These organic sources of carbon (both non-pyrogenic and pyrogenic carbon, the latter being among the most stable form of carbon resistant to decomposition) and plant nutrients such as nitrogen, sulfur and phosphorus, as well as inorganic salts and sources of plant nutrients potassium, calcium, magnesium etc., along with various microorganisms are available for use in most cases as direct organic amendments or ingredients of compost; and applied into homestead multistory agroforestry systems or on croplands closer to households. The higher soil organic carbon, plant nutrient content and nutrient retention and exchange capacity of soils under the agroforestry systems and in croplands where PSNP's integrated soil and water conservation coupled with integrated soil fertility management was implemented (Figure 20, Figure 21, Figure 22, Figure 23 and Figure 24) are possibly the combined the results of the physical and biological soil and water conservation measures that helped to decrease soil erosion, conserve water, and increase the vegetation and crop cover, as well as the incorporation of carbon and nutrients from the various organic and inorganic sources implemented as part of the integrated soil fertility management intervention measures. Agriculture is one of the high priority sectors where the impacts of climate change exceed tolerance limits with implications for the livelihoods of millions of smallholder farmers dependent on this sector (Sheikh et al., 2014). Agroforestry interventions, because of their ability to provide economic and environmental benefits, are considered to be the best “no regrets” measures in making communities adapt and become resilient to the impacts of climate change. Therefore, agroforestry systems when combined with soil and water conservation and other integrated soil fertility measures could have a direct near-term carbon storage capability in trees and soils, and have the potential to offset immediate greenhouse gas emissions associated with deforestation and conventional agriculture (Dixon, 1995). Agroforestry practices like alley cropping and silvopastures have been also shown to have the greatest potential for conserving and sequestering carbon because of the close interaction between crops, pasture, trees and soil (Nair, 1998). Similar results were reported by Demelash and Stahr (2010) for carbon, phosphorus and cation exchange capacity of surface and deep soil profile samples collected from micro-watersheds under integrated soil and water conservation practice compared to soils from control sites in Ethiopia. Million (2003) also found the mean total nitrogen content of terraced site with the original slope of 15, 25 and 35% were higher by 26, 34 and 14%, respectively, compared to the average total nitrogen contents of their corresponding non-terraced sloping lands. Terraced area with original slope of 25 and 35% were also found to have mean CEC value of 6 and 49%, respectively, higher than the average CEC of the corresponding non-terraced slope. Demelash and Stahr (2010) suggested that accelerated soil erosion which is primarily caused by unsustainable land use practices is the main cause of such soil fertility and soil carbon benefits decline in the majority of Ethiopia's croplands.

Overall, Ethiopia's PSNP soil carbon and fertility impact assessment show that the ongoing agricultural land degradation in Ethiopia's food insecure regions clearly require a scaled action to continue introducing the current innovative participatory watershed management interventions into the country's croplands, and the integration of these climate-smart land management practices with more sustainable framing practices such as agroforest systems in manner similar to the ones introduced by PSNP to reduce erosion, significantly enhance soil carbon stock and other soil fertility co-benefits to rehabilitate and boost the productivity of Ethiopia's degraded agricultural lands. The results especially highlighted the potentials of integrating physical and biological soil and water conservation measures with integrated soil fertility management interventions that involve the use of non-competitive direct agricultural and household residues, manure and cattle bedding materials, as well as applications of compost prepared from household and agricultural waste-stream (including wastes that contain pyrogenic carbon sources) in multipurpose and multistory agroforestry systems and croplands where the highest increases in soil carbon stocks, and thereby climate change mitigation potential among the investigated agricultural management systems. However, in situations where such measures are not practical to implement in highly degraded croplands because of lack of organic residues or the sheer size the watershed to implement soil and water conservation along with integrated soil fertility management interventions, the effective implementation of soil and water conservation interventions alone could provide more soil organic carbon accrual and soil fertility co-benefits in the agricultural soils of these food insecure regions of Ethiopia and could deliver significant climate change mitigation potential to support the country's climate resilient green economy (CRGE) and INDC, where up to 86% of the expected abatement potential is anticipated to come from the agriculture, forestry and other land use (AFOLU) sectors.

Forestry and other land use systems: - Land degradation, which is alternatively defines as the decline of the biological or economic productivity of land resources resulting from unsustainable land management practices has a strong impact on ecosystem services and co-benefits (MEA, 2003). Land use and land cover changes from one system (e.g., undisturbed natural frosts or grasslands) to another (e.g. overgrazed and highly degraded grasslands or agricultural fields) can impair ecosystem services and co-benefits through excessive de-vegetation and vegetation degradation, deterioration of soil structure, loss of soil organic carbon and organisms, and soil contamination (Mekuria, 2013; Falkowski et al., 2000). As part of the efforts to restore degraded ecosystems, enhance availability of animal feed, improve soil carbon and health and other ecosystem services and co-benefits in the forestry and other land use sectors of the food insecure parts of the country, Ethiopia's PSNP established permanent area enclosures in six most vulnerable regional states of the country. These permanent enclosure or simply called area closures are areas within the PSNP watersheds closed to humans and domestic grazing animals with the goal of promoting natural or assisted regeneration of plants and other biodiversity, and reducing land degradation of formerly degraded grasslands (grassland permanent enclosures with integrated soil and water conservation measures, ISWC-PE-GL), woodlands (woodland permanent enclosures with integrated soil and water conservation measures, ISWC-PE-WL) and forestlands (forestland permanent enclosures with integrated soil and water conservation measures, ISWC-PE-FL). Although not exclusively, they are usually established in steep, eroded, and degraded and marginal areas of the watershed for agriculture along with integrated soil and water conservation measures or in some cases without such interventions (e.g., no intervention grassland permanent enclosures with unassisted natural regeneration (NINR-PE-GL) and no intervention woodland permanent enclosures with unassisted natural regeneration (NINR-PE-WL)). Ethiopia's PSNP soil carbon and fertility impact assessment evaluated the changes in soil carbon stocks and other soil fertility co-benefits in the managed and unmanaged area closures by comparing them with sites that received no intervention (NI).

The surface (Figure 20a) and deep soil profile (Figure 20c) carbon content values from the permanent enclosures show that soil carbon stocks increased in the order: no interventions (NI) < woodland permanent enclosures with integrated soil and water conservation measures (ISWC-PE-WL) ≤ grassland permanent enclosures with integrated soil and water conservation measures (ISWC-PE-GL) < forestland permanent enclosures with integrated soil and water conservation measures (ISWC-PE-FL). Figure 20c show that the soil carbon stocks in forestland permanent enclosures with integrated soil and water conservation are in fact up to 1.8 and 4 times higher in the surface (0-15 cm) and deep soil profiles (0-100 cm), when compared with the surface and deep soil profile carbon stocks of the degraded sites with no interventions (NI), respectively. The surface and deep soil profile carbon stocks of the CSI watersheds in the grassland and woodland permanent enclosures with integrated soil and water conservation measures are also 0.7 and 3 and 0.9 and 2 times larger than the surface and deep profile carbon stocks of the no intervention sites (NI), respectively. Besides what is interesting in this investigation is the fact that surface and deep soil profile soil carbon stocks in grassland (NINR-PE-GL) and woodland (NINR-PE-WL) ecosystems doubled as a result of the introduction of permanent enclosures with unassisted natural regeneration implemented without integrated soil and water conservation measures when compared to the corresponding amounts obtained from the surface and deep soil profiles of grassland and woodland without any form of interventions (NI). The lowest carbon stocks were found in the surface soils of severely degraded gullies recently rehabilitated with integrated soil and water conservation measures. The influence of permanent enclosures with or without soil and water conservation measures on the macronutrient content, as well as on the soils ability to retain and exchange plant nutrients were also clearly visible both from the aggregated soil and deep soil profile results shown in Figure 21 to 24. According to Figure 21 and 23 largest increase in the surface soil total nitrogen, available phosphorus and potassium concentrations, as well as the cation exchange capacity of soils under permanent enclosures with assisted natural regeneration were observed under forestland with soil and water conservation measures (ISWC-PE-FL) followed by woodland with soil and water conservation measures (ISWC-PE-WL) and under grassland area closures with soil and water conservation measures (ISWC-PE-GL). However, higher concentrations of total nitrogen, available phosphorus and potassium, and cation exchange capacity were also observed in surface soils of watersheds where area closure and unassisted natural regeneration was implemented in grasslands without soil and water conservation measures (NINR-PE-GL) compared to woodlands (NINR-PE-WL) that received similar treatments (Figure 21 and Figure 23).

Permanent forest, grassland and woodland enclosures implemented preferably with assisted regeneration and along with integrated soil and water conservation (ISWC) measures as part of Ethiopia's PSNP have significant positive impact in improving the surface and deep soil carbon stocks, soil nutrient contents, and the soils' capacity to hold and exchange plant nutrients among other soil fertility co-benefits, and could help to rehabilitate, increases vegetation cover, productivity and biodiversity of the highly degraded forest, grassland and woodland ecosystems to combat ecological deterioration and support the livelihoods of the (agro)pastoralist and pastoralist communities in the country's food insecure regions. Therefore, these approaches in scaled-up manner should be considered as among the various socio-economically viable and environmentally sustainable options available to Ethiopia PSNP to mobilize the local communities to enhance ecosystem services and co-benefits such as soil and aboveground carbon sequestration and climate change mitigation potential, restoration of soil fertility, health and productivity, and restoration and improvement of the vegetation composition, species diversity and richness of the ecosystem, as well as the livelihood of the resource-poor rural communities living in these highly degraded and food insecure parts of the country.

