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Salinity Prediction and Mitigation Measures to Reduce Soil Salinity on Irrigated Land in Awash Basin, Ethiopia

by
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Declaration

I hereby declare to the University of Natural Resources and Applied life Sciences, Vienna that this dissertation is my original work and no material in this thesis has previously been submitted at this or any other university.

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Dedications

*I dedicated this doctoral thesis to my father Kessie Gelaye Gebremariam who passed away in 2000, he was always dreaming to see my academic success (*ቀሴ ገላዬ ገብረማርያም፥ ይህን ባየህ ነበር አባቴ፥ ነብስህን ይማርልኝ። ሲሳክልኝ ያንተን ህልም አስቤ አለቅሳለሁ።*).*

And

*to my mother Enyish Jenber Tashu (*ኧሙሀይ እንይሽ ጀንበር ጣሹ፥ ኑሪልኝ እናቴ*).*

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“Thanks to Almighty God | ለሁሉም ነገር እግዚያብሄር ይመስገን ”

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Abstract

The arid and semi-arid plain areas of Awash basin favored for easy diversion of water for irrigation usage, hence irrigated agriculture is developed in this area than other river basins. However, soil salinity reduces the basin irrigated land productivity. The objectives of this research were to predict soil salinity, to study the influencing factors for the leaching effectiveness and to study remediation crops on saline soil and their effectiveness for remediating salinity. Salinity was predicted with multiple linear regression modeling. The leaching investigation was launched at saline fields varied with soil texture and groundwater depth (1.5–3 m). The leaching requirement levels were 15, 20, 25, and 30% higher than the water loss due to evaporation of the bare field were added for the consecutive four weeks, respectively. The bioremediation experimented with Rhodesgrass, Alfalfa, Sudangrass and Blue Panicgrass (BPG) were grown in saline (3–13.9 dS/m) plots and its biomass regularly incorporated. These plots were supplied addition 15% higher than irrigation water. The salinity tolerance of the crops and its ability to reduce soil salinity, salinity causing ions and modification of soil hydraulic conductivity (HyCo) of each crop were evaluated. The research result shows that, for deeper water table (>1.7 m) situation, sandy loam fields salt was more effectively reduced ($P < 0.05$) than clay loam field. Field with 1.5 m water table shows slightly increased salinity (+2.6 dS/m) after consecutive leaching. Among planted crops, BPG reduces salinity by -3.2 dS/m, as well as ions, and increased bulk density and HyCo. This research concluded that in Awash basin salinity is highly accumulated in sandy loam soils due to shallow water table and to reduce soil salinity in a short period of time leaching is an effective method to mitigate salinity And, BPG bioremediation combined with leaching application effectively reduces soil salinity and maintain soil properties.

Keywords: soil salinity, furrow irrigation, Awash basin, prediction, bioremediation, leaching, Ethiopia

Vorherbestimmung von Salzgehalten und Milderungsmaßnahmen zur Reduktion der Bodenversalzung von bewässertem Land im Awash Becken, Äthiopien

Zusammenfassung

Das aride und semi-aride Flachland des Awash Einzugsgebiets weist eine günstige Lage für Bewässerungslandwirtschaft (BLW) auf, weswegen in diesem Gebiet intensiver als in umliegenden Gebieten bewässert wird. Der durch Bewässerung erhöhte Salzgehalt (SG) reduziert jedoch die Produktivität. Ziele dieser Studie waren, Salzgehalte mittels mult. lin. Regressionsmodelle vorherzubestimmen und Einflussfaktoren für Melioration sowie das Potential von ausgewählten Kulturpflanzen zur Sanierung von Salzböden zu untersuchen. Die Untersuchungen wurden auf salinen Feldern durchgeführt, die sich in Bodentextur und GW-Tiefe (1,5–3,0m) unterschieden. Die erforderlichen Bewässerungsstufen für Leaching auf brachem Feld für 4 aufeinanderfolgende Wochen waren 15, 20, 25 und 30% höher als für Evaporation. Die Bioremediation wurde für Rhodesgrass, Alfalfa, Sudangrass und Blue Panicgrass (BPG) untersucht, welche in salinen Feldabschnitten (3–13.9dS/m) angebaut wurden und deren Biomasse regelmäßig eingearbeitet wurde. Um Perkolation zu steigern, wurden Parzellen mit zusätzlichen 15% Wassergabe versorgt. Die SG-Toleranz der Pflanzen und ihre Fähigkeit den Bodensalzgehalt (BSG) zu reduzieren sowie Veränderungen der hydr. Leitfähigkeit (k) des Bodens wurden für jede Pflanzenart evaluiert. Die Ergebnisse zeigen, dass der SG bei tieferem GW-Spiegel (>1,7m) von sandig lehmigen Böden deutlicher (P<0,05) als von lehmig tonigen Böden reduziert werden konnte. Felder mit einem WS 1,5m unter GOK zeigten leicht erhöhten SG (+2,6dS/m). Unter den angebauten Pflanzen reduzierte BPG den Salz- (auf -3,2dS/m) und Ionengehalt und erhöhte die Schüttdichte sowie k am Effektivsten. Die Untersuchung kam zum Schluss, dass sich Salz bei seichten WS in sandigen Lehmböden stark anreichert und Melioration effektiv ist um BSGe in der BLW im mittleren Awash in kurzer Zeit zu reduzieren. Besonders Bioremediation mittels BPG in Kombination mit Perkolationsbew. reduziert den BSG effektiv und erhält die Bodeneigenschaften.

Schlüsselwörter: Bodensalzgehalt, Furchenbewässerung, Awash Becken, Bioremediation, Perkolation, Melioration, Äthiopien

ጥቅል ሀሳብ: የአፈር ጨዋማነት ትንበያ እና በመስኖ ከሚለሙ ማሳዎች ጨውን ለመቀነስ የሚረዱ ዘዴዎችን መተግበር ፤ በአዋሽ ተፋሰስ ኢትዮጲያ

የደረቅ እና ዝናብ አጠር የአዋሽ ተፋሰስ አካባቢ ሜዳማ ስለሆነ መስኖን በቀላሉ ከወንዙ ጠልፎ ለመጠቀም ቀላል ስለሆን የመስኖ ግብርና በዚህ አካባቢ ከሌሎች የኢትዮጲያ ተፋሰሶች በበለጠ ጥቅም ላይ እየዋለ ይገኛል። ነገር ግን የአፈር ጨዋማነት የመስኖ ግብርናውን ምርታማነት በከፍተኛ ሁኔታ እየቀነሰ ይገኛል። የዚህ ምርምር ዋና አላማ በመስኖ ወቅት የሚከማችን ጨው መተንበይ፥የአፈር ጨዋማነትን በውሀ የማስዎገጃን ዘዴ ስንጠቀም ስለሚያስፈልጉ ወሳኝ ሁነቶችን ማጥናት እና ጨውን በሀይወታዊ ዘዴ ለማስወገድ የሚያስችሉትን እፅዋቶችን በሙከራ ጨውን የማስወገድ አቅማቸውን መለየት ነበር። ጨውን በውሀ የማስወገድ ሙከራው የተካሀደው ከፍተኛ ጨዋማ በሆኑ ሶስት የመስኖ ሜዳዎች ሲሆን ሁሉም በአፈር ይዘታቸውና በመሬት ውስጥ የውሀ ጥልቀት (1.5–3 ሜ) ይለያያሉ። ጨውን ለማስወገድ 15፥ 20፥ 25 እና 30 በመቶ ግልጥ ሜዳው ለትነት ከሚያስፈልገው በላይ መጠን ያለው ውሀ ለአራት ተከታታይ ሳምንታት እንደሚያሰፈልግ ተደርጎ ነው በቅደም ተከተላቸው ለየሳምንቱ የተጨመረው። የስነ ህይወታዊ ዘዴ ምርምር የተካሄደው ርሆደስ ሳር፥ አልፋልፋ፥ ሱዳን ሳር እና ብሉፓኒክ ሳርን ጨዋማ አፈር (3–13.9 ዴሲ ሴመንስ በሜትር) ላይ በማሳደግ ሲሆን በየወቅቱ እየታጨዱ ወደ መሬት በመጨመር ነው። በዚህም ጨዋማው አፈር ላይ በከፍተኛ ደረጃ የሚያድጉት እፅዋቶች የአፈሩ ጤናማነት እንደሚስተካከል ስለሚጠበቅ በአፈር ውስጥ የውሀ ዝውውርን ስለሚሻሻል ለመስኖ ከሚጨመረው 15 በመቶ የሚሆን ውሀ ተጨምሯል ይህም ጨውን በውሀ አጥቦ ለማስወገድ ይረዳል። የዚህ ምርምር ውጤት እንደሚያመለክተው የጨው መጠን በያንዳንዱ የመስኖ ወቅት እየጨመረ ይገኛል። በሌላ በኩል ጥልቅ የመሬት ውስጥ ውሀ (1.7 ሜ. በላይ) እና በአብላጫው አሸዋማ የሆነው አፈር ከሸክላማ አፍር በበለጠ (95 በመቶ የተረጋገጠ) ጨውን በውሀ ለማጠብ ተችሏል። ነገር ግን 1.5 ሜ የውሀ ጥልቀት ያለው ሜዳ ከእጥበቱ በኋላ የጨው መጠን በ2.6 ዴሲ ሴመንስ በሜትር ሊጨምር ችሏል። ይህም የሆነው የመሬት ውሀው ከፍተኛ ጨዋማነት ስላለው ሲሆን ይህ ውሀ መሬቱ ላይ ሲተን ጨው የላይኛው የመሬቱ ክፍክ ስለተከማቸ ነው። ከተዘሩት እፅዋቶች ውስጥ ብሉፓኒክ ሳር ከሌሎች እፅዋቶች በተለየ ጨዋማው ማሳ ላይ ሲያድግ በዚህን የጨውን መጠን በ3.2 ዴሲ ሴመንስ በሜትር ሲቀንሰው፥ እንዲሆም የጨው ንጥረ ነገሮችን፥ የተጠቀጠቀውን አፈር፥ እንዲሁም የአፈሩን የውሀ ዝውውር ሊያሻሽለው ችሏል። ከነዚህ ምርምሮች ለመደምደም እንደተቻለው የመሬት ውስጠዕ የውሀ ጥልቀቱ ከፍተኛ እሰከሆነ ድረስ በአጭር ጊዜ ውስጥ ጨውን በአዋሽ ተፋሰስ ከመስኖ ማሳዎች ለማስወገድ ጨውን በውሀ አጥቦ የማስወገድ ስልት ሁነኛ ዘዴ ነው። በሌላ በኩል ብሉፓኒክ ሳር እና ጨውን በውሀ አጥቦ የማስወገድን ዘዴ በአንደነት በመጠቀም የመስኖ መሬቶችን ጨው ከመቀነሱም ባለፈው የአፈሩን ሁለንተናዊ ጤናማነት ማስተካከል ይቻላል።

መሪ ቃላቶች። የአፈር ጨዋማነት፥ መስኖ፥ አዋሽ ተፋሰስ፥ ስነ ህይወታዊ፥ ጨውን በውሀ አጥቦ ማስወገድ፥ ኢትዮጲያ

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1. Structure of the thesis

This cumulative form of the dissertation consists of eight chapters. A general introduction in chapter 2 elucidates the general overview of the irrigated land soil salinity challenges, potential causes and review the soil salinity mitigation mechanisms in arid and semi-arid parts of Awash Basin, Ethiopia. Chapter 3 mentions the hypothesis and objectives of the whole research. The subsequent chapters 4 to 6 contain three papers articles that two full versions the articles that were published in a scientific journal and the other one is the summary of manuscript that expected to be submitted in a scientific journal, while chapter seven clarifies the framework summary and conclusions for the research as a general and the general references listed in chapter 8.

List of scientific publications in journals that are under Thomson Reuters/SCI Web of Science list, manuscript, and international scientific conference proceeding.

