Characterization of the Soil Physical and Chemical Properties of Metema Irrigation Research Station

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Abstract

Soils are affected by human activities, including agricultural activities, which often result in soil degradation. To prevent soil degradation and rehabilitate the potentials of degraded soils, a critical and detailed study of the description, characterization, and classification of the major soil types in a given area is important. Therefore, the soil physical and chemical properties were characterized based on the FAO 2006 manual at Metema irrigation station, which is one of the irrigation research stations of Gondar Agricultural Research Center. For laboratory analysis, three profiles were opened, described, and sampled from each generic horizon. Twenty-four soil profile samples and 10 PF (p of power, F of free energy of water) rings samples (core sampler) were collected for laboratory analysis. Soil observations on parallel fixed grids of 30 m apart were laid across the land, and auger observations were taken every 30 m along the grid line. The auguring was made staggered with "Edelman" auger to a depth of 1.20 m. The soil characterization result revealed that three mapping units such as Eutric Orthofluvic Fluvisols (Loamic), which are somewhat excessively drained soils that occur in the northern part of the research site along the Guang River, Pellic Vertisols (Hypereutric), which is poorly drained soils that occur in the southern part of the research site, and Pellic Vertisols (Hypereutric) which refer to well-drained soils that occur in the eastern part of the research site are identified in the research site. Generally, the dominant soils of the Metema Irrigation Research station are Vertisols and Fluvisols, which are very deep and less eroded. The major constraints are water-logging, poor workability, and depletion of nutrients, leading to low productivity. Therefore, soil and water management strategies that cope with these constraints should be identified further.

Keywords: *Fluvisols, generic horizon, soil characterization, soil profile, soil property*

Introduction

Soil is one of the vital land resources which is a basis for agricultural production; it influences crop suitability and choice of land utilization types. An increase in food production will require an integrating sustainable use of natural resources (Zelleke *et al*., 2010;United Nations, 2013). Soils are affected by human activities, such as industrial, municipal, and agriculture, which often result in soil degradation and loss or reduction in soil functions (Keesstra *et al*., 2016). The consequence tracks back to humans and nature; it affects yield reduction, forest degradation, and uncomfortable condition for micro-organisms (United Nations, 2013). Reliable soil data are the most prerequisite for the design of appropriate land-use systems, soil management practices (to rehabilitate degraded soils). Soil survey needs to understand the natural properties, dynamics, and function of soils (FAO, 2006). Thus, extensive soil surveys and investigations have to be carried out to meet the goal of sustainable agricultural production of an area. Accurate soil information about the current status of surface soil characteristics and soil factors is critical in achieving the goals of sustainable agriculture in the 21st century (Scherr & McNeely, 2008; United Nations, 2013).

Soil potential management and exploitation is based on the critical and detailed study of the description, characterization, and classification of the major soil types in a given area. It serves as the basis for soil classification, site evaluation, and interpretations of the genesis and environmental functions of the soil (FAO, 2006; Mesfin *et al*., 2017).

The assessment of soil suitability for different agriculture uses usually requires details on land resources inventory for the future crop management system. The soil studies of the Metema irrigation site were done during the Metema woreda soil study at a 1: 50,000 scale in 1995. However, taking into account the objective of the present study, it was carried out at a 1:2000 scale achieving a density of eleven auger hole observations per hectare (ha) as required under the terms of reference (TOR).

Objectives of the Study

The overall objective of the soil survey study is to provide detailed information on the soil of the Metema Irrigation Research Site for irrigated agricultural purposes. The specific objectives of the study were:

1. To investigate and identify different soil types of Metema Irrigation Research Station
2. To describe soils' physical and chemical characteristics
3. To map the distribution of the soil units at 1:2,000 scale, and
4. To identify constraints and potentials of major soils before development intervention.

Materials and Methods

Area description: Metema irrigation research site is located in Amhara National Regional State, West Gonder Administrative Zone in Metema Yohanes woreda, at about 47 km northwest of Genda Wuha town (on Gendawuha to Metema road and bifurcates to the North at 39 km). This irrigation research site lies in the Tekeze River Basin, and its geographic extent in UTM (WGS 84) ranges from 1433455 m to 1433710 m North latitude and 202922 m to 203355 m East longitudes. The lowest altitude is 680 meters above sea level, while its highest is 690 meters above sea level. A map showing the location of the Metema irrigation research site is provided in Figure 1.

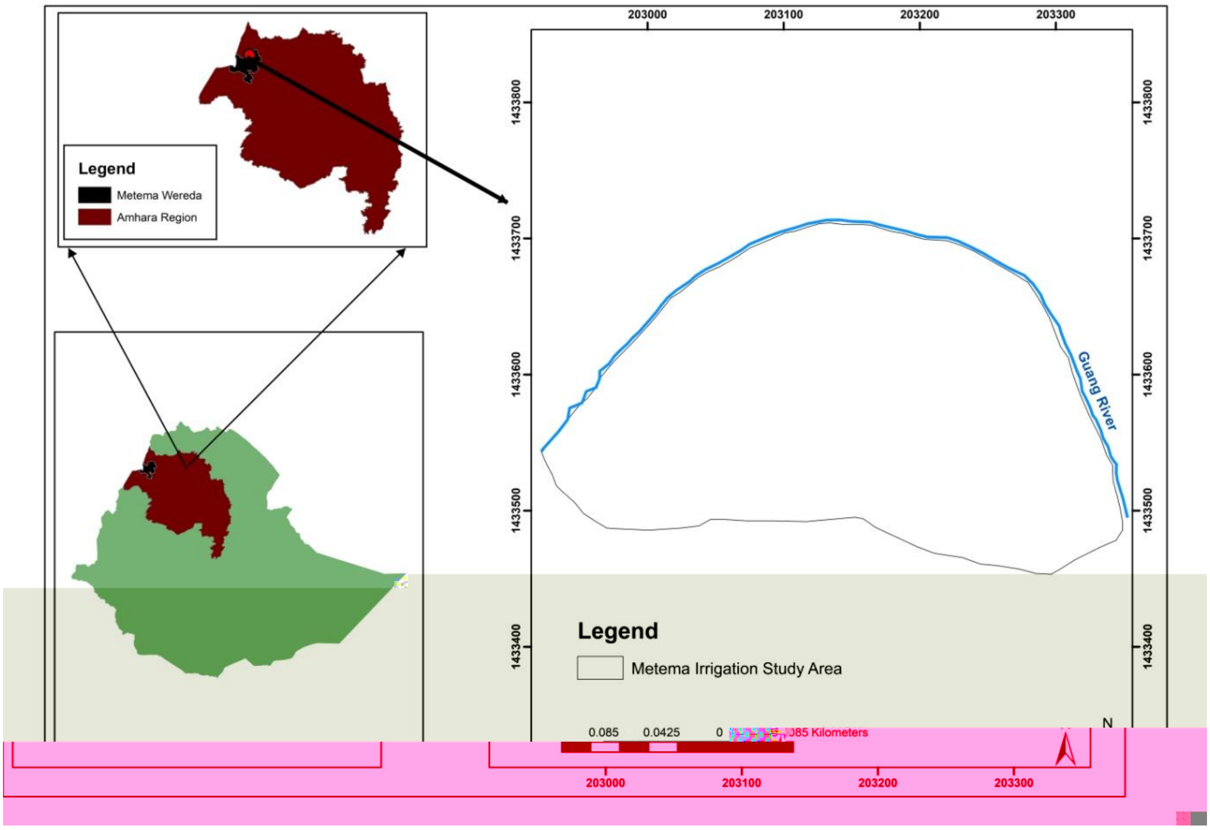

Figure 1. Location of Metema Irrigation Research Site

Climate: There is a meteorological recording station located in the close vicinity of the study area. The meteorological data were obtained from Ethiopia National Meteorological Agency (NMA) at Metema station. The meteorological parameters like monthly mean minimum and maximum temperature and mean annual rainfall is presented in annex 3a and 3b. According to the Ethiopia National Meteorological Agency (NMA) data records at Metema station (from 1997 to 2015), the annual rainfall ranges between 663mm to 1371mm with the mean annual value of 987.81mm. It has a uni-modal rainfall pattern where the rainy season is from June to September, during which 86.6% of the annual rainfall occurs (annex 3a). However, 25.5% of the mean annual rainfall occurs in August. It indicates that the area has an uneven distribution of rain that causes soil erosion in sloping topography. The mean monthly average rainfall records of the last 19 years are shown in Figure 2.

