Effects of irrigation water quality on soil properties and crops in urban gardens of Ouagadougou, Burkina Faso

Juliane Dao

Dissertation for acquiring the academic degree of
Doktor der Agrarwissenschaften (Dr. agr.)
Presented to the Faculty of Organic Agricultural Sciences
at Universität Kassel (Germany)

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To Fiete

without whom I would never have started a PhD

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Summary

Urban food production is an important supplier of fresh produce in the rapidly growing West African cities. In year-round vegetable production of the semi-arid tropics, low quality water is often use for irrigation. This results in health risks for producers and consumers, and causes environmental pollution, followed by soil contamination and crop yield reduction. In the presented PhD thesis quality and effects of irrigation water in urban vegetable gardens of Ouagadougou, Burkina Faso, were examined. The aim of these studies was to quantify contamination of water, vegetables and soil, in urban locations of Ouagadougou, as well as to identify strategies to reduce contamination risks and its consequences.

The first study focused on pathogenic contamination of lettuce along the trade chain and aimed to identify microbial inputs during post-harvest handling. Water and lettuce samples were analysed for total coliforms, *Escherichia coli* (*E. coli*) and *Salmonella* spp. at different post-harvest stages. Results showed that 60 % of the irrigation water samples were above the international thresholds for *E. coli* and 30 % of the samples were contaminated with *Salmonella* spp.. Total coliform and *E. coli* loads on lettuce increased along the trade chain. Half of the 60 lettuce samples were tested positive for *Salmonella* spp.. Appropriate post-harvest handling of lettuce, including washing with tap water, prevented the increase of total coliforms.

The second study evaluated effects of sodic alkaline wastewater irrigation, on soil chemical properties. A literature review allowed an overview of reduced soil quality in semi-arid climate regions, induced by industrial wastewater with a sodium (Na) content above 100 mg l^{-1}. Worldwide various industrial wastewaters, such as effluents from beverage industry, tanneries and papermills, were documented to provoke Na hazards in soils. The study allowed to conduct a case study of the industrial area of Ouagadougou, where sodic wastewater was used to irrigate urban gardens. Irrigation with those water sources irreversibly damaged soil structure, reduced soil productivity and thus leads to a loss of farmland. The importance of sampling the surrounding area as well as the subsoil in order to gain knowledge about soil Na status was highlighted. The study not only revealed that irrigation with sodic water induced hazards, but also that seepage of wastewater channels likely affected soil quality negatively.

The experiment of the third study tested if gypsum as a soil amendment could reverse negative impacts of sodic industrial wastewater on soil quality and crop development. For this an on-farm experiment was carried out in the industrial area of Ouagadougou. Depending on the level of soil degradation, either 0, 6.8 or 10 t ha^{-1} of finely powdered gypsum were incorporated into the topsoil. Rainfed maize (*Zea mays* L.) as well as spinach (*Spinacia oleracea* L.) irrigated at two water qualities (clean and wastewater) were cultivated.

Results showed that gypsum and clean water treatment reduced soil pH and sodium adsorption ratio, while aggregate stability was increased. Although Na uptake of plants was reduced and root length density of maize was increased, no yield effects of gypsum were found.

Overall, irrigation water composition in urban areas of Ouagadougou varied widely, depending on whether the sources of pollution were industrial effluents or wastewater of domestic origin containing faeces. Furthermore, natural water amounts in streams, and seasonal changes influenced dilution of the wastewater in the channels. On the one hand, irrigation of urban vegetables provokes pathogenic risks which could be significantly reduced through careful washing of the produce with tap water. Industrial wastewater that induces Na hazards to soils was found to cause serious lasting damage to the agricultural production area. The necessity of wastewater treatment prior to disposal as well as the need to recover degraded soil by melioration was highlighted.

Zusammenfassung

Die urbane Landwirtschaft liefert in westafrikanischen Städten einen wichtigen Beitrag zur Versorgung der rasch zunehmenden urbanen Bevölkerung mit frischen Lebensmitteln. In den semiariden Regionen wird zur Bewässerung oft Wasser mit mangelhafter Qualität verwendet, um eine ganzjährige Gemüseproduktion zu gewährleisten. Dies führt zu Gesundheitsrisiken für Produzenten und Konsumenten sowie Umweltverschmutzung durch Kontaminierung des Bodens und daraus resultierende Ernteeinbußen.

In der vorliegenden Dissertation wurden die Qualität und Effekte des genutzten Bewässerungswassers in urbanen Gemüsegärten Ouagadougous in Burkina Faso untersucht. Ziel war es, die Belastungen von Wasser, Gemüse und Boden zu dokumentieren, zu evaluieren und Risikovermeidungsstrategien herauszuarbeiten.

Die erste Studie befasste sich mit der pathogenen Belastung von Kopfsalat entlang der Handelskette und sollte Kontaminierungsereignisse aufdecken. Hierfür wurden Wasser- und Kopfsalatproben auf die Belastung mit coliformen Bakterien, *Escherichia coli* (*E. coli*) und *Salmonella* spp. in verschiedenen Abschnitten der Handelskette analysiert. Von den Bewässerungswasserproben lagen 60 % über den internationalen Standards für *E. coli*, während in 30 % der Proben Salmonellen nachgewiesen wurden. Die Belastung mit coliformen Bakterien und *E. coli* wies einen Anstieg entlang der Handelskette auf. Außerdem waren die Hälfte aller getesteten Kopfsalatproben mit Salmonellen kontaminiert. Ein weiteres durchgeführtes Experiment erwies, dass auf jenen Salatköpfen, welche vor dem Verkauf mit Leitungswasser gewaschen wurden, der Anstieg der coliformen Bakterienbelastung verhindert werden konnte.

In der zweiten Studie wurden die bodenchemischen Auswirkungen von zur Bewässerung genutztem alkalischen und natriumhaltigen Abwasser analysiert. Es wird ein Überblick über Literatur gegeben, welche sich mit der Verminderung von Bodenqualität durch die Nutzung von Bewässerungswasser mit einer Natriumkonzentration von über 100 mg l^{-1} befasst. Natriumstress kann von verschiedenen Industrieabwässern verursacht werden, welche zum Beispiel in der Getränkeindustrie, Gerbereien und Papierfabriken entstehen. Die Studie impliziert ein Fallbeispiel einer gartenbaulich genutzten Fläche im Industriegebiet Ouagadougous, auf welcher natriumhaltige Industrieabwässer zur Bewässerung eingesetzt werden. Diese zerstören nachhaltig die Bodenstruktur, verringern die Ertragsleistung der Böden und führen dadurch zum Verlust von Agrarflächen. Es wird angenommen, dass nicht nur die direkte Bewässerung mit natriumhaltigem Wasser, sondern auch Sickerwasser aus den Abwasserkanälen die umliegenden Böden beeinträchtigt.

Ziel der dritten Studie war es, in einem Experiment zu testen, ob Gips als Bodenzusatz die negativen Auswirkungen des Na auf Bodeneigenschaften und Pflanzenwachstum beheben kann.

Zu diesem Zweck wurde ein Experiment im Industriegebiet Ouagadougous durchgeführt, bei welchem 0, 6.8 oder 10 t ha^{-1} feiner Gips in Abhängigkeit des Degradationsstatus des Bodens in den Oberboden eingebracht wurde. Während der Regenzeit wurde Mais (*Zea mays* L.) und während der Trockenzeit Spinat (*Spinacia oleracea* L.) angebaut. Im Spinatfeld wurden zwei unterschiedliche Bewässerungsqualitäten getestet, sauberes sowie natriumhaltiges Abwasser. Gipsgaben und sauberes Wasser verringerten den pH und die Natrium-Adsorptions-Rate des Bodens, während die Aggregatstabilität verbessert wurde. Der Gips hatte zwar keinen direkten Einfluss auf den Ernteertrag, reduzierte allerdings die Natriumaufnahme der Kulturen Spinat und Mais und erhöhte die Durchwurzelungsdichte beim Mais.

Insgesamt waren die Abwässer in urbanen Gebieten Ouagadougous unterschiedlich zusammengesetzt, abhängig davon ob die Einleitungen aus der Industrie stammten oder aus Haushaltsabwässern, welche Fäkalien beinhalten. Auch muss der Zeitpunkt der Probennahmen berücksichtigt werden, da es in der Regenzeit zu einem Verdünnungseffekt in den Kanälen kommen kann.

Zusammenfassend kann man feststellen, dass die aktuell betriebene Bewässerungsstrategie im urbanen Gemüseanbau eine pathogene Belastung der Produkte hervorruft, welche aber durch gründliches Waschen der Produkte wieder kompensiert werden kann.

Des Weiteren verursacht die Nutzung von Industrieabwässern eine Sodifizierung des Bodens, welche mit einer ernsten und irreversiblen Schädigung von Agrarflächen einhergeht. Die Einhaltung internationaler Umweltstandards durch Abwasserklärung vor der Einleitung in öffentliche Gewässer sowie die Meliorierung der bereits kontaminierten Flächen ist nötig.

Resumé

La production alimentaire urbaine est un important fournisseur de produits frais dans les villes en croissance rapide d'Afrique de l'Ouest. Dans les régions tropicales semi-arides, l'irrigation pour la production des légumes toute l'année est souvent faite avec de l'eau de mauvaise qualité. Cela entraîne des risques pour la santé des producteurs et des consommateurs ainsi que la pollution de l'environnement. Il s´en suit une contamination du sol et la réduction du rendement des récoltes.

Dans la thèse de doctorat présentée, la qualité et les effets de l´eau d´irrigation dans les jardins potager urbains de Ouagadougou, au Burkina Faso ont été examinés. L´objectifs de cette étude est (i) de documenter et d'évaluer la contamination de l'eau, des légumes et du sol dans les zones urbaines de Ouagadougou, (ii) d'identifier des stratégies pour réduire les risques.

La première partie de l´étude porte sur la contamination de la laitue par des agents pathogènes, tout au long de la chaîne commerciale, particulièrement lors des manipulations après la récolte. Des échantillons d'eau et de laitue ont été analysés pour détecter la présence de coliformes totaux, d'*Escherichia coli* (*E. coli*) et de *Salmonella* spp. à différentes étapes post-récolte. Les résultats ont montré que 60 % des échantillons d'eau d'irrigation dépassaient les objectifs sanitaires d'*E. Coli* et que 30 % des échantillons étaient contaminés par Salmonella spp.. De plus, les charges totales de coliformes et d'*E. Coli* sur la laitue augmentent le long de la chaîne commerciale. La moitié de tous les échantillons de laitue ont été testés positifs pour *Salmonella* spp.. L´étude montre par ailleurs que la manipulation appropriée de la laitue après la récolte, notamment le lavage à l'eau du robinet, empêche l'augmentation des coliformes totaux.

Dans la deuxième partie de l´étude, les effets de l'irrigation par eaux usées alcalines sodiques sur la chimie du sol ont été évalués. L´étude bibliographique s´intéresse à la dégradation des sols et donne un aperçu de la qualité réduite du sol dans les régions climatiques semi-arides induites par l´irrigation avec des eaux usées ayant une teneur en Na supérieure à 100 mg l^{-1}. Dans le monde entier, diverses eaux usées telles que les effluents de l'industrie des boissons, des tanneries et des usines de papier, peuvent être à l´origine d´un stress dû au Na. Une étude expérimentale a été mise place dans la zone industrielle de Ouagadougou, où des eaux usées sodiques ont été utilisées pour irriguer les jardins urbains. Ces résultats ont prouvé que l'irrigation des jardins urbains avec ces sources d'eau endommage la structure du sol durablement, réduit la productivité du sol et entraîne une perte de terres agricoles. Il a été constaté non seulement que l'irrigation avec des eaux sodiques induisait des risques, mais aussi que l'infiltration au travers des canaux d'eaux usées affectait négativement la qualité du sol.