1. **Gelaye K.K**., Zehetner F., Loiskandl W., Klik A., 2019. Effects of Soil Texture and Groundwater Level on Leaching of Salt from Saline Fields in Kesem Irrigation Scheme, Ethiopia. Soil and water research. DOI: https://doi.org/10.17221/137/2018-SWR [SCI]
   (Chapter 4)
2. **Gelaye K.K.,** Zehetner F., Loiskandl W., Klik A., 2019. Comparison of growth of annual crops used for salinity bioremediation in the semi-arid irrigation area. Plant Soil Environ, 65:4. DOI: https://doi.org/10.17221/499/2018-PSE [SCI]
   (Chapter 5)
3. **Gelaye K.K.** et al. Predicting shallow groundwater contributions to irrigated land salinity and leaching strategies at Awash Basin of Ethiopia (Manuscript summery)
   (Chapter 6)
4. **Gelaye K.K.,** Zehetner F., Loiskandl W., Klik A., 2018. Effectiveness of a Leaching Mitigation for Abandoned Saline Fields in Awash River basin, Ethiopia. In: European Geosciences Union General Assembly April 4-13, 2018, Vienna, Austria. Vol. 20: p.15927.

2. General Introduction

Soil salinity is a major problem in arid and semi-arid areas (Smedema and Shiati, 2002; Ahmad *et al.*, 2008; Hasanuzzaman *et al.*, 2014; Hussain *et al.*, 2015). In some developing regions, there are millions of hectares of salinized farmland resulting from poor irrigation practices (Goodin *et al.*, 1990). In irrigated areas, salts often originate from a high saline water table or from salts in the applied water (Ayers and Westcot, 1985). Most irrigation waters contain some salts; consequently, after evapotranspiration takes place the salt is left behind in the soil (Brouwer *et al.*, 1985). Hence, salts are added to the soil with each irrigation application (Ayers and Westcot, 1985). When the irrigation water contains less salt, the soil salinity accumulation will take long years until it affects crop productivity. For instance, in the irrigated area of the semi-arid Awash basin uses less salt contained irrigation water. However, extreme soil salinity mainly developed due to shallow groundwater that enhanced by improper irrigation management. In such areas, salinity accumulation occurs when groundwater is near to the ground surface, capillary up flow results in the movement of water and salts towards the soil surface potentially leading to salt accumulation in the root zone (Northey *et al.*, 2006).

In the eastern and southern arid and semi-arid parts of Ethiopia, nearly 12 million hectares of land are affected by salt (Taddese, 2001), which is mainly caused by natural seepage (Gebrehiwot, 2017), saline groundwater fluctuation due to improper irrigation practices and high percolations from earthen irrigation canals. The Ethiopian rift is characterized by many perennial rivers and lakes occupying volcano-tectonic depressions with the highly variable hydrogeological setting (Ayenew, 2007). Awash River is in the rift valley area and one of the longest flow rivers inside Ethiopia. The Awash River flows entirely in Ethiopia, from the highlands (4195 m) to the arid (semi) and arid flat lowland of Afar depression (210 m). The middle and lower parts of the Awash River basin are characterized by high evapotranspiration, shallow saline water table and lack of natural drainage, and the irrigated lands experienced with salinity.

Kesem is one of the river catchments of Awash basin. Kesem irrigation scheme is located in the middle part of the basin. The flatland of Kesem scheme is located at the edge of the highland. The scheme groundwater table is shallow and inherently contained high salt. A feasibility study on Kesem area showed that the natural seepage of soil salinity is sourced by subsurface volcanic spring flow from the underlying bedrock aquifers, infiltration in the beds of the rivers and after floods over wide areas across the plain (FAO, 1987). All these source waters contributed to the high saline water table, that rises to evaporation zone and the capillary movement accumulates the salinity in the soil surface. For natural seepage and faulty irrigation practices interacted with high evapotranspiration, less precipitation, shallow groundwater table, river bed lateral flows, high percolation from applied furrow irrigation, lack of natural and artificial drainage facilities at the plain area contribute to the groundwater discharge and prompt fluctuation that aggravates the salinity impacts on agricultural productivity.

In the Awash basin, long term salinity mitigation is important for the sustainable productivity of irrigated land. Therefore, this research used soil salinity mitigation mechanisms like leaching and bioremediation. The notion of bio-remediation is to increase the soil organic carbon which in turn increases the soil hydraulic conductivity, reduces bulk density, and transforms free existing sodium ions to the soluble salt and enhances microbial activities of saline degraded land. As the soil properties are modified, that could leach the root zone salt through percolation water. Hasanuzzaman *et al*. (2014) reported that plants having the capability to remove the maximum quantity of salts by producing higher biomass. Bioremediation techniques, a supplement of leaching can be accelerating the salt removal from the root zone. Consequently, this research focused on reclaim saline abandoned fields with leaching plus flushing methods, and the evaluating annual crops which can produce high biomass in high saline soil, by supplementing some extra leaching irrigation water. The produced high biomass by mitigating crop expected to modify the soil physical and chemical properties.

Irrigated lands require the control of soil salinity by means of leaching and drainage of excess water and salt (Beltran, 1999). Leaching-induced soil desalinization method is an effective established method recommended by several authors (Rhoades, 1974; U.S. Salinity Laboratory Staff, 1954; van Hoorn *et al.*, 1969). Among existing salinity mitigation methods, by far leaching is the most effective procedure for removing salts from the root zone of soils (Ayers and Westcot, 1985; Abrol *et al.*, 1988; Oster, 1994). The effectiveness of leaching and application of leaching required surplus water influenced by soil factors and water table depth. Hence, this research also dealt with location-based leaching investigations based on soil texture, at different water table depth which could support the effective leaching mitigations in arid and semi-arid irrigated areas of Awash basin.

3. Hypotheses and objectives

Hypothesis:

This research focused on the two basic irrigated land salinity mitigation mechanisms, called leaching and biological mitigations. The main research hypothesis was assumed,

- The leaching effectiveness potentially influenced by soil texture or depth of the groundwater table,
- Different annual crops vary in growth for different soil salinities,
- There possibly variations among annual crop growth, in soil organic carbon, and accumulations, salinity reduction and modification in soil properties
- Due to shallow groundwater depth, in each irrigation seasons more salts accumulated in sandy loam than clay loam soils.

Research objectives:

- To study the influence of soil texture types and groundwater on the leaching effectiveness (Chapter 4)
- To compare the annual crop growth on saline soil for bioremediation use (Chapter 5)
- To observe the influence of mitigating crop biomass on selected soil properties of saline degraded the land (Chapter 5)
- To predict the topsoil salinity accumulations that potentially influenced the depth of groundwater and applied irrigation water (Chapter 6)

4. Effects of soil texture and groundwater level on leaching of salt from saline fields in Kesem irrigation scheme, Ethiopia[1]

Abstract

In Ethiopia, soil salinity has become a challenge for agricultural production in irrigated arid areas. This research investigates the effectiveness of leaching salt remediation under different soil textures and groundwater tables. Leaching was conducted in the bare parts of three saline abandoned fields. Soil texture of Field1 is sandy loam while Field2 and Field3 are clay loam. The Field1, Field2, and Field3 groundwater were located at 1.8, 1.5 and > 3 m, respectively. The leaching requirement water levels were 15, 20, 25, and 30% higher than the evaporation of bare field needed for four consecutive weeks, respectively. The results of this study show that, after four days of leaching, the salinity of Field1 with sandy loam texture was significantly ($P < 0.05$) and more strongly reduced than for the other fields exhibiting clay loam texture. For Field1, salinity was reduced from 16.3 to 6.2 dS/m and from 12.4 to 5.5 dS/m at depths between 0–30 and 30–60 cm, respectively. In head parts of Field1 and Field3, the salinity level reduced to 2.0 dS/m. However, in Field2 with shallow groundwater and clay loam texture, the salinity levels slightly higher after leaching, i.e. from 11.2 to 12.0 dS/m and from 8.1 to 11.6 dS/m at 0–30 and 30–60 cm depth, respectively. In our experiment, effective leaching was achieved only in the field with sandy soil and the deeper groundwater table. We saw that the application of leaching with surface drainage at shallow groundwater levels may further exacerbate salinity problems. For such situations, the use of subsurface drainage could sustain the groundwater depth and prevent additional salinization. On clay-textured fields with shallow groundwater table, prolonged leaching application is necessary to reduce the salt contents.

Keywords: arid; furrow irrigation; leaching; soil salinity; water

[1] Published as Gelaye *et al.* (2019)
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4.1. Introduction

Awash River basin is the most utilized basin in Ethiopia for irrigated agriculture and hydropower generation (Awulachew *et al.*, 2007). The Awash River flows entirely in Ethiopia, from the highlands (4195 m) to the arid and semi-arid flat lowland of Afar (210 m). Hence, the structure of Afar lowland topography is favoring easy diversion of the Awash River for use in irrigation. As a result, in recent years irrigated agriculture has expanded more strongly in these arid and semi-arid areas than ever before.

However, soil salinity problems have severely compromised the crop productivity of the established dryland areas' irrigation schemes. Lack of a functional drainage system (Taddese, 2001), uncontrolled irrigation practice, and poor irrigation management (Ayenew, 2007), shallow and highly saline groundwater and improper irrigation canal installations (Gelaye *et al.*, 2019) were the main causes of soil salinity problems. It becomes obvious, that in the long run, soil salinity will become a major environmental, economic and social challenge for Ethiopian arid areas' irrigated agriculture. Proper irrigation management and timely salinity reclamation are needed to sustain the productivity of irrigated agriculture in these areas. Otherwise, over time, the salt added to the soil by irrigation water will accumulate in the soil which causes significant crop yield loss. When salinity develops in the crop root zone and exceeds crop salinity tolerance thresholds, yield declines or total crop failure can lead to food insecurity and a severe financial loss on irrigation agriculture investments.

In areas with high evapotranspiration, the accumulation of salinity is high as large amounts of irrigation water are added to the soil every season. For such situations, the scheduled application of leaching or leaching requirement (LR) based on the soil salt content is a way to mitigate soil salinity. Leaching-induced soil desalinization method is an effective established method recommended by several authors (Rhoades, 1974; U.S. Salinity Laboratory Staff, 1954; van Hoorn *et al.*, 1969). Among existing salinity mitigation methods, by far leaching is the most effective procedure for removing salts from the root zone of soils (Abrol *et al.*, 1988; Oster, 1994). Indeed, leaching may be effective to reduce severe soil salinity within a short time. However, for effective leaching remediation, area-based leaching investigations and precise recommendations are required based on soil texture, depth of groundwater table, and soil salinity levels. Field-based studies addressing these issues are crucial for future soil salinity mitigations and provide important input for arid areas' irrigation policymakers to identify irrigated land management options.

The goal of this study was to investigate the final spatial distribution of soil salinity of formerly irrigated, abandoned bare fields with different soil texture and depth of groundwater table, and to determine the effectiveness of leaching using furrow irrigation for the reduction of soil salinity.

4.2. Materials and Methods

4.2.1. Description of the study area

The study was conducted at Kesem River catchment in the middle part of the Awash River basin (Fig. 6.1) which is in the eastern part of Ethiopia. Kesem irrigation scheme is one of the newly established (in 2009) irrigation schemes in middle Awash basin to irrigate 20,000 hectares Sugarcane plantation using furrow irrigation method. However, after ten years of sugarcane production under irrigation, over 200 hectares of the land cannot be cultivated due to high soil salinity accumulation. Before Sugarcane plantation in 2009, most parts of the Kesem scheme have not any irrigation or rained cultivation history. The study area is located between 9°7' to 9°26' N and 40°9' to 40°30'E at elevations ranging from 760 to 850 meters. Soil textures vary from clay loam to sandy loam. Mean soil bulk density is 1.3 g/cm^3 and the root zone soil salinity varies from 2 to ≥20 dS/m. Annual temperature varies from 18 to 41 °C. Mean annual rainfall is about 590 mm and annual evapotranspiration in the area has been estimated at approximately 1800 mm. The Kesem River dam, water is conveyed to the fields by an open primary canal to tertiary canals, and then hydro-flumes discharge the water to the field furrows. In terms of water salinity, the Kesem irrigation water is high-quality water, which originates from the highland areas. The lower stream canal average salinity level of the irrigation water was 0.32 dS/m and the pH was 7.6.