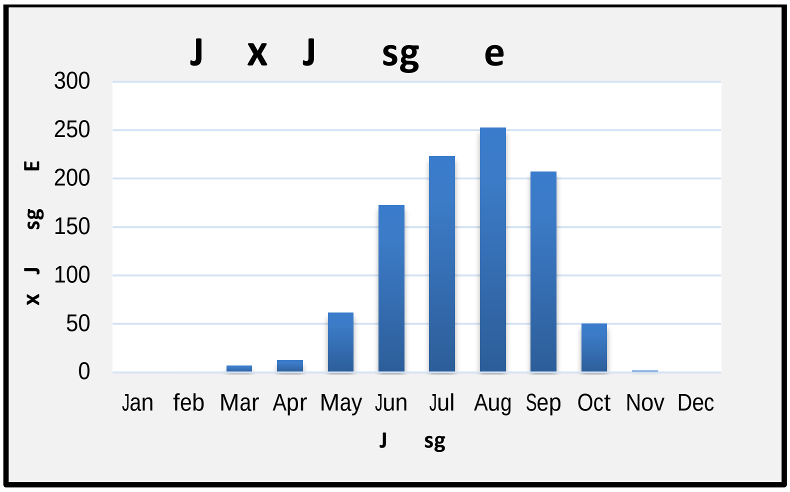

Figure 2. Mean monthly rainfall of the study area

The mean annual temperature is 27.25^{0}c, and the yearly mean minimum and maximum temperatures are 19.24^{0}c, and 35.25^{0}c, respectively (Annex 3b). August is the coldest month (24.83^{0}c), while March and April are the hottest (30.22 to 31.67^{0}c). According to the climatic classification developed in the Agroecological zones of Ethiopia, the study area falls in the category of warm sub-moist lowlands with a characteristic temperature of 24.83^{0}c 31.67^{0}c and length of growing 61-120 days. The altitude of the study area varies from 680 690 m.a.s.l. The slope of the land goes down towards the North.

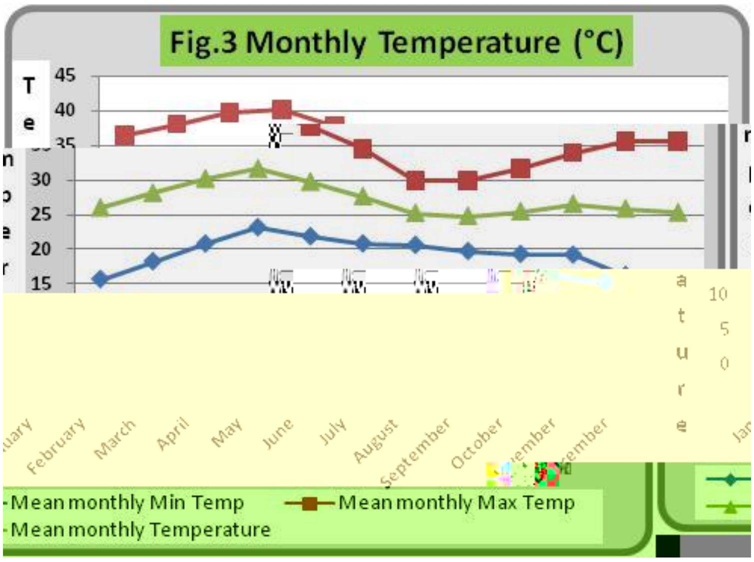

Figure 3. Mean minimum and maximum monthly temperature

Physiography and Geology: The Metema Irrigation Research Site has two physiographic units, ranging from very gently to gently sloping lowlands with a 1.5 to 3% slope. It has a relief difference with ree

rese30(a)-5(rc)7(h(si)-2(teis c)-3(ha)-5(ar)-2(e)4(tre)5hi)-11zee bgyqu(a)4(e)-6rnrary ag (ti)-3(a

ee54d( )199aeccing Munsel(m)11[(C)24o7o(h)186(C)24(ha145(tm)186(Muns(ulm)219(c)4o7o(,m)1 the study site were classified according to the World reference base for soil resources 2014 measured in the suspension of a 1:2.5, while the electrical conductivity was measured in a 1:5 soil to water ratio. Organic carbon was determined using the Walkley-Black oxidation method (Walkley & Black, 1934). Total nitrogen was determined by the micro-Kjeldahl digestion, distillation, and titration method (Bremner, 1960) and the available P was determined using the standard Olsen extraction method (Olsen et al., 1954). Total exchangeable bases were determined after leaching the soils with ammonium acetate (Reeuwijk, 2002). The concentrations of K^+, Na^+, Ca^{2+}, and Mg^{2+} in the leachate were analyzed by Ammonium Acetate leachate Solution. Cation exchange capacity was determined at a soil pH level of 7 after displacement by using the 1N ammonium acetate method (Schollenberger & Simon,). The available micronutrient contents of the soil were extracted by diethylenetriaminepentaacetic acid (DTPA) method (Tan, 1996) and concentrations were determined by Atomic Absorption Spectrometry (AAS).

Data Elaboration and Manipulation: All the data collected in the field survey and laboratory results have been entered into a database in Microsoft Excel for storage and data processing. The soil database consists of location and site description, soil horizon description, and soil physicochemical properties. To characterize properly the final soil-mapping units, the soil databases were checked and all the field observation points (profile pits and auger holes) were plotted in the digital map. All homogeneous observations within one mapping unit were used to characterize that specific mapping unit.

Soil Mapping Units and Classification: The field observation and laboratory data interpretation were carried out. The data was analyzed for various soil properties and the preliminary field soil mapping unit was reclassified accordingly. Location map of the different soil observation sites, detailed mapping units, and soil map digitized produced at the scale of 1:2,000 with an extended legend from the data collected during the field

depth, surface soil texture, and dominant soil type.

The soil mapping unit symbol (e.g., 2a11-FL-of.eu-lo) is explained as follows: The first Arabic number represents the slope class (2), the lower case letter (a) represents the soil depth class, the second Arabic number (11) represents the surface soil texture class, and the two upper case letters (FL) after hyphen represent soil reference group followed by lower case letters (of.eu-lo) principal and supplementary qualifiers, respectively. These symbols in combination form the soil mapping unit as per WRB 2014.

2a11-FL-of.eu-lo wherein,

- 2= slope class (1-2 % slope, very gently sloping)
- a= soil depth class (>150cm soil depth, very deep)
- 11= soil surface texture code (Sandy loam)
- FL= soil reference group (Fluvisols)
- of = principal qualifier (Orthofluvic)
- eu= principal qualifier (Eutric)
- lo= supplementary qualifier (Loamic)

Therefore, this soil mapping unit can be read as Eutric Orthofluvic Fluvisols (Loamic). The distinguishing criteria for each unit are stated in Table 1.

Table 1. Distinguishing criteria of the mapping unit

Slope %		Soil depth (cm)		Surface soil texture (0-30cm)		Dominate Soil Type	
Range	Code	Range	Code	Type	Code	2nd level classification	Description
0-1	1	>150	a	Heavy clay	1	Eutric Orthofluvic Fluvisols (Loamic)	2a11-FL-of.eu-lo
1-2	2	100-150	b	Clay	2	Pellic Vertisols (Hypereutric)	3a1-VR-pe-je
2-5	3	50-100	c	Silty clay	3		
5-10	4	30-50	d	Sandy clay	4		
10-15	5	<30	e	Silt	5		
15-30	6			Loam	6		
30-45	7			Clay loam	7		
45-60	8			Silty clay loam	8		
>60	9			Silty loam	9		
				Sandy clay loam	10		
				Sandy loam	11		
				Loamy sand	12		
				Sand	13		

Accordingly, three soil mapping units were identified in the project area (Table 2). The soil mapping unit and soil map of the project area are presented at 1:2,000 scale in Figure 5.

Table 2. Soil mapping units of Metema irrigation research site

Soil Mapping Unit	**Profile No.**	**Soil classification**		**Area**	
		1st level classification	**2nd level classification**	**ha**	**%**
2a11-FL-of.eu-lo	Gmp3	Fluvisols	Eutric Orthofluvic Fluvisols (Loamic)	3.34	44.95
3a1-VR-pe-je	Gmp1	Vertisols	Pellic Vertisols (Hypereutric)	2.30	30.96
3a2-VR-pe-je	Gmp2	Vertisols	Pellic Vertisols (Hypereutric)	1.79	24.09
			TOTAL	7.43	100

Results and Discussion

Physico-Chemical Characteristics of the Mapping Units

Three mapping units such as **2a11-FL-of.eu-lo**, **3a1-VR-pe-je, 3a2-VR-pe-je** were identified at the research site. The distribution of these soil units at the site is shown in Figure 5 and the soil units are characterized and mapped using different land and soil distinguishing parameters (Table 3). The analytical data of the three opened soil profiles are given in annex 2. The physical and chemical characteristics of each soil mapping unit are as follows:

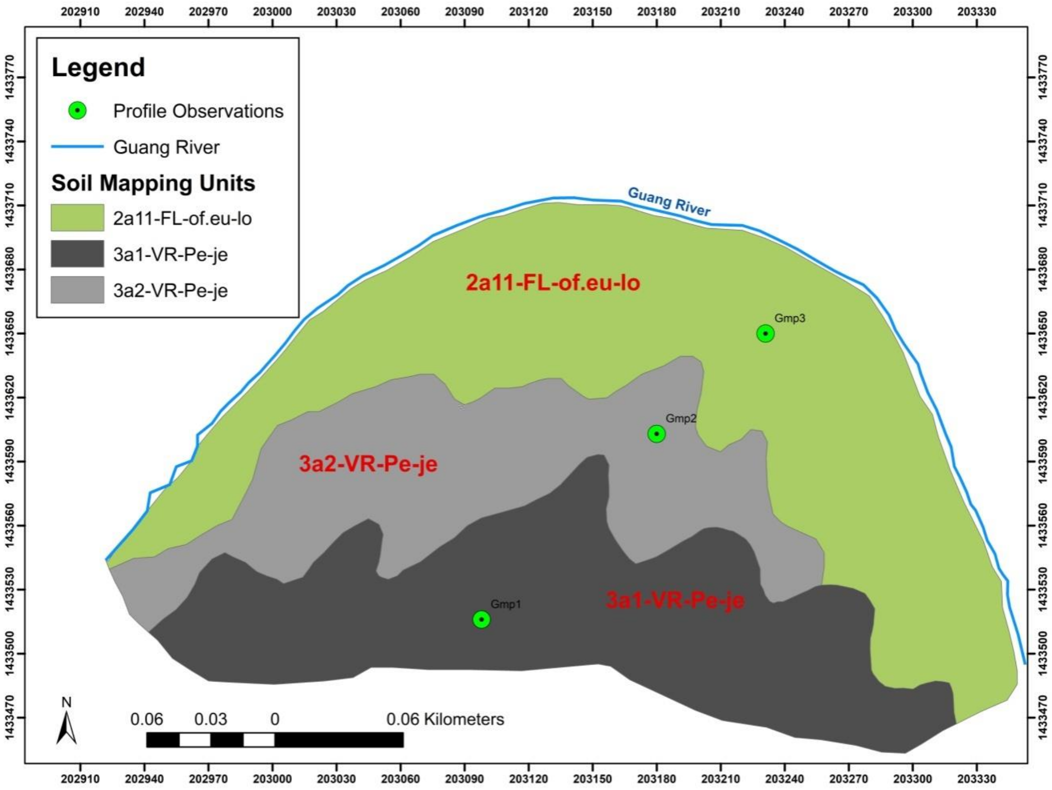

Figure 5. Soil map of Metema irrigation research site

Table 3. Soil map legend

Soil symbol/ description	Represent ative Pits	Slope range	Soil depth (cm)	Soil texture	Soil Unit	Area	
						ha	%
2a11-FL-of.eu-lo	Gmp3	1-2	>150	Sandy loam	Eutric Orthofluvic Fluvisols (Loamic)	3.34	44.95
3a1-VR-pe-je	Gmp1	2-5	>150	Heavy clay	Pellic Vertisols (Hypereutric)	2.30	30.96
3a2-VR-pe-je	Gmp2	2-5	>150	Clay	Pellic Vertisols (Hypereutric	1.79	24.09
Total						**7.43**	**100**

Note: GMP3 is a profile code stands for profile 3, GMP1, profile 1, GMP2, profile

Mapping Unit 2a11-FL-Of.Eu-Lo (Eutric Orthofluvic Fluvisols (Loamic))

This unit refers to somewhat excessively drained soils that occur on a very gently sloping (1-2%) valley bottom landscape in the northern part of the research site along the Guang River. It covers 3.34 ha or 44.95 % of the research site. Soils of this mapping unit are very deep (>150 cm), excessively drained, and black (7.5YR3/4) color in moist. The surface texture is sandy loam with a weak medium sub-angular blocky structure. These soils have a very friable consistency when moist, sticky, and slightly plastic when wet.

According to the pH category of (Jones, 2002), the pH value of the surface soil is 7.27 (neutral) and varies in the subsurface horizons from 7.17 to 7.64, which are neutral to slightly alkaline. The smaller pH values were obtained at the surface soils with higher pH values at the depth. Similar results were confirmed and reported (Sebnie et al., 2021). The rise of soil pH with depth could be because of vertical movements of exchangeable bases and fewer H+ ions released from the decomposition of organic matter (Bekele et al., 2021).

The electrical conductivity ranges between 0.023 and 0.041dS/m. The EC values indicate non-saline soils. The EC values measured in the Irrigation Research Station soils showed that the concentrations of soluble salts are below the threshold at which growth and productivity of most crops are affected due to soil salinity (Jones, 2001).

The cation exchange capacity is high (39.74 to 60.71 cmol(+)/kg soil) throughout the horizons based on London (1991) as cited by (Ali et al., 2010) CEC values are rated < 5 as very low, 5 - 15 as low; 15 - 25 as a medium, 25 - 40 as high and > 40 as very high. The studied soil has a higher base saturation (82 to 100%), suitable for crops. Base saturation indicates the percentage of the cation exchange capacity (CEC) of the soil colloids by the cations calcium (Ca2+), magnesium (Mg2+), potassium (K+), and sodium (Na+) (Jones, 2002).

According to (Jones, 2002) rating, the organic matter content is very low to medium (0.08 -3.88 %), while the total nitrogen (TN) content of the studied surface and subsurface soils for this profile is low to medium (0.020-0.153%) throughout the horizons. That could be due to the land use of the area; in a cropland use system, there are burning of grass cover in the lowland for land preparation which lower SOM content of the topsoil, or all above ground biomass is removed for fodder or grazed by animals (Sebnie et al., 2021). In addition, fast mineralization of soil organic matter because of cultivation that ables disturbs soil aggregates, thereby increasing aeration and microbial accessibility to organic matter (Emiru and Gebrekidan, 2013).

Carbon to nitrogen ratio (C: N ratio) is <10:1 except 21:1 at the second horizon. The C: N ratio of the site indicating optimum microbial activity for the humification and mineralization of organic residues (Sebnie *et al*., 2021).

According to the sufficiency range of P (Horneck et al., 2011 and Eyasu *et al*., 2020), the available phosphorus (Olsen) is medium to high (7.93 to 13.37 ppm) in the upper two horizons, and it is very low to medium in the lower horizons. High available P values in the surface horizon compared to the subsurface horizons might be related to the difference in organic matter contents and application of P-containing fertilizer (Ali *et al*., 2010).

Available potassium is very low in all horizons (51 to 74 ppm), except it is medium in the eighth and twelfth horizons (89 - 156 ppm). Exchangeable sodium percentage (ESP) is medium throughout the horizons but low and high at the second and fifth horizons, respectively. The diethylenetria- menepentaacetic acid (DTPA) iron is sufficient (4.26 - 17.98 ppm) in the upper six horizons, and it varies low to marginal in the lower horizons. The DTPA copper is high (1.13 to 5.45 ppm) throughout the horizons. Zinc is low in the upper three horizons and low to high in the lower horizon.

Table 4. Analytical data of Eutric Orthofluvic Fluvisols (Loamic))-Mapping unit 2a11-FL-of.eu-lo in Metema irrigation

Horizon	Gmp3/01	Gmp3/02	Gmp3/03	Gmp3/04	Gmp3/05	Gmp3/06	Gmp3/07	Gmp3/08	Gmp3/09	Gmp3/10	Gmp3/11	Gmp3/12
Depth (cm)	0-23	23-50	50-70	70-90	90-103	103-120	120-130	130-145	145-155	155-172	172-190	190-205+
% Sand	54	20	30	40	30	56	72	50	70	64	70	88
% Silt	28	44	42	36	42	28	16	30	18	20	22	6
% Clay	18	36	28	24	28	16	12	20	12	16	8	6
Textural class	Sandy loam	Silty clay loam	Clay loam	Loam	Loam	Sandy loam	Sandy loam	loam	Sandy loam	Sandy loam	Sandy loam	Loamy sand
PH-H_2O (1:2.5)	7.27	7.17	7.41	7.43	7.64	7.45	7.33	7.55	7.55	7.55	7.49	7.52
EC (ds/m)	0.041	0.033	0.030									

Av. Cu "ppm	5.41	2.07	5.45	2.11	1.67	1.13	2.15	4.13	1.37	3.39	1.57	2.27
Av. Zn ppm	0.77	0.71	0.58	0.23	1.09	0.40	1.32	0.92	0.82	0.43	0.30	0.44
Av. Fe ppm	14.2	17.26	17.98	4.59	4.26	3.44	7.92	8.80	5.98	9.64	6.54	0.72
Ca/Mg	2.45	2.27	2.10	2.83	2.47	2.52	2.72	2.03	1.92	2.99	1.74	2.95
Mg/K	61.85	115.23	119.21	92.75	43.18	92	70.47	36.93	128.43	55.89	100.14	50.09
(Ca+Mg)/K	221.16	384.54	379	365	165.36	332.53	269.47	115.88	383.57	230.94	282.43	204.68
K:CEC Ratio	230	467	382	373	167	334	271	116	394	232	284	208
Bulk Density (g/cm^3)	1.23	1.23	1.16									
FC (% vol)	37.29	49.47	45.49									
PWP (%vol)	20.50	27.46	24.54									

Figure 6: Profile view of soil mapping unit 2a11-FL-of.eu-lo (profile code Gmp3)

Mapping Unit 3a1-VR-Pe-Je

This unit refers to poorly drained soils that occur on gently sloping lands (3%) in the southern part of the research site. It covers 2.30 ha or 30.96% of the research site. The soils of the unit are very deep (>150 cm) and very dark gray (10YR3/1) color in moist. The surface texture is heavy clay with a strong medium and coarse sub-angular blocky structure. These soils have a firm consistency when moist, very sticky, and very plastic when wet.

According to (Jones, 2002) the soil pH value in the first two horizons is 7.3 (neutral), which increased from 7.43 to 8.97 (slightly alkaline to strongly alkaline) in lower horizons. Soil pH can significantly influence plant growth by affecting the composition of the soil solution and the availability (sufficiency or toxicity) of essential and nonessential elements (Jones, 2002). The electrical conductivity ranges between 0.036 and 0.162ds/m nonsaline, indicting salinity effects mostly negligible (Jones, 2002).