Similar to the deep soil profile carbon stocks, higher concentrations of total nitrogen, available phosphorus and potassium, and higher values of cation exchange capacity were found in forestland area closures with soil and water conservation measures (ISWC-PE-FL) followed by grassland area closures with soil and water conservation measures (ISWC-PE-GL) and woodland area closures with soil and water conservation measures (ISWC-PE-WL) when compared with the corresponding amounts obtained in the deep soil profiles with no interventions (NI). Mekuria, et al. (2010) and Mekuria (2013) demonstrated that permanent area enclosures are among the viable options for restoring degraded soils and vegetation, and in almost all cases such intervention lead to higher soil and above-ground carbon stocks and soil fertility co-befits in northern Ethiopia. Similar trends were reported from case studies conducted in the semi-arid lowlands of Ethiopia (Abebe et al., 2006; Angassa and Oba, 2010). Permanent area enclosures in combination with integrated soil and water conservation measures have been also widely used in Asia to combat ecological deterioration caused by land degradation and rehabilitate degraded ecosystems. These approaches have been showed to increases vegetation cover, biodiversity, soil fertility and water conservation capacity, and even improvements in the herders' livelihoods (Pei et al., 2008; Shang et al., 2008; Wu et al., 2010). Smit et al. (1999), Angassa and Oba (2010) and Mekuria (2013) reported substantial increase in ecosystem carbon sequestration with increased maturity of the area enclosures in southern Africa, southern lowlands of Ethiopia and in the norther highlands of Ethiopia, and suggested that the age of enclosure has significant role in influencing restoration of soil carbon and soil fertility co-benefits. Overall, the results of the present study confirm that establishment of permanent enclosures with or without assisted regeneration along with integrated soil and water conservation measures on highly degraded PSNP watersheds in Ethiopia's food insecure regions have a positive effect in improving surface and deep soil profile carbon stocks, soil nutrient contents and the soils' capacity to hold and exchange plant nutrients among other edaphic parameters. Therefore, these integrated watershed management approach should be considered as among the various viable socio-economically and environmentally sustainable options available to Ethiopia PSNP to mobilize the local communities in the efforts to enhance soil and aboveground carbon sequestration, improving ecosystem services and co-benefits such as soil and aboveground carbon sequestration and climate change mitigation potential, restoration of soil fertility, health and productivity, and restoration of vegetation composition and improvement of species diversity and richness of the ecosystem, as well as the livelihood of the resource-poor rural communities living in these highly degraded and food insecure parts of the country. Our study also show that the positive changes in soil carbon stocks and the various soil fertility co-benefits following the establishment of permanent enclosures with or without integrated soil and water conservation measures can be effectively explained by using easily measurable soil-management related biological, physical and chemical ecosystem and soil health co-benefits indicators (the details of which is discussed both in the current report and also in the national baseline database in Solomon et al., 2015) in the investigated PSNP watersheds. Mekuria (2013) indicated that such information is necessary for establishment of baseline information for carbon sequestration projects, for evaluation of whether community-based participatory permanganate enclosures establishment should be encouraged and also expanded, as well as for development practitioners, land managers and for policy makers to take into account the value of implementing area enclosures with assisted or unassisted natural regeneration and integrated soil and water conservation measures with as part of their participatory integrated watershed management decision making process. Our results show that consideration of enclosures as by quantifying climate mitigation (and environmental, social) and ecosystem services and benefits of such land use interventions projects, and thereby generating financial compensation from climate financing or payments for ecosystem services and benefits to support the local communities in their effort to sustainably restore degraded lands might be a way to increase benefits for local communities. The findings of the present study provide important information for local decision makers, which might enhance the establishment and management of enclosures that are ecologically sound, economically profitable, and widely accepted by the local communities in Ethiopia's six food insure regions where PSNP's participatory integrated watershed interventions are currently being implemented.

3.4 Mid infrared (MIR) spectroscopy-based cost-effective approaches to measure soil carbon stocks and soil fertility co-benefits in Ethiopia's PSNP watershed

Ethiopia's CSI was assigned to evaluate the soil carbon and soil fertility co-benefits of PSNP's participatory integrated watershed management intervention projects, an effort which also aims to build the livelihood of the food insecure population and enhance the societal and (agro) ecosystem rehabilitation efforts of the country, and support Ethiopia's transition towards low-carbon, climate-resilient growth and development. The initiative also aimed to establish geospatially-referenced database in the selected CSI watersheds to lay the foundation for Ethiopia's PSNP to recognize the location of emissions reduction or sequestration activities for the MRV of such activities in order to secure climate finance and payments for ecosystem services and benefits generated as a result of the implementation of PSNP's participatory integrated watershed management projects. It is expected that these efforts will incentivize the rural community living in the project watershed among other things to protect the exiting project and enhance sustainability, improve implementation and increase scale for stakeholders to see appreciable reductions in GHG emissions and a return on their investment.

Soil is an integral component of Ethiopia's PSNP land-based climate-smart food security initiative. It provides a number of essential ecosystem services and benefits, and its health is critical for the foundation for all (agro)ecosystems, and for sustainable food production and livelihoods of communities living on these ecosystems in Ethiopia's food insecure regions. Soil provides the physical support system for plants and retains and delivers macro and micro nutrients to plants growing in these regions. Heathy soil can hold and release water, providing flood and erosion control. It is the medium through which nutrients like nitrogen, phosphorous, and potassium are continually exchanged in the ecosystem, and is a critical participant in hydrological and biogeochemical cycling of water and elements, respectively. In fact healthy soil, aided by complex macro and micro flora and fauna activities, is expected to continuously maintain its fertility. Soil have also great potential to mitigate the effects of anthropogenic climate change through carbon sequestration (Brussaard, 1997; Lal, 2004; Millennium Ecosystem Assessment, 2005). Adoption of a restorative landscape-level participatory integrated watershed management interventions in degraded PSNP watersheds and ecosystems, as well as judicious management of agricultural soils via integrated soil and water conservation and integrated soils fertility measures could be considered as an important strategy for enhancing soil carbon sinking capacity of degraded ecosystems and agricultural soils, respectively, and for reducing the rate of enrichment of atmospheric CO_2 while having positive impacts on reduction in siltation of waterways and reservoirs, water availability and quality, food security, and on the sustainability environment (Lal, 2004; Woolf et al 2015; Jirka et al., 2015). Soil fertility of (agro)ecosystems could, however, be threatened by erosion, loss of nutrients, overgrazing, and deforestation among other factors as a result of the unsustainable agricultural practices implemented in the various CSI watersheds under business-as-usual scenarios .Carbon emissions from the various PSNP watersheds and ecosystems could also be exacerbated by the rampant soil degradation and catastrophic-level soil cover and fertility loss observed in Ethiopia's six regional states. These place sustainable food production and supplies, as well as the carbon sinking potential and other ecosystem co-benefits of the soils at unacceptable risk, and results in increased vulnerability threatening the livelihoods of the resource-poor PSNP rural households.

Although the role of soil in serving as a sink for atmospheric CO_2 and providing ecosystem co-benefits has been documented and discussed, gaps still exist in terms of operationalizing the monitoring and quantification of these climate and ecosystem services across diverse environments (Bello et al., 2010; Dominati et al., 2010). Historically, understanding of the soil and assessment of its quality and contribution to well-functioning ecosystems, agricultural productivity and its potential to mitigate climate change have been gained through routine standardized soil chemical, physical and biological laboratory analytical techniques (Vågen et al., 2010). Vagen et al (2010) indicated that soil chemical and physical information is needed on sustainable land management to give advice for growers, extension agents, development practitioners and land managers. This is especially true in developing countries, where soil diagnostic surveillance systems have been proposed to overcome data shortages (Shepherd and Walsh, 2007). Shepherd and Walsh (2002) indicated that these conventional assessments of the soils capacity to perform production, environmental and climate related functions rely on local calibration of observations on soil functional capacity to soil properties measured by conventional standardized laboratory techniques. However, measuring soil physical, chemical and biological properties using standardized laboratory methods is laborious, and expensive. The effective understanding of the drivers of change and the metrics of soil productivity and health across diverse landscapes and ecosystems often also requires intense sampling, handling and processing of the samples to adequately characterize spatial variability of an area, making broad-scale and cost-effective quantitative evaluation of the soils' potential to mitigate climate change, and its contribution to (agro)ecological and societal resilience a very long and time-consuming process (Dhawale et al., 2015).

Viscarra Rossel et al. (2006) indicated that diffuse reflectance spectroscopy (i.e., visible-VIS [400–700 nm], near infrared-NIR [700–2500 nm], and mid infrared-MIR [2500–25,000 nm]) provides a good complementary alternative that can be used to augment conventional methods of soil analysis, as it overcomes some of their limitations. Spectroscopy is rapid, timely, less expensive, and non-destructive soil analytical approach than the conventional analysis. Furthermore, a single spectrum allows for simultaneous determination of numerous soil chemical, physical and biological properties, and it has a potential for adaption to be "on-the-go" field use using hand-held spectrometers. Moreover, spectroscopic techniques do not require expensive and time-consuming sample pre-processing or the use of (environmentally harmful) chemical extractants (Viscarra Rossel et al., 2006). Soil infrared spectral laboratory networks have also already developed a cost-conscious and effective prioritized modular approach to the soil standard reference measurements, where the number of subsamples for reference measurements are constrained among other things by available budget. For example the Africa Soil Information Service (AfSIS) technical specifications indicates that the reference analysis modules which will be used for calibration are implemented on a subsample of only about 10% of the total soil samples required for the implementation of a particular project (Vågen et al., 2010).