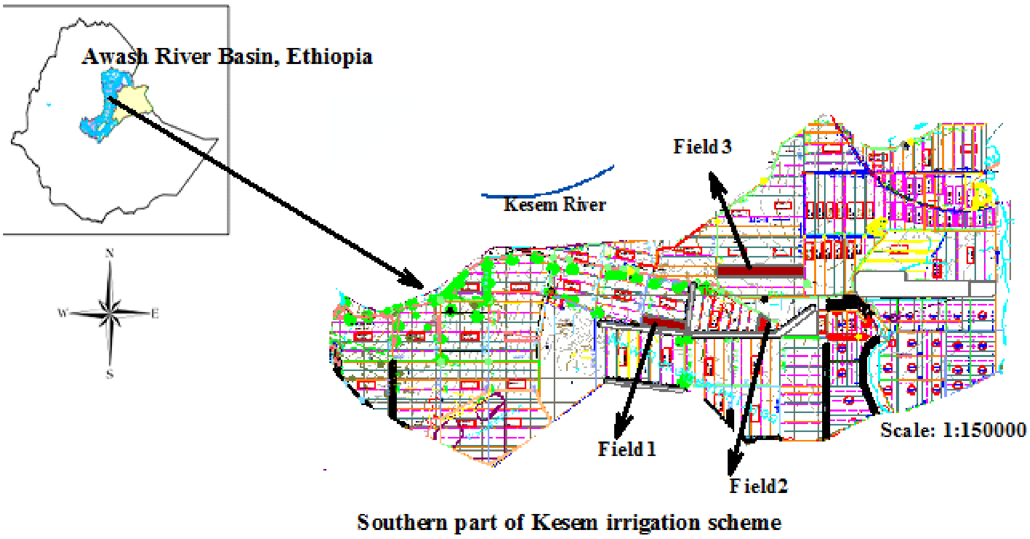

Figure 4.1. Map of the study area in Kesem irrigation scheme; where the three experimental fields are found.

4.2.2. Data collection and methods

Experiment setup and field selection

The study area covers different soil textures with varying groundwater. Field-based experiments were launched at three separate highly saline sugarcane fields, i.e., Field1 (F1), Field2 (F2), and Field3 (F3). These saline fields are found in different parts of the irrigation scheme (Fig. 4.1). Due to high salinity in these three fields, there was no sugarcane grown on some part of the field. The leaching experiments were carried out on these bare areas of the fields.

Table 4.1. Experimental plot soil properties and particle size distribution

Soil Properties		F1	F2	F3
	Texture type	Sandy loam	Clay loam	Clay loam
Particle size distribution (%)	Sand	64	25	27
	Silt	17.5	43	42
	Clay	18.5	32	31
pH		7.3	8.1	7.3
Salinity (dS/m)		16.4	12.0	18.9
Saturated hydraulic conductivity (mm/h)		10.3	6.9	8.7

The soil texture of F1 is sandy loam while F2 and F3 are clay loam. After three continuous irrigation seasons, the groundwater table raised up from 2.8 to 1.8 m for F1 and from 1.7 to

1.5 m for F2. F3 had a deep groundwater table of 2.8 m and no change was detected. For the field measurements, plots of 42 x 42 m, 22 x 32 m and 22 x 22 m were selected for F1, F2, and F3, respectively.

The particle size distribution was determined using a combined wet sieving and sedimentation method (Bernhardt 1994). Saturated hydraulic conductivity was measured in each plot at 30-cm depth using a Guelph permeameter (Soilmoisture Equipment Corp, 2012). Both soil pH and electric conductivity (EC) were measured using HI 991300 (HannaInstruments, 2000). The main soil properties of these plots are presented in Table 4.1.

A one-meter-deep trapezoidal surface drainage ditch was excavated and used as a temporary drainage outlet (Fig. 4.2). This procedure was adopted because the excavated soil was used to form a ridge at the end of the field to prevent uncontrolled water outflow and to enhance prolonged ponding. Impermeable plastic has placed on the ditch canal surface, to prevent percolation at the ditch and for precise drainage water depth measurement.

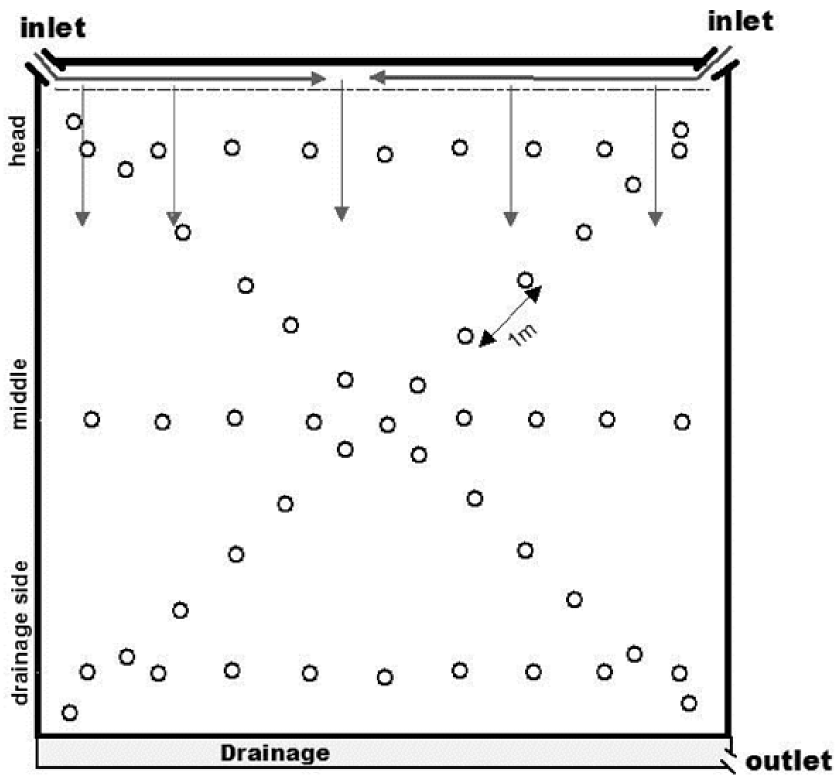

Figure 4.2. The layout of the experimental plots. The water distribution in the plot represented by arrows and the circles represent the location of the soil sampling points.

To cover the entire high ridge (40 cm deep) furrow field with water, accelerate the leaching process and flush the surface accumulated salt efficiently, the fields' high ridge furrows were demolished (Fig. 4.5). The depth of incoming water to the experimental fields and of outgoing drainage water was measured using Parshall-flumes. To detect the groundwater table level during the experiment, piezometers were installed at the center of the experimental fields.

Salinity measurement and leaching requirement estimations

In addition to the soil salinity levels, the leaching requirement (LR) estimation depends on the irrigation methods. For furrow irrigation, Savva and Frenken (2002), recommend about 10-30% more irrigation water than needed by the crops to be applied for leaching purpose.

For LR and total applied water determination, the experiment site's seasonal evaporation (E) was considered. The leaching experiment has done on bare land, and, hence, the crop coefficient was not included for LR estimation. The leaching experiments were conducted from June to August. The seasonal evaporation was estimated with the pan evaporation method (Penman, 1948) to about 1800 mm/season and there was no rainfall event recorded a week before and during the experiments. The total applied water (AW) per season was estimated according to (Ayers and Westcot, 1985):

$$\mathrm{AW\ (mm/season)} = \mathrm{ET}/(1 - \mathrm{LR}) \qquad (1)$$

However, the bare soil's AW was estimated base on the seasonal evaporation as,

$$\mathrm{AW\ (mm/season)} = \mathrm{E}/(1 - \mathrm{LR}) \qquad (2)$$

The practiced irrigation schedule at the experimental site is one time per week. In this experiment, each irrigation day's applied water is estimated from seven days (Eq. 2) of the estimated total applied seasonal irrigation water.

As soil properties do not directly affect the LR (Corwin *et al*., 2007), we used the same LR value for the three fields. LRs of 15, 20, 25, and 30% of the evaporation were considered, resulting in LR values of 0.13, 0.17, 0.2, and 0.23, or 40, 42, 43, and 45 mm surplus water during four consecutive weeks (Table 4.2). After total applied water was estimated, four days of leaching application were conducted for four consecutive weeks, i.e. one day per week. Additionally, on the second day of leaching, extra 15 mm water was supplied for flushing.

Table 4.2. Estimated applied water (same values used for each experiment plot)

Period	Soil Evapo. (mm/season)	Leaching requirement	Total Applied Water (mm/week)
Period1 (1-7 days)	1800	0.13	40
Period2 (7-14 days)	1800	0.17	57 = 42+15(flushing)
Period3 (14-21 days)	1800	0.20	43
Period4 (21-28 days)	1800	0.23	45

Disturbed soil samples were collected using an auger before and immediately after the experiment at depths of 0-30 cm and 30-60 cm. The field layout of soil sampling is shown in Figure 4.2. From five transects soil samples were taken along each line in 1 m distance. The quantity of drainage water and its salinity content (EC_{dw}) were measured using a portable EC measuring device in 1:5 soil/water ratios. The portable EC device capable of measuring a maximum range from 0 to 3.999 dS/m; however, the salt was diluted using a 1:5 soil/water ratio, hence, the salinity reading was multiplied by five and the device's maximum measuring range extended to 20 dS/m.

4.2.3. Data analysis

One-way analysis of variance (ANOVA) was performed and comparisons of means were conducted using Tukey's post-hoc test ($p < 0.05$) with SPSS 20 (IBM Corp, 2011).

4.3. Results

4.3.1. Salinity reduction and distribution after leaching

After four days of leaching, a substantial amount of salt was removed from the root zones of F1 and F3 (Table 4.4). However, F2 with a shallow groundwater table showed little effect in the topsoil and even a salinity increases in the subsoil after days of water ponding. While the groundwater table was the main determinant factor for effective leaching, soil texture also affected leaching efficiency. For the sandy soil (F1), average salinity decreased from 16.3 to 6.2 dS/m at depth of 0-30 cm and from 12.4 to 5.5 at depth of 30-60 cm. The less salt reduction was observed for the clay loam of F3 where salinity decreased from 19.0 to 12.3 dS/m and from 13.3 to 8.7 dS/m at depths 0-30 and 30-60 cm, respectively (Fig. 4.3). The salinity extent is shown in Figure 4.3. In some parts of F1 and F3, the salt levels were strongly reduced (down to 2 dS/m) by the employed leaching treatment. Generally, more salt was removed from the sandy soil, and from the top part of the soil rather than from the lower depth.

Table 4.3. Mean soil salinity distribution after leaching (mean±SD), at three parts of each plot with 0-30 and 30-60 cm depth

Part of the field	F1 Salinity (dS/m)		F2 Salinity (dS/m)		F3 Salinity (dS/m)	
	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
Head	5.5±2.2[a]	5.2±2.7[a]	14.0±6.5[a]	14.1±5.9[a]	14.3±5.7[a]	11.9±7.9[a]
Middle	5.3±2.2[a]	6.6±3.8[a]	11.8±5.1[a]	11.2±3.9[a]	13.1±4.1[a]	7.8±3.8[a]
Drainage	7.7±2.7[b]	4.8±1.8[a]	8.3±5.3[b]	7.1±3.7[a]	9.1±4.9[a]	6.0±3.0[a]

Means followed by the same letter represent non-significant difference among the part of one field (P < 0.05 level).

The initial salt concentration in the soil was extremely high in all plots. It ranged between 5.2 and 20 dS/m in F1, between 1.3 and 20 dS/m in F2 and between 13.5 and 20 dS/m in F3. After the leaching application, significantly less amount of salt was detected in 0-30 cm depth at the drainage side of F2 (Table 4.3). On the other hand, high salinity accumulation was detected in the head part of F2 (0-30 cm depth), after leaching. However, there was no significant salt accumulation at both depths for F3 and at 30-60 cm for F1 and F2.

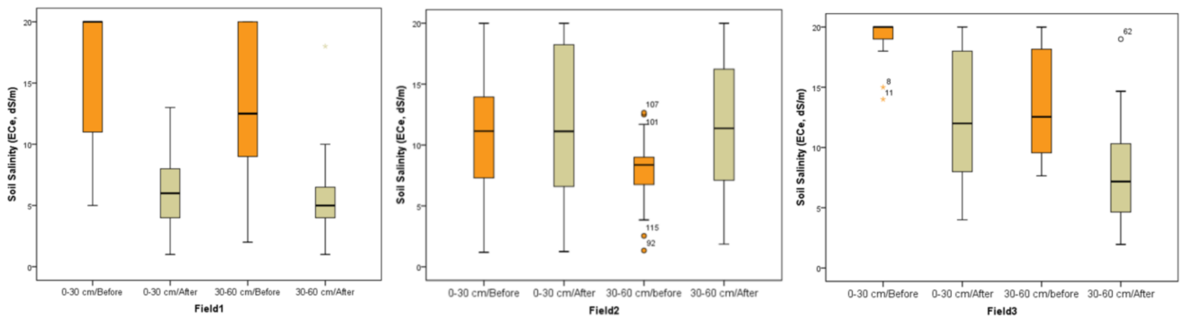

Figure 4.3. Soil Salinity distribution before and after the leaching remediation at 0-30 cm and 30-60 cm depth.