Dans un troisième temps, il a été testé si des amendements en gypse peuvent inverser les impacts négatifs des eaux usées industrielles sodiques sur la qualité du sol et le développement des cultures. Pour cela, une expérience a été réalisée dans la zone industrielle de Ouagadougou. Selon le niveau de dégradation du sol; 0, 6, 8 ou 10 t ha^{-1} de gypse réduit en poudre fine ont été incorporés dans la couche arable. Pour des cultures de maïs (*Zea mays* L.) non irriguées et d´épinards (*Spinacia oleracea* L.), irriguées selon deux modalités: avec des eaux propres ou des eaux usées, les résultats ont montré que le traitement au gypse et à l'eau propre réduisait le pH du sol et le taux d'adsorption de sodium, tandis que la stabilité des agrégats augmentait. Par contre, les amendements en gypse n´ont pas d´influence sur le rendement, alors que l´absorption de sodium par les plantes est moindre et la longueur racinaire par unité de volume de sol augmente chez le maïs. Globalement, la composition des eaux usées dans les zones urbaines de Ouagadougou est variable, selon que les sources de pollution sont issues des effluents industriels ou des eaux usées d'origine domestique, contenant des excréments. En outre, la qualité de l´eau est directement influencée par les quantités de précipitations, qui varient au cours des saisons, provoquant une dilution des polluants dans les canaux.

D'une part, l'irrigation des légumes urbains provoque des risques pathogènes, qui pourraient être considérablement réduits grâce à un lavage soigneux à l'eau du robinet. D´autre part, les eaux usées industrielles entraînent des dommages considérables voire irréversibles aux sols agricoles par sodification. Le respect des recommandations internationales en matière d´épuration des eaux usées avant leur rejet dans l´environnement, ainsi que la réhabilitation des surfaces contaminées seraient nécessaires.

Chapter 1

General introduction and research objectives

1.1 Irrigation water quality

The sustainable development goals of the United Nations target water and sanitation as goal number six and aims to “improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally” (UN-Water 2016). A recent report stated that 80 % of all human wastewaters is discharged without any treatment and further that 1000 children die daily due to diarrhoeal water-related diseases (UN-Water 2017). Overall Africa faces the highest burden of foodborne diseases, whereby 70 % are diarrhoeal diseases caused by *Salmonella* spp. and the faecal bacteria *Escherichia coli* (*E. coli*) and *Vibrio cholerae* (*V. cholerae*) (WHO 2015). In Burkina Faso, 22 % of all deaths in 2004 were related to water, sanitation and hygiene (WHO 2010). This is mainly caused by a lack of sanitary infrastructure such as nonexistent or inadequate wastewater treatment plants (Maconachie and Binns 2006).

Additionally, the high urbanization rate increases water utilization and discharge in cities so that the level of wastewater treatment infrastructure can barely be improved despite investment (Thebo et al. 2017).

The urbanization rate of West African cities is generally very high and Ouagadougou, the capital of Burkina Faso, faces with 9.2 % the highest annual growth rate in the region (UN-Habitat 2014). This results in a further increasing demand for agricultural products in which urban and peri-urban agriculture (UPA) plays an important supply role. Due to the short unimodal rainy season, intensively managed farms are restricted to places where water sources, such as well water, channels or dams with wastewater of uncertain quality are available (Kiba et al. 2012).

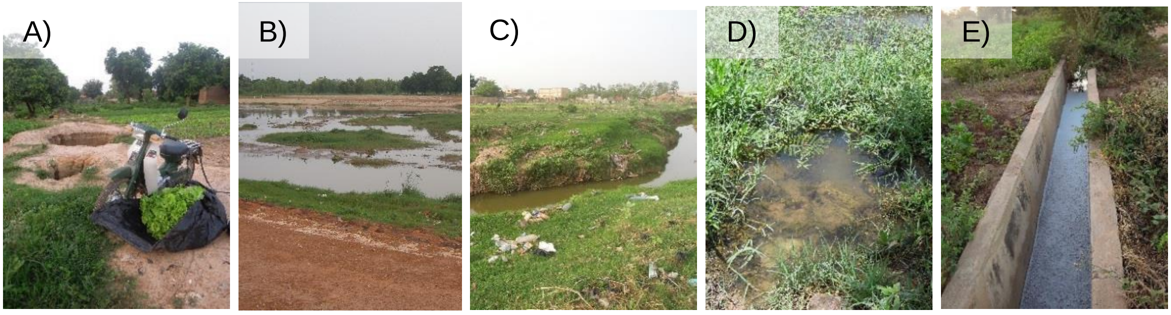

Figure 1.1. Sources of irrigation water in Ouagadougou, Burkina Faso: A) well B) wastewater polluted channel C) polluted natural stream D) water withdrawal point at a dam E) industrial wastewater channel.

Profits for the irrigated vegetables are highest during the long lean season (Drechsel et al. 2006; Karg et al. 2016), wherefore gardens are commonly located along the channels of the city (Figure 1.2). Cissé et al. (2005) reported that 52.3 % of Ouagadougou's discharged wastewater was utilised for crop irrigation in the two biggest open-space gardens.

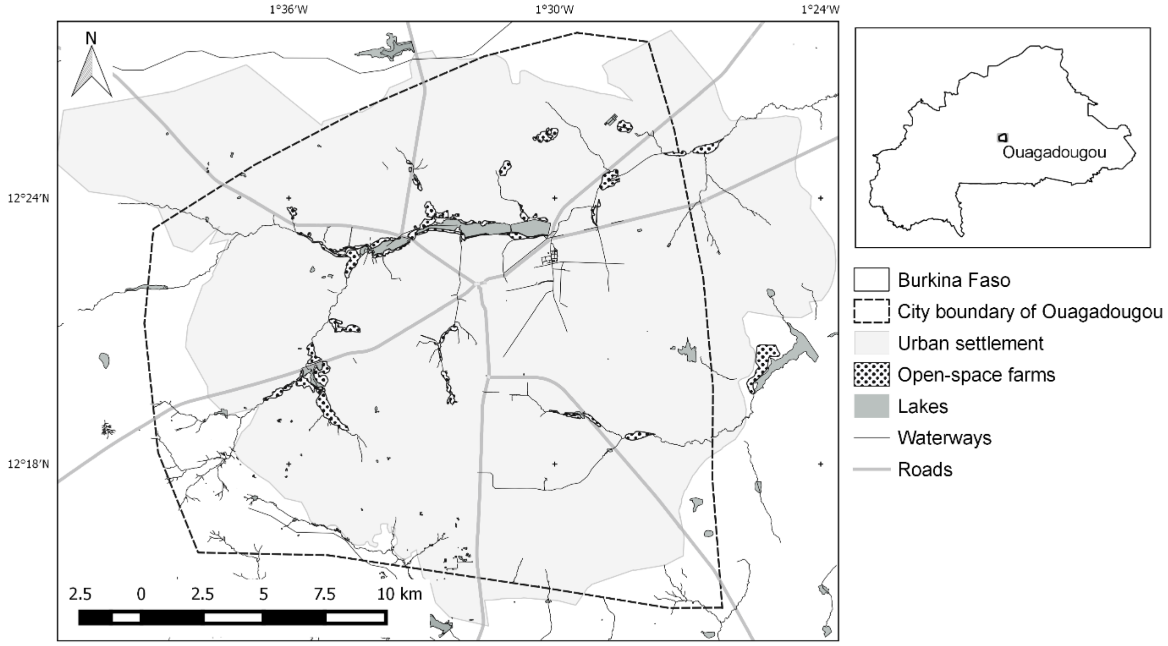

Figure 1.2. Map of urban agricultural areas in Ouagadougou, Burkina Faso, adapted from Dr. H. Karg, unpublished.

This thesis focuses on commercial urban gardens which arose in non-build up areas in Ouagadougou. These will be referred to as open-space farms. The cultivation of unutilized urban spaces for vegetable production is mainly done by families, who have migrated from the villages to the city (Drechsel and Dongus 2010). They often use swampy areas which flood during the rainy season and dry out in the lean season. However, land tenure is generally unclear or farmers lack of farmland formal titles (Korbéogo 2017). Therefore, the urban gardeners are vulnerable to displacement (Cissé et al. 2005).

In an attempt to reduce the number of unofficial gardens in the city, land in Kossodo, an industry and farming area in the northeast of Ouagadougou, was given to the urban farmers. In order to do this the original settlers of this land were first expropriated of their fields. The land was then divided into plots which were distributed between the resettled urban gardeners and the local Kossodo farmers (Korbéogo 2017). Concrete channels established by the municipality supply the farms with industrial wastewater.

Wastewater in general can be defined as water that has been detrimentally used by humans. It can be classified by its origin as (WHO 2006b):

- blackwater (human faeces and urine),
- greywater (domestic wastewater from washing etc.)
- sewage or municipality wastewater (combination of black and greywater),
- industrial wastewater

To reduce environmental pollution and health risks generated by polluted wastewater, it should be treated in three phases in a treatment plant which follows standard procedures: Firstly, the physical phase removes solids and oily substances by sedimentation and filtration. Secondly, in a biological phase decomposition of carbon and nitrogen compounds takes place. The third phase involves chemical processes to eliminate nitrate, phosphor, colloids, heavy metals and salts. Included is also the neutralisation of water pH, destruction of nondegradable organic structures and the disinfection of the wastewater (Draxler 2007; LfU 2013).

In Ouagadougou the composition of channel water and therefore the quality of irrigation water differs between locations depending on discharged effluents. Most of the municipality's household wastewater, including faecal sewage, is discharged into natural streams or rain water drainage channels resulting in the pollution of the water bodies of the capital. Further pollutants are industrial effluents that are released into streams without adequate treatment. Pathogenic risks due to wastewater irrigation at the farm level in West Africa whereby the health of producers and consumers can be affected are well documented (Amoah et al. 2005; Diogo et al. 2010; Amadou et al. 2014).

However research of pathogen loads on raw edible vegetables along the trade chain, including the very effects of traders' strategies to reduce the contamination, has been neglected, although this is of major concern as transport and storage facilities are poor (Bellwood-Howard et al. 2015).

Therefore, the first study compares the effects of well and channel water irrigation on pathogen loads of raw edible vegetables. It focuses on the faecal bacteria *E. coli* and *Salmonella* spp. on lettuce and on detecting post-harvest strategy effects on microbial loads on lettuce leaves along the trade chain from field to end-consumer. It evaluates post-harvest washing practices, commonly done by female marketers, which reflect patterns found in UPA across West Africa (Bellwood-Howard et al. 2015).

Not only human health can be affected by wastewater usage, but also soil quality and environment can be negatively impacted by using contaminated wastewater for crop irrigation. The chemical compounds of the wastewater, such as salts, heavy metals, toxic organic compounds, nutrients as well as bases and acids can lead to severe problems (WHO 2006a).

The second and third study focuses on sodium (Na) accumulation due to industrial wastewater use. Wastewater, especially of industrial origin, contains more salts than clean water sources. Therefore, irrigation with wastewater can change soil conditions and create salt affected soils, which are grouped in saline, sodic or saline-sodic soils (Abd El-Halim and Lennartz 2017). In this study soil pH, electrical conductivity (EC) and soil cations were measured to quantify the chemical soil characteristics.

Saline soils are defined by an EC above 4000 µS cm^{-1}, sodic soils have a high Na concentration, whereby the exchangeable sodium percentage (ESP) is above 15 % (Brady and Well 2002) and the EC is below 4000 µS cm^{-1}. Saline-sodic soils have a ESP above 15 % as well as an EC above 4000 µS cm^{-1}. The ESP can be calculated as follows (Abrol et al. 1988; Graaff and Patterson 2001):

$$\mathrm{ESP}\ [\%] = \frac{\text{Exchangable sodium } [\mathrm{cmol_c/kg}]}{\text{Cation exchange capacity } [\mathrm{cmol_c/kg}]}$$

where: units are given in concentration and are equal to meq 100 g^{-1}.