In a 2006 assessment of various soil properties, Viscarra Rossel et al. (2006) investigated the value of VIS, NIR, and MIR spectroscopic analysis and compared the simultaneous predictions of a number of different soil properties in each of these regions and the combined VIS–NIR–MIR values to determine whether the combined information produces better predictions of soil properties than each of the individual regions using partial least squares regression (PLSR, McCarty et al., 2002) techniques for spectral calibration and prediction. The soil properties examined were soil pH, lime requirement, organic carbon, clay, silt, sand, cation exchange capacity, exchangeable calcium, exchangeable aluminum, nitrate-nitrogen, available phosphorus, exchangeable potassium, and electrical conductivity. The results demonstrated that the MIR was more suitable than the VIS or NIR for this type of analysis due to the higher incidence spectral bands in this region as well as the higher intensity and specificity of the signal. The authors also indicated that quantitatively, the accuracy of PLSR predictions in each of the VIS, NIR, MIR and VIS–NIR–MIR spectral regions varied considerably amongst properties. However, more accurate predictions were obtained using the MIR for pH, lime requirement, organic carbon, clay, silt, sand, cation exchange capacity, available phosphorus, and electrical conductivity. Dunn et al (2002) MIR is judged to be superior than NIR for the prediction of soil properties because of the wavelength range it operates in is strongly related with the functional group's common in soil mineral and organic matter. Therefore, in Ethiopia's PSNP soil carbon and fertility impact assessment, MIR spectroscopy-based cost-effective approaches and the technical specifications developed by AfSIS were implemented to measure soil carbon stocks and soil fertility co-benefits from the soil samples collected from the country's six food insecure regional states.

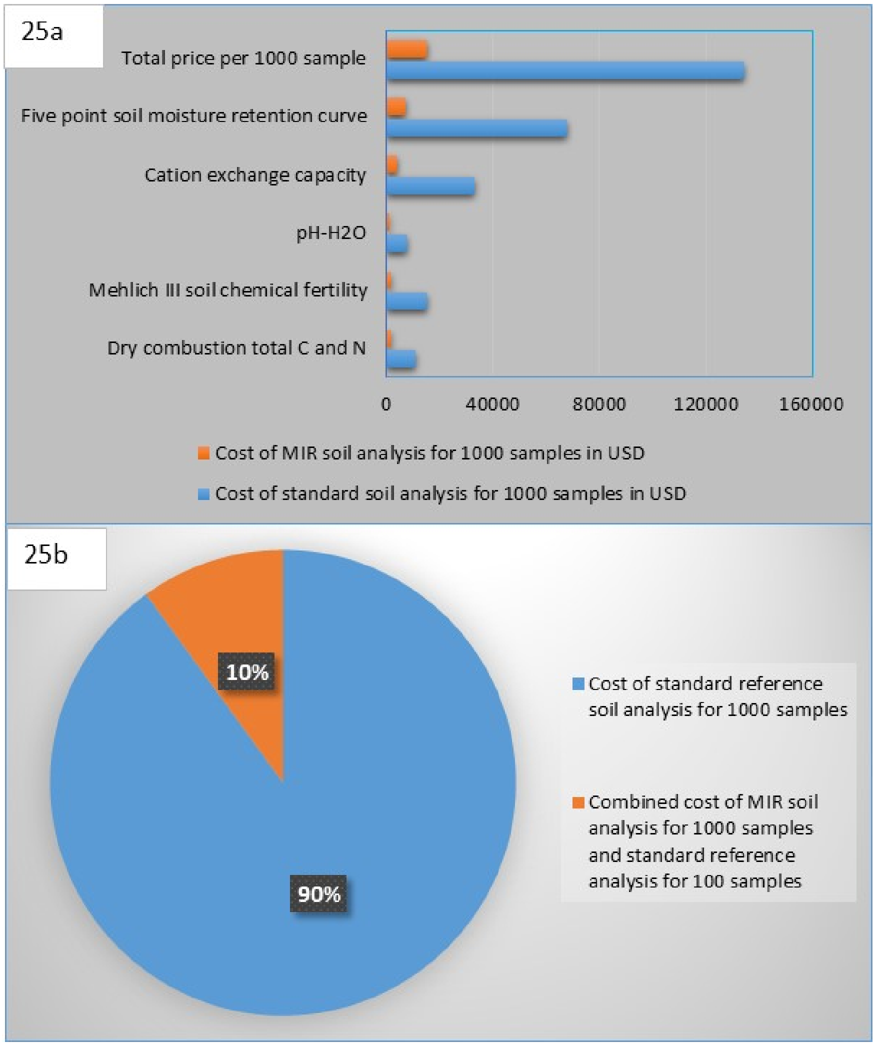

Figure 25. Cost breakdown for soil carbon and soil fertility co-benefits analysis of 1000 soil samples using standard soil carbon and for soil physical and chemical characteristics analysis in the US and MIR spectroscopy soil carbon and co-benefits analysis at AfSIS. 25a represent cost breakdown in USD for the analysis of 100 soils samples using standard reference soil analysis and MIR, while 25b represent cost of standard reference soil analysis for 1000 soil samples and the combined cost of MIR soil analysis for 1000 soil samples and standard reference analysis for 100 soil samples as a percentage of the total cost. On-line published fees for dry combustion total carbon and nitrogen, Mehlich III soil chemical fertility, pH-H2O, cation exchange capacity, five point soil moisture retention curve for the 2015-2016 period from Cornell University's Nutrient Analysis Laboratory (CNAL) and Stable Isotope Laboratory (COIL) were used for the standard reference analysis cost calculation, while the fee for the MIR sample analyses was fixed at $1.50 per sample close to the per unit sample MIR soil analysis fee structure of AfSIS.

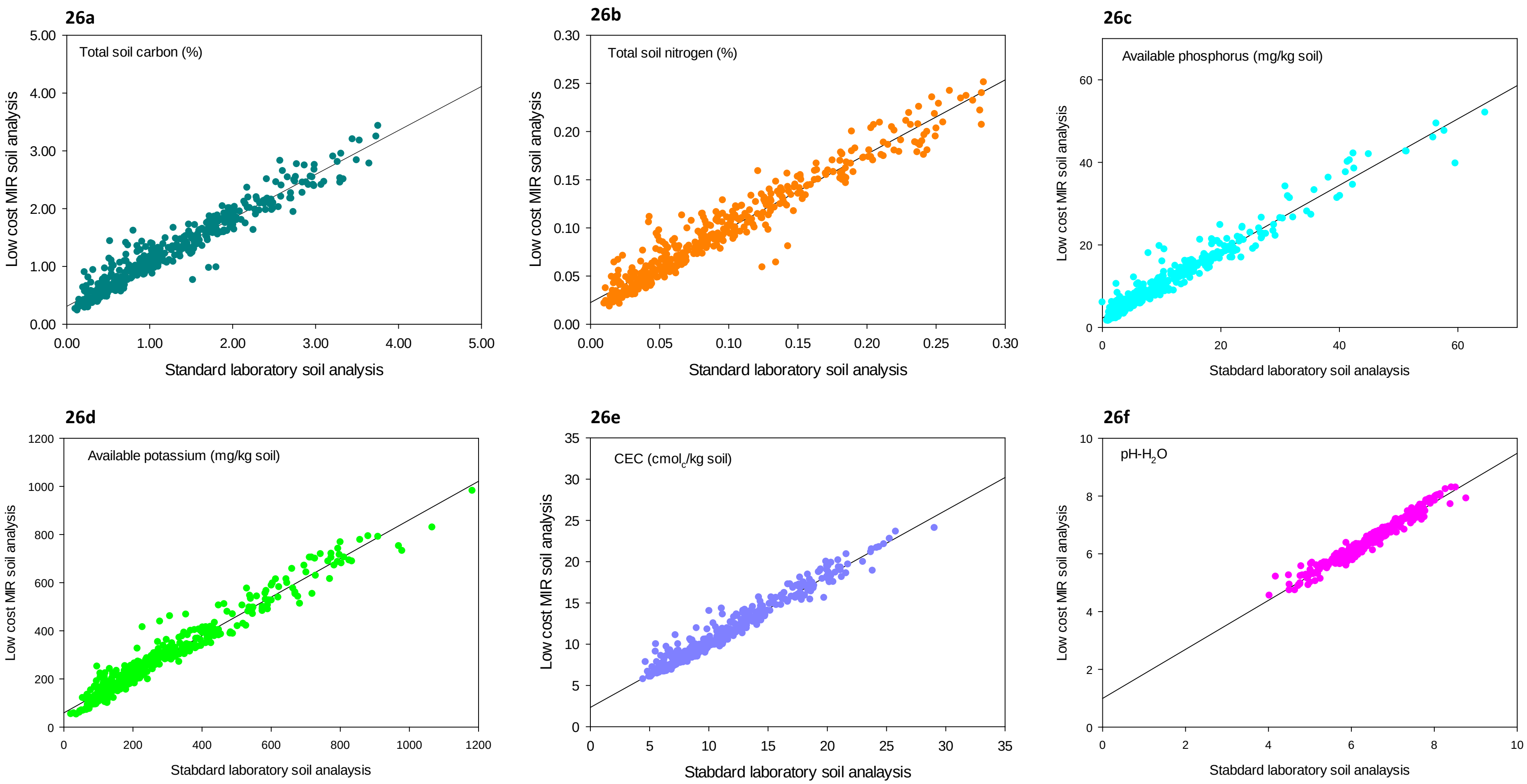

Figure 26. Linear regressions for the validation set (n = 627) of predicted values based on MIR spectroscopy against measured total soil carbon (26a) and other selected soil chemical fertility (26b, total soil nitrogen; 26 c, available phosphorus; 26d, available potassium; 26e, CEC; and 26f, pH-H2O) indicator results of samples collected from Ethiopia's six food insecure regional states PSNP watersheds.