In the Kesem irrigation scheme, due to high salinity accumulation in the middle part of the field, the sugarcane plants often show stunted growth and late drying. Indeed, there is no functional drainage for irrigation farming in the Kesem scheme, but there are other ways of salinity level reduction/distribution in the fields. Surface irrigation water may run off over the ridge at the drainage side, which happens during over-irrigation events. This reduces the salt load on the drainage side of the cropped lands. On the other hand, salt from the head side of the fields is washed by the incoming irrigation water, which is less in salt content, compared to the middle part of the fields.

Table 4.4. The effectiveness of leaching for the three different fields

Plots	Salinity before leaching (dS/m)	Salinity after leaching (dS/m)
F1	**14.4[a]**	**5.8[a]**
F2	**9.9[b]**	**11.8[b]**
F3	**16.2[c]**	**10.1[b]**

Means followed by the same letter represent non-significant difference at the $P < 0.05$ level.

4.3.2. The implications of high-ridge furrows on salinity decrease and uniform water distribution

For F1, after the high ridge molding furrow (40 cm) was demolished combined with surface water flushing at the beginning of leaching day two, a high amount of salt was removed from the soil profile and carried away with the drainage water (Fig. 4.4). Hence, the depth of applied non-saline water (0.32 dS/m) increased from 39 mm at the first leaching day to 57 mm on the second leaching day (Fig. 4.4). On the second leaching day, 15 mm extra water was supplied to compensate for the surface flushing water. This provided an opportunity to dissolve and transport more salts from the top layer of the field to the ditch through flushing. As a result, for F1 and F3 salinity was decreased rapidly. The water distribution with and without the high ridge furrow is shown in Figure 4.5. The demolition of the ridge helped to submerge the surface of the field with water and to promote uniform distribution of water to the entire plot and deep percolation. After demolishing the furrow, the EC of the drainage water was ≥20 dS/m on the second leaching day (Fig. 4.4). This salt load flushed out before it could infiltrate into the soil profile. The remaining leaching water (4.2 cm) stayed ponded to down percolate and some amount drained through the ditch. With this flushing and draining, the F1 salinity level of the soil declined from 15 to 9.2 dS/m at 0-30 cm and from 13.2 to 11.0 dS/m at 30-60 cm depth. After this, the soil salt levels further declined through the fourth day of leaching. Indeed, as a high amount of drainage water flowed out from the plot, the drainage water salinity concentration declined fast over the leaching days (Fig. 4.4).

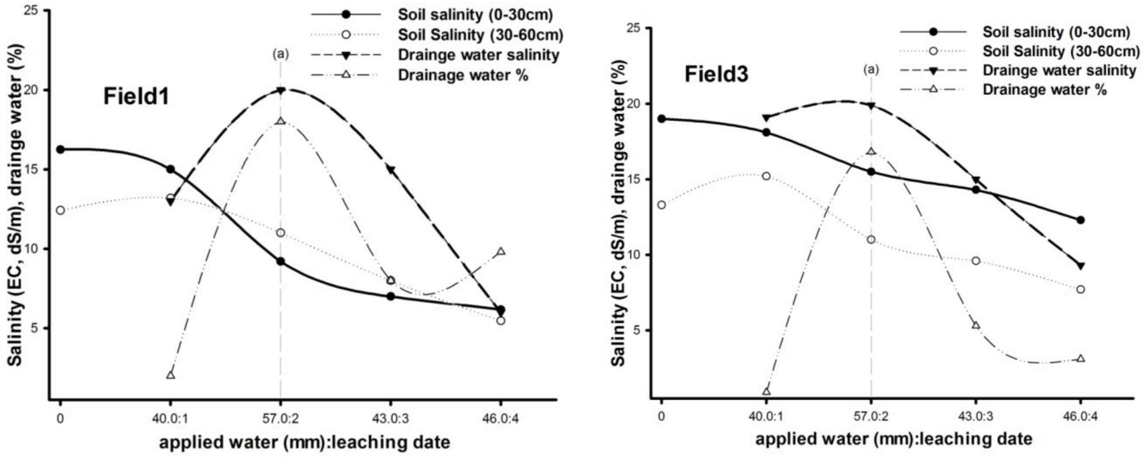

Figure 4.4. Effect of flushing and sequential application of surplus water on drainage water carrying salt (ECdw, dS/m) and a temporal decrease of soil salinity. Line (a) at leaching day two represents the time of furrow demolishing and extra flushing.

4.4. Discussion

With the tested leaching method, unproductive abandoned saline land could be reclaimed back into the productive land. Effective leaching was observed at fields with deeper groundwater table, especially when soil texture was sandy. After leaching, soil salinity levels were reduced to as low as 2 dS/m in some parts of F1 and F3. Such significantly reclaimed parts of fields have turned into promising productive land to grow even moderately salinity-sensitive crops like sugarcane, maize, alfalfa, and others. In a furrow irrigation field experiment, Devkota *et al* (2015) found a comparable result, in which salts were reduced to less than 3 dS/m after three to four leaching events. According to Ayers and Westcot (1985), this level of soil salinity (2 dS/m) could increase the yield potential of sugarcane by 90 percent without consideration of other crop production constraints. According to the above authors, the overall yield potential for sugarcane production in the reclaimed fields of our study was improved from 0 to 75 percent for F1 and to 50 percent for F2 considering the post-leaching overall salinity level.

Figure 4.5. Leaching water distribution before (A) and after (B) furrow ridge demolition.

The experimental fields of this study experienced extremely high salinity. To reclaim these fields in a deeper groundwater situation, a large amount of leaching water and continuous leaching application is needed to promote salt leaching from soil (Heidarpour *et al*., 2009). In F1, the salt content of the drainage water was rapidly increased along with the increase in drainage water amount until a certain period. This is because a sequential application of leaching water is important to allowing time for the soil to drain after each application (Ali, 2011). However, on the last leaching day of our experiment, the drainage water salinity was reduced again as the applied water and drainage water increased.

Although the groundwater table depth threshold may vary depending on soil hydraulic properties and climatic conditions (Rengasamy, 2006), our result shows that the employed procedure involving sequential days of ponding worked only for fields with more than 1.8 m groundwater table. If the groundwater table is too close (in our case F2), the leaching technique may bring adverse effects of increasing salinity. This happens through the upward movement of shallow saline groundwater and its subsequent evaporation at the surface (Ayars *et al*., 2011). In other recent studies, salt accumulation due to groundwater table rise was high in the absence of an efficient irrigation drainage system (Nabiollahi *et al*., 2017). It is therefore important that subsurface drainage systems are installed to control groundwater uprising before irrigation application and leaching treatments (Savva and Frenken, 2002). As shown in Figure 4.6, there is an indication of groundwater rising in F2 of our experiment, because after leaching treatment, the salinity level of the subsoil (30-60 cm) was approaching that of the topsoil (0-30 cm). Usually, with no rise of groundwater, higher salinity levels were found in the topsoil. In the lower and middle Awash basin, over-irrigation has indeed caused shallow groundwater fluctuations, which have contaminated productive irrigated lands.

For the high salinity situation of our study area, leaching combined with surface runoff flushing seems to be a promising strategy to decrease salinity problems, because flushing supports the removal of salts from the soil surface by runoff and overland flow (Ayers and Westcot, 1985). If the water is not flushed the surface crusted salt, the ponding water will transport the high salinity of the topsoil to the lower profile, and this will require prolonged leaching application, which, in turn, could raise the groundwater table rendering the treatment ineffective.

Leaching efficiency has been shown to vary with soil texture (Van Hoorn, 1981). The results of our experiment show that the light (sandy loam) soil of F1, which had the highest saturated hydraulic conductivity was more effectively and significantly reclaimed than the heavy (clay loam) soils of F2 and F3.

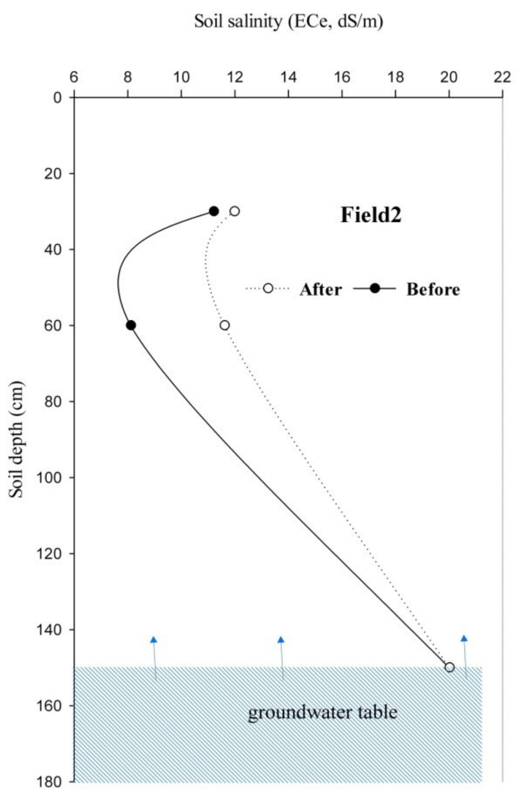

Figure 4.6. Leaching technique for the field with shallow-groundwater table field and its effect on soil salinity accumulation.

Several factors have been shown to influence the leaching reclamation of saline fields, including soil and irrigation water salinity levels, groundwater table of the land, irrigation application methods and time of water application (Corwin *et al.*, 2007; Ayars *et al.*, 2011). In addition to these main factors, we recognized through our experiment that leaching efficiency could be strongly enhanced through certain field structural conditions. For larger-scale field application of leaching treatments with furrow irrigation, gently sloping fields and low ridge furrow depths are advantageous. During our experiment, salt was depleted exponentially after the high ridge furrow was demolished for F1 and F3, and the temporal measurements showed that the salinity level of the drainage water was high after furrow demolishing. Meanwhile, high saline leachate management will sustain the reclaimed land. Otherwise, the leachate water brings a challenge for downstream irrigation users and high saline groundwater may rise up, as currently observed in Awash basin, the *Gewane* swampland expansions, and the growth of Lake *Beseka* (Gelaye *et al.*, 2018).

4.5. Conclusions

In this experiment, groundwater depth we the main factor for effective leaching; soil texture also affected leaching efficiency. With the tested leaching technique with surface drainage, two of the three experimental fields were reclaimed from degraded land to marginally productive land. However, fields with shallow groundwater table showed slightly salinity increment after leaching. For shallow water table situations, subsurface drainage may be an option for effective salt remediation. On the other hand, effective leaching (per applied surplus water) was achieved field with sandy loam soil than clay loam fields. In this case for clay loam fields with deeper groundwater, prolonged leaching application needed. In the Kesem scheme, middle parts of the long-term irrigated fields were more salt-affected. After leaching the drainage part sandy loam field shows less salt than the middle and head parts. Generally, the special salt distribution of long-term irrigated fields without drainage system and leached fields with surface drainage were did not shown similar salinity distribution. Sustainable irrigation practice requires that the highly saline leachate water be collected through drainage systems, and either properly disposed or re-used to irrigate salt-resistant crops. This study concluded that immediate relief of salinity-induced productivity loss, leaching and flushing techniques, appears to be an effective method in tackling irrigated agriculture constraint in Middle Awash irrigation schemes.