The cation exchange capacity is very high (53. 6 to 70.26 cmol (+)/kg soil), and it is highly base saturated (85 to 98%), which indicates a sound soil fertility status for crop production. The base saturation (BS), calculated as the sum of exchangeable bases divided by the CEC and multiplied by 100. The organic matter content is very low (0.80 %) at surface horizons, and its range is 0.58 to 1.35% in the subsurface horizons is very low. Total nitrogen content is low in the upper horizons (0.0.060 to 0.107%), and it has low to medium in the lower horizons (0.0.031 to 0.226%). Available phosphorus is very low (0.11 to 2.04 ppm) throughout the horizons. Available potassium is medium in the surface horizon (121ppm) and low to medium in the lower horizons (66-199 ppm).

According to the sufficiency range of K (Landon, 2013), the balance of potassium to other cations is very low. Exchangeable sodium percentage (ESP) is medium (2.01 to 3.22%) throughout the horizons, except it is high (8.51%) and low (1.79%) at the fourth and fifth horizons, respectively. Soil iron content is sufficient at the surface, and it ranges low to marginal in the sub-surface horizons. Soil copper content is high (0.63 to 5.09 ppm) throughout the horizons, while zinc is low (0.50 ppm) in the upper horizons and low to high (0.34 to1.08 ppm) in the lower horizons. The carbon to nitrogen ratio is good (<10), except it is medium (14) in the lowest horizon.

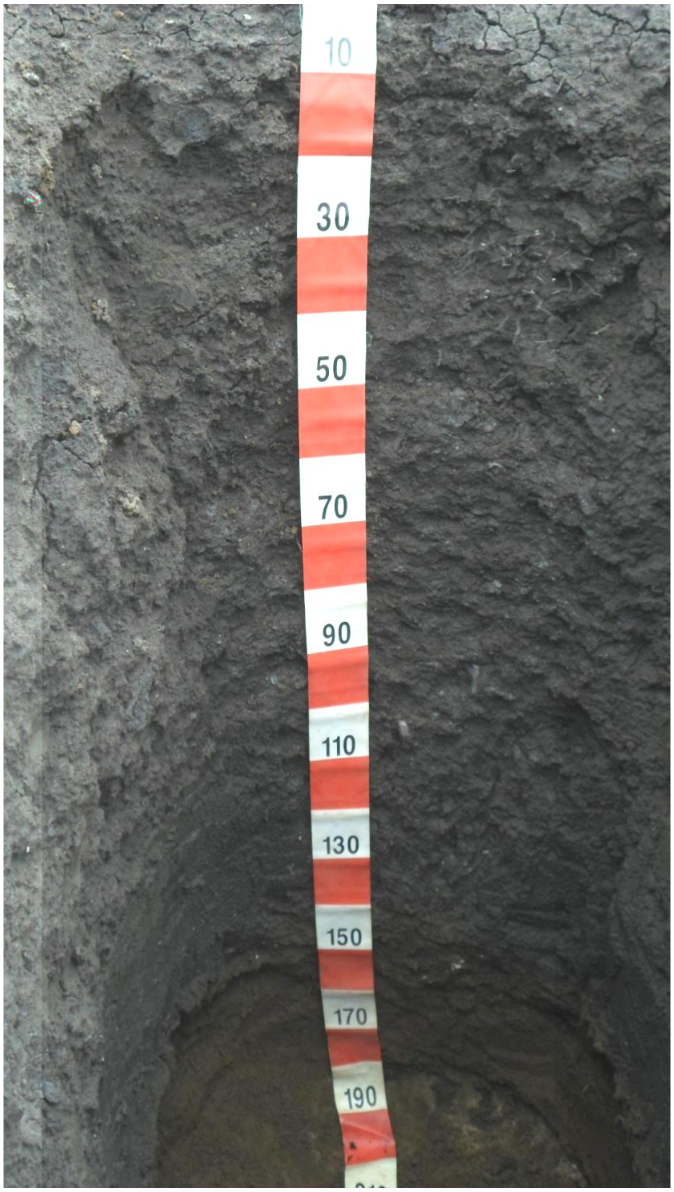

Figure 7. Profile view of soil mapping unit 3a1-VR-pe-je (profile code Gmp1)

Mapping Unit 3a2-VR-Pe-Je

This unit refers to well-drained soils that occur on gently sloping lands (2-5%) in the eastern part of the research site. It covers 1.79 ha or 24.09% of the research site. The soils of the unit are very deep (>150cm) and black (10YR2/1, moist). The surface texture is clay with a strong medium and coarse sub-angular blocky structure. These soils have a firm consistency when moist, very sticky, and very plastic when wet.

The pH values of the first two horizons are neutral (7.33 to 7.36), which are slight to strongly alkaline (7.43 to 8.24) (Jones, 2002). The pH values in the lowest horizons are strongly alkaline (8.02 to 8.24); similar results were confirmed and reported by (Sebnie et al., 2021). The rise of soil pH with depth could be because of vertical movements of exchangeable bases and fewer H+ ions released from the decomposition of organic matter (Bekele et al., 2021).

The electrical conductivity ranges between 0.022 to 0.102 ds/m. According to (Jones, 2002) the EC results obtained in soils of the study area indicated that the concentration of soluble salts in soils of the irrigation research site were below the levels at which most crop cultivation is not affected by salinity.

According to the sufficiency range of CEC (Landon, 2013), the cation exchange capacity is very high (48.19 to 63.74 cmol (+)/kg soil) throughout the horizons, and it is very highly base saturated (74 to 98%). The high amount of CEC in the soils of the study area may be due to the presence of active clay mineralogy (Mohammed et al., 2018) and indicating that the soils have adequate basic cation to support plant growth (Chekol & Mnalku, 2012).

The organic matter content is very low (0.08 to 2.52%) throughout the horizons. Nitrogen is low in the upper horizons and low to medium (0.034 to 0.175%) in the lower horizons.
The difference in organic matter and nitrogen content along soil depth could be attributed to variation in land-use systems along the topo-sequence. Intensive and continuous cultivation aggravated organic carbon oxidation and resulted in the reduction of total N compared to fallow land (Ali et al., 2010).

The carbon to nitrogen ratio (C: N) is medium at the surface and sub-surface horizon (0.7 to 14), generally less than 25%. That showed that decomposition might undertake at the maximum rate possible under environmental conditions (Mohammed et al., 2018). In general, a C: N ratio of about 10:1 shows a relatively better decomposition rate, serving as an index of improved nitrogen availability to plants and possibilities to incorporate crop residues into the soil without having any adverse effect of nitrogen immobilization (Assen & Yilma, 2010).

According to Eyasu (2013), available phosphorus is medium (9.07 ppm) at the surface and very low in sub-surface horizons. The available phosphorus is medium at the surface

Table 6. Analytical data of Pellic Vertisols (Hypereutric) /3a2-VR-pe-je/ in Metema Irrigation Research Site

Horizon	Gmp2/01*	Gmp2/02	Gmp2/03	Gmp2/04	Gmp2/05	Gmp2/06	Gmp7
Depth (cm)	0-20	20-60	60-95	95-130	130-150	150-200	390-400
% Sand	24	24	22	28	50	62	56
% Silt	24	24	26	32	26	26	30
% Clay	52	52	52	40	24	12	14
Textural class	Clay	Clay	Clay	Clay	Sandy clay loam	Sandy loam	Sandy loam
pH-H_2O (1:2.5)	7.33	7.36	7.47	7.64	7.91	8.24	8.02
EC (ds/m)	0.068	0.028	0.016	0.022	0.052	0.102	0.042
TN%	0.102	0.083	0.175	0.043	0.034	0.063	
OC %	1.46	0.83	0.37	0.05	0.18	0.05	
OM %	2.52	1.43	0.64	0.09	0.31	0.08	
C/N	14	10	2	1.16	5.2	0.7	
Ex. Ca (Cmol+/kg)	33.28	38.84	40.55	37.99	34.78	32.31	26.54
	11.45	17.23	14.12	20.54	15.41	13.16	20.22
Ex. Na "	0.85	3.43	1.3	1.28	1.3	1.65	2
Ex. K "	0.54	0.27	0.31	0.17	0.14	0.09	0.14
Sum Bases "	46.12	59.77	56.28	59.98	51.63	47.21	48.9
Base Satutation. %	74	98	89	95	96	98	99
CEC (Cmol+/kg)	62	60.75	63.34	63.32	53.91	48.19	49.2
Av. P (mg/kg)	9.07	1.70	0.11	2.38	2.72	0.96	
ESP (%)	1.37	5.65	2.05	2.02	2.41	3.42	4.06
Av. Cu (mg/kg)	4.43	5.09	7.23	4.23	1.99	1.19	
Av. Zn (mg/kg)	0.40	1.27	1.19	0.73	0.14	0.04	
Av. (Fe mg/kg)	12.78	9.90	10.90	3.58	0.76	1.86	
Ca/Mg	2.91	2.25	2.87	1.85	2.26	2.46	1.31
Mg/K	21.20	63.81	45.55	120.82	110.07	146.22	144.43
(Ca+Mg)/K	85.41	221.37	181.55	352.82	368.79	524.56	349.29
K:CEC Ration	115	225	204	372	385	535	351
Bulk Density (g/cm^3)	1.01	1.20	1.41				
FC (%vol)	52.73	53.69	54.45				
PWP (%vol)	33.52	34.49	35.60				