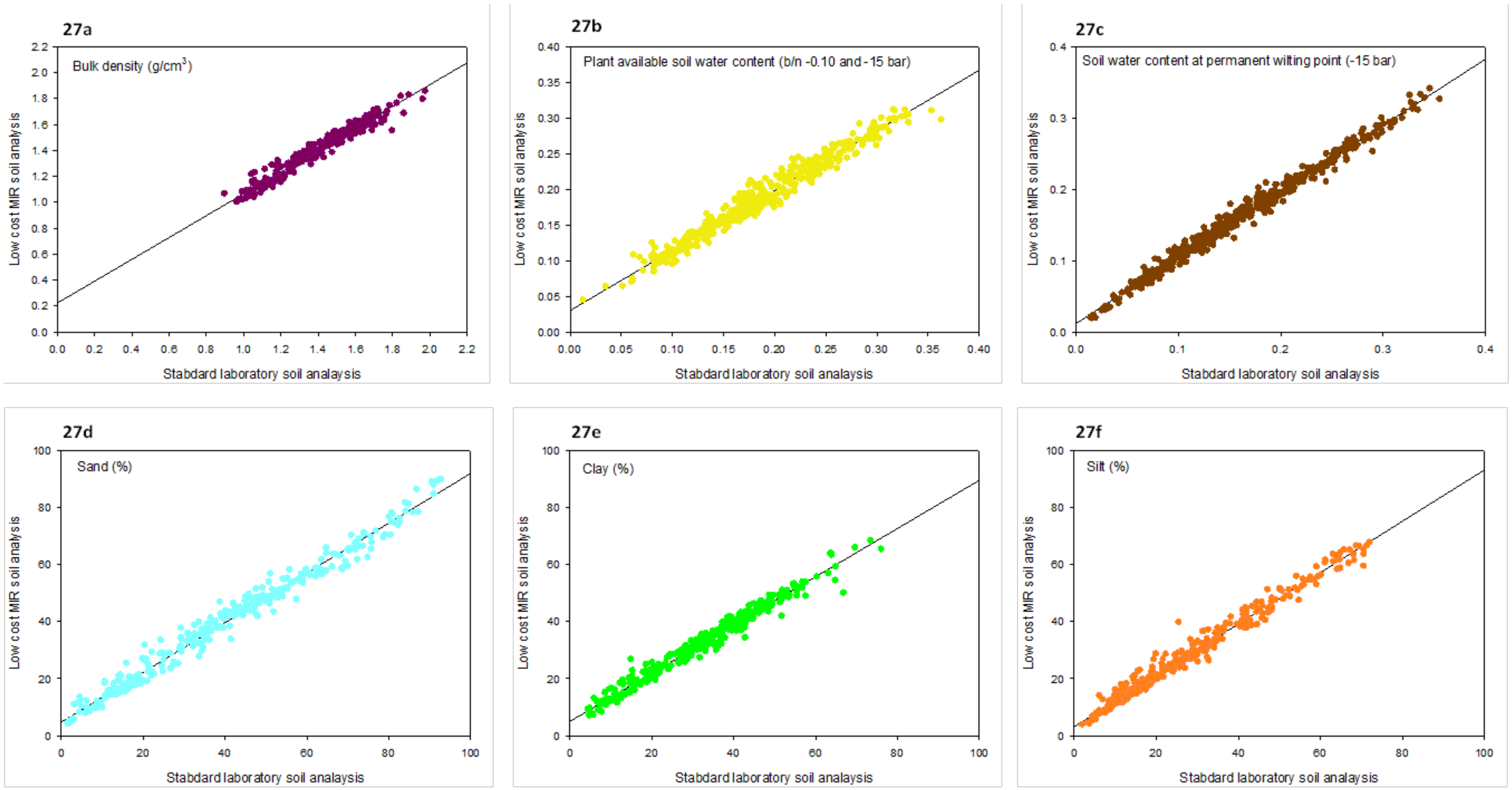

Figure 27. Linear regressions for the validation set (n = 627) of predicted values based on MIR spectroscopy against measured selected soil physical characteristic (27a, bulk density; 27b, soil water content at field capacity; 27c, moisture retention at 15bar; 27d, sand content; 27e, clay content; and 27f, silt content) results of samples collected from Ethiopia's six food insecure regional states PSNP watersheds.

The soil carbon stocks, nutrient contents, and other soil physical and chemical co-benefits were determined for all samples using predictions via mid-infrared Random Forest (RF) regression model-based analysis calibrated to the data collected directly from analysis of soil carbon using dry combustion and other standard soil wet-chemical and physical measurements as described in section 2.3 of this assessment. Unlike investigations that use PLSR, the calibration and prediction of soil carbon and other soil properties for all soil samples were conducted using MIR-Random Forest (RF) regression model-based analysis to the all data collected directly from standard reference analysis of soil carbon and other soil physical, chemical and biological characteristics. Despite the recommended reference analysis modules which requires only 10% standard soil subsample analysis for calibration Ethiopia's PSNP MIR RF predictions were generated from direct standard analyses of 436 samples (69%) of the total 628 samples. The application of RF ensemble models in soil science is a relatively recent phenomenon (Grimm et al., 2008; Vågen et al., 2016). However, it has been effectively demonstrated to have potential to be a powerful approach that can significantly improve the prediction of soil functional properties and mapping of land degradation prevalence in Ethiopia (Vågen et al., 2013) and in general in Africa (Hengl et al., 2015). According to Figure 25, the combined cost for soil MIR RF calibration and predictions of 1000 samples is only 10% of the total cost required for standard soil carbon and soil fertility co-benefits analysis of 100 samples, suggesting that MIR spectroscopy soil carbon and co-benefits analysis at its current AfSIS's cost structure could be a great option for cost-effective rapid geospatially explicit landscape level soil carbon stocks and soil fertility co-benefits measurement approach in Ethiopia's PSNP watershed.

As described in the description of Ethiopia's PSNP CSI study sites (section 2.1 of this report), the sampling sites from Ethiopia's six food insecure regions represent a wide range of soils and biophysical conditions. However, similar to previous investigations of East African soils by other researchers (Winowiecki et al., 2016) MIR spectroscopy-based cost-effective approaches overall provided a satisfactory prediction of the soil carbon and other soil characteristics (Figure 26 and Figure 27) implemented to assess the soil fertility co-benefits Ethiopia's PSNP integrated watershed interventions. According to Figure 26a, the linear regression for the validation set (n = 627) of predicted total soil carbon values based on MIR spectroscopy against soil total soil carbon results measured using standard reference technique was very good ($r^2 = 0.93$) indicating a good fit and performance of the cost-effective approach when applied to the test datasets. Winowiecki et al. (2016) also reported r^2 value > 0.95 for the prediction of soil organic carbon in a study conducted to quantify soil organic carbon stocks across Tanzania and assess the effect of land cover and erosion on soil organic carbon under diverse land uses, and indicated that MIR spectroscopy-based approaches produced over all a good fit for investigations involving the relationship between inherent and dynamic soil properties under diverse land uses. Similar results were also reported by Terhoeven-Urselmans et al. (2010), Viscarra Rossel et al. (2006) and by Amare et al. (2013) for diverse validation set of soil samples selected from the International Soil Reference and Information Centre, Australia and for samples collected for prediction of soil organic carbon from Ethiopian highlands, respectively. This is also consistent with the results of a number of previous MIR spectroscopy-based studies

for soils from various parts of the world including eastern and southern Africa (e.g., Ben-Dor and Banin, 1995; Brown et al., 2006; Shepherd and Walsh, 2002).
Nitrogen, available phosphorus, and available potassium are the most important nutrition element for crops, and the rapid and non-destructive detection. However, research detecting available phosphorus and potassium based on infrared spectroscopy is scarce (Shao and He, 2011). Earlier research on these elements by Krischenko et al. (1991) obtained determination coefficients (r^2) of 0.42 and 0.84 for P and K, respectively. However, Chang and Laird (2002) reported a determination coefficient of >0.86 for total N in soils by NIR, and the results were deemed very satisfactory. Similarly, in more recent investigation using infrared spectroscopy to analyze soil nitrogen, phosphorus and potassium Shao and He (2011) reported much higher correlation coefficients of 0.83, 0.85 and 0.85 for these three important plant nutrient elements, respectively. This work demonstrated the potential of infrared spectroscopy for more efficient soil analysis of these important plant nutrients and the acquisition of soil information. The linear regression for the validation set (n = 627) of predicted total nitrogen (r^2 = 0.94, Figure 26b), available phosphorus (r^2 = 0.95, Figure 26c) and available potassium (r^2 = 0.96, Figure 26d) values based on MIR spectroscopy against the soil test results of these essential plant nutrient elements measured using standard reference technique were very satisfactory.