The sodium adsorption ratio (SAR) is a further indicator for sodicity hazards. Here cations are measured in water or in soil extracts and calculated as follows:

$$\mathrm{SAR} = \frac{\text{Sodium } [\mathrm{cmol_c/l}]}{\sqrt{(\text{Calcium } [\mathrm{cmol_c/l}] + \text{magnesium } [\mathrm{cmol_c/l}])/\ 2}}$$

where: SAR is a ratio and units are given in concentration and are equal to meq l^{-1}.

The term “alkaline soil” refers to soils with a pH > 7 (Brady and Well 2002). Sodic and saline-sodic soils are alkaline with a soil pH > 8.2 (Abrol et al. 1988).

Industrial wastewater leads to negative effects on soil. Through decreased osmotic potential of soil solution, Na can rise to a toxic level for plants (WHO 2006a), soil disperses and aggregate stability decreases, subsequently soil tends to crust at the surface and becomes impermeable, soil pH increases leading to the formation of magnesium and calcium carbonates which are unavailable to plants (Abrol et al. 1988). In addition, hydraulic conductivity and infiltration rates are low and negatively affect air and water movements in the soil causing oxygen deficiency in the rooting zone (Mahanta et al. 2015).

The structural damages described above decrease in consequence plant root development (Bernstein 1975). Furthermore, sodicity inhibits plant development in two phases (Munns 1993): In the first phase, the osmotic stress reduces water availability and decreases plant growth. In the second phase, the toxicity of Na limits further development. Due to the strong driving force into the plant roots Na enters the plant passively (Zhang et al. 2010) and slowly accumulates in the plant. Also, increasing sodicity results in a cation competition for nutrient uptake by plant roots (Gransee and Führs 2013), causing deficiencies of calcium (Ca), potassium (K) and magnesium (Mg) to the plant (Lawlor and Milford 1973; Robinson and Downton 1984; Schubert 2006; Gao et al. 2014). Besides effects on plant development, changes in soil quality also influence soil fauna (Dunxiao et al. 1999).

1.2 Research area

The research was conducted in the capital of Burkina Faso during 2013 to 2015. Usually rainfall varies between 600 and 900 mm and lasts from late May until the end of September in the sub-Shelian zone central of Burkina Faso (Ibrahim et al. 2012). In 2015 rainfall at the Urban Food^{Plus} climate station in Ouagadougou was 820 mm and annual average temperature was 28°C. During the dry winters the northeaster winds, called Harmattan, deposit mineral dust and produce dry hazes (Mbourou et al. 1997).

The terrain of Ouagadougou is flat, dominant soil types are Arenosols and Lixisols. These soils are severely weathered and dominated by non-expansive 1:1 clay minerals such as kaolinite, leading to a low nutrient-retention capacity and low water-holding capacity (Jones et al. 2013). Generally, organic carbon, phosphors, and nitrogen contents are low (Bationo et al. 2003). Lixisols, such as those in the urban farms examined in study 2 and 3, are characterized by a lower clay content in the topsoil than in the subsoil due to leaching of clay particles. Parent materials are basic rocks that are highly weathered, resulting in a fine texture which is susceptible to erosion and slaking (IUSS Working Group 2014). Lixisols have generally a higher pH than Ferralsols and Acrisols (Driessen et al. 2000).

The natural vegetation of the Sudanian savanna (Mistry 2000) is characterized by grassland, shrubby steppes and woody savannas (Sop and Oldeland 2013). Traditional farming systems in the peri-urban area of Ouagadougou are characterized by extensive rainfed cultivation of staple crops (Prudencio 1993), such as sorghum (*Sorghum bicolor* Moench), pearl and finger millet (*Pennisetum glaucum* L. and *Panicum* sp.) and maize (*Zea mays* L.), often in rotation or intercropped with peanut (*Arachis hypogaea* L.), okra (*Abelmoschus esculentus* (L.) MOENCH) and roselle (*Hibiscus sabdariffa* L.). Fields often accommodate acacia shrubs and trees (*Acacieae* Dumort.) used for fodder and fencing as well as spontaneous food trees, such as mango tree (*Mangifera indica* L.), shea tree (*Vitellaria paradoxa* C.F.Gaertn.), African locust bean (*Parkia biglobosa* (Jacq.) R.Br. ex

G.Don) and planted trees such as moringa (*Moringa oleifera* Lam.) or eucalyptus (*Eucalyptus camaldulensis* Dehnh.).

Besides the traditional extensive farming practice, intensive irrigated garden systems can be found in the urban and peri-urban area of Ouagadougou. Commonly grown cash crops are cabbage (*Brassica oleracea* convar. *capitata* L.), tomato (*Solanum lycopersicum* L.) and leafy vegetables such as lettuce (*Lactuca sativa* L.), spinach (*Spinacia oleracea* L., Figure 1.3), amaranth (*Amaranthus* sp.) and jute mellow (*Corchorus olitorius* L.).

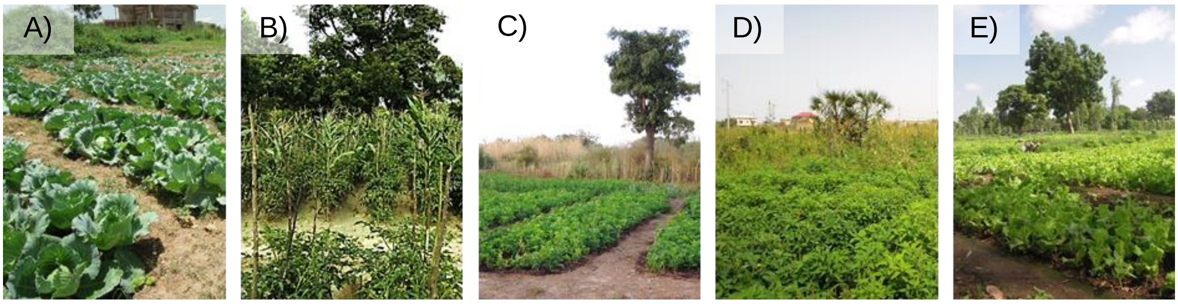

Figure 1.3. Cash crops grown in urban gardens of Ouagadougou, Burkina Faso: A) cabbage, B) tomato intercropped with maize, C) spinach, D) amaranth, E) lettuce.

1.3 Overall research objectives

The UrbanFood^{Plus} project focused on the efficient use of resources in urban production systems of West Africa. This PhD study was conducted to determine the risks of contaminated irrigation water in vegetable production and implemented the monitoring of strategies to improve food safety, sustain crop production and maintain soil quality.

Study 1

Hypotheses:

- Contamination through total coliform, *E. coli* and *Salmonella* spp. is higher on lettuce irrigated with sewage polluted channel water than on lettuce irrigated by well water;
- Lettuce contamination further increases throughout the trade chain;
- The increase in biological lettuce contamination depends on post-harvest handling.

Objectives:

(i) To verify to what degree the used irrigation water sources contaminate lettuce with pathogens such as *E. coli* and *Salmonella* spp.
(ii) To assess whether pathogen inputs occur during the trade chain due to washing the produce with contaminated water or due to other post-harvest handling effects
(iii) To compare the pathogen loads on lettuce with and without appropriate post-harvest washing under experimental conditions.

Study 2

Hypotheses:

- Long term irrigation with industrial sodic wastewater reduces yields due to soil degradation.

Objectives:

(i) To verify to what extent industrial sodic wastewater irrigation in tropical and subtropical regions lead to sodification of crop land;
(ii) To assess the impact of wastewater irrigation on top- and subsoil sodification in the farming area Kossodo, Ouagadougou;
(iii) To evaluate the impact of continuous irrigation with sodic wastewater on farming systems in Kossodo, Ouagadougou.

Study 3

Hypotheses:

- Gypsum as a soil amendment can reverse negative effects of sodic alcaline wastewater irrigation on soil quality and crop development

Objectives:

(i) To assess the effects of gypsum application on soil pH and ESP
(ii) To assess the effects of gypsum application on the yield of maize and spinach.

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Chapter 2

Effects of water quality and post-harvest handling on microbiological contamination of lettuce at urban and peri-urban locations of Ouagadougou, Burkina Faso

2.1 Abstract

Vegetable production in urban and peri-urban open gardens of Ouagadougou (Burkina Faso), contributes to food security by supplying the rapidly increasing number of city residents with fresh produce all year round. Especially in semi-arid tropics, water sources are often of low quality and the absence of environmental safeguarding policies and food safety standards may lead to health risks for producers and consumers. This is particularly acute if irrigation water for vegetable production is taken from wastewater polluted channels. The purpose of this study was to (i) verify the degree of pollution in irrigation and wash water with pathogens such as *Escherichia coli* (*E. coli*) and *Salmonella* spp., (ii) identify pathogen inputs during the trade chain as a consequence of contaminated washing water or other post-harvest handling effects (iii) compare the results with controlled conditions by applying appropriate post-harvest washing in an experimental setting. Irrigation water of ten production areas showed a mean total coliform contamination of 3.4 x 10^6 CFU 100 ml^{-1} and a mean *E. coli* load of 2.1 x 10^5 CFU 100 ml^{-1}. In 60 % of the cases irrigation water did not meet the health based target for lettuce of less than 10^3 *E. coli* CFU 100 ml^{-1} irrigation water and in 30 % of the cases irrigation water samples were contaminated with *Salmonella* spp.. Loads of total coliforms on lettuce leaves ranged from 2.9 x 10^3 CFU g^{-1} to 1.3 x 10^6 CFU g^{-1}, while *E. coli* averaged 1.1 x 10^2 CFU g^{-1}. Postharvest data showed that regardless of how the lettuce was treated along the trade chain average total coliform and *E. coli* loads increased until two hours after reaching the sales point by one log unit. Overall half of all lettuce samples (n = 30) tested positive for *Salmonella* spp.. The experiment showed that appropriate postharvest handling could prevent the increase of total coliforms. In conclusion inappropriate lettuce handling after harvest constitutes a considerable risk for produce contamination in Ouagadougou.

2.2 Introduction

The rapidly growing population of West African cities results in an increasing demand for agricultural products (UN-Habitat 2014). Urban and peri-urban agriculture (UPA) supplies cities with vegetables especially during the rainy season, but is in the long lean season restricted to places where sources of irrigation water are present (Karg et al. 2016). During this period UPA farmers rely on well water, wastewater polluted channels or dams (Kiba et al. 2012). In Ouagadougou concrete channels run through the city to drain it of water after heavy rainfalls. They carry a mixture of natural streams and human sewage. The proportion of natural stream water, rain water and wastewater depends on the season. The use of wastewater for irrigation and vegetable washing brings pathogens to the fields and ultimately the vegetables resulting in food borne diseases (FBD). Africa faces the highest burden of FBD, whereby 70 % are diarrhoeal diseases caused by *Salmonella* spp. and the feacal bacteria *Escherichia coli* (*E. coli*) and *Vibrio cholerae* (*V. cholerae*) (WHO 2015). Faecal contamination is particularly severe in raw edible vegetables, such as lettuce which is in particularly high demand as shown by a recent study (Bellwood-Howard et al. 2015). Lettuce on local markets was exclusively produced in UPA of Ouagadougou and 50 % of all open-space urban vegetable farms, gardens which arose in non-build-up areas without official permission, were producing lettuce. In Ouagadougou lettuce is sold fresh on official urban markets, informal markets that are well-known open spaces along the main streets and in individual small street shops.

The production as well as the trade of vegetables is commonly informal. Only in official markets are at least ownership of market stalls and opening hours coordinated and controlled by public authorities. Over the years traders have developed different strategies to keep vegetables fresh under the hot climatic conditions governing the trade chain. Rinsing the lettuce in the field or during transport with water of different origins is one such strategy.