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5. Comparison of growth of annual crops used for salinity bioremediation in the semi-arid irrigation area[2]

Abstract

The decline of soil organic carbon (SOC) has aggravated salinity-related problems in semi-arid irrigation areas of Awash River basin, Ethiopia. The aims of this study were to evaluate the performance of potential remediation crops on saline soil and their effectiveness for remediating soil salinity and improving pH, SOC, bulk density (BD) and hydraulic conductivity (HyCo). Rhodesgrass (RHG) Alfalfa (ALF), Sudangrass (SUG) and Blue Panicgrass (Retz) (BPG) were grown in saline (3-13.9 dS/m) field plots. The crop biomass was incorporated into the soil immediately before flowering. The results show that at high soil salinity levels, BPG and SUG grew well, with the harvesting frequency of BPG being much higher than for SUG. Conversely, the growth of ALF and RHG was strongly inhibited by high soil salinity. Significant ($P<0.05$) reduction of soil salinity levels (-3.2 dS/m) and related ionic concentrations, an increase of SOC (0.8 to 1.6%) and improvement of BD and HyCo were observed in BPG plots. The fast-growing nature of BPG in the hot climate of the experimental area resulted in harvests every three weeks and promoted the incorporation of high amounts of biomass to the soil and efficient soil salinity remediation. At moderately saline conditions, ALF also showed great potential for salinity reclamation (-1.8 dS/m) and SOC accumulation. The cultivation of fast-growing annual crops proved an efficient and low-cost strategy for soil salinity mitigation and the reclamation of salinity-associated soil degradation in irrigation agriculture in Ethiopia.

Keywords: salt tolerance; arid conditions; drought; land degradation; forage

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5.1. Introduction

Soil salinity is a major constraint in arid and semi-arid agricultural production. Soil salinity problems are more severe in situations where inadequate irrigation drainage leads to salt accumulation in the soil (Hanin *et al.*, 2016). In the eastern and southern arid and semi-arid parts of Ethiopia, nearly 12 million hectares of land are affected by salt (Taddese, 2001). Compared to other Ethiopian rivers, the Awash River is the river most used for irrigation purposes. However, due to rapid salt accumulation, Awash River irrigation farms were losing between 200 and 300 hectares of cultivated land annually (Behnke and Kerven, 2011). Lack of functional drainage systems, poor irrigation management, shallow groundwater fluctuation (Taddese, 2001), improper irrigation canal installations and continuous loss of soil organic carbon (SOC) in mono-cropping fields are the main causes for salinity and land degradation in Awash basin.

The large-scale Awash basin irrigation schemes are cultivated with commercial cash crops, such as cotton and sugarcane. The commercial crops have been cultivated for years with mono-cropping methods. Such practice caused a decline in soil organic carbon in the irrigated fields, which, in turn, led to structural degradation and increased the risk of soil salinity and sodicity. Beyond the irrigation farmlands, in Awash basin overgrazing and unexpected droughts have had a negative impact on soil (Taddese, 2001). Nowadays, low SOC contents, high sodicity, and salinity have degraded the grazing land ecosystems and favored opportunistic invasive species in arid areas of the basin. This poses ecological challenges, cultural and socio-economic for the pastoralism of the Afar people.

The use of bioremediation for irrigated and grazing lands may constitute a vital strategy for sustainable agriculture. Fast-growing and salt resistant crops may be planted on fallow irrigated land or inter-planted for animal feed or salinity bioremediation. A study by Wong *et al.* (2009) showed that the addition of organic material to saline soils resulted in increased soil microbial biomass and enhanced the decomposition and conversion of plant biomass into SOC. Especially, the entire plant biomass regularly incorporated into the soil at an early growth stage will heighten the accumulation of SOC and promotes the restoration to crop favorable soil bulk density and hydraulic conductivity. Accumulation of SOC near the soil surface was shown to improve soil hydraulic properties (Benjamin *et al.*, 2007), (Ammari *et al.*, 2013), thus promoting drainage and favoring the leaching of accumulated salts.

An essential prerequisite for devising salinity mitigation strategies using bioremediation is the identification of plants that are salt-tolerant and fast-growing under given environmental conditions. Therefore, this field study was conducted to compare the performance and mitigation efficiency of four annual crops with potential for forage production on saline fields in Ethiopia. The aim was to identify the crop(s) with highest biomass production rate under saline conditions and evaluate their potential for soil salinity reduction and improvements of basic soil properties, such as pH, SOC, bulk density and hydraulic conductivity.

5.2. Materials and Methods

5.2.1. Study area

Kesem River is one catchment in the middle part of the Awash River basin in Ethiopia (Fig. 5.1). This research was conducted at Kesem irrigation scheme, which is located at 9°8’54.8” N and 40°1’6.57” E and at an elevation of 770 m above sea level. According to the world reference base, the excremental soil grouped to Fluvisols (IUSS Working Group WRB. 2015). The soil texture of the experimental field was sandy loam and Mean soil bulk density was 1.3 g/cm^3. The groundwater table is at 2.8 m below the soil surface. Annual temperature varies from 18 to 41 °C. Mean annual rainfall is approximately 590 mm. The salinity of the irrigation water was 0.32 dS/m, the pH 7.6. The mean soil salinity of the experimental plots varied 3.0-16 dS/m and soil pH was 7.7.

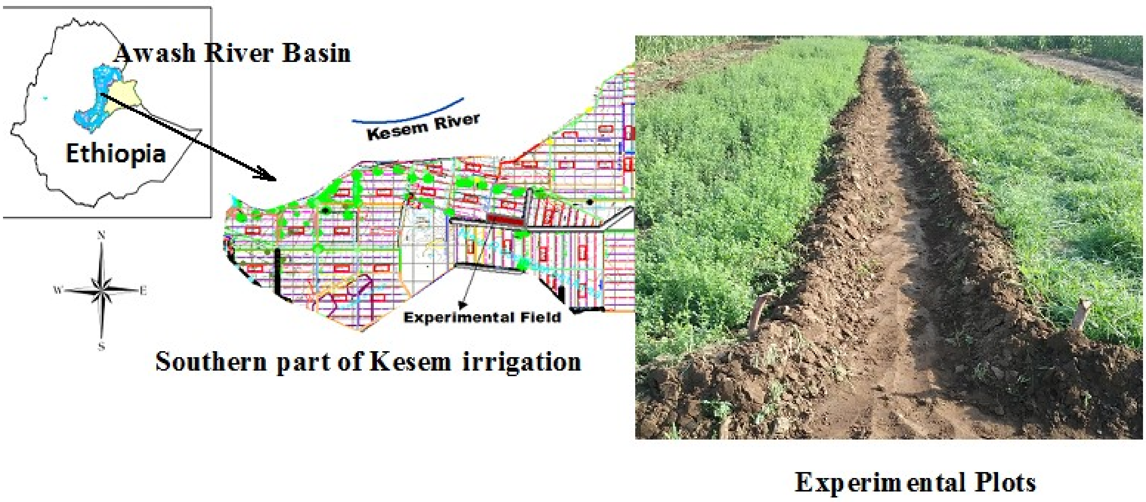

Figure 5.1. Map of the study area in the southern part of Kesem irrigation scheme.

5.2.2. Data collection and methods

Experimental Setup

The experiment was arranged in a randomized complete block design with three replications. Fast-growing annual crops were used for this experiment: (1) Rhodesgrass (RHG) (*Chloris gayana*), (2) Alfalfa (ALF) (*Medicago sativa*), (3) Sudangrass (SUG), *(Sorghum × drummondii*), (4) Blue Panicgrass (BPG) (*Panicum antidotale*, Retz), and (5) an open bare field/control. Hence, a total of 15 experimental plots were established. The size of each plot was 3 m width and by 33 m length. The experimental crops were densely planted in early Feb. 2016 and grown until end of July. 2017. An equal amount of irrigation water was supplied to each planted plot using a surface irrigation method and a surface drainage ditch was established across all experimental plots. No soil fertilization was used. weeds ware removed manually every week, however, during the experimental season neither plant diseases nor pests were observed. During the experimental seasons, fresh plants biomass was cut before flowering, chopped manually (3–5 cm) and immediately after harvesting incorporated into the soil (at 0–20 cm depth). Plant dried biomass was determined by weighing the total air-dried above ground biomass yield.

Soil properties measurement

Soil sample prior to seed sow (Initial) and sampling after two months of the final biomass incorporation (Final) was taken from 0-30 and 30-60 cm soil depth. Each experimental plot of disturbed composite soil sample was prepared out of four soil probes. Soil salinity ($EC_{1:5}$) and $pH_{1:5}$ were measured at a 5 g/25 ml soil/water ratio (Khorsandi and Yazdi, 2011). The soil SOC was oxidized with 1N potassium dichromate ($K_2Cr_2O_7$) solution and determined according to Walkley and Black (1934). For soluble cations and anions, soil samples were extracted at 1:2 soil/water ratio. In the extract, Mg^{2+} and Ca^{2+} were determined by titration with disodium dihydrogen-ethylenediaminetetraacetate (EDTA) (Tucker and Kurtz, 1960) and Na^{+} and K^{+} were measured by the flame photometric method (Woldring, 1953). The anions CO_3^{2-} and HCO_3^{-} were determined by titration with H_2SO_4. Chloride was determined by titration with $AgNO_3$, and SO_4^{2-} was determined gravimetrically after precipitation with $BaCl_2$. For each plot, (*in-situ*) saturated hydraulic conductivity was measured using a Guelph permeameter (Soilmoisture Equipment Corp, 2012). For soil bulk density, undisturbed soil core samples were taken with cylinders and oven-dried to constant mass (McIntyre and Loveday, 1974).

Soil property improvement was expected through mitigation effects of the tested crops, supported by salinity removal with the irrigation water; approximately 15% of the irrigation water was applied as surplus leaching water to the experimental plots (0.13 estimated required leaching water). The leachate water was drained through the established surface drainage or down-migrated to the groundwater.

5.2.3. Statistical analysis

One-way analysis of variance (ANOVA) was performed and comparisons of means were conducted using Tukey's post-hoc test ($p < 0.05$) with R (R Core Team, 2018).

5.3. Results

5.3.1. Crop performance on saline soil

The growth performance of the tested mitigation crops was visually examined at regular intervals. Among the four mitigation crops planted, BPG and SUG performed well regardless of the soil salinity level of the experimental plots. However, ALF and RHG showed poor tolerance at higher soil salinity levels. BPG was evaluated at medium to high salt contents (4.3-13.9 dS/m), but the growth performance was slightly affected by higher salt levels (Fig. 5.2). Conversely, at more saline plots, RHG and ALF showed stunted growth and large parts of the plots were uncovered by vegetation (Fig. 5.2). Nevertheless, RHG at 3.4 dS/m and ALF at 3.0 dS/m showed dense growth, similar to BPG. After 1.5 months growth establishment, BPG started growing fast with high numbers of tillers and its height reached 1.5 m; its fresh biomass could be incorporated into the soil every three weeks. However, for RHG, ALF, and SUG, the required growth periods until biomass incorporation were extended beyond a month.

Figure 5.2. Crop performance evaluation at different soil salinity levels.

5.3.2. Effect of crops biomass on soil SOC, Bulk Density and hydraulic conductivity

The significant ($P<0.05$) amount of biomass was shown in BPG plant than ALF and RHG plants (Fig. 5.3). As a result, BPG caused a strong increase in SOC down to 60 cm depth (Table 5.1). Per harvesting 7.5 t/ha dried biomass was continuously incorporated into BPG plots, and cumulatively SOC increased by 100%. ALF and RHG plants had incorporated smaller biomass and accumulation less SOC than BPG because the germination, growth, and biomass of these two crops were compromised in highly saline plots. On the other hand, the produced biomass SUG plant was slightly higher than ALF and RHG. Meanwhile, in the bare soil of the control, SOC declined by 0.1% (Table 5.1).