Soil pH is a measure of soil acidity or alkalinity. It is an important soil chemical characteristics and indicator of soil health. It impacts nutrient availability, productivity and critical biological processes which influence key soil processes. The pH of a soil is regulated by a variety of soil forming factors such as parent material, climate, time, topography, and soil organisms, as well as mineral content and texture and management. Soil pH or proton activity is not expected to have a direct spectral response, but has still been more or less well predicted in several cases (Stenberg et al., 2010). Chang et al. (2001) suggested that this was due to co-variation to spectrally active soil constituents such as organic matter and clay. In fact r^2 values at the country or state scale ranging between 0.55 and 0.77 indicate the existence of fairly general correlations to vis–NIR spectra (Stenberg et al., 2010). Likewise, CEC is a measure of the soil's ability to hold positively charged ions. It is a very important inherent soil property and significantly influences the soil's ability to hold onto essential nutrients influencing nutrient availability, soil pH since it provides a buffer against soil acidification and it also affects the soil's reaction to fertilizers and other ameliorants (Hazleton and Murphy 2007). CEC is in turn related to the clay fraction and organic matter content. Cation exchange properties of soil clay systems are a function of permanent and pH dependent surface charge. Soils with a higher clay fraction generally tend to have a higher CEC. Similarly, soils with high organic matter and thus high soil carbon content have a very high CEC, since organic matter has a very high cation exchange capacity. According to Figure 26e and Figure 26f, the regression for the validation set (n = 627) of predicted CEC (r^2 = 0.96) and pH (r2 = 0.96) values of MIR spectroscopy against the soil CEC and pH results measured using standard reference technique were with a very high level of accuracy. Minasny et al (2009) demonstrated that these two soil chemical properties i.e., soil pH (r^2 = 0.90) and CEC (r^2 = 0.96) can be predicted accurately with MIR spectroscopy in tropical soils. These authors concluded that MIR spectroscopy provide rapid, inexpensive and relatively accurate predictions for a number of soil properties.

MIR-spectroscopy is a non-destructive analytical tool that preserves the integrity of the soil system while analyzing several soil properties simultaneously. Compared to the conventional standardized laboratory techniques-based assessments, it clearly provide a rapid and cost-effective analysis of soil carbon, and other soil chemical and physical characteristics of large number of samples collected from various agricultural, forestry, pastureland and other land use systems. It is appropriate to region, scale and varying landscapes and land use types of Ethiopia's PSNP. The technique enable rapid but effective assessment, monitoring and reporting of carbon stock changes and other climate smart co-benefits as a result of the implementation of safety net public works projects in food-insecure regions of the country. This makes it very attractive complementary option to Ethiopia's PSNP to: (i) develop downscaled geospatially-referenced soil-based baseline database, (ii) to conduct fast and reliable broad spatial scale assessment, monitoring and reporting of soil carbon sequestration activities, and (iii) for assessing soil fertility and health, land degradation and other soil-related ecosystem services and co-benefits in PSNP watersheds to understand the soils' s ability to perform production, environmental and climate related functions, as well as to support the country's effort to secure climate finance and payments for ecosystem services and benefits generated as a result of the implementation of PSNP's participatory integrated watershed management projects.

Infrared spectroscopy is based on the transitions in the vibrational and rotational states of a molecule (Minasny et al., 2008). It can detect the absorbance or reflectance of organic bonds and mineral components. For soil samples, the absorbance of infrared bands is determined by the soil's surface and solid composition, and thus many chemical properties such as carbon content and CEC can be predicted well (Janik et al., 1998; Minasny et al., 2008). Similarly, soil physical properties, which are related to the surface area and solid composition such as texture, clay content, air-dry moisture content and specific surface area, can also be predicted (Minasny et al., 2008). These authors suggested that soil physical properties that are partly based on pore-space relationships such as bulk density, water retention and hydraulic conductivity may not be predicted well using MIR spectroscopy. However, in a review paper by Shepherd and Walsh (2007) stated that infrared spectroscopy can predict such soil physical characteristics, since these properties are related to their clay content and biochemical composition. However, under certain conditions bulk density can be predicted as it is strongly related to the interactions between clay, sand, organic materials, depth and structural conditions of the soil. Terhoeven-Urselmans et al. (2010) further indicated that that such soil properties could be predicted either by direct absorption of the light associated with functional groups (properties such as organic carbon, total nitrogen or clay composition or by correlation to such properties and the mineral composition of the soil (properties such as CEC, bulk density etc.).

Soil water properties vary widely with texture, organic matter content and other soil components, but as discussed in the report, measurements are often time consuming and expensive to determine using traditional laboratory methods. Janik et al. (2007) stated that MIR spectroscopy is sensitive to soil composition, allowing multivariate calibrations to be derived between volumetric soil water retention and MIR spectra. In a 2007 study conducted to develop rapid prediction of soil water using MIR spectroscopy for broad variety of soils from southern Australia, these authors reported cross validation produced coefficient of determination values ranging from 0.67 to 0.87 for laboratory-determined volumetric water retentions at matric suctions from 1 to 15bar and values predicted by MIR PLS analysis. Soil organic matter, clay and sand content, as well as bulk density have been described as the most important soil properties to predict the water retention at field capacity and wilting point, although soil organic matter content has been shown to be of some importance. The results in Figure 27a, Figure 27b and Figure 27c show that the cost-effective MIR spectroscopy approach resulted in good prediction for the validation set (n = 627) of soil bulk density, plant available soil water content and soil water content at permanent wilting point with coefficient of determination of $r^2 = 0.96$, $r^2 = 0.97$ and $r^2 = 0.98$, respectively. These results are in line with the results Dalal and Henry (1986) who reported considerably good predictions for soil profile samples from Queensland, Australia.

Stenberg et al. (2010) indicated that when it comes to soil texture, most focus has been on clay content because it has a large influence on structure by promoting the formation of soil aggregates and its swelling and shrinking properties forming cracks. Water dynamics and aeration in soil are highly dependent on texture and structure and the latter are therefore important for plant growth both directly, but also through the regulation of microorganisms – the engine in decomposition and nutrient cycling processes. These authors indicated that there are also environmental aspects, as structure influences the risk of nutrient and pesticide leaching (Stenberg et al., 2010). Although clay is defined as particles smaller than 2 mm, clay particles mainly consist of clay minerals. Therefore the influence of mineralogy on infrared spectroscopy can be assumed to be a valuable feature for predictions of clay content. Hence, compared with calibrations for sand and silt content, those for clay usually perform well over large geographical regions (Chang et al., 2001; Shepherd and Walsh, 2002; Stenberg et al., 2010). MIR responds to quartz in the fingerprint region of the spectrum and it is expect that sand predictions would perform better after exclusion of specular reflection. Unlike clay were the important wavebands are concentrated in the mineral regions of the spectrum, however, the important wavebands for sand and may be to silt (which is mostly a micro-sand particle coated with clay) were distributed across the entire spectrum, suggesting that prediction was indirect (Terhoeven-Urselmans et al., 2010). These authors reported strong predictions for clay for particle size separates (r^2 = 0.73), while their prediction for sand (r^2 = 0.64).was much lower that clay. However, in the present investigation the linear regression for the validation set (n = 627) of the predicted sand, clay and silt values based on MIR spectroscopy against sand, clay and silt content results measured using standard reference technique provided also most similar results (r2 = 0.98 for sand, r2 = 0.97 for clay and r2 = 0.98 for silt) for these three particle size separates.). Our results are broadly similar to those of previous researchers where the prediction for sand and silt are very close or in some case better performing than for clay.

Overall the results show that MIR-spectroscopy is a non-destructive analytical tool that preserves the integrity of the soil system while analyzing several soil properties simultaneously. Compared to the conventional standardized laboratory techniques-based assessments, MIR-spectroscopy clearly provide a rapid and cost-effective analysis of soil carbon, and other soil chemical and physical characteristics of large number of samples collected from various agricultural, forestry, pastureland and other land use systems. This makes it very attractive option to Ethiopia's CSI to (i) develop downscaled geospatially-referenced soil-based baseline database, (ii) to conduct fast and reliable broad spatial scale MRV of soil carbon sequestration activities, and (iii) for assessing soil fertility and health, land degradation and other soil-related ecosystem services and co-benefits in PSNP watersheds to understand the soils' s ability to perform production, environmental and climate related functions as well as to support the country's effort to secure climate finance and payments for ecosystem services and benefits generated as a result of the implementation of PSNP's participatory integrated watershed management projects.
Expanding CSI's current soil sampling effort to the remaining PSNP watersheds in the food insecure regions of Ethiopia, measuring soil carbon and other physical and chemical characteristics using standard analysis to cover 10-20% to develop a more robust calibration for PSNP as a whole and measuring all soil samples from Ethiopia's remaining PSNP watersheds using with MIR-spectroscopy is expected to provide more effective understanding of the drivers of soil carbon and fertility losses and land degradation. It will also facilitate the development of strong geospatially-referenced soil baseline database, as well as allow the better understanding of the metrics of soil carbon sequestration, soil productivity and health assessment across diverse landscapes and ecosystems across PSNP's watersheds, making broad-scale and cost-effective quantitative evaluation of the soils' potential to sequester carbon and mitigate climate change to support the country's CRGE and INDC, where up to 86% of the expected abatement is expected to come from the agriculture, forestry and other land use (AFOLU) sectors, and its contribution to (agro)ecological and societal resilience following implementation of PSNP's land-based climate smart food security interventions in Ethiopia's six food insecure regional states.