Previous studies have shown that in West Africa produce is polluted with pathogens as a consequence of wastewater usage on farmers fields and on markets (Amadou et al. 2014; Amoah et al. 2005; Amoah et al. 2007; Diogo et al. 2010). However, in these works the development of pathogen loads along the trade chain and especially the effects of post-harvest handling on the contamination level were neglected even though microbial loads on lettuce leaves along the trade chain from field to end-consumer heavily depends on vegetable handling by the market women involved.

Hence, this study aimed at (i) verifying to what degree the used irrigation water sources contaminated lettuce with pathogens such as *E. coli* and *Salmonella* spp. in comparison to well water irrigated lettuce, (ii) assessing if there are pathogen inputs during the trade chain due to produce washing with contaminated water or other post-harvest handling effects, and (iii) comparing the results to the change of pathogen loads on lettuce under controlled conditions by applying appropriate post-harvest washing under experimental conditions. This paper comprises ten case studies, in which trading women and their harvested lettuce were followed during the complete trading way – from the field to the end consumer.

2.3 Materials and methods

2.3.1 Study area

Our study was conducted in Ouagadougou, the capital of Burkina Faso, a landlocked country in West Africa. The city is located in the sub-Sahelian climate zone and faces a short unimodal rainy season lasting four months from end of May to end of September with a precipitation of 600 – 900 mm per year (Ibrahim et al. 2012).

A total of ten open-space gardens that produced fresh vegetables for local markets were selected along typical water bodies and produce selling networks were identified (Figure 2.1). The selection was done on the bases of 53 interviews and with respect to the size of the location.

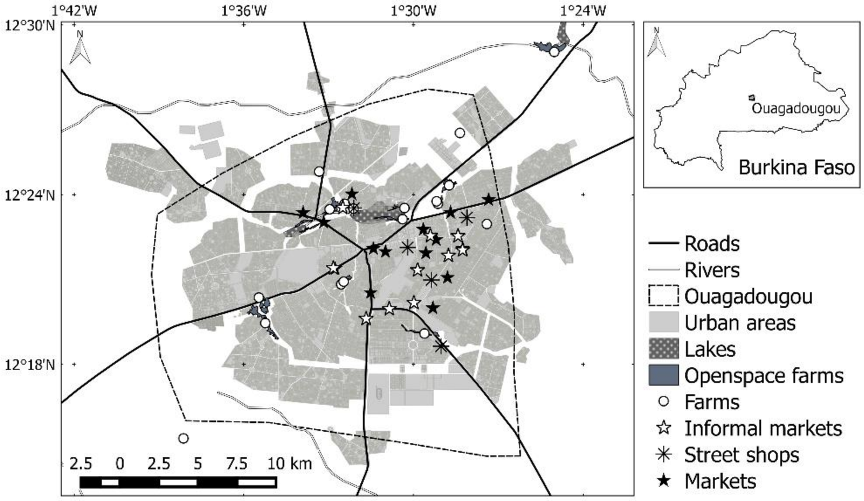

Figure 2.1. Location of the studied lettuce production farms (circle) in Ouagadougou, Burkina Faso, in 2014 with three different types of markets (official market (n = 15), informal markets (n = 10) and street shops (n = 5); asterisks).

2.3.2 Trader interviews

From October 2013 to March 2014, 53 randomly selected traders who sold lettuce either on a public market, street market or informal market in different locations were interviewed (Figure 2.1) using a semi-structured questionnaire. The interviews took place directly at the urban production sites where traders purchased the lettuce from the producer or at the point of sale. Key questions of the interview addressed origin and final selling point of lettuce, times and regularity of trading activities, persons involved and post-harvest handling, including washing procedures and sources of washing water.

2.3.3 Pathogen contamination of lettuce leaves by irrigation water and post-harvest handling

Monitoring

To examine the relationship between the pathogen load of lettuce leaves and the quality of irrigation water quality used by producers on farm and for post-harvest handling by traders, ten market women were accompanied from lettuce harvest to the market place where women offered the lettuce for sale. From the evaluation of the interviews the most important gardening sites were selected, within those market women from the previously conducted interviews have been randomly selected. Traders were additionally interviewed in depth using open and reflective questions. All activities of the market women that were related to lettuce and trading activities were recorded. We also took geographic coordinates from each farm site, market womens' transport routes and points of sale.

During the monitoring procedure, a total of 60 lettuce samples were taken. Each sample consisted of three lettuce heads that were mixed and placed in one sterile plastic bag. Two samples were taken at each time and location. Six of ten traders obtained the lettuce from farms where well water was used for irrigation and four traders from farms where polluted channel water was used for irrigation. The lettuce samples of each trader were taken at three time points during one day: at harvest, at arrival at the market and two hours after arrival. On-farm site water samples of five litres were taken from the irrigation water (n = 10). Additionally, samples of wash water were taken, if market women rinsed the lettuce before or during the selling process (n = 9). To test irrigation water for counts of helminth eggs 40 additional water samples comprising two samples at each time and location, were taken and analysed separately. Each of these samples consisted of one litre and sampling was repeated after two weeks.

Post-harvest handling experiment

To analyse the effect of appropriate post-harvest washing on the pathogen load of lettuce leaves, two experimental fields with a size of 7 x 3 m each were cultivated with lettuce in November and December 2014. One field was irrigated regularly with tap water (total coliform load: 48 CFU 100 ml^{-1}) and the second field with polluted channel water (total coliform load: 6.3×10^4 CFU 100 ml^{-1}) collected from the biggest channel of Ouagadougou, which is located at the outlet of the city and receives not only the river stream passing through the city forest, but also serves as consolidation drainage avenue for all wastewater channels of Ouagadougou.

At harvest stage, 18 lettuce heads were taken from both fields and separated into two batches (n = 9), one batch was kept unwashed for four hours and the other batch was washed directly after harvest with tap water. Three samples per batch, each consisting of three lettuce heads, were taken immediately after harvest and again after two hours and after 4 hours. Lettuce and water samples of the experiment were analysed for total coliform load as specified below.

For each sample taken, gloves were used and samples were cooled and transported on ice to the laboratory and analysed within 24 hours.

2.3.4 Laboratory analysis

Lettuce microbiological analysis

For laboratory analysis, 25 g each of the mixed lettuce sample was added to 225 ml of buffered peptone water (BPW, Liofilchem, Teramo, Italy, Traore et al. 2015). For the analyses of total coliforms and *E.coli* dilutions until log six were performed and added to the dish before filling the fluid Chromocult ES agar (Merck KGaA, Darmstadt, Germany). Two dishes per dilution were incubated at 37 °C for total coliform and two dishes per dilution at 44 °C for the count of *E.coli*. The colonies were counted after 24 h and recounted after 48 h.

The load of *Salmonella* spp. was determined by standard methods (ISO: 6579:2002). Pre-enrichment was done by using a stoke solution with 25 g lettuce in 225 ml BPW. As a second solid selective plating-out medium Salmonella Shingella Agar (SS, Oxoid Ltd., Hampshire, UK) was used. After the identification of sulfur-positive colonies on SS and Xylose lysine deoxycholate agar (XLD, Merck KGaA, Darmstadt, Germany), three suspected *Salmonella* spp. colonies per plate were confirmed by the AP20 gallery test (BioMérieux, Lyon, France, Nucera et al. 2006; O'Hara et al. 1993).

Water microbiological analysis

Cellulose nitrate membrane filters with a pore size of 0.47 µm (Sartorius AG, Göttingen, Germany) were used in combination with a Sartorius Combisart® system to filter the serial dilutions of the collected water samples. Filters were placed on the selective medium Chromocult to cultivate total coliforms and *E. coli*. To identify the counts of total coliforms plates were incubated at 37 °C, for *E.coli* the incubation temperature was 44 °C. For *Salmonella* spp. identification 2 l of the samples were filtered and the membranes were placed in BPW for 24 h at 37°C. After 1 ml was taken from the pre-enrichment and added to 9 ml of the selective enrichment broth Rappaport Vassiliadis Soya broth (RSB, Oxoid Ltd., Hampshire, UK) and incubated at 44°C overnight. One µl of enriched broth was streaked onto the XLD agar (Oxoid Ltd., Hampshire, UK) and incubated at 37°C for 24 h. Identity of the red colonies with black centre was confirmed biochemically by API 20E strips (Traore et al. 2015). To analyse water samples for the presence of *V. cholerae* 2 l of substrate were filtered and membranes were enriched in alkaline peptone water (APW, Oxoid Ltd. Hampshire, UK) at 37 °C for 24 h. In case of very tribute water more than one membrane was used and added to the enrichment broth. One µl of enriched broth was streaked onto the Vibrio selective agar, Thiosulfate Citrate Bile Salt Sucrose (TCBS, Merck KGaA, Darmstadt, Germany). Presumptive *V. cholerae* colonies on TCBS must be flat, circular, yellow, and sucrose-fermenting (Traore et al. 2014). Helminth were tested following Fulleborn´s flotation method (Fuelleborn 1925).

2.3.5 Statistical analysis

The statistical analyses of the case studies, was done using a generalized linear mixed model, in which penalized quasi-likelihood was used (glmmPQL). The “trader” was used as random factor in the model, as two samples per trader and time were taken. The model tested if contamination was dependent from time, microbial load of irrigation water and its source. The model was conducted in R version 3.2.3 (R Core Team 2015) with additional functions provided by the R package MASS (Venables and Ripley 2002). Statistical analyses of the experiment were done with log transformed data by ANOVA using SPSS (Version 24, IBM Corporation, Armonk, NY, USA) using time, irrigation water source and washing as fixed factors, followed by examining the significant effects by a post hoc LSD test. ANOVA and LSD tests, as well as visualizations were done with SPSS and Excel 2013 (Microsoft Corporation, Redmond, WA, USA). The map was generated with Quantum GIS (Chugiak 2.4.0., QGIS Development Team 2012).

2.4 Results

2.4.1 Lettuce trade chain

The survey with lettuce traders (n = 53) showed that most of the lettuce was harvested in the morning (on average 6:30 a.m.) so that the markets could be reached by the official opening at 8 a.m. Some traders preferred to harvest in the afternoon, around 2 p.m. to sell at the market or at informal street markets, starting at 5 p.m., as this is the time when most people drive home and stop along their way to buy fresh vegetables for dinner. Occasionally, left over charges were sold in the morning on the markets. Older outer leaves were sold as cattle feed. Most of the interviewed lettuce traders sold their produce at markets (49 %) and informal markets (34 %), but also at individual street shops (17 %). More than two thirds of the traders harvested the lettuce them self, others bought the lettuce from resellers. Nearly all traders (98 %) washed the lettuce: either with tap or well water and often with both (Table 2.1). Further, 41.5 % of the traders responded that the consumers are interested in the origin of the lettuce, 37.7 % and 20.8 % stated that consumers are not or only sometimes interested in the origin. Trading of lettuce was a women’s domain, as all but one trader were female. They transported the lettuce in big baskets, mostly covered with a well water soaked cloth, on the back of the small motorcycles or on bicycles to the selling point.

Table 2.1. Information about selling point and washing practices of 53 interviewed urban and peri-urban lettuce traders in Ouagadougou, 2014.

Activity	Time	n	Selling location	n	Wash water source				Overall washing events	n
					On farm	n	On market	n		
Harvest	Morning (5 – 9 a.m.)	28	Official market	21	Well	26	Tap	8	Washed twice	24
	Afternoon	2	Informal market	8	Not washed	8	Well	4	Not washed	2
	Morning and afternoon	6	Street shop	7						
Resell without harvesting		17	Informal market	10	No information if lettuce was washed on farm		Tap	13	No information	
			Official market	5			Not washed	4		

Table 2.2. Monitoring results of the post-harvest handling of ten lettuce traders from harvest at urban and peri-urban gardens to their selling points.