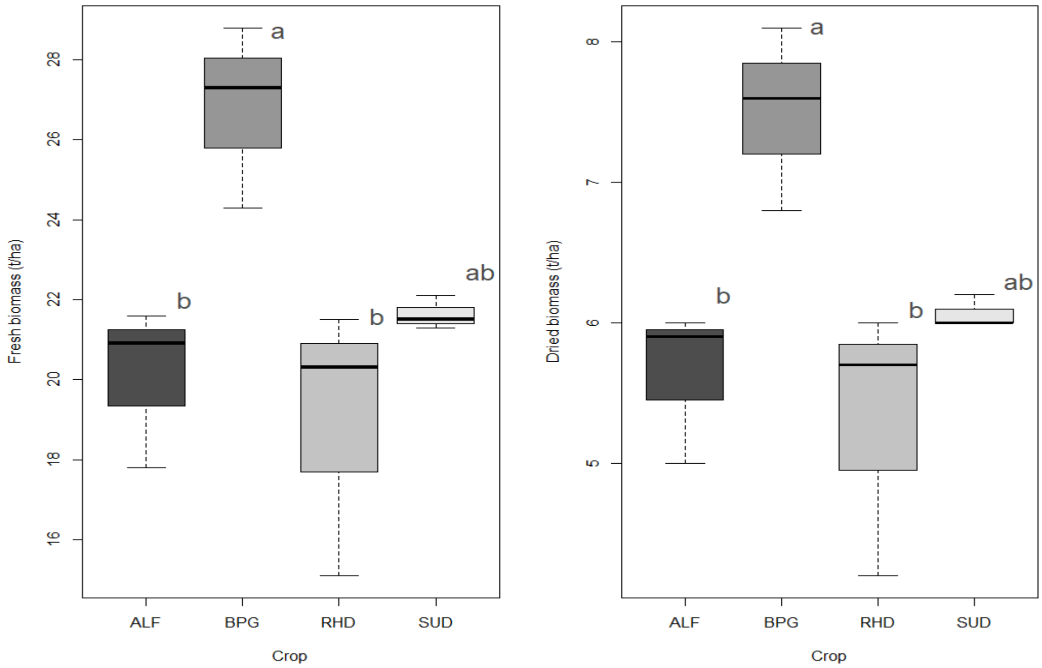

Figure 5.3. Incorporated aboveground plants fresh and dried biomass mean comparison. Different letters indicate a significant difference between treatment means at P < 0.05. RHG – rhodesgrass; SUG – sudangrass; BPG – blue panicgrass; ALH – alfalfa; CRL – control

The planted mitigation crops led to decreases in soil bulk density, especially in BPG and SUG plots (Table 5.1). These changes were most pronounced in the upper layer (0-30 cm), but for BPG and SUG, they were also discernable at 30-60 cm soil depth. Also, saturated hydraulic conductivity was enhanced by the tested mitigation crops, most notably in the BPG plots (Table 5.1).

Table 5.1. Initial (prior to crop planting) and final soil physical properties (after the experiment) (mean ± standard deviation; n = 4).

Depth (cm)/Crop	Organic carbon (%)		Bulk Density (g/cm^3)		Saturated hydraulic conductivity (Kfs, mm/h)	
	Initial	Final	Initial	Final	Initial	Final
0-30					**0-40 cm**	**0-40 cm***
RHG	0.9±0.1	1.3±0.5^{ab}	1.3±0.1	1.2±0.1^{ab}	4.8±1.4	5.8±1.3^{a}
SUG	0.9±0.1	0.9±0.2^{b}	1.4±0.0	1.1±0.1^{ab}	4.5±2.3	5.9±1.0^{a}
BPG	0.8±0.1	1.6±0.1^{a}	1.4±0.1	1.0±0.0^{a}	7.0±2.2	9.2±0.4^{b}
ALF	0.7±0.1	1.2±0.4^{ab}	1.4±0.0	1.2±0.1^{ab}	8.0±1.6	9.0±1.4^{b}
CRL	0.8±0.2	0.7±0.2^{b}	1.3±0.1	1.3±0.1^{b}	6.0±1.5	6.3±1.6^{a}
30-60						
RHG	0.6±0.2	0.7±0.2^{ab}	1.2±0.2	1.0±0.0^{a}		
SUG	0.5±0.1	0.5±0.1^{b}	1.3±0.2	1.0±0.0^{a}		
BPG	0.5±0.2	1.1±0.3^{a}	1.3±0.1	1.0±0.0^{a}		

ALF	0.6±0.2	0.8±0.4[ab]	1.3±0.1	1.0±0.0[a]
CRL	0.6±0.1	0.6±0.1[b]	1.2±0.1	1.0±0.0[a]

* measured soil depth using permeameter. Different letters indicate a significant difference between treatment means at P < 0.05. RHG – rhodesgrass; SUG –sudangrass; BPG – blue panicgrass; ALH – alfalfa; CRL – control

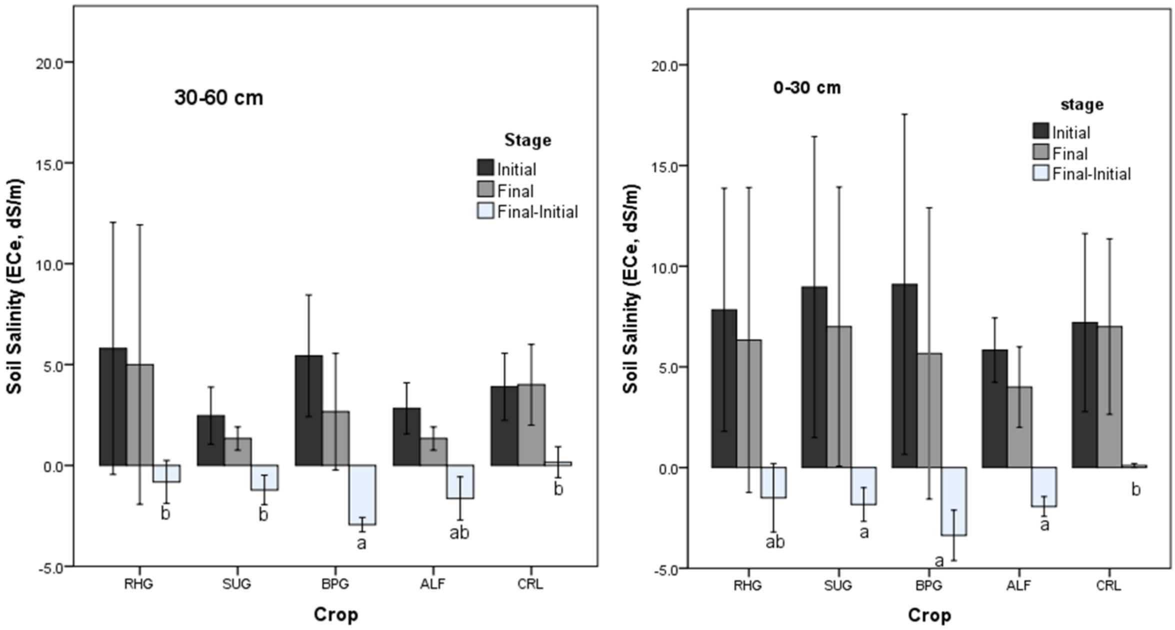

Figure 5.4. Initial and final soil salinity and changes from initial to final. Error bars represent standard deviation. Different letters indicate a significant difference between treatments at P < 0.05 using LSD F-test. RHG – rhodesgrass; SUG –sudangrass; BPG – blue panicgrass; ALH – alfalfa; CRL – control

5.3.3. Changes in soil salinity and pH

Our results show that salinity was substantially reduced at both depths in all planted plots (Fig. 5.4), while except in control plots, soil pH showed a slight increase with salt reduction (Fig. 5.5). The observed salinity reduction ranged between 1.5 and 3.4 dS/m (Fig. 5.4) and was most pronounced for BPG, which was able to significantly reduce soil salinity also in 30-60 cm soil depth. Among the investigated crops, the minimum salt reduction was observed for RHG. In the top part of the root zone (0-30 cm), salinity reduction was higher than in the lower part (30-60 cm) (Fig. 5.4). Before the experiment, salt was predominantly accumulated at the top layer of the soil, but after the experiment, the differences between upper and lower depth decreased.

For soil pH, the final pH result showed highly significant (P<0.01) variation between the tested crops and control field at 0-30 cm and 30-60 cm depths (Fig. 5.5). However, insignificant pH variations were observed among mitigates plants. Differently, from the control plots, the pH increased in all planted plots as salt content was reduced during the experiment.

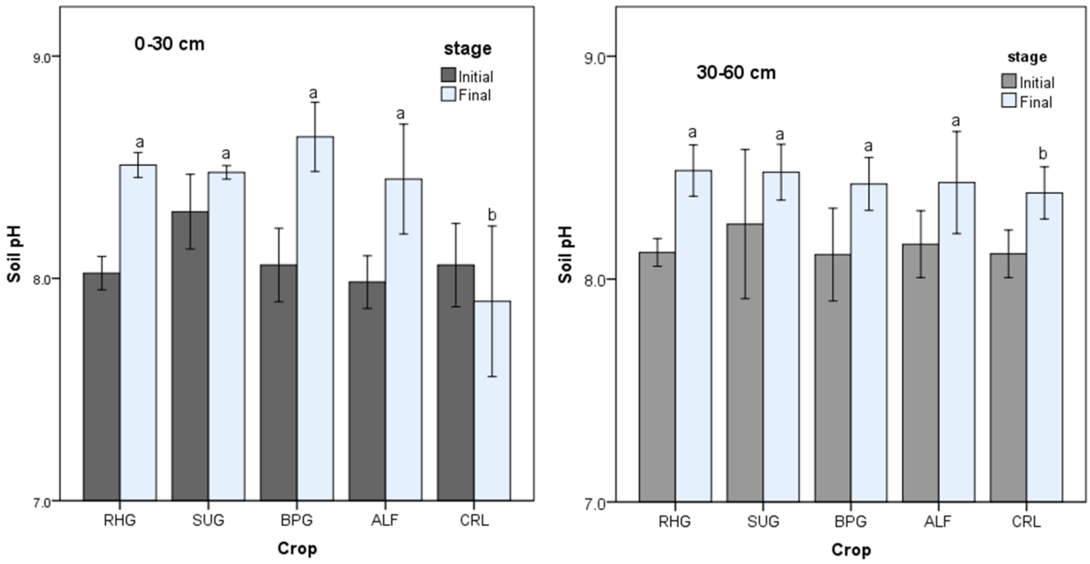

Figure 5.5. Initial and final soil pH. Error bars represent standard deviation. Different letters indicate a significant difference between treatments at P < 0.01 using LSD F-test. RHG – rhodesgrass; SUG – sudangrass; BPG – blue panicgrass; ALH – alfalfa; CRL – control

5.3.4. Changes in soluble saline ions

Calcium cations and chloride anions were the dominant soluble ions in the studied plots, followed by sodium and sulfate (Table 5.2). Hence, the dominant salt in the experimental field was $CaCl_2$. Our results show that BPG was most effective among the tested crops in reducing the levels of the investigated cations from both soil depths. For instance, at 0-30 cm depth, the average concentrations of soluble Ca^{2+} and Na^{+} were reduced by 9.6 and 4.0 $mmol_c/L$, respectively. On the other hand, the changes of most anions were non-significant (P<0.05) between treatments, while Cl^{-} and SO_4^{2-} ions were reduced by 4.4 and 1.9 $mmol_c/L$ at BPG plots (Table 5.2). Depletion of these salinity-causing ions has a direct impact on soil salinity reduction. Besides BPG, ALF and RHG showed a notable reduction of saline-causing ions at 0-30 cm soil depth.

Table 5.2. Cations and anions (mmol$_c$/L) in soil water extracts; initial and final levels (mean± standard deviation; n = 4).