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5 Bibliography of related project documents

Further details about the national soil carbon and fertility co-benefits data, climate change mitigation potential and climate financing opportunities and guidelines on how to prepare climate finance projects for PSNP can be found in the following related project documents:

Jirka S, Woolf D, Solomon D and Lehmann J. 2015. Climate finance and carbon markets for Ethiopia's Productive Safety Net Programme (PSNP): Executive Summary for Policymakers. A World Bank Climate Smart Initiative (CSI) Report. Cornell University. https://ecommons.cornell.edu/handle/1813/41302

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6 Annex

6.1 Annex 1 results of plant growth bioassay on soils collected from PSNP watersheds

The plant growth potential of soils is best measured by actual plant growth (bioassay) on selected soils. A comparison of soil chemistry and bioassay results then allows the prediction of plant growth from soils for which chemical data only are available. Plant bioassays are recommended by AfSIS for benchmarking relative productivity of soils without added ameliorant and comparative quantitation across soils of responses to nutrient inputs (Vågen et al., 2010). It is usually conducted using pot studies a useful tool to supplement field testing for diagnosis of plant nutrient deficiencies and development of soil fertility management recommendations. As part of Ethiopia's PSNP soil carbon and fertility impact assessment, surface soil samples (0-15 cm) were collected from the business-as-usual and various PSNP integrated watershed intervention sites in the Amhara (Tach Gayent, Sefed Amba and Simada), Oromia (Daro Lebu), SNNPRS (Godaye-Damot Gale), and Tigray (Ahferom) regional states for the purpose of conducting plant growth bioassay. Greenhouse trials were conducted to assess the productivity of these soils under the control and project scenarios at Jimma University, Ethiopia.

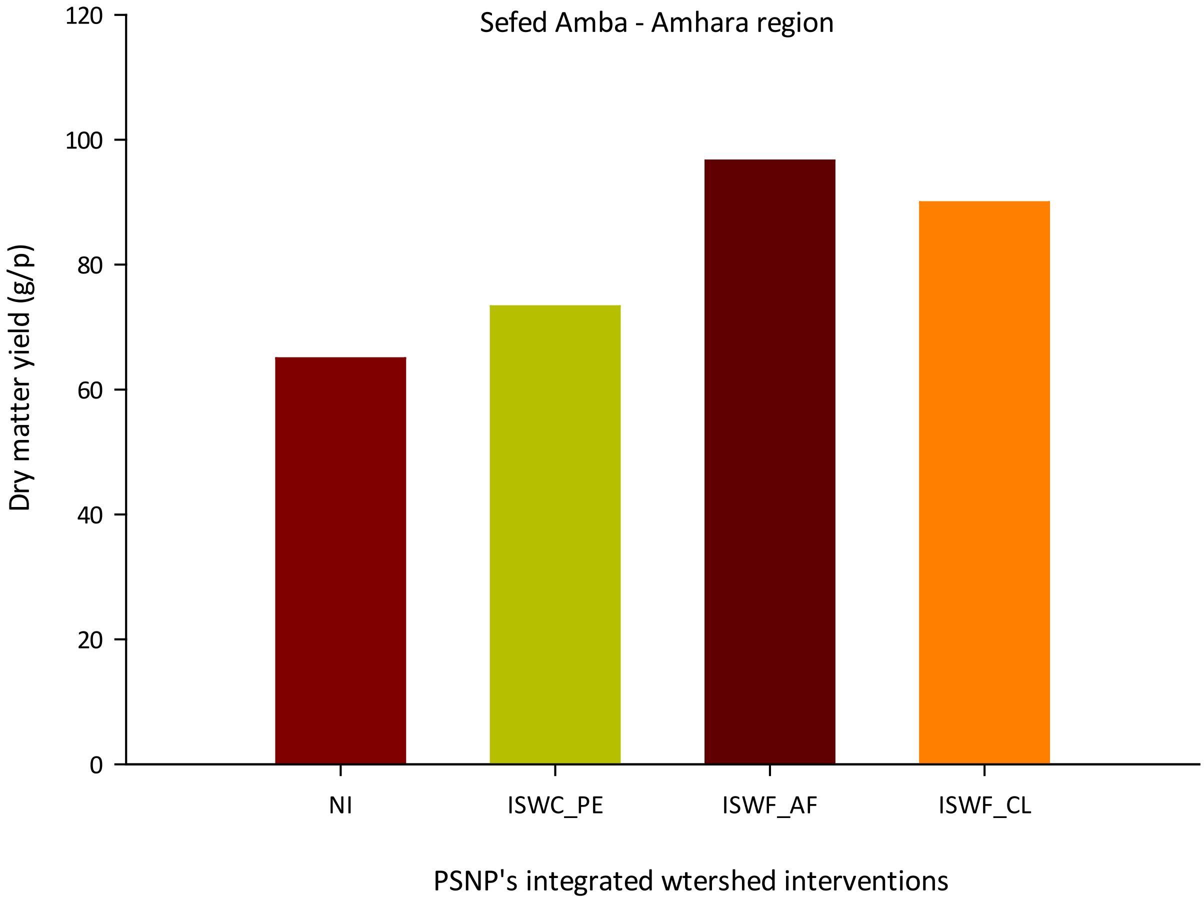

Figure 28. Plant bioassay results from greenhouse trials of surface soil samples collected from PSNP's Sefed Amba watershed in Amhara regional state of Ethiopia.

Treatments:

NI: *No intervention*

ISWC_PE: Integrated soil and water conservation implemented in five years old permanent enclosures with cut and carry system

ISWF_AF: Integrated soil and water conservation and integrated soil fertility measures implemented in five years old multistory agroforestry systems

ISWF_CL: Integrated soil and water conservation and integrated soil fertility measures implemented in five years old cereal crop-based cropland

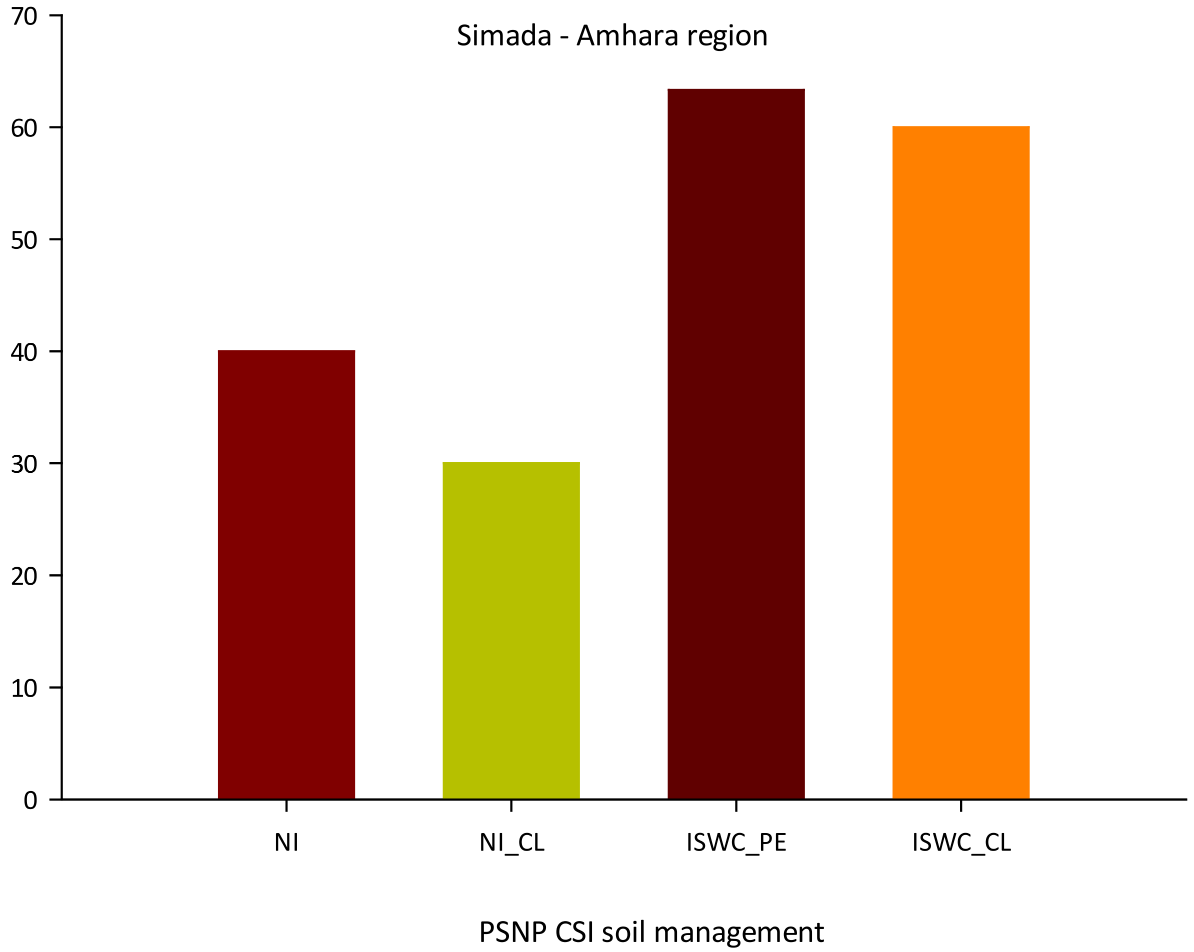

Figure 29. Plant bioassay results from greenhouse trials of surface soil samples collected from PSNP's Simada watershed in Amhara regional state of Ethiopia.