Irrigation water	Wash water source on farm	Prewash of roots	ID	Harvest time	Begin of sale	Location of sale	Type of lettuce cover	Washing practice	Transport by	Total distance (km)
Well	Well	Yes	T7	7:00 AM	8:15 AM	Official market	Old washed leaves and plastic sheed	Washed small portion with used tap water	Bicycle	3.75
		No	T3	8:00 AM	9:40 AM	Official market	Jute sack or cloth	Washed small portion with used tap water and sprinkled with wash water, later washed all with used water	Motorbike	13.3
					↓*Change sellining location*					
					5:00 PM	Informal market				
		Yes	T4	10:30 AM	3:00 PM	Informal market	Old washed leaves Jute sack after washing	Wash all with tap water	Motorbike	16.5
		No	T9	9:30 AM	10:30 AM	Official market	Washed plastic sheed	No post-harvest wash, just wetens with tap water	Motorbike	14.2
Channel			T2	8:00 AM	9:00 AM	Markets & houses	Dry cloth	No post-harvest wash	Motorbike	11.75
					↓*Change trader*					
						Official market	Not covered	Washed small portion with used tap water		17.3
		No roots harvested	T10	6:30 AM	7:30 AM	Official market	Old washed leaves and cloth	No post-harvest wash	Motorbike	1.7
					↓*Change trader*					
					5:00 PM	Street shop	Not covered	Wash with tap water at home and sprinkled with tap water	Bicycle	8.3
		No	T5	8:00 AM	9:00 AM	Official market	Well water wet cloth	No post-harvest wash	Motorbike	
					↓*Change trader*					
					11:00 AM	Official market	Plastic sheed	Washed two times with tap water		2.95
	Channel	Yes	T6	3:00 PM	3:30 PM	Street shop	Old washed leaves and jute sack	No post-harvest wash	Bicycle	1.35
Well	Not washed		T8	3:00 PM	3:30 PM	Street shop	Not covered	Washed with well water	Walking	0.05
			T1	8:00 AM	5:00 PM	Street shop	Old washed leaves and wet cloth	Washed at home with tap water	Bicycle	1.47

The monitoring of ten lettuce traders showed similar results as the survey: The majority of the traders harvested in the morning and sold the lettuce on markets (Table 2.2). Those who harvested in the afternoon sold lettuce at street shops. In eight out of ten cases the women washed the lettuce directly after harvest, mostly with well water. In half of the cases women washed roots separately or took them of. Most of the lettuce was washed with tap water post-harvest. In all cases the lettuce was washed at least once before being sold, in six cases lettuce were even washed twice. Traders transported the lettuce over a distance of 0.05 km to 17.3 km, with an average distance of 8 km. Half of the observed lettuce charges reached the final selling point in less than 4 km and all lettuces were sold in less than 14 h.

2.4.2 Microbiological contamination

Relationship between pathogen contamination of lettuce and irrigation water source

Water contamination levels of both irrigation water sources (well and channel) were similar with a wide range of total coliform of 3.6 x 10^3 to 1.87 x 10^7 CFU 100 ml^{-1} and *E. coli* from 1 x 10^2 to 4.25 x 10^4 CFU 100 ml^{-1}.

Microbiological contamination of lettuce on farm did not exceed 10^2 *E. coli* counts per g lettuce. Total coliform counts on lettuce leaves at harvest ranged between 2.89 x 10^3 and 1.25 x 10^6 CFU g FM^{-1} (Figure 2.2A) and also not differ between well and channel water irrigated plants.

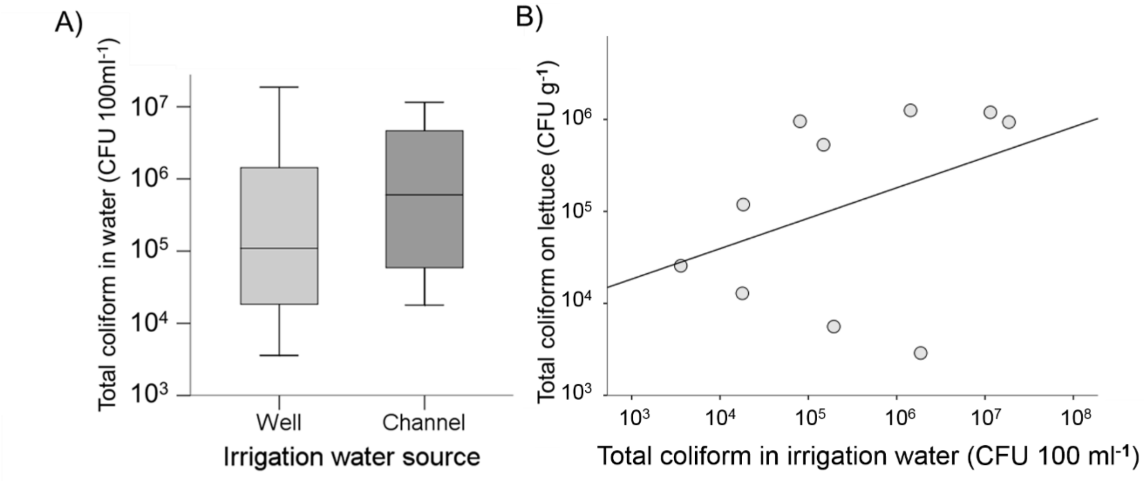

Figure 2.2. Total coliform load on lettuce A) irrigated with well (n = 6) or channel water (n = 4) in Ouagadougou (Burkina Faso), error bars indicate +/- one standard deviation; B) in correlation with total coliform load of irrigation water of ten case studies in urban gardens of Ouagadougou in 2014.

No relation was found between irrigation water and harvesting time on counts of *E. coli* on lettuce, but total coliform load on lettuce was positive related to the total coliform load of the irrigation water (glmmPQL; $P < 0.05$, $t = 2.64$, Figure 2.2 B).

Changes in pathogen load along the trade chain and the effect of post-harvest handling

At the selling point the contamination of lettuce through *E. coli* ranged from 0 to 4.45 x 10^3 and total coliform ranged from 4.95 x 10^4 to 1.35 x 10^7 CFU g^{-1} (Figure 2.3). The bacterial load increased from farm to selling location significantly.

The documented post-harvest handling parameters, namely hours after harvest, number of washing events, distance to the market, as well as the *E. coli* of the wash water did not affect the *E. coli* load on lettuce at the selling point. Likewise, no affect was found for total coliform load at selling point, besides the effect of initial total coliform load of lettuce (glmmPQL, t = 3.35, P < 0.01).

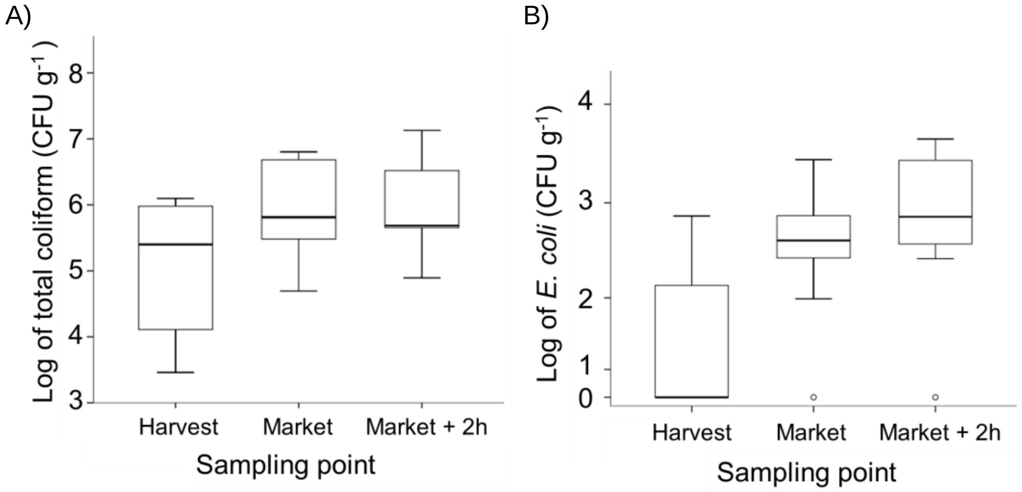

Figure 2.3. Total coliform (A) and *E. coli* (B) load on lettuce at harvest, arrival on the market and two hours after arrival on the market in Ouagadougou (Burkina Faso); n = 40.

Wash water quality

Tap water in Ouagadougou was characterised by a low contamination with *E. coli* at 0.5 CFU 100 ml^{-1} and of total coliform with 117 CFU 100 ml^{-1} as well as no contamination with *Salmonella* spp. and *V. cholera*. If tap water was used for washing, total coliform reached 5 log CFU and *E. coli* 3 log CFU 100 ml^{-1}. The use of tap-originated water for washing lettuce at the selling point tended to decrease the load of *E. coli* on the lettuce plants (glmmPQL, t = -1.51, P = 0.17, Figure 2.4).

Nearly 20 % of the water samples and half of the lettuce samples tested positively for *Salmonella* spp., irrespective of irrigation water source or washing procedure. One channel water sample was positive for *Salmonella* spp., as well as two well water samples and one wash water sample.

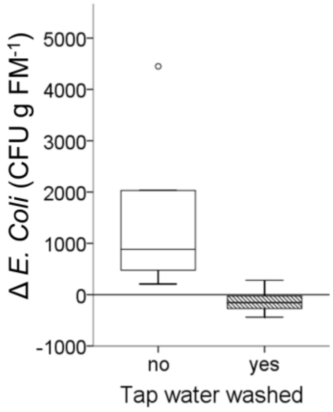

Figure 2.4. Effects of tap-water washing of lettuce on the *E. coli* load during the 2 h storage time on the market in Ouagadougou.

Overall, 62.5 % of samples that were washed with channel or well water, 50 % of the unwashed and 20 % of the tap water washed samples were positive for *Salmonella* spp. All water samples tested negatively for *V. cholerae* and therefore no lettuce samples were examined. Two water samples tested positively for eggs of the helminth *Strongtlus* spp..

Effects of appropriate post-harvest lettuce handling on total coliform load under controlled conditions

Results gathered from our experiment under controlled conditions showed a significant effect of irrigation water source (tap or channel water), washing procedure (washed or not washed) and time after harvest (two and four hours) on total coliform load of lettuce ($P < 0.001$).

Total coliform contamination of lettuce irrigated permanently with tap water had 1.6×10^3 CFU g FM^{-1} at harvest and was significantly different (LSD, $P < 0.01$) to channel water irrigated lettuce with 2.4×10^4 CFU g FM^{-1} on average (Figure 2.5). The difference between total coliform load on tap and channel water irrigated unwashed lettuce was still significant at later time points (after two and four hours, LSD, $P < 0.001$).

Without washing total coliforms on channel-water irrigated lettuce increased significantly after two hours (LSD, $P < 0.001$), whereas this effect was not significant in tap water irrigated lettuce. Results of the experiment showed further that the post-harvest washing of lettuce with tap water effectively limited the growth of coliforms during storage. This effect was more pronounced on lettuce plants cultivated with tap water irrigation for which post-harvest washing resulted even in a significantly lower total coliform load (2 h after harvest) than at harvest.

Channel water irrigated lettuce, which was washed with tap water after harvest, showed a significant lower total coliform load after 2 and 4 hours compared to unwashed samples (Figure 2.5). In tap-water irrigated lettuce the washing effect was less, but still significant. Lettuce which was irrigated with channel water and was washed with tap water had a constant amount of total coliform, whereas total coliforms on unwashed lettuce increased after 2 h and 4 h. In tap-water irrigated lettuce washing reduced the total coliform load significantly.