***Gmp2**: field code for profile 2, CEC:cation exchange capacity, FC:field capacity, PWP: permanent wilting point*

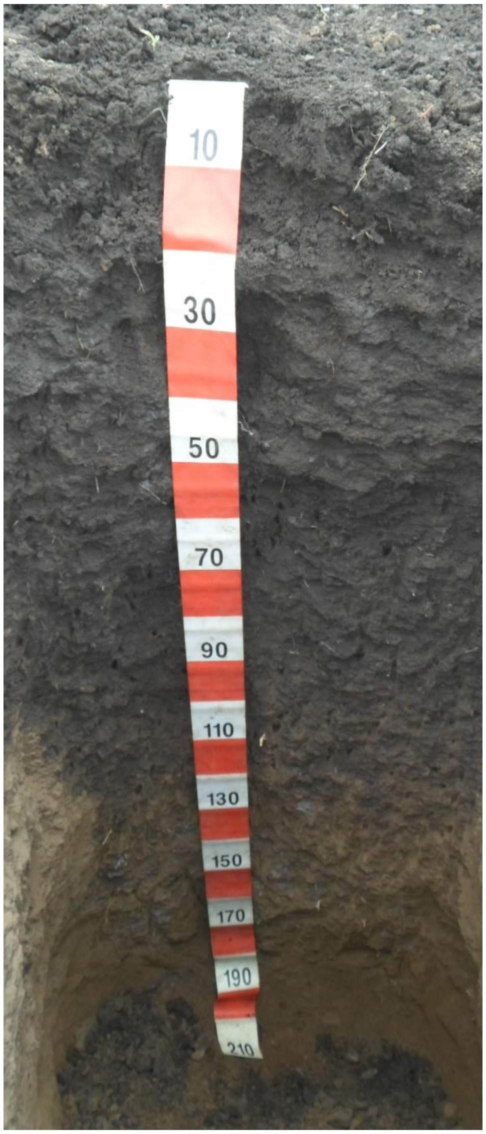

Figure 8. Profile view of soil mapping unit 3a2-VR-pe-je (profile code Gmp2)

Major Soil Units, Their Potentials and Limitations

Fluvisols

Fluvisols accommodate genetically young soils in alluvial soils (FAO, 2006). They developed in alluvial deposits along Guang River and on the valley bottom part of the research site. Only Eutric Orthofluvic Fluvisols (Loamic) were found in the northern part of the research site at valley bottoms and mapped as 2a11-FL-of.eu-lo. This soil is neutral, deep, excessively drained and its organic matter and total nitrogen contents are very low and medium, respectively. Fluvisols have a high range of available phosphorus, base saturation, iron, and zinc at the surface. According to the rating of Landon (2013), the available potassium is low, but the cation exchange capacity is very high. The phosphorus level is high at the surface and low at subsurface horizons. This high-level phosphorus at surface soil indicates the residual effect of applied fertilizer in recent cropping seasons. This soil has a medium to coarse texture, leading to poor available water holding capacity.

Since Fluvisols are under cultivation, Applying phosphorus, potassium, nitrogen fertilizers, and organic fertilizers such as manure will improve soil fertility and increase crop yield. Appropriate irrigation scheduling will be necessary when this soil is cultivated during dry months. Their area coverage is 3.34 ha or 44.95% of the research site.

Vertisols

Vertisols are heavy clay soils with a high proportion of swelling clays that form deep, wide cracks from the surface downward when they dry out. Cracks result from the swelling and shrinking of expanding clays in dry seasons. The formation of slickensides and wedged-shaped structural elements in the subsurface horizons is the effect of swelling and shrinking of expanding clays (FAO, 2006).

Vertisols found in the research site are very deep, poorly drained, and have more than 30% clay texture, with coarse, angular, blocky structure elements. They have slickensides and wedge-shaped structural elements in the subsurface horizons. In the research site, these soils are mapped as 3a1-VR-pe-je and 3a1-VR-pe-je and cover 4.09 ha, representing 55.05% of the total project area.

These soils are neutral, very deep, poorly drained, and slightly eroded. Currently, these soils are under cultivation of cereal and oil crops. They have very low organic matter and total nitrogen content in the surface horizons. Available phosphorus and potassium are very low to medium in the surface horizons. Their cation exchange capacity, base saturation, and iron contents are very high, while copper and zinc contents vary from low to high. This finding is in line with various works that stated that Zn contents are variable and Fe and Mn contents are usually at an adequate level in Ethiopian soils (Fisseha 92 as cited by (Chekol & Mnalku, 2012). The physical properties and soil moisture regime of Vertisols represent severe management constraints. The heavy soil texture and domination of expanding clay minerals result in a narrow soil moisture range between moisture stress and water excess. Tillage is hindered by stickiness when the soil is wet and hardness when dry. Therefore, these soils' major constraints are poor workability and low infiltration rate (FAO, 2006). According to FAO (2006), management practices for crop production in vertisol should be water control in combination with soil fertility improvement.

Overall Physical and Chemical Characteristics of the Study Soils (Fluvsols and Vertisol)

Physical Properties

Texture: The particle analysis results indicate that most of the soils (fluvisol and vertisol) within the research site are clay textured, containing a relatively high proportion of clay. Only sandy loam textured soils occur in Fluvisols in the eastern and western parts of the research site.

Soil Structure: About 65% of watershed soils have strongly developed angular structures with poor workability. In contrast, the remaining soils have weakly developed subangular blocky structures with poor water holding capacity.

Bulk Density: It is an indicator of soil compaction. It is calculated as the dry weight of soil divided by its volume. This volume includes the volume of soil particles and the volume of pores among soil particles. The calculated bulk density values of surface soils are medium, ranging from 1.01 to 1.55 g cm-3. These bulk density values indicate that the soils are not compacted to restrict root development.

Soil Depth: The soil depth of the research site is very deep. There is no soil depth limitation to crop types in the research site.

Chemical Properties

Soil Reaction: The pH values range between 7.2 and 7.3 in surface soils. The pH values increased with depth, and its values are between 7.43 to 8.24, which are slight to moderately alkaline soils, which cover the research site. The pH values of the surface soil in the research site are ideal for crop production.

Cation Exchange Capacity and Base Saturation Percentage: The cation exchange capacity of the soils ranges between 43.76 to 62.72cmol (+)/kg soil in the surface horizons. In general, is the values are within the acceptable CEC range. The base saturation percentage increases with depth, which could be due to the leaching of bases to the subsurface horizons, except in Fluvisols, which is variable due to its formation nature.

Cation Balance: Soils of the Metema irrigation research site are very high base saturated. However, this does not prove a balanced proportion of the exchangeable bases. Thus, the cations ratio is used to evaluate the status of the relative proportions of cations. The ratios of Ca to Mg, Mg to K, and Ca+Mg to K range between 2.45 to 3.38, 21.20 to 61.95, and 85.41 to 221.16, respectively. According to Frank (1990), these ratios indicate the presence of an unfavorable balance between the cations (Table 16). The balance of Ca to Mg is less favorable in the soil mapping unit of 2a1-VR-pe-je and 2a2-VR-pe-je and unfavorable in the mapping unit of 2a11-FL-of.eu-lo. The balance of Mg to K and (Ca+ Mg)/K is low, indicating a lack of potassium in all soil mapping units (Esayas et al., 2005).

Table 7. The basic cation saturation ratio in the surface horizons of mapping units

Soil mapping unit	Ca/Mg		Mg/K		(Ca+Mg)/K	
	ratio	status	ratio	status	ratio	status
2a11-FL-of.eu-lo	2.45	Low Ca, not favourable	61.95	Lack of K	221.16	Lack of K
2a1-VR-pe-je	3.38	Low to moderate Ca, less favourable	41.42	Lack of K	186.65	Lack of K
2a2-VR-pe-je	2.91	Low to moderate Ca, less favourable	21.20	Lack of K	85.41	Lack of K

Conclusion

The dominant soils of the Metema irrigation research site are classified as Vertisols and Fluvisols. These soils are very deep and less eroded. All soil types have very low organic matter content, very low to medium levels of total nitrogen, available phosphorus, and potassium in the surface horizons, except available phosphorus, which is high in Fluvisols. All the research site soils have almost neutral pH values and have unfavorable (Ca+Mg)/K cation balance. There is no risk of salinity throughout the site. The primary constraints are waterlogging, poor workability and depletion of nutrients, low productivity, and poor water holding capacity in the mapping unit of 2a11-FL-of.eu-lo. These constraints could be alleviated by applying NPK fertilizers, bio-fertilizers, green manure, drainage improvement, and adopting appropriate agronomic practices after determining the application rate based on crop types. The balanced availability of cations in the soil will significantly improve crop production.

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References

Ali, A., Esayas, A., & Beyene, S. (2010). Characterizing soils of Delbo Wegene watershed , Wolaita Zone , Southern Ethiopia for planning appropriate land management. *Journal of Soil Science and Environmental Managemen*, *1*(8), 184 199.

Assen, M., & Yilma, S. (2010). Characteristics and Classification of the Soils of Gonde Micro-Catchment, Arsi Highlands, Ethiopia. *SINET: Ethiopian Journal of Science*, *33*(2), 101

South Wollo Zone, Northeastern Ethiopia. *Journal of Biology, Agriculture and Healthcare*. https://doi.org/10.7176/jbah/11-3-06

Hailu, H., Mamo, T., Keskinen, R., Karltun, E., Gebrekidan, H., & Bekele, T. (2015). Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia. *Agriculture and Food Security*, *4*(1), 1 10. https://doi.org/10.1186/s40066-015-0038-0

Jones, J. . J. B. (2002). Agronomic Handbook. In *Agronomic Handbook*. https://doi.org/10.1201/9781420041507

Kazmin, V., & Warden, A. J. (1975). *Explanation of the geological map of Ethiopia*. Geological Survey of Ethiopia.