Treatments:

NI: *No intervention*

NI_CL: *Cereal crop production without integrated soil and water conservation and soil fertility measures*

ISWC_PE: *Integrated soil and water conservation implemented in five years old permanent enclosures with cut and carry system*

ISWC_CL: *Integrated soil and water conservation measures implemented in five years old cereal crop-based cropland*

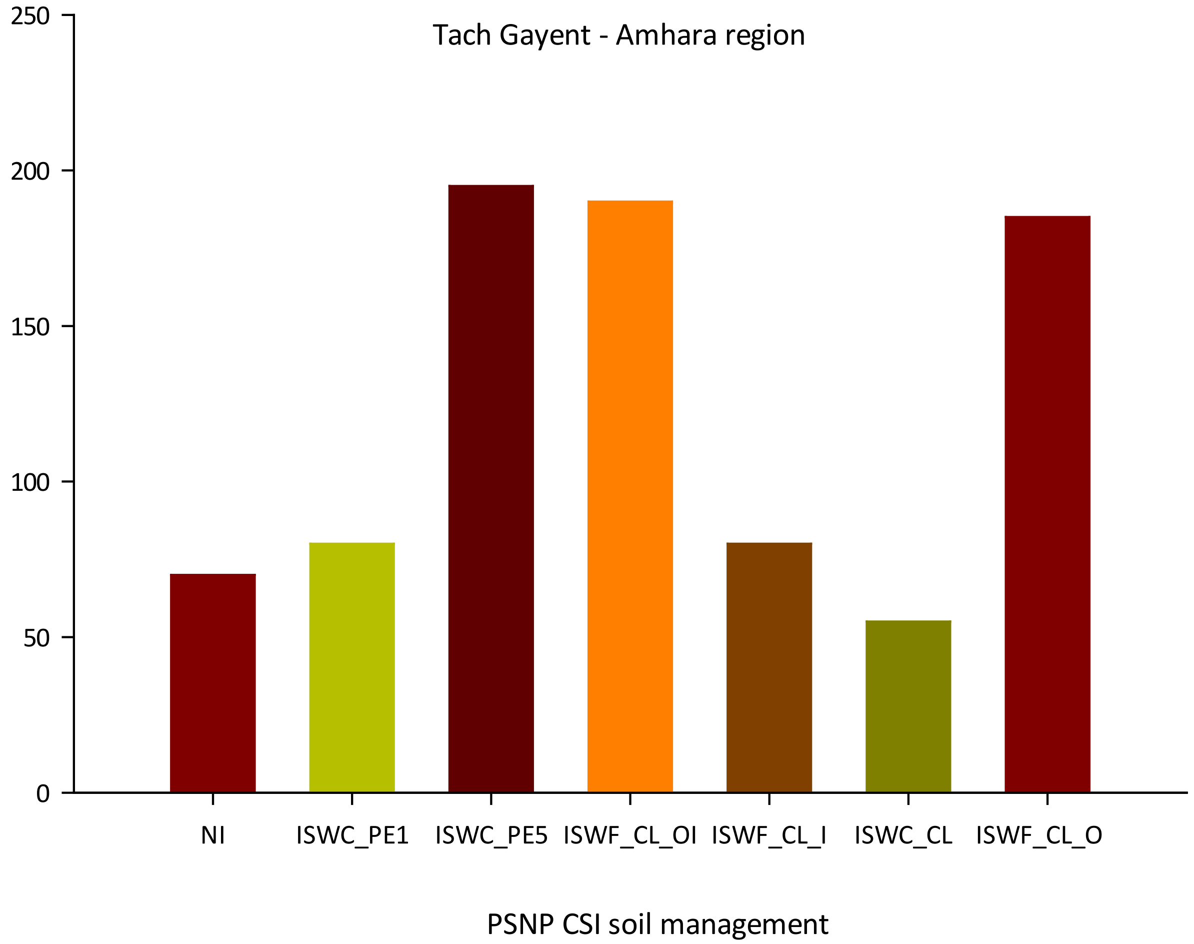

Figure 30. Plant bioassay results from greenhouse trials of surface soil samples collected from PSNP's Tach Gayent watershed in Amhara regional state of Ethiopia.

Treatments:

NI: *No intervention*

ISWC_PE1: *Integrated soil and water conservation implemented in one years old permanent enclosures with cut and carry system*

ISWC_PE5: *Integrated soil and water conservation implemented in five years old permanent enclosures with cut and carry system*

ISWF_CL_OI: *Integrated soil and water conservation and integrated soil fertility measures with a combination of organic and inorganic amendments implemented in five years old cereal crop-based cropland*

ISWF_CL_I: *Integrated soil and water conservation and integrated soil fertility measures with inorganic fertilizer amendment implemented in five years old cereal crop-based cropland*

ISWF_CL_ O: *Integrated soil and water conservation and integrated soil fertility measures with organic fertilizer amendments implemented in five years old cereal crop-based cropland*

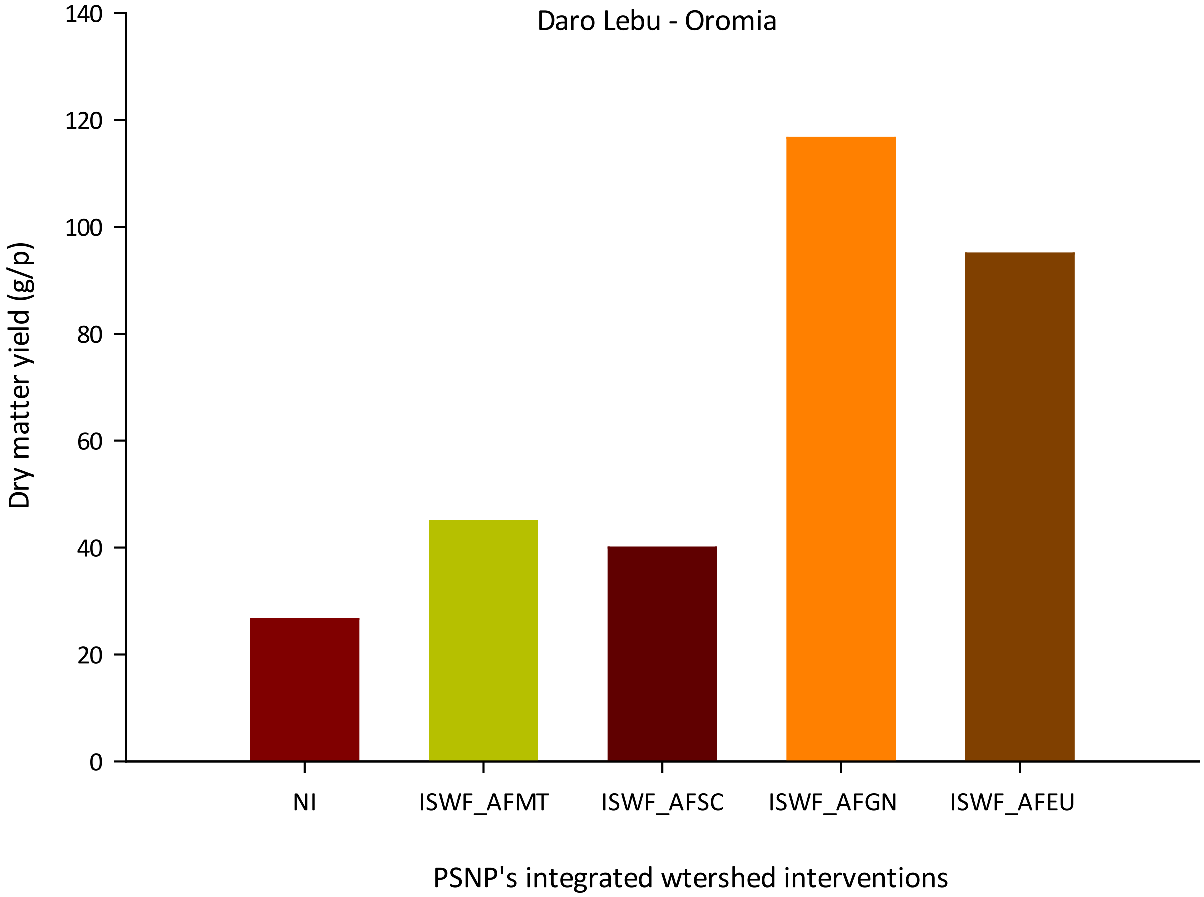

Figure 31. Plant bioassay results from greenhouse trials of surface soil samples collected from PSNP's Daro Lebu watershed in Oromia regional state of Ethiopia.