Depth (cm) / Crop	Na^+		K^+		Mg^{2+}		Ca^{2+}		HCO_3^-		Cl^-		SO_4^{2-}	
	Initial	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
0-30														
RHG	8.2±6.7	6.8 ± 7.8^{a}	0.9±0.3	0.8 ± 0.9^{a}	3.6±1.7	1.0 ± 0.4^{ab}	21.1±12.8	18.0 ± 14.4^{a}	0.9±0.2	0.5 ± 0.3^{a}	17.7±19.0	14.2 ± 20.5^{a}	6.3±2.6	4.6 ± 3.6^{a}
SUG	5.1±4.2	3.6 ± 3.6^{a}	0.5±0.1	0.3 ± 0.1^{a}	2.7±2.0	0.7 ± 0.8^{a}	13.3±4.5	10.4 ± 4.6^{a}	1.4±0.4	1.1 ± 0.4^{b}	8.7±4.6	5.9 ± 3.4^{a}	6.3±2.6	4.1 ± 1.8^{a}
BPG	9.8±8.0	5.8 ± 6.3^{a}	1.0±0.9	0.6 ± 0.7^{a}	6.5±3.7	3.5 ± 2.7^{bc}	26.1±24.9	16.5 ± 18.6^{a}	1.6±0.3	0.5 ± 0.1^{a}	21.5±19.3	17.1 ± 20.0^{a}	5.7±2.6	3.9 ± 2.4^{a}
ALF	4.0±0.9	3.1 ± 0.9^{a}	0.6±0.3	0.3 ± 0.2^{a}	3.6±1.8	1.6 ± 1.2^{ab}	15.3±4.6	12.4 ± 4.2^{a}	1.4±0.2	0.9 ± 0.3^{ab}	8,.5±3.2	4.3 ± 3.8^{a}	5.1±3.0	3.9 ± 1.3^{a}
CRL	4.3±0.6	3.6 ± 0.5^{a}	0.6±0.2	0.6 ± 0.7^{a}	4.3±0.8	4.0 ± 0.6^{c}	19.0±11.5	19.4 ± 10.7^{a}	1.3±0.1	0.6 ± 0.2^{ab}	16.5±11.6	15.9 ± 11.3^{a}	4.0±1.0	4.0 ± 1.0^{a}
30-60														
RHG	5.2±3.2	4.2 ± 3.3^{a}	0.6±0.3	0.6 ± 0.8^{a}	2.0±1.6	3.1 ± 2.2^{a}	11.6±2.6	8.6 ± 3.5^{a}	0.7±0.4	0.3 ± 0.6^{a}	9.8±11.8	8.4 ± 11.8^{a}	3.4±1.7	3.4 ± 1.7^{ab}
SUG	3.5±1.0	2.9 ± 0.6^{a}	0.2±0.1	0.1 ± 0.0^{a}	1.3±0.7	4.3 ± 0.6^{a}	7.0±0.6	4.7 ± 0.9^{a}	0.9±0.5	0.7 ± 0.6^{ab}	5.3±4.3	3.8 ± 3.5^{a}	2.8±1.0	1.1 ± 1.0^{a}
BPG	6.3±4.3	4.7 ± 3.3^{a}	0.5±0.4	0.2 ± 0.0^{a}	2.5±2.3	2.5 ± 1.1^{a}	13.5±13.3	9.3 ± 10.5^{a}	1.3±0.3	1.0 ± 0.0^{ab}	13.3±10.2	11.2 ± 9.8^{a}	4.6±2.6	3.9 ± 2.8^{ab}
ALF	3.6±0.5	3.2 ± 0.9^{a}	0.4±0.2	0.3 ± 0.2^{a}	1.2±1.0	4.4 ± 1.7^{a}	9.7±2.3	5.8 ± 1.2^{a}	1.3±0.5	1.0 ± 0.0^{ab}	5.3±2.2	2.3 ± 1.0^{a}	4.0±1.0	2.8 ± 1.0^{ab}
CRL	4.0±0.2	4.0 ± 0.8^{a}	0.2±0.1	0.4 ± 0.4^{a}	1.6±1.9	2.7 ± 1.3^{a}	9.4±7.7	9.3 ± 7.3^{a}	1.2±0.2	1.3 ± 0.6^{b}	9.8±8.5	11.0 ± 8.7^{a}	4.6±2.0	4.5 ± 1.8^{b}

Different letters indicate a significant difference between treatment means at $P < 0.05$. RHG – rhodesgrass; SUG –sudangrass; BPG – blue panicgrass; ALH – alfalfa; CRL – control

5.4. Discussion

The growth of the mitigation crops and the continuous incorporation of their biomass to the soil changed the soil properties in many aspects. We found that besides mitigating soil salinity and the concentrations of soluble saline ions, the crops also affected pH, soil SOC content, bulk density, and hydraulic conductivity. The as a high amount of biomass was incorporated to the soil by BPG plant, as the result salinity reduction and modification in soil properties were most pronounced with BPG. Next, to BPG, the SUD incorporated high biomass, however, in these plots, the SOC, bulk density and hydraulic conductivity were not improved like other crops plots. Harvesting frequency was playing a considerable role in high incorporation of biomass and improvements of soil properties. During this experiment BPG was harvested every 21 days, SUG, ALF, RHG was harvested in 35 days interval. This crop's ability to grow under high salinity guaranteed good growth performance at the salinity levels encountered in our experimental field (4-13.9 dS/m) and resulted in considerable improvements of soil physical and chemical properties. Similarly, Hussain *et al.* (2015) reported that moderate sodium chloride salinity (12.5 dS/m, NaCl) had little effect on the growth of BPG. Remarkably, we observed similar growth performance of BPG at each experimental plot despite different salinity levels; however, we observed (relatively) more salinity reduction in plots with lower salt content. For instance, the salt level of 13.9 dS/m was reduced to 10 dS/m, while 4.0 dS/m was reduced to 1 dS/m.

The fast-growing nature of BPG in the hot climate of the experimental site shortened the harvesting interval of BPG to only three weeks. At flowering initiation, BPG was already 1.5 m tall. This observation was corroborated by Ahmad *et al.* (2010) who reported that BPG can reach a height of 2 m or more. By comparison, the other tested crops required more than one month until harvest. The superior biomass production of BPG in our experiment was also reflected in superior salinity mitigation and stronger improvement of soil physical and chemical properties when compared to the other tested crops. Despite water and salinity stress under arid conditions, BPG forage production has been observed to be high compared to the other forage crops such as ALF (Ismail and El-Nakhlawy, 2018). Also, Hussain *et al.* (2015) recommended that BPG can sustainably be grown as a fodder crop in saline arid regions. Our results support this recommendation for the Ethiopian context of the Awash River basin, Ethiopia, this will constitute a promising strategy to restore saline abandoned irrigated fields and to supplement needed forage.

In our experiment, BPG's high biomass production resulted in a pronounced increase in SOC contents, with favorable effects on bulk density and hydraulic conductivity (Table 5.1). OC and soil organic matter is a direct effect of biomass incorporation. SOC accumulation plays an important role in this context as it helps stabilize soil structure and thus promotes water infiltration/percolation. Benjamin *et al.* (2007) reported that increasing organic matter in soil has the potential to improve soil hydraulic properties by increasing macro porosity.

This experimental result shows that the importance of soil SOC accumulation in promoting soil conditions that favor salinity mitigation with the reduced amount of leaching water. As the soil's hydraulic conductivity increases, the migration of salts from the root zone topsoil to the groundwater is promoted (Bayabil *et al.*, 2015). This experiment result shows that the biomass accumulation, bulk denticity reduction, promotes the hydraulic conductivity of the soil that resulted in the down percolation of salts and some free existing cations remain on the top layers of the soil and that promotes to increase the soil pH.

Several studies have shown the negative relationships between SOC and soil compaction (Zhang *et al.*, 1997), (Brevik *et al.*, 2002), (Mamman *et al.*, 2007. SOC reduce soil compaction and amend other soil properties. For instance, the increases hydraulic conductivity (Benjamin *et al.*, 2007), reduces soil bulk density and increases the probability of salt removal from the surface to lower in the soil profile through applied leaching water.

The distribution of salts in the field is neither uniform nor constant (Ayars *et al.*, 2011). In our experiment, saline ions were dominant near the soil surface (0-30 cm), with double the amount compared to the lower profile (Table 5.2). However, after the experiment, when other ions were preferentially removed, the (relatively increased) remaining Na^+ increased the pH level of the soil (Fig. 5.5). However, the irrigation water used in this experiment had low salinity levels, which could not have had significant effects on the sodium levels in the soil.

5.5. References

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6. A summary: Irrigated land soil salinity accumulation prediction in Awash Basin of Ethiopia[3]

6.1. Introduction

In the Awash basin, soil salinity reduces the productivity of irrigated land. In arid and semi-arid Awash basin irrigators uses relatively low saline river water which is between 0.65 and 0.34 dS/m (Asmamaw *et al.*, 2018; Gelaye *et al.*, 2019). In this regard, the arid and semi-arid parts of the basin, the shallow saline water table is a major problem for topsoil salt occurrence (Zewudu *et al.*, 2017). On the other hand, Taddese (2001) reported that the established large and small-scale irrigation schemes in the Awash basin are with no functional drainage system. Also, in these schemes, improper irrigation water management is practiced (Ayenew, 2007). Predicting salinity accumulation using multiple linear regression (MLR) will support an irrigation management system for future proper irrigation planning and strategies soil salinity mitigation actions. Lesch *et al*. (1995) reported that the merits of the MLRs approach are cost-effectiveness, multiple prediction capabilities, and parametric model-testing abilities. Therefore, the aim of this study was to predict topsoil salinity accumulations over irrigation seasons and seasonal groundwater level with MLR modeling.

6.2. Material and Methods

Two fields with different soil texture (clay loam and sandy loam) were selected. In 2m by 2 m grid soil samples were taken in 30 cm increments down to 3 m depth. Sampling was repeated every three months. To predict soil salinity with MLR modeling groundwater depth, the spatial distribution of soil salinity within the profile down to 3 m depth, irrigation seasons (2 years), depth of applied irrigation water (m^3/m^2), and soil texture of irrigated land were considered as a factor. Soil salinity ($EC_{1:5}$) and $pH_{1:5}$ were measured at a 5 g/25 ml soil/water ratio (Khorsandi and Yazdi 2011). The Kesem dam irrigation water is conveyed to the fields by an open primary canal to tertiary canals, and then BARTLETT hydro-flumes convey the water to the field furrows. Thus, irrigation water depth was estimated from the history of the irrigated field, which was recorded by the farm, called irrigation diagram. Irrigation diagram estimated from the enclosed hydro-flumes which have 20 outlets, each outlet estimated to

[3] This summary is based on a manuscript by Gelaye et al.
Will be submitted to SCI journal

discharges 5 l/s. Groundwater depth was manually assessed with drill bucket augur which have a different length (0.5-3 m) of extension shaft.

6.3. Result and Discussion

The MLR result ($r^2 = 0.66$) shows that the sandy loam soil salinity increases with irrigation seasons while the irrigation water mainly percolated to the groundwater (Figure 6.1). This is due to the capillary rise with the evapotranspiration process leading for topsoil soil salinity accumulation. However, the clay loam field with deep water table did not show a variation in salinity with irrigation seasons (Figure 6.2). And also, groundwater was seasonally influenced ($r^2 = 0.94$) by the applied irrigation water.

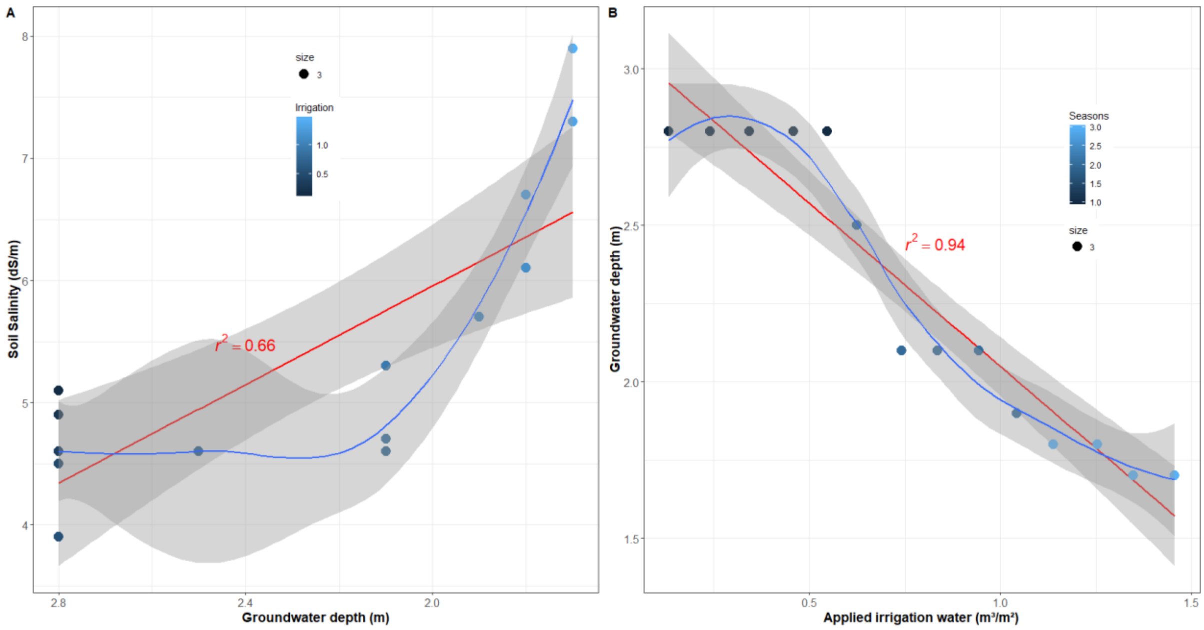

Figure 6.1. The relationship of groundwater table and seasonal applied irrigation water (m^3/m^2) on sandy loam field salinity accumulation (A) and seasonal due to groundwater shallowed as amounts of irrigation water added (B) over.