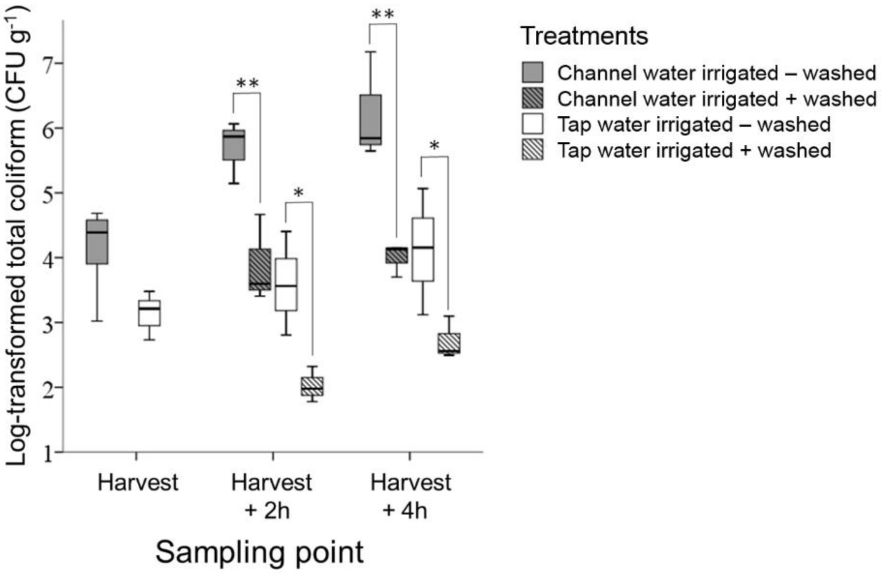

Figure 2.5. Experiment to evaluate the effect of irrigation water source (channel and tap water) and post-harvest washing on total coliform load of lettuce cultivated in an urban production farm in Ouagadougou, Burkina Faso in 2014. Stars indicate significant differences between washed and unwashed samples * $P < 0.01$, ** $P < 0.001$.

2.5 Discussion

2.5.1 Typology of urban traders

In Ouagadougou the lettuce trade seems largely informal and is only partly regulated by governmental institutions at the official urban markets. Food trade of West African cities is often a women's domain, as has been reported earlier (Porter et al. 2007) and run by individuals that are vulnerable to evictions (Smit 2016). In Ouagadougou traders operated independently from associations those documented in Ghana (Lyon 2003). Contrary to Robineaus (2015) findings from Bobo Dioulasso, the second biggest city of Burkina Faso, trading women of our research were not married to lettuce farmers. In the capital women mainly harvested the lettuce and sold it at their own shop or they were wholesalers who harvested and transported the lettuce to sell it to other traders. Still personal networks were important, as reported by Porter et al. (2007), because a particular field may belong to a family or friends and determines where the women harvested the lettuce. This is one reason why up to 30 % of the trading women chose to gather the lettuce from farms that were located on the opposite side of the city and transport the fresh vegetables through the crowded city center to reach their selling point.

Nevertheless, transport ways of lettuce to urban markets are short as the highly populated city area does not exceed a 30 km diameter and lettuce is exclusively produced in urban and peri-urban open-space systems in close proximity to the inner city area.

Overall the survey and monitoring documented how individual traders are managing the lettuce trade, including details about irrigation quality, washing practice, selling locations, transport as well as harvesting and selling time. The complexity of lettuce post-harvest handling and possible contamination sources during their daily routine could only be detected through the use of qualitative methods.

The monitoring indicated that it was common to first wash lettuce directly on farm. Afterwards traders who remained in one location over many hours presented a small tap water washed portion on their stand and left the rest of the charge in a covered basket or bowl under the table. If more than one water source for washing was available, traders chose the one which appeared to be cleaner even if they had to pay for it. Mostly it was well water on farm, preferable to channel water and tap water on market, preferable to well water.

As already highlighted by Smit (2016), the availability of tap water on markets - an infrastructure provided by the government- results in improved vegetable quality as use of tap water reduced lettuce contamination. The choice of better quality wash water indicated the awareness of the trading women about contamination of water. In the in-depth interview as well as in the survey women explained that farming areas, where polluted channel water was used for irrigation, were not favored for lettuce harvest. For the same reasons consumers asked about the origin of the lettuce. All interviewees knew that lettuce had to be carefully washed before consumption. In contrast to Qadir (2010) these results show that consumer awareness of produce contamination was widespread. Still, producers, traders and consumers may find it difficult to trust information about the crop trade chain, as trading is not regulated by policies and reliability of information depends on individual willingness and honesty. In addition to the contamination risks that traders are aware of, unconscious contamination risks were observed. For example, the daily habits of traders who washed lettuce with water used prior for babies' personal care or allowed free-running poultry to have contact with the produce. Selling points were also often dirty and particularly under these conditions the placement of the perforated lettuce baskets on the floor seems to be inadequate.

2.5.2 Relationship between irrigation water quality and pathogen load on lettuce leaves

Only three out of ten water sources that were used for irrigation of lettuce in Ouagadougou were below the health based target of WHO, which restricts irrigation water for labour intensive and row edible crops to 3 log units *E. coli* per 100 ml (WHO 2006). Urban channels in Ouagadougou drain combined water sources, and therefore contamination varies greatly depending not only on dilution effects, but also on location and season, as described. The studied wells in Ouagadougou were similarly contaminated with faecal bacteria, as reported earlier about rural and urban West African wells (Barrell and Rowland 1979; Bordalo and Savva-Bordalo 2007; Jackson et al. 1998; Uesbeck 2009). The bacterial contamination of well water through pathogenic loaded runoff water is most likely caused by the widespread lack of sanitary infrastructure in West African cities (Rosillon et al. 2012) but also by the intensive application of manure on urban vegetable fields in Ouagadougou (Bellwood-Howard et al. 2015; Kiba et al. 2012).

Contamination of irrigation water above the health based target was even found in a water basin that receives water from a modern solar pump connected to a borehole (*E. coli* of 3.9 x 10^4 per 100 ml), as it is the case in a peri-urban village of Ouagadougou. Contamination must have been introduced in between pumping and storing the water uncovered in the for local farmers free accessed basin as drillings are normally not contaminated with *E. coli* (Savadogo et al. 2013).

Even if lettuce was irrigated with inappropriate water, *E. coli* was not typically present on lettuce leaves. One reason might be that lettuce had not been irrigated that same day, so that due to the low survival rate of *E.coli* in dry condition, (Winfield and Groisman 2003), as well as the additional deactivation of *E. coli* by sunlight (Maiga et al. 2009), loads on plants decreased.

2.5.3 Effect of post-harvest handling on lettuce contamination

Winfield and Groisman (2003) described how *E. coli* can reproduce in tropical humid non-host conditions. In favourable conditions therefore natural bacterial growth can lead to the observed increase of total coliform and *E. coli* load on lettuce along the trade chain from the field to the end-consumer. Furthermore, vegetable traders in West African have limited facilities to cool produce (Glover 2017) and with it to slow down natural bacterial growth. However, low cost alternatives such as sprinkling lettuce with water and covering the produce with plastic to prevent cross-contamination and to keep it fresh, can also foster bacterial growth (Elisha et al. 2016).

Besides the initial contamination of lettuce and the increase due to favourable growing conditions, cross-contaminations are commonly to occur due to contact with soil, manure, free-running chickens or even due to binding the leaves into bunches and exposing them to dirt and dust (Beuchat and Ryu 1997). At least six traders tried to clean off the soil by washing roots or taking them off to prevent contamination from soil and manure. Still, it has to be taken into account that *E. coli* is also able to enter and survive in plants (Solomon et al. 2002), which can further increase bacterial load, but this was not investigated in this study.

Sprinkling water, which is in our study identical with wash water, did not seem to be a source of a cross-contamination. Furthermore, the number of washing events and transport distance from farm to market did not significantly affect lettuce contamination. Washing with tap water reduced the bacterial load, as tap water quality in Ouagadougou met the WHO standards. However, as contaminated lettuce gets washed, successive lettuce heads washed with the same water may suffer cross-contamination due to the pathogenic bacteria transfer by the wash water (Maffei et al. 2016). *Salmonella* spp. is known to contaminate water and by this infect previously uncontaminated lettuce samples as it is long-term persistent in non-host environments (Baudart et al. 2000; Winfield and Groisman 2003; Wright 1989). In our study *Salmonella* spp. contamination of lettuce was comparable to Traore et al. (2015), as 50 % of the lettuce samples taken in Ouagadougou were loaded with this pathogen. Cross-contamination by covering lettuce with plastic, older leaves or wetted cloth could not be proven and is unfortunately also neglected by literature.

To support our findings from the field work, the experiment, which excluded cross-contamination, showed that (i) irrigation with clean water can significantly reduce initial bacterial contamination, (ii) it is possible to reduce bacterial loads of lettuce by washing once with clean water. The effect of adequate post-harvest handling may be optimized by using additives in the wash water as reported by Amoah et al. (2007).

2.6 Conclusions

Except for tap water, all water sources were contaminated with pathogens. In view of the normal practice of the trading women, it can be stated that (i) the use of irrigation water for washing did not sufficiently reduce microbial loads on lettuce and (ii) washing with clean tap water reduces microbial loads, but the wash water has to be changed more often in order to prevent pathogen transfer. Contamination pathways other than water, such as soil, personal hygiene of traders, free-running animals, contaminated transport material, dust and dirt are of importance. If lettuce is handled adequately and washed with tap water after harvest, it is possible to keep microbial loads low even if the crop was irrigated with low quality wastewater.

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Chapter 3

Effects of sodic alkaline industrial wastewater as irrigation source on agrarian soil in semi-arid regions

3.1 Abstract

Utilisation of industrial wastewater in urban and peri-urban gardens comprises risks of contamination of humans, animals, soils and plants. Irrigation with sodic alkaline wastewater is common worldwide and can lower soil quality especially in semi-arid, hot climates where evapo-transpiration is high. Our study reviews literature in which agricultural cultivation utilizing wastewater with > 100 mg l^{-1} sodium (Na) and in which effects on soils exposed to semi-arid climates were documented. The findings were compared to those of a case study from an urban garden in Ouagadougou, Burkina Faso. Our aims were to (i) examine to what extent Na in irrigation water can induce soil sodicity; (ii) evaluate the effect of industrial wastewater on top- and subsoil sodification in the farming area of Kossodo, Ouagadougou, and (iii) compare the results of our case study with those reported in the literature.

To characterise the soil of the study area, soil samples taken from 45 randomly selected fields were analysed for pH, electrical conductivity (EC) and exchangeable cations. Farmer interviews were used to record information on irrigation and cultivation, including management practices used over the last decade. Wastewater originating from tanneries and beverage producers exhibited pH values ranging from 8.5 to 9.8. The same wastewater – in addition to effluent from a power plant and papermill - had Na concentrations of 300 to 1200 mg l^{-1}. Wastewater irrigation induced a reduction in soil quality by increasing soil pH by up to 2 units, increasing EC by 14 % to 500 % and increasing Na up to 28 times compared with the initial value. Both continuous and short-term irrigation with sodic wastewater led to Na accumulation in the soil. Our study further indicated that dissolved Na percolated both vertically and horizontally, thereby contaminating the subsoil and the surrounding non-irrigated area, respectively.

In conclusion, the utilisation of untreated sodic wastewater of industrial origin is not advisable, as even low Na concentrations or even only temporary use may diminish soil quality.

3.2 Introduction

This study was conducted to combine results from existing literature about sodification of agricultural soil as a consequence of industrial wastewater irrigation in semi-arid regions with a case study from an urban farming area in the industrial zone of Ouagadougou, Burkina Faso. Its aim was to investigate to what extent Na accumulates in an agricultural soil due to the use of inadequately treated water and how this accumulation affects soil characteristics.

Burkina Faso, as most West African nations, is facing a rapid urbanisation with an urban growth rate of 9.2 % (UN-Habitat 2014) and enhanced industrial activities in peri-urban areas. Since many industrial processes demand high volumes of water, the utilisation of surface water leads to the pollution of water bodies and channels in these zones (Huang et al. 2006; Zhang et al. 2007). Industrial effluents are often discharged (Haroon et al. 2013) untreated because purification plants are lacking or are only partly functioning (Maconachie and Binns 2006). Nevertheless, agricultural use of such wastewater is rapidly expanding (IWMI 2008) in the urban and peri-urban zone where small scale urban and peri-urban farmers produce vegetables with wastewater because i) water is scarce, ii) vegetable production is a lucrative source of income and any available water source for irrigation enables year-round production (Cissé 1997), and iii) the reuse of nutrients from wastewater can make production more efficient despite produce contamination or environmental problems (Khai et al. 2007).