Keesstra, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J. N., Pachepsky, Y., Van Der Putten, W. H., Bardgett, R. D., Moolenaar, S., Mol, G., Jansen, B., & Fresco, L. O. (2016). The significance of soils and soil science towards realization of the United Nations sustainable development goals. *Soil*, *2*(2), 111 128. https://doi.org/10.5194/soil-2-111-2016

Landon J. R.(2013). Booker Tropical Soil Manual, A hand book for soil survey & agricultural land evaluation in the tropics and & sub tropics.

Mesfin, K., Tesfaye, S., Girma, K., Dejene, A., & Tsegaye, G. (2017). Description, characterization and classification of the major soils in Jinka Agricultural Research Center, South Western Ethiopia. *Journal of Soil Science and Environmental Management*, *8*(3), 61 69. https://doi.org/10.5897/JSSEM2015.0498

Mohammed, S., Kibret, K., & Mohammed, M. (2018). Characterization and Classification of Soils along Toposequence of Gobeya Sub-Watershed, South Wello Zone, Ethiopia. *Asian Journal of Soil Science and Plant Nutrition*, *2*(4), 1 17. https://doi.org/10.9734/ajsspn/2017/38426

Mohr, P. A. (1971). Ethiopian rift and plateaus: some volcanic petrochemical differences. *Journal of Geophysical Research*, *76*(8), 1967-1984.

Nega Emiru and Heluf Gebrekidan. (2013). Effect of Land Use Changes and Soil Depth on Soil Organic Matter , Total Nitrogen and Available Phosphorus Contents of Soils in Senbat Watershed , Western Ethiopia. *ARPN Journal of Agricultural and Biological Science*, *8*(3), 206 212.

Richards, L. A., & Fireman, M. (1943). Pressure-plate apparatus for measuring moisture sorption and transmission by soils. *Soil Science*, *56*(6), 395-404.

Scherr, S. J., & McNeely, J. A. (2008). Biodiversity conservation and agricultural su *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1491), 477 494. https://doi.org/10.1098/rstb.2007.2165

Schollenberger, C. J., & Simon, R. H. (1945). Determination of exchange capacity and exchangeable bases in soil ammonium acetate method. *Soil science, 59*(1), 13-24

Sebnie, W., Adgo, E., & Kendie, H. (2021). Characterization and Classification of Soils of Zamra Irrigation Scheme, Northeastern Ethiopia. *Air, Soil and Water Research*, *14*(2018). https://doi.org/10.1177/11786221211026577

United Nations. (2013). World Economic and Social Survey 2013: Sustainable Development Challenges. In *United Nations, Department for Economic and Social Affairs*. http://esa.un.org/wpp/documentation/pdf/WPP2012_ KEY FINDINGS.pdf

Walkley, A., & Black, I. A. (1934). An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. In *Soil Science* (Vol. 37, Issue 1, pp. 29 38). https://doi.org/10.1097/00010694-193401000-00003

WRB-IUSS. (2014). World Reference Base for Soil Resources. World Soil Resources Reports 106. In *World Soil Resources Reports No. 106*.

Zelleke, G., Agegnehu, G., Abera, D., & Rashid, S. (2010). *Fertilizer and soil fertility potential in Ethiopia: Constraints and opportunities for enhancing the system*. *July*. http://www.ifpri.org/publication/fertilizer-and-soil-fertility-potential-ethiopia

Annex 1. Profile descriptions

Profile number: GMP1 **Date:** 04/07/2018

Soil classification (FAO): Pellic Vertisols (Hypereutric)

Profile description status: Routine profile description

Coordinate (WSG84) N: 1433516

Local soil name: Mezega **E:** 203098

Location: Metema Irrigation station

Author(s): Gebeyehu Belay **Map unit symbol:** 3a1-VR-pe-je

Land form: Plain

Position in land form: South to north **Elevation (asl):** 688m

Micro topography: Termite hills **Depth to bedrock:** >200cm

Slope class: 3 **Depthtogroundwater:** Not encountered

Rootable depth: > 190cm **Sealing/capping:** Medium

Slope gradient: 3% **Bleached sand:** None

Rock out crops: None **Flooding frequency:** None

Surface cracks: Medium closely spaced deep cracks **Flooding duration:** None

Slope form: Straight **Permeability:** Slow

Position: Upper slope **Surface stones & boulders:** None

Surface coarse fragments: None **Fertilizer:** DAP and UREA

Parent material: Quaternary aged undifferentiated alluvial deposits **Climate:** Warm sub moist lowlands

Soil drainage class: Poorly drained

Moisture status: 0-30cm moist and slightly moist below **Human influence:** Ploughing

Surface drainage: Rapid

Land cover: Harvested field of sesame **Salt status:** None

Land use: Annual field cropping **Effective soil depth:** >190cm

Crop Type: Oil crop

Erosion status: a. Site: About 20% of the unit is affected by slight sheet erosion

b. Surrounding: About 25% of the unit is affected by slight rill and severe sheet water erosion

PROFILE DESCRIPTION

AP 0-15cm Very dark gray (10YR 3/1) moist; heavy clay; strong medium and coarse sub angular blocky structure; none mottles; very sticky and very plastic when wet, firm when moist; wide closely spaced deep racks; none coatings; none coarse fragments; not cemented and compacted; none mineral concentrations; non calcareous; many fine and medium roots; many fine interstitial pores; clear and smooth boundary.

A1 15-30cm Very dark brown (10YR 2/2) moist; heavy clay; strong coarse and medium sub angular blocky structures; none mottles; very sticky and very plastic wet, firm when moist; medium closely spaced deep racks; none coatings; none coarse fragments; not cemented and compacted; none mineral concretions; none calcareous; few fine roots; many fine interstitial pores; gradual and smooth boundary.

A2 30-55cm Black (10YR2/1); heavy clay; strong coarse angular blocky structure; none mottles; very sticky and very plastic wet, friable when moist; fine moderately widely spaced surface racks; few distinct partly intersecting slickenside; none coarse fragments; not cemented and compacted; none mineral concretions; none calcareous; few fine roots; common fine interstitial pores; clear and smooth boundary.

A3 55-120cm Black (10YR 2/1) moist; heavy clay; strong medium angular blocky; none mottles; very sticky and very plastic wet, firm when moist; none surface cracks; common distinct predominantly intersecting slickensides; none coarse fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; very few fine roots; few fine interstitial pores; clear and smooth boundary.

A4 120-150cmVery dark gray (10YR 3/1) moist; clay; moderate medium sub angular blocky; none mottles; sticky and plastic wet, firm when moist; none surface cracks; ; common distinct predominantly intersecting slickensides; none coarse fragments; not cemented and compacted; none mineral concretions; slightly calcareous; none abundance of roots; few fine interstitial pores and few termite channels; abrupt and smooth boundary.

AC 150-190+cmDark brown (10YR 3/3) moist; clay loam; moderate medium sub angular blocky; none mottles; slightly sticky and non plastic wet, firm when moist; none surface cracks; none coatings; very few fine fresh coarse fragments; non-cemented and non-compacted; none mineral concretions; moderately calcareous; none abundance of roots; few fine interstitial pores and few termite channels.

Profile number: GMP2 **Date:** 05/07/2018
Soil classification (FAO): Pellic Vertisols (Hypereutric)
Profile description status: Routine profile description
Coordinate (WSG84) N: 1433603
Local soil name: Mezega **E:** 203180
Location: Metema Irrigation station
Author(s): Gebeyehu Belay **Map unit symbol:** 3a2-VR-pe-je
Land form: Plain
Position in land form: South to north **Elevation (asl):** 687m
Micro topography: Termite hills **Depth to bedrock:** >200cm
Slope class: 3 **Depth to ground water:** Not encountered
Rootable depth :> 200cm **Sealing/capping:** Medium
Slope gradient: 2.5% **Bleached sand:** None
Rock out crops: None **Flooding frequency:** None
Surface cracks: Fine moderately widely spaced

medium cracks

Flooding duration: None

Slope form: Straight

Permeability: Slow

Position: Lower slope

Surface stones & boulders: None

Surface coarse fragments: None

Human influence: Ploughing

Moisture status: 0-30cm moist and slightly moist below

Fertilizer: DAP and UREA

Salt status: None

Parent material: Quaternary aged undifferentiated alluvial deposits

Climate: Warm sub moist lowlands

Effective soil depth:>200cm

Soil drainage class: Imperfectly drained

Surface drainage: Moderately rapid

Land cover: Harvested field of sesame

Land use: Annual field cropping

Crop Type: Oil crop

Erosion status: a. Site: About 25% of the unit is affected by slight sheet erosion

b. Surrounding: About 30% of the unit is affected by slight rill and severe sheet water erosion

PROFILE DESCRIPTION

AP 0-20cm Black (10YR 2/1) moist; clay; strong medium and coarse sub angular blocky structure; none mottles; very sticky and very plastic when wet, firm moist when moist; none surface cracks; none coatings; none coarse fragments; not cemented and compacted; none mineral concentrations; none calcareous; common fine roots; many fine interstitial pores and few termite channels; clear and smooth boundary.