To irrigate a hectare of land with furrow irrigation method, sandy loam field required a prolonged irrigation hour than clay loam field (Figure 6.3). The sandy loam (25 mm/hour) and clay loam (7.5 mm/hour), thus during irrigation events clay loam fields show a low infiltration rate leads to high runoff (Critchley and Chapman, 1991). Therefore, more irrigation water is added to the sandy loam fields, in consequence, the groundwater table closer to the surface that leads to salinity accumulation. In the Kesem irrigation scheme (in Awash basin) alone more than 200 hectares of sandy loam fields become saline unproductive due to such a high irrigation water application (Gelaye *et al.*, 2019). On the other hand, this research area irrigation scheme clay loam fields were less vulnerability to high salinity and the salinization process is slow compared to sandy loam fields. Figure 3 indicates that in sandy loam field salt sourced from groundwater moved upward to the topsoil. And also, the water table becomes shallow between 2016 and 2017. As the water table closer to the main evapotranspiration zone, capillary up flow leading to salt accumulation in the root zone (Northey *et al.*, 2006). For the clay loam field down percolation from the adjacent main earthen canal and high amount of applied irrigation water contribute to the groundwater.

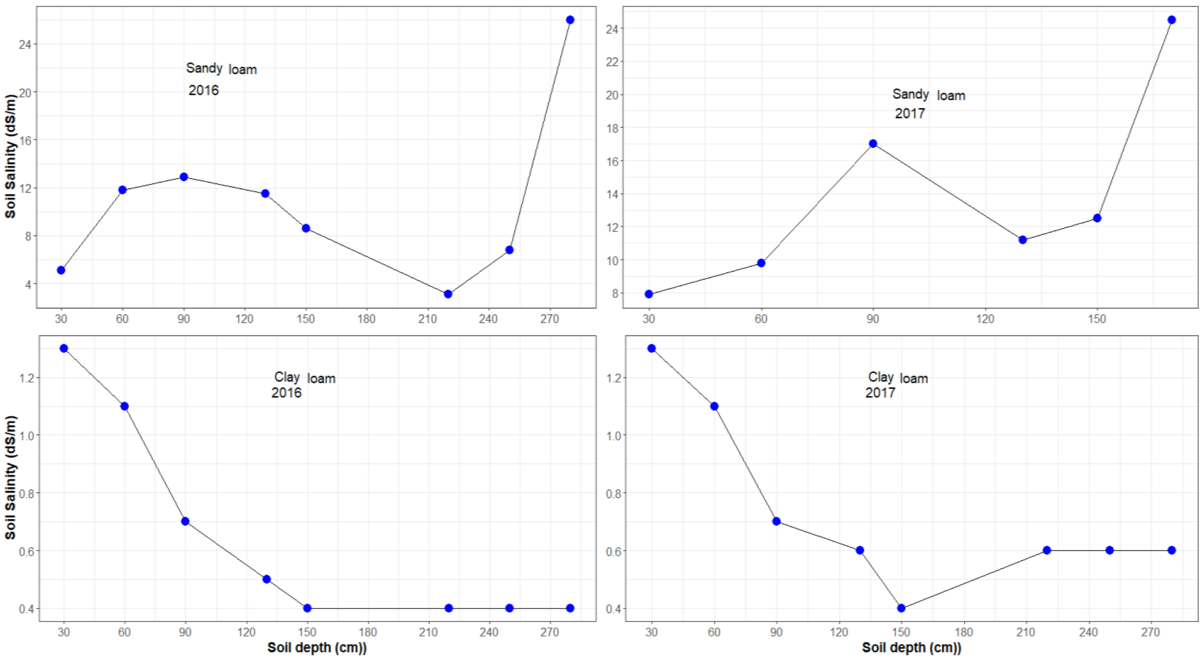

Figure 6.2. Soil salinity along with the soil depth. Groundwater level of clay loam field was not detected in 3 m, while the sandy loam field was located at 2.8 m and 1.7 m for the irrigation year of 2016 and 2017 respectively.

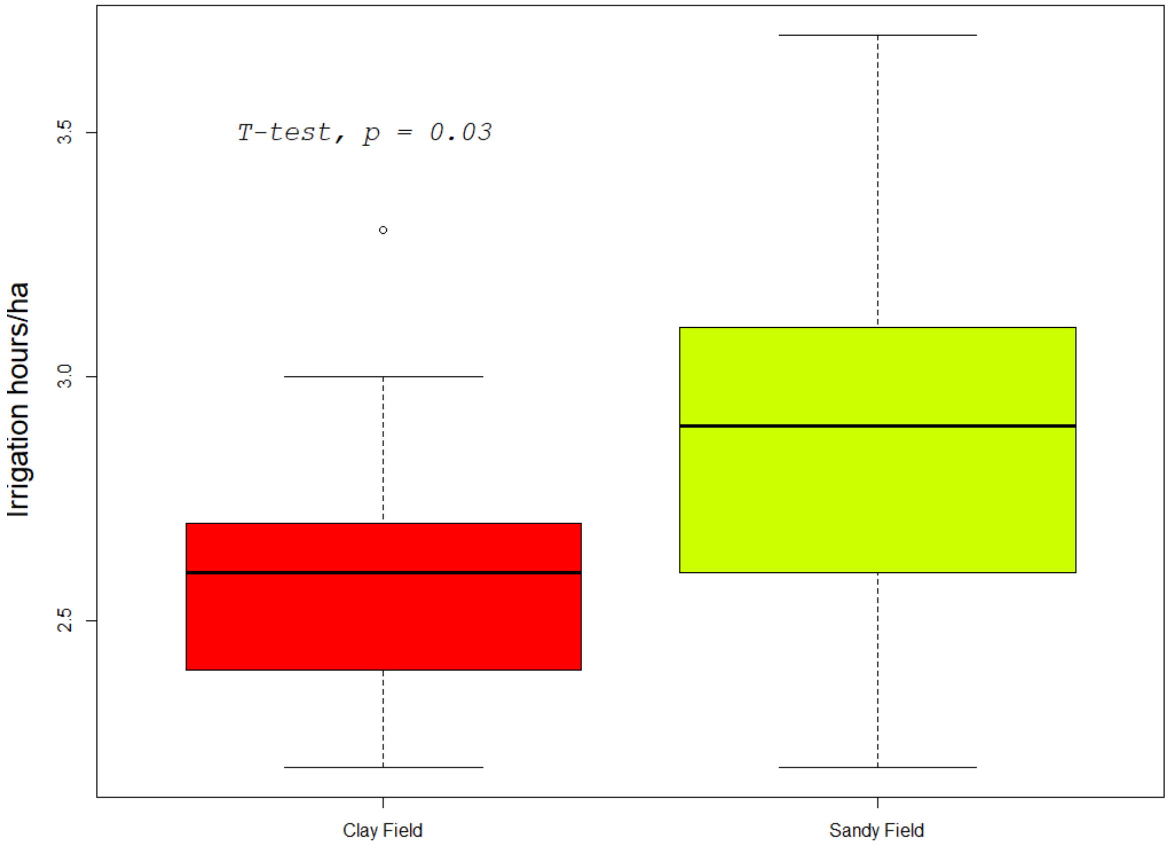

Figure 6.3. Average two years required hours to irrigate a hectare of sandy loam and clay loam fields using furrow irrigation method.

6.4. Conclusion

The predicted results show that during the irrigation season soil salinity is much more accumulated in sandy loam soil than in the clay loam soil. Due to high infiltration rate of sandy loam field 12% more irrigation water was applied than on the clay loam. This applied irrigation water and high percolation from the earthen canal contributed to the groundwater recharge. Consequently, groundwater level raised, and salt was moved by capillary raise to root zone and surface top soil and accumulated there. Therefore, to control the groundwater level and to reduce the risk of soil salinity at sandy loam fields installation of drainage systems, application of salinity mitigation methods, and use of water efficient irrigation methods and management, potentially reduce soil salinity.

6.5. References

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7. Synthesis and Conclusions

In the Awash basin of Ethiopia soil salinity is the major problem for irrigated land productivity. This research was aimed on to predict temporal and special soil salinity accumulation and to study selected mitigation measures that potentially reduce soil salinity challenges in the Awash basin. Thus, the main goal of these studies was to predict irrigated land salinity accumulation, to investigate the leaching and bioremediation soil salinity mitigation methods for saline affected irrigated land in the Awash basin of Ethiopia. The leaching experiments were conducted at three saline abandoned fields (Field1, Filed2, and Field3). These fields were irrigated for more than ten years. Soil texture of Field1 is sandy loam while Field2 and Field3 are clay loam. The Field1, Field2, and Field3 groundwater were situated at 1.8, 1.5 and > 3 m, respectively. The leaching requirement water levels were 40, 42, 43, and 45 mm higher than the evaporation of bare field needed for four consecutive weeks, respectively. To flush out the soil surface accumulated salt, additional 15 mm water was supplied on the second day of leaching. The bioremediation experiment was conducted with annual saline mitigate crops such as Rhodesgrass (RHG) Alfalfa (ALF), Sudangrass (SUG) and Blue Panicgrass (Retz) (BPG). The mitigate crops were grown in saline (3–13.9 dS/m) field plots and its biomass was continuously incorporated into the soil. In monthly intervals, 40 mm surplus leaching water was supplied to enhance salt reduction from the experimental plots.

The results found in the experiment confirmed that in Awash basin leaching salinity mitigation appears to be an effective method to reduce irrigated agriculture constraints as long as the groundwater table is deeper. Thus, the Field1 salinity was reduced from 16.3 to 6.2 dS/m and from 12.4 to 5.5 dS/m at depths between 0–30 and 30–60 cm, respectively. In some head parts of Field1 and Field3, the salinity level reduced to 2.0 dS/m. However, in Field2 with shallow groundwater and clay loam texture, the salinity levels slightly higher after leaching, i.e. from 11.2 to 12.0 dS/m and from 8.1 to 11.6 dS/m at 0–30 and 30–60 cm depth, respectively. It seems the Field2 leaching effectiveness was highly influenced by a shallow water table. On the other hand, the substantial amounts of salt were removed in a short period of time at the field with deeper (> 1.8 m) water table and sandy loam fields than clay loam field. Hence, to reduce salts from the clay loam field that requires prolonged leaching application.

The tested mitigate crops BPG and SUG perform well in high saline soil. Therefore, substantially salinity was reduced (-3.2 dS/m) and related ionic concentrations, an increase of SOC (0.8 to 1.6%) and improvement of BD and HyCo were observed in BPG plots. The fast-growing nature of BPG in the hot climate of the experimental area resulted in harvests every three weeks and promoted the incorporation of high amounts of biomass to the soil and efficient soil salinity remediation. At moderately saline conditions, ALF also showed great potential for salinity reclamation (-1.8 dS/m) and SOC accumulation.

Therefore, for the semi-arid irrigation areas of Middle Awash, Ethiopia, at the deeper water table situation, leaching significantly reduces soil salinity in a short period of time. On the other hand, the high biomass production by BPG supplemented with 40 mm/month leaching water high than irrigation water considerably reduces the soil salinity and improves soil productivity. This research concludes that either continuous leaching application or supplemental leaching combined with bioremediation reduces the high salinity of abandoned land and assures the future irrigation sustainability of the semi-arid areas. For effective salinity mitigation and sustainable irrigated land productivity, proper irrigation management, accessing drainage facility, and revoke the use of earthen canals could reduce the salinity risk of irrigated land and downstream water users.

In Ethiopia, there is not an adapted regulation to protect irrigated lands from soil salinity and waterlogging. Thus, the Awash basin large/small scale irrigating schemes established without any irrigating drainage facilities (Taddese, 2001), while in this basin shallow water table is a common natural occurrence. Our predicted salinity result showed that groundwater table seasonally becomes shallow in light (sandy loam) soils and consequently salt is significantly accumulated. In the future, gradually soil salinity affects the established irrigation schemes in the Awash basin. This is mainly due to over irrigating that enhancing the rising of the water table. This severe salinity accumulation observed in light soil with a shallow water table situation. The research result by Zewudu *et al*. (2017) showed that in the Awash basin, soils on deep water table are not affected by salinity. In this regard, irrigated areas with shallow water table need more irrigation drainage system, efficient irrigation supply, timely leaching mitigation measure and prevent high percolations form earthen canals will be a potential solution to prevent irrigated lands from salinity in Awash basin.

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9. List of Tables

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