Problems differ according to types of industrial effluents. In the textile and tannery industry of Nigeria Na content and alkalinity predominated (Kanu and Achi 2011) while other studies documented Na hazards in paper mills (Almeida et al. 2017) and beverage effluents (Sou et al. 2013; Haroon et al. 2013). However, little attention has been given to the wastewater irrigation-derived accumulation of Na in soils despite the fact that the rapid accumulation of Na in certain soils can cause irreversible productivity changes and that millions of hectares of agrarian land worldwide have been degraded due to sodification (Simmons et al. 2010). Degradation occurs as the physical soil structure deteriorates and clay particles of the soil disperse. Subsequently, the field and air capacity decreases (Bernstein 1975), soil aggregates disperse, swelling and slaking occurs and the soil becomes impermeable or waterlogged (Hamilton et al. 2007). Furthermore, excessive Na ions in the soil solution lead to the replacement of cations such as calcium (Ca) and magnesium (Mg) at the exchange complex (Bernstein 1975; Parween et al. 2017), which will then precipitate as plant unavailable calcium and magnesium carbonates (Abrol et al. 1988).

As a result of the physical damage to the soil structure, root growth was found to be reduced (Hamilton et al. 2007) and seed germination was hindered as documented in oat seedlings by Gao et al. (2014).

Towards a comprehensive understanding of the problem the chemical parameters pH, electrical conductivity (EC), Na concentration, sodium absorption ratio (SAR) and exchangeable sodium percentage (ESP) of wastewater irrigated soils were analysed in this study. The FAO characterized sodic soils as having a pH above 8.2, an EC below 4000 µS cm^{-1} and an ESP above 15 % (Abrol et al. 1988). Sodium in wastewater can increase the ESP to about 30 % (Menneer et al. 2001). The effects on plant growth on sodic soils is far less frequently reported than on saline soils (pH > 8.2, EC > 4000 µS cm^{-1}), but are known to lead to osmotic stress and deficits in nutrient uptake. Sodium stress leads to problems in plant development and decreases yields (WHO 2006), since the Na concentration of wastewater is higher than the plants' demand (Abaidoo et al. 2010). Still, many plants will accumulate Na due to passive ion uptake in the roots (Kramer et al. 1977; Gao et al. 2014), resulting in a cation imbalance that leads to water stress and Mg and potassium (K) deficits in the plant.

3.3 Literature review

3.3.1 Water parameters

Our review focuses on wastewater irrigation with alkaline, sodic water. Islam et al. (2015) tested different types of industrial wastewater in Dhaka, Bangladesh and documented that tannery effluents contained the highest Na concentrations, followed by effluents from the pharmaceutical industry and municipal wastewater (Table 3.1). These effluents were discharged into a channel, in which increased Na concentrations were consequently detected. In Islam's study only effluents from the beverage industry were low in pH and Na.

Table 3.1. Water quality parameters of different wastewater sources in Dhaka, Bangladesh, adapted from Islam et al. 2015.

Type of effluent	pH	EC (µS cm^{-1})	Na (mg l^{-1})	SAR (mmol $l^{-1})^{0.5}$
Pharmaceutical	8.6	3400	350	13
Beverage	6.1	440	27	2
Tannery	9.1	9490	1200	43
City wastewater	7.6	1240	205	10
Channel water with mixed effluents	7.5	2720	173	8

Nevertheless, composition and contaminant loads can vary considerably from place to place due to different industrial procedures. The reviewed articles listed in Table 3.2 show sodic wastewaters with Na > 100 mg l^{-1}, which was described as damaging to soil and crop development (WHO 2006). The pH was highest in the four effluents from beverage industries (Binns et al. 2003; Sou et al. 2013; Hussain et al. 2013; Abubakari et al. 2016) with values between 8.6 and 9.8.

Sodium concentrations were slightly elevated in treated sewage effluents (Leal et al. 2009; Netzer et al. 2014), distillery effluents (Singh and Swami 2014) and in beverage effluents (Binns et al. 2003; Hussain et al. 2013). Very high values of Na and SARs were reported in the effluents of a paper mill (Almeida et al. 2017) and a power plant (Jalali et al. 2008) with concentrations above 1000 mg Na l^{-1} and SARs above 25 (mmol l^{-1})$^{0.5}$. In four cases the water was also saline, with EC reaching values over 4000 µS cm^{-1} (Hussain 2002; Jalali et al. 2008; Singh and Swami 2014; Abubakari et al. 2016).

Table 3.2. Chemical quality parameter of industrial wastewater used to irrigate agricultural fields in the reviewed literature.

Author (year)	Study area	Water source	pH	EC (µS cm^{-1})	Na (mg l^{-1})	SAR (mmol l^{-1})$^{0.5}$
Binns (2003)	Nigeria, Kano	Beverage industry effluent	9.8	1245	134	8
Jalali et al. (2008)	Iran, Hamadan	Powerplant effluent	7.8	6040	1172	25
Leal et al. (2009)	Brazil, Sao Paulo state	Secondary-treated sewage effluent	n.a.	840	121	10
Sou/Dakouré et al. (2013)	Burkina Faso, Ouagadougou	Mixture of beverage, tannery, abattoir effluent	8.6	1600	326	17
Hussain (2013)	Pakistan, Haripur	Beverage industry effluent	8.9	4374	120	n.a.
Netzer et al. (2014)	Israel, Lachish	Secondary-treated municipality sewage	7.7	1830	135	4
Singh and Swami (2014)	India, Rhajastan	Distillery effluent	7.2	4220	138	2
Abubakari et al. (2016)	Ghana, Tema	Stream with beverage industry effluent	8.8	2150	n.a.	n.a.
		Stream with abattoir effluent	7.5	5250	n.a.	n.a.
Almeida et al. (2017)	Brazil, Minas gerais state	Treated paper mill effluent	7.9	1910	1030	63

Kanu and Achi (2011) listed tanneries, chemical plants, laundromats and textile manufacturers as the main producers of highly alkaline wastewater. Additionally, the beverage industry often contributes to the high pH and Na concentration of wastewater polluted channels in industrial zones of capital cities such as Accra (Abubakari et al. 2016) and Ouagadougou (Sou et al. 2013). Sodium hydroxide (NaOH) is often used to clean brewery and bottling equipment and is subsequently discharged untreated into rivers. In fact, half of the beverage wastewater was generated from bottle washing (Balks et al. 1998; Haroon et al. 2013). Also distillery effluents contained more than 100 mg l^{-1} Na, according to the study by Singh and Swami (2014). Chhonkar et al. (2000) reported that Na concentration of spent wash was 250 mg l^{-1}, which could have been used for methane production prior to being used for irrigation (Kaushik et al. 2005). The post methanation distillery wastewater used by Chhonkar contained 50 mg Na l^{-1} less. The paper mill effluents in Almeida et al. (2017) were very high in Na concentration and SAR due to the use of sodium sulfate (Na_2SO_4), sodium hydroxide (NaOH), sodium sulfide (Na_2S) and sodium carbonate ($NaCO_3$) during the production process (Chhonkar et al. 2000). Hower and Wagner (1996) reported lower but still high Na concentrations (421.9 mg l^{-1}) and SAR (13.6 mmol l^{-1})$^{0.5}$ in paper mill effluents of Arizona, USA.

Removal of Na from beverage wastewater as well as the reduction of the wastewater pH are technically possible through a coagulation reaction with aluminium sulphate ($Al_2(SO_4)_3$), as a laboratory test of Hussain et al. (2013) demonstrated. Sodium was reduced by 97 % and pH was decreased by two units. The study of Haroon (2013) demonstrated that pH of wastewater from bottle washing could be reduced by one unit if an ionic exchange unit with exchange resin for cation and anion removal was added to a treatment plant.

3.3.2 Changes in soil quality

Different types of wastewater were found to introduce soil sodification and thereby reduce soil quality of agrarian soils in semi-arid and arid climates on nearly all continents. Irrigation with industrial wastewater increased soil pH, EC and soil Na, leading to an increased ESP and SAR (Table 3.3). Soil pH after wastewater irrigation was highest in Rajasthan (Singh and Swami 2014), with an increase of more than 1.5 units compared to control plots. High pH increases of 1.5 to 2 units were also found in Burkina Faso (Sou et al. 2013) and Brazil (Almeida et al. 2017). Irrigation with sodic water had an enormous effect on EC, increasing EC by up to 600 % in comparison to plots irrigated with tap water in the study of Sou et al. (2013), and tripling EC values in experiments conducted in Brazil, India and Mexico (Almeida et al. 2017; Singh and Swami 2014; Alvarez-Bernal et al. 2006).

In all reviewed studies, the accumulation of Na in the soil due to irrigation was significant. A minimum increase by 30 % in soil Na concentration (measured in saturated soil paste, Na_{sol}) was found, when irrigation utilized treated municipality sewage (Netzer et al. 2014). Increases of exchangeable soil Na (Na_{exc}) from 414 to 802 mg kg^{-1} and of total soil Na (Na_{tot}) from 109 to 198 mg kg^{-1} were observed when distillery and power plant effluents were used, by Jalali et al. (2008) and Singh and Swami (2014) respectively. Treated sewage, tannery effluent and polluted river water increased Na_{exc} content by a factor of 5 - 6 compared with the control (Leal et al. 2009; Alvarez-Bernal et al. 2006; Adamu and Dawaki 2008).

Irrigation with papermill effluent in Almeidas' study in Brazil (2017) led to a 10-fold increase in soil Na_{exc}. The greatest increases in soil Na_{exc} content were found to be due to the utilization of industrial wastewater in Sou's study (2013) from Burkina Faso's capital where it was increased by a factor of 28. Among all the papers reviewed, the highest soil Na values were observed by Alvarez-Bernal et al. (2006) and Jalali et al. (2008) with 1014 mg Na_{tot} and 836 mg Na_{exc} kg^{-1}, respectively.

An increased ESP above 15 % was found to have negative impacts on soil quality (Abrol et al. 1988; Richards 1969). In all reviewed articles soil ESP increased, ESPs measured after sodic water utilization ranged from 6 to 78 %. Overall, not only did continuous irrigation with sodic water over many years lead to extreme accumulations of Na - as was the case in Alvarez-Bernal et al. (2006) - but Na contamination can also evolve from even a short irrigation period with polluted irrigation water, as the laboratory test of Jalali et al. (2008) proved.

3.3.3 Coherence of water and soil concentrations

Comparing the irrigation water quality with the change in soil quality, it was noticed that firstly the water pH was affecting soil pH. In Almeida (2017) the increase of soil pH was highest. The soil was very strongly acidic and improved due to wastewater irrigation by increasing pH to an almost neutral level. A different situation was found by Singh and Swami (2014) where soil pH increase was not caused by water pH, as the soil pH was found to be higher than that of the irrigation water. In the case of Ouagadougou, an alkaline water pH of 8.6 led to an increase in the pH of the upper soil layer from 6.7 to 8.2 (Sou et al. 2013). Overall, continuous irrigation with sodic water often leads to a progressive increase in soil pH (Choudhary et al. 2011).