A1 20-60cm Very dark brown (10YR 2/2) moist; clay; strong coarse and medium angular blocky structures; none mottles; very sticky and very plastic wet, firm when moist; none surface cracks; few distinct partly intersecting slickensides; none coarse fragments; not cemented and compacted; none mineral concretions; none calcareous; common fine roots; many fine interstitial pores and few termite channels; clear and smooth boundary.

A2 60-95cm Very dark gray (10YR3/1); clay; strong medium angular blocky structure; none mottles; sticky and plastic wet, firm when moist; none surface cracks; common distinct predominantly intersecting slickensides; none coarse; fragments; not cemented and compacted; none mineral concretions; none calcareous; few fine roots; few fine interstitial pores and few termite channels; clear and smooth boundary.

A3 95-130cm Very dark grayish brown (10YR 3/2) moist; clay; strong medium sub angular blocky; none mottles; sticky and plastic wet, firm when moist; none surface cracks; few faint partly intersecting slickensides; few fine fresh coarse fragments; non-cemented and non-compacted; none mineral concretions; slightly calcareous; none abundance of roots; many fine interstitial pores and few termite channels; gradual and smooth boundary.

AC 130-150cm Dark grayish brown (10YR 4/2) moist; sandy clay loam; moderate medium sub angular blocky; none mottles; slightly sticky and slightly plastic wet, friable when moist; none surface cracks; none coatings; few fine fresh coarse fragments; not cemented and compacted; none mineral concretions; moderately calcareous; none abundance of fine roots; common fine interstitial pores and coarse termite channels; abrupt and smooth boundary.

C 150-200+cm Brown (10YR 4/3) moist; sandy loam; moderate medium sub angular blocky; none mottles; non sticky and non plastic wet, friable when moist; none surface cracks; none coatings; few fine fresh coarse fragments; non-cemented and non-compacted; few fine black soft manganese mineral concretions; strongly calcareous; none abundance of roots; common fine interstitial pores and common coarse termite channels.

Profile number: GMP3 **Date:** 05/07/2018

Soil classification (FAO): Eutric Orthofluvic Fluvisols (Loamic)

Profile description status: Routine profile description

Coordinate (WSG84) N: 1433650

Local soil name: Shina **E:** 203231

Location: Metema Irrigation station

Author(s): Gebeyehu Belay **Map unit symbol:** 3a11-FL-of.eu-lo

Land form: Plain

Position in land form: South to north

Elevation (asl): 681m

Micro topography: Termite hills **Depth to bedrock:** >200cm

Slope class: 2 **Depth to ground water:** Not encountered

Root able depth :> 200cm **Sealing/capping:** Medium

Slope gradient: 1.5% **Bleached sand:** None

Rock out crops: None **Flooding frequency:** None

Surface cracks: None **Flooding duration:** None

Slope form: Straight **Permeability:** Rapid

Position: Bottom slope **Surface stones & boulders:** None

Surface coarse fragments: None **Human influence:** Ploughing

Parent material: Quaternary aged undifferentiated alluvial deposits **Climate:** Warm sub moist lowlands

Salt status: None

Moisture status: 0-30cm moist and slightly moist below **Effective soil depth:** >200cm

Soil drainage class: Somewhat excessively drained

Land cover: Harvested field of sesame **Surface drainage**: Slow

Land use: Annual field cropping **Fertilizer:** DAP and UREA

Crop Type: Fruit and fiber crop

Erosion status: a. Site: About 5% of the unit is affected by slight sheet erosion

b. Surrounding: About 10% of the unit is affected by slight rill and severe sheet water erosion

PROFILE DESCRIPTION

AP 0-23cm Black (7.5YR 2.5/1) moist; sandy loam; weak medium sub angular blocky structure; none mottles; sticky and slightly plastic when wet, very friable when moist; none surface cracks; none coarse fragments; not cemented and compacted; none mineral concentrations; non calcareous; many fine roots; many fine interstitial pores; clear and smooth boundary.

1A 23-50cm Very dark brown (7.5YR 2.5/2) moist; silty clay loam; weak medium sub angular blocky structures; none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; not cemented and compacted; none mineral concretions; none calcareous; common fine roots; few fine interstitial pores and few termite channels; clear and smooth boundary.

2A 50-70cm Very dark gray (7.5YR3/1); clay loam; weak fine sub angular blocky structure; none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; not cemented and compacted; none mineral concretions; none calcareous; common fine roots; few fine interstitial pores and few termite channels; gradual and smooth boundary.

3A 70-90cm Dark brown (7.5YR 3/2) moist; loam; weak fine single grain structure; none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine roots; common medium interstitial pores; clear and smooth boundary.

4A 90-103cm Very dark gray (10YR 3/1) moist; loam; weak fine sub angular structures;

none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; not cemented and compacted; none mineral concretions; none calcareous; very few fine roots; common medium interstitial pores; clear and smooth boundary.

5A 103-120cm Very dark brown (7.5YR 2.5/2) moist; sandy loam; weak fine sub angular blocky; none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; non-cemented and non-compacted; few fine black soft manganese mineral concretions; none calcareous; common fine roots; common medium interstitial pores; clear and smooth boundary.

6A 120-130cm Dark brown (7.5YR 3/2) moist; sandy loam; weak fine sub angular blocky; none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; non-cemented and non-compacted; few fine black soft manganese mineral concretions; none calcareous; common fine roots; common medium interstitial pores; clear and smooth boundary.

7A130-145cm Very dark brown (7.5YR 2.5/3) moist; loam; weak fine sub angular blocky; none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; non-cemented and non-compacted; few fine black soft manganese mineral concretions; none calcareous; few fine roots; common medium interstitial pores; clear and smooth boundary.

8A 145-155cm Dark brown (7.5YR 3/3) moist; sandy loam; weak fine sub angular blocky; none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; non-cemented and non-compacted; few fine black soft manganese mineral concretions; none calcareous; few fine roots; common medium interstitial pores; clear and smooth boundary.

9A 155-172cm Dark brown (7.5YR 3/3) moist; sandy loam; weak fine sub angular blocky; none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; non-cemented and non-compacted; few fine black soft manganese mineral concretions; none calcareous; few fine roots; common medium interstitial pores; clear and smooth boundary.

10A 172-190cm Dark brown (7.5YR 3/3) moist; sandy loam; weak fine single grains; none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; non-cemented and non-compacted; few fine black soft manganese mineral concretions; none calcareous; few fine roots; few fine interstitial pores; abrupt and smooth boundary.

11A 190-205cm Dark brown (7.5YR 3/2) moist; loamy sand; massive structures; none mottles; sticky and plastic wet, friable when moist; none surface cracks; none coarse fragments; non-cemented and non-compacted; few fine black soft manganese mineral concretions; none calcareous; none abundance of roots; porous. Abundant of rounded shaped fresh gravels and stones at 230cm. Deep auguring stopped due to gravels and stones