Treatments:

NI: *No intervention*

ISWC_AFMT: *Integrated soil and water conservation and integrated soil fertility measures implemented in seventeen years old multistory fruit and coffee-based agroforestry systems*

ISWC_AFSC: *Integrated soil and water conservation and integrated soil fertility measures implemented in seventeen years old sugarcane-based agroforestry systems*

ISWF_AFGN: *Integrated soil and water conservation and integrated soil fertility measures implemented in seventeen years old* Grevillea *and Neem tree-based agroforestry systems*

ISWF_AFEU: *Integrated soil and water conservation and integrated soil fertility measures implemented in seventeen years old Eucalyptus-dominated agroforestry systems*

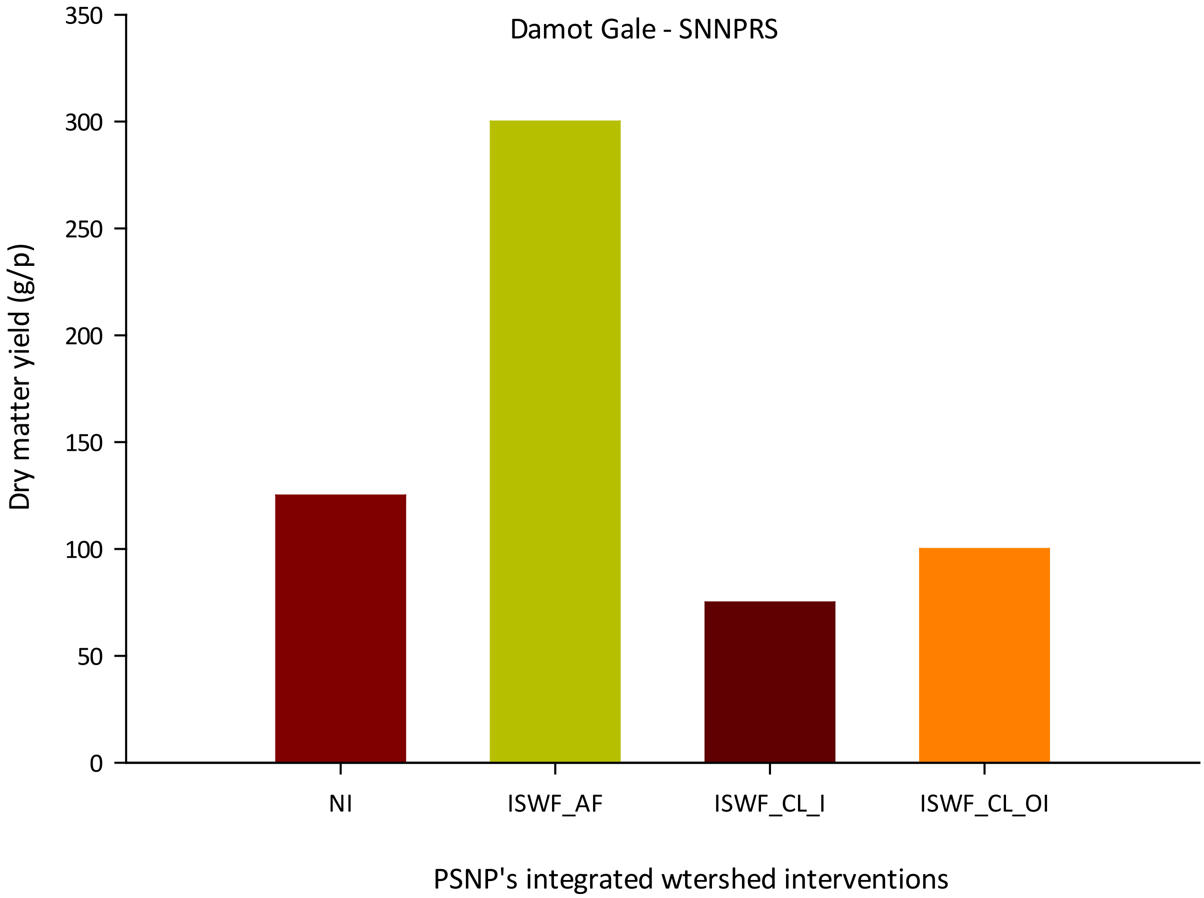

Figure 31. Plant bioassay results from greenhouse trials of surface soil samples collected from PSNP's Damot Gale watershed in SNNPR state of Ethiopia.

Treatments:

NI: *No intervention*

ISWC_AF: *Integrated soil and water conservation and integrated soil fertility measures implemented in twenty years old multistory fruit and coffee-based agroforestry systems*

ISWF_CL_I: *Integrated soil and water conservation and integrated soil fertility measures implemented with inorganic fertilizer amendments in twenty years old cereal-based croplands*

ISWF_CL_OI: *Integrated soil and water conservation and integrated soil fertility measures implemented with organic and inorganic fertilizer amendments in twenty years old cereal-based croplands*

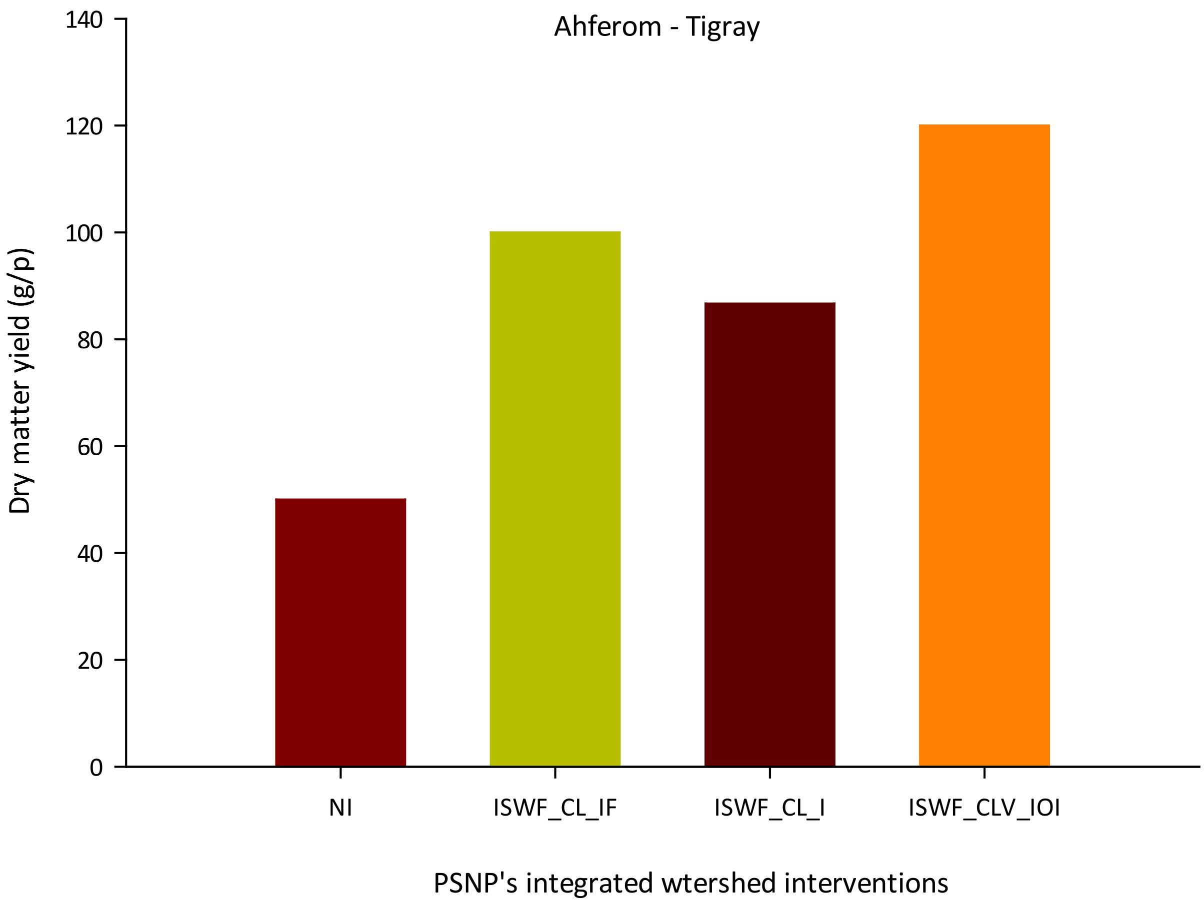

Figure 32. Plant bioassay results from greenhouse trials of surface soil samples collected from PSNP's Aheferom watershed in Tigray regional state of Ethiopia.

Treatments:

NI: *No intervention*

ISWC_CL_IF: *Integrated soil and water conservation and integrated soil fertility measures implemented with inorganic fertilizer amendments and bare-fallow in fifteen years old cereal-based croplands*

ISWC_CL_I: *Integrated soil and water conservation and integrated soil fertility measures implemented with inorganic fertilizer amendments in fifteen years old cereal-based croplands*

ISWC_CL_IF: *Integrated soil and water conservation and integrated soil fertility measures implemented with irrigation and inorganic and organic fertilizer amendments in fifteen years old in vegetable and cereal-rotation croplands*

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