Annex 2. Metema irrigation research site soil analytical data

J s x xs x g s x x s x cxsx

										Exchangeable bases												
E c c	c sg	x c	s	x	s sttf x		C		J	x+		x	J			C (meq/ 100g soil)	ttf e x		Cu ppm	Zn ppm	Fe ppm
Gmp1	0-15	16	20	64	Heavy Clay	7.3	36	0.46	0.80	43.34	0.31	1.37	12.84	0.061	2.040	62.72	57.86	92	5.092	0.5	10.682
Gmp1	15-30	18	14	68	Heavy Clay	7.3	26.2	0.46	0.80	37.02	0.19	1.63	20.87	0.060	0.453	70.26	59.71	85	1.932	0.504	4.112
Gmp1	30-55	14	18	68	Heavy Clay	7.43	46.3	0.46	0.80	40.45	0.18	2.21	16.69	0.107	2.040	68.65	59.53	87	3.092	1.08	6.662
Gmp1	55-120	22	14	64	Heavy Clay	8.35	72.1	0.46	0.80	34.67	0.18	4.56	13.27	0.226	0.113	53.56	52.68	98	0.632	0.34	5.462
Gmp1	120-150	24	22	54	Clay	8.48	81.2	0.46	0.80	26.75	0.51	1.17	33.71	0.085	0.170	65.23	62.14	95	4.392	0.878	4.022
Gmp1	150-190+	42	20	38	Clay loam	8.97	162	0.46	0.80	31.14	0.17	1.19	25.36	0.031	0.397	59.09	57.86	98	3.532	0.544	0.582
Gmp2	0-20	24	24	52	Clay	7.33	67.6	0.46	0.80	33.28	0.54	0.85	11.45	0.102	9.065	62	46.12	74	4.432	0.404	12.782
Gmp2	20-60	24	24	52	Clay	7.36	28.3	0.46	0.80	38.84	0.27	3.43	17.23	0.083	1.700	60.75	59.77	98	5.092	1.265	9.902
Gmp2	60-95	22	26	52	Clay	7.47	16.03	0.46	0.80	40.55	0.31	1.3	14.12	0.175	0.113	63.34	56.28	89	7.232	1.194	10.902
Gmp2	95-130	28	32	40	Clay	7.64	21.7	0.46	0.80	37.99	0.17	1.28	20.54	0.043	2.380	63.32	59.98	95	4.232	0.728	3.582
Gmp2	130-150	50	26	24	Sandy clay loam	7.91	52	0.46	0.80	34.78	0.14	1.3	15.41	0.034	2.720	53.91	51.63	96	1.992	0.144	0.762
Gmp2	150-200+	62	26	12	Sandyloam	8.24	102.7	0.46	0.80	32.31	0.09	1.65	13.16	0.063	0.963	48.19	47.21	98	1.192	0.038	1.862
Gmp2	390-400	56	30	14	Sandy loam	8.02	41.9	0.46	0.80	26.54	0.14	2	20.22			49.2	48.9	99			
Gmp3	0-23	54	28	18	Sandy loam	7.27	40.6	0.46	0.80	28.78	0.19	1.28	11.77	0.153	13.371	43.76	42.02	96	5.412	0.768	14.122
Gmp3	23-50	20	44	36	Silty clay loam	7.17	32.9	0.46	0.80	34.03	0.13	0.85	14.98	0.107	7.932	60.71	49.99	82	2.072	0.71	17.262
Gmp3	50-70	30	42	28	Clay loam	7.41	29.5	0.46	0.80	35.1	0.14	1.13	16.69	0.071	4.873	53.44	53.06	99	5.452	0.584	17.982
Gmp3	70-90	40	36	24	Loam	7.43	24.2	0.46	0.80	31.46	0.12	1.09	11.13	0.047	2.776	44.77	43.8	98	2.112	0.232	4.586
Gmp3	90-103	30	42	28	Loam	7.64	20.78	0.46	0.80	29.85	0.28	4.08	12.09	0.130	0.283	46.8	46.3	99	1.672	1.088	4.262
Gmp3	103-120	56	28	16	Sandy loam	7.45	37.8	0.46	0.80	34.78	0.15	1.15	13.8	0.042	3.456	50.03	49.88	100	1.132	0.4	3.442
Gmp3	120-130	72	16	12	Sandy loam	7.33	20.1	0.46	0.80	32.53	0.17	1.13	11.98	0.020	2.153	45.99	45.81	100	2.152	1.324	7.922
Gmp3	130-145	50	30	20	Loam	7.55	22.5	0.46	0.80	29.96	0.4	1.22	14.77	0.052	5.099	46.35	46.35	100	4.132	0.918	8.802
Gmp3	145-155	70	18	12	Sandy loam	7.55	16.52	0.46	0.80	34.45	0.14	1.13	17.98	0.022	1.360	55.15	53.7	97	1.372	0.824	5.982
Gmp3	155-172	64	20	16	sandy loam	7.55	25.9	0.46	0.80	30.07	0.18	1.26	10.06	0.039	8.839	41.69	41.57	100	3.392	0.43	9.642
Gmp3	172-190	70	22	8	Sandy loam	7.49	17.38	0.46	0.80	24.4	0.14	0.98	14.02	0.074	7.479	39.74	39.54	99	1.572	0.304	6.542
Gmp3	190-205+	88	6	6	Loamy sand	7.52	20.8	0.46	0.80	32.53	0.22	1.26	11.02	0.036	4.136	45.73	45.03	98	2.272	0.44	0.718

E c c	c sg		E	
Gmp1	0-15	1.130	58.444	39.519
Gmp1	15-30	1.240	56.824	40.353
Gmp1	30-55	1.546	55.649	39.047
Gmp1	55-120	1.246	58.250	40.248
Gmp2	0-20	1.015	52.725	33.519
Gmp2	20-60	1.203	53.685	34.491
Gmp2	60-95	1.408	54.446	35.604
Gmp3	0-23	1.227	37.289	20.499
Gmp3	23-50	1.235	49.472	27.461
Gmp3	50-70	1.162	45.488	24.541

Annex 3. Metema irrigation research site climate data

X X eX

X	x	E	J x g		J x	ttf	ttf	ttfttfs	s	s			ttfx R sx
1997	0	0	91	23.6	89	156.7	194.5	271.2	166.1	32.5	0	0	
1998	0	0	0	2	67.1	138.7	258.4	204.3	208.9	15.6	0	0	
1999	0	0	0	0.3	77	143.8	265.5	251	223.2	164.6	0	0	
2000	0	0	0	25.5	133.3	327.6	202.6	127	163.7	86.5	0	0	
2001	0	0	0	0.2	5.1	161.4	331.1	324.5	138.5	23	0.1	0	
2002	0	0	0	10.9	35.1	244.9	158.1	218.3	178.7	35.4	3	0	
2003	0	0.3	0	0.1	37.9	332.3	262.1	296.5	185.9	3.4	0	0	
2004	0	0	0	0	28.6	160.4	119.9	119.8	144.6	85.4	4.2	0	
2005	0	0	4.7	3.2	64.9	213.3	271.8	260.9	243	66.2	0	0	
2006	0	0	0	18.6	177.6	171.8	203.4	297.9	207.8	33.2	0	0	
2007	0	0	0	22.5	43	142.1	320.5	332.5	254.2	52.7	25.5	0	
2008	0	0	0	61	85.6	163.7	369.2	286.5	326.6	78.4	0	0	
2009	0	0	0	3.3	64.4	163	189.2	223.2	88.1	0	0	0	
2010	0	0	0	0	67.9	165.7	228.1	213.6	215.3	35	0	0	
2011	0	0	31.6	0	0	93.7	121.2	217.4	138.2	22.6	0	0	
2012	0	0	0	0	55.9	216.5	230.8	327.7	381.6	0.7	0.8	0	
2013	0	0	0	1.2	40.4	196.5	214.1	352.7	150.4	40.1	0	0	
2014	0	0	0	60.4	57.2	89.3	198.7	223.2	324	127.9	0	0	
2015	0	0	0	0	40.1	0	103	244.2	199	46.7	0.5	0	
sg x													

J s x xs x g s J ttf x c J x ttf R xsttf

	1997		1998		1999		2000		2001		2002		2003	
Month	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
January	15.59	36.69	14.83	36.12	14.71	37.47	16.07	37.33	13.55	35.71	14.94	35.65	15.62	37.21
Februar	18.37	37.24	15.72	37.21	18.09	40.88	17.01	37.37	17.88	38.38	18.59	38.81	19.46	36.92
March	22.89	39.85	20.89	39.99	15.79	39.55	21.51	40.02	20.36	39.32	22.34	38.92	21.85	39.67
April	22.88	39.09	23.04	42.10	22.93	39.85	23.16	38.93	24.17	41.08	24.78	38.32	18.44	41.17
May	21.97	35.84	23.29	40.78	21.90	37.80	21.95	37.09	14.83	25.28	24.24	40.01	19.12	40.32
June	20.84	33.55	21.50	36.15	20.56	35.19	20.72	34.33	20.51	33.13	21.97	34.36	19.48	34.55
July	20.32	31.27	20.88	30.19	20.29	29.59	19.74	30.38	19.99	29.44	20.63	31.62	19.67	30.69
August	18.16	28.62	20.05	30.27	19.64	29.63	19.23	29.62	20.22	29.25	20.01	30.15	19.62	29.82
Septem	20.01	34.12	19.39	31.09	18.88	31.07	18.69	31.99	19.67	31.03	19.18	31.96	18.06	31.80
Octobe	19.63	34.84	19.98	33.67	18.84	31.39	18.63	33.45	19.93	33.34	19.21	35.87	19.34	34.98
Novemb	15.30	29.60	14.86	29.50	15.79	36.54	15.61	35.42	13.85	36.87	17.67	37.43	16.25	36.93
Decemb	16.39	36.89	14.43	35.63	15.73	36.38	14.93	36.41	11.09	27.30	15.18	35.60	15.42	35.94
J C														

	2004		2005		2006		2007		2008		2009		2010	
Month	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
January	16.40	35.12	15.71	34.97	17.02	39.32	15.20	34.65	17.40	34.99	15.25	36.76	17.28	37.19
Februar	16.14	35.68	19.81	38.76	19.13	40.17	16.64	37.86	18.56	36.84	20.57	38.34	19.86	38.59
March	17.46	38.57	21.10	38.88	20.45	39.84	21.65	40.29	20.99	40.08	22.22	40.32	21.82	39.60
April	18.68	38.56	25.58	41.50	23.39	40.46	23.32	40.53	24.29	38.38	23.70	40.37	26.00	42.00
May	18.50	37.17	23.22	39.91	21.65	37.05	23.76	39.20	22.89	38.69	23.95	39.75	24.91	38.54
June	18.52	32.65	21.20	34.50	21.00	33.82	21.38	35.40	21.13	35.30	21.73	36.36	21.09	34.19
July	18.17	22.82	20.31	30.62	20.58	31.30	27.93	31.43	19.74	30.51	20.86	31.44	19.61	27.44
August	18.71	30.25	20.25	30.69	20.12	30.08	19.89	29.10	19.81	30.01	20.39	31.14	20.17	30.25
Septem	18.41	32.32	19.93	31.73	18.98	29.33	19.52	31.00	20.22	31.70	19.62	33.75	19.83	31.06
Octobe	17.15	35.09	19.52	34.68	20.01	31.78	19.11	33.26	18.89	33.13	19.37	36.01	19.44	33.76
Novemb	17.40	36.40	16.78	38.15	16.41	33.44	17.29	36.14	15.68	36.35	17.73	37.55	17.00	37.39
Decemb	16.97	35.16	15.06	38.63	15.59	33.01	14.93	36.95	15.26	36.58	16.31	36.55	15.65	36.22
J C														