The Na hazard of soil is directly related to high Na concentrations in irrigation water according to Jalali et al. (2008) and Almeida et al. (2017), where treatments increased the ESP from 9 % to 23 % and from 1 % to 12 %, respectively. Additionally, Sou (2013) reported that high Na content of irrigation water was capable of increasing soil ESP from 3 % in the control to 78 % in wastewater irrigated fields. In Leal's (2009) study, a 16-month long irrigation period with water containing 121 mg Na l^{-1} led to an ESP increase from 2 % to 9 % in the upper soil layer (0-10 cm), whereas a long-term irrigation application (12 years) with a similar sodic water solution (135 mg l^{-1}) increased soil ESP in the upper 30 cm from 2 % to 6 % in Netzer's study (2014). In Almeida (2017) and the laboratory test of Jalali et al. (2008), the irrigation wastewaters contained similarly elevated Na concentrations. The change in soil Na_{exc} in Almeida's study was lower compared to the changes observed in Jalal's soil, where an increase of 338 mg soil Na_{exc} kg^{-1} due to irrigation was documented, even though the initial concentration prior to irrigation was already high at 414 mg kg^{-1}. Sodium accumulation was likely avoided in Almeida's study due to the high annual precipitation of 1163 mm a^{-1} which had a dilution effect on the irrigation water, as well as due to the sandy soil texture, which might allow faster leaching of Na than a silt loam. The accumulation is therefore not only dependent on Na concentration, irrigation duration and concentration, but also on the local climate and soil conditions.

Singh and Swami (2014) proposed that sodic irrigation water could be used safely for some years, but Jalali (2008) proved that the Na_{exc} concentration in a soil could double in a short time.

Local restrictions, such as the threshold of 230 mg Na l^{-1} by the government of Israel for industrial effluents (Weber and Juanico 2004) are insufficient to prevent sodification of agrarian soils. Our review indicated that concentrations > 100 mg l^{-1} already effect soil and plants negatively, meaning that an application threshold of 100 mg l^{-1} is more appropriate; this concentration is also recommended by the WHO's guidelines for safe use of wastewater in agriculture (WHO 2006).

Table 3.3. Summary of reviewed literature on irrigation with sodic wastewater including details about study area, source of wastewater, treatments and methods.

Author (year)	Study area (climate)	Soil	Crop	Irrigation history (a)	Source of irrigationwater	Irrigation treatments	Soil depth	CEC (cmol kg^{-1})	pH	EC (µS cm^{-1})	Na (mg/kg^{-1})	Na$_{sol}$ (mg l^{-1})	ESP (%)	SAR (mmol l^{-1})$^{0.5}$	Methods
Alvarez-Bernal	Mexico - Guanajuato	Clayey	Alfalfa	25	Tannery effluent	Full river water irrigation	0-20	19	6.4	2290	1014				pH: 1:2.5 water suspension
et al. (2006)	(Hot semi-arid)				pollutet river	Occasionally riverwater	0-20	19	6.6	1430	724				Na$_{tot}$: flame atomic absorbtion spectrometry
						Wellwater	0-20	18	6.2	640	161				
Jalali et al.	Iran - Hamadan	Xeroortent		0	Powerplant	Before wastewater	0-30		7.5	20	414	506	9		pH, EC, Na$_{sol}$: in soil solution of saturation extract 1:5, with flame photometer (Rowell, 1994)
(2008)	(Hot semi-arid)	Silt loam			effluent	After wastewater	0-30				802	1087	23		Na$_{exc}$,ESP: leached with glycol-ethanol and alcoholic ammonium chloride (Rowell, 1994)
Adamu and	Nigeria - Kano	Hydromorphic		n.a.	Polluted river	Peri-urban riverwater	0-20	15	7.3		607			5	pH: 1:2.5 with CaCl$_2$
Dawaki (2008)	(Tropical savanna)	Clayey				Urban riverwater	0-20	7	6.6		99			1	Na$_{exc}$: ammonium acetate extraction, flame photometer (Hesse 1971)
Leal et al.	Brazil - Sao Paulo state	Oxisol, Haplustox	Sugarcane	1.3	Secondary-	Treated wastewater	0-10			550	73	83	9	6	Na$_{exc}$,ESP: extraction with Mehlich-I solution, flame emission photometer (Embrapa 1999)
(2009)	(Tropical humid)	Sandy clay loam			treated sewage		10-20			480	111	85	13	5	EC, Na$_{sol}$, SAR: saturation extract (Van Raij 2001)
		Kaolinite			effluent		20-40			610	101	94	12	8	
							40-60			320	95	72	13	9	
						Fresh water	0-10			380	14	18	2	1	
							10-20			330	36	41	4	3	
							20-40			320	63	44	8	5	
							40-60			270	78	36	10	6	
Sou/Dakouré	Burkina Faso -	Sandy loam	Eggplant	7	Industrial	Wastewater	0	5	8.2	1639	836		78	17	pH: 1:1 water suspension
et al. (2013)	Ouagadougou	Kaolinite			wastewater		10	5	7.4	617	567		49	7	Na$_{exc}$: atomic absorption spectroscopy with cobald hexamine method
	(Hot semi-arid)				from tannery,		20	4	7.5	366	177		19	5	
					brewery and	Tap water	0	4	6.7	271	30		3	1	
					abattoir		10	4	6.7	231	46		6		
							20	5	6.6	271	39		3		
Netzer et al.	Israel - Lachish	Haploxerert^1	Vine	12	Secondary-	Treated wastewater	0-30	27		1710		183	6^1	3	pH, EC, Na$_{sol}$: in saturated paste extract (Page et al. 1982)
(2014)	(Hot summer mediterranean)	Clay loam			treated		30-60			1590			6^1	5	^{1}according to Levy (2014) with Na$_{exc}$, ESP: Ammonium acetate extraction (Thomas, 1986)
					municipality	Fresh water	0-30			1500		141	2^1	2	
					sewage		30-60			1150			2^1	4	
Singh and	India - Rhajastan		Wheat	n.a.	Distillery effluent	100% wastewater	0-15		8.9	6750	198				Na$_{tot}$: extraction with ammonium acetate buffer (Allen et al., 1986), flame photometer
Swami (2014)	(Tropical arid/semi-arid)					50% wastewater	0-15		8.4	3250	143				
						0% wastewater	0-15		7.4	2060	109				
Almeida et al.	Brazil - Minas gerais state	Udifluvent	Eucalyptus	6	Treated paper	Treated wastewater	0-10	6	6.5	1200	122	300	12	11	Na$_{exc}$, ESP: routine chemical soil analysis
(2017)	(Tropical arid/semi-arid)				mill effluent	Stream water	0-10	8	4.6	400	12	12	1	0	EC, pH, Na$_{sol}$, SAR: in saturated soil paste extraction (Richards 1954)

3.4 Industrial wastewater irrigation of an urban garden in Ouagadougou

3.4.1 Materials and methods

The case study presented in this paper was conducted at an urban site, the industrial zone of Ouagadougou, Burkina Faso. The area is located in the sub-Sahelian zone (Ibrahim et al. 2012) and has a hot semi-arid climate according to the Köppens classification. Average annual rainfall of 820 mm rain is unimodal distributed from end of May to end of September. The industrial area of the capital is concentrated at the boundary of the city, where agricultural fields were formerly extensively used by peri-urban villagers. In the traditional agricultural system, rainfed crops such as sorghum (*Sorghum bicolor* Moench), millet (*Pennisetum glaucum* L.) and maize (*Zea mays* L.) were grown during the rainy season. During the dry season fields were left fallow and used for extensive grazing. In 2006 a vacant lot of 20 ha located near an outlet of an industrial wastewater treatment plant was converted to farmland. A channel system was constructed to supply intensively managed small plots of 100 to 150 m² with wastewater for year-round irrigation.

After the rainy season in October 2014 an orthophoto was taken followed by a detailed mapping of the vegetation and land cover. The map was used to randomly select 45 fields of which 13 were fallow, 13 were rainfed and 19 were irrigated (Figure 3.1).

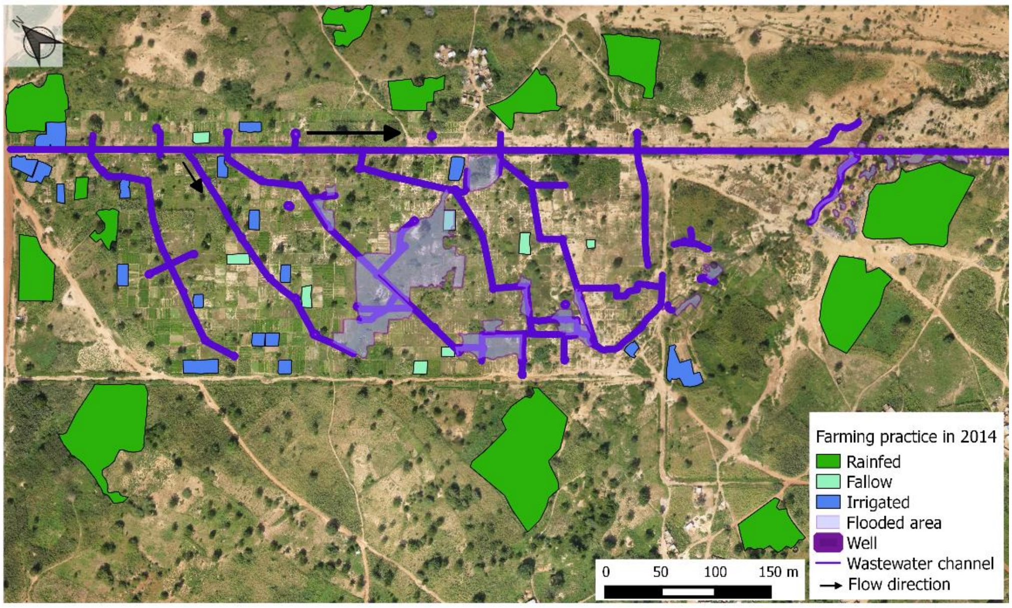

Figure 3.1. Map of Kossodo urban farming area with type of agricultural practice (rainfed, fallow, industrial wastewater irrigated) in Ouagadougou, Burkina Faso in October 2014; Aerial photograph by Dr. J. Schlesinger.

Soil texture was analysed in two representative soil pits, one located in the centre of the irrigated area and one in the surrounding area within a traditional sorghum field. Soil horizons were defined, sampled and analysed by laser diffraction with an Analysette 22 MicroTec Plus including a wet dispersion unit (Fritsch GmbH, Idar-Oberstein, Germany). The topsoil (0 - 10 cm) contained 11 % clay, 72 % silt and 17 % sand, subsoil (10 - 50 cm) contained 18 % clay, 82 % silt and 0.1 % sand according to the German soil texture classification (Eckelmann et al. 2006). The soil had been defined as an intensively weathered Lixisol and featured an increase in clay content over a short vertical distance (Driessen et al. 2000). The dominant clay mineral was kaolinite (Sou et al. 2013).
Five soil samples per field were taken at 0 – 20 and 20 – 40 cm, were chosen according to texture analysis and common ploughing depth, dried and passed through a 2 mm sieve. Soil pH was measured in a soil-water solution of 1:2.5 and EC in a soil-water solution of 1:2. Exchangeable cations were analysed by the cobalt hexamine chloride method (Ciesielski et al. 1997; Dohrmann and Kaufhold 2009) with a ICP-OES (Ciros CCD, SPECTRO Analytical Instruments GmbH, Kleve, Germany). SAR and ESP were calculated according to FAO (Abrol et al. 1988) and Scheffer/Schachtschabel (Blume et al. 2016).
During the 2015 dry season four wastewater samples were taken and analysed for pH, EC and cations. Mg was measured with a spectrophotometer (Automatic wavelength selection photometer 7100, Palintest, Gateshead, UK). Sodium, Ca and K were measured by flame photometry (Aanalyst 300, Perkin Elmer, New York, USA). Well water from two concrete and two dug wells were tested for pH.

Interviews

Corresponding to the randomly selected fields, 45 farmers were interviewed with the help of a semi-structured questionnaire. Questions regarding their cultivation strategy provided details on crop rotation, irrigation intensity, intensification level (use of manure, fertilizer, pesticide) and management history of the plot.

Statistical analyses and visualisation

Calculations and visualisations were done with the help of Excel 2016 (Microsoft Corporation, Redmond, WA, USA). Statistical analyses of the case study were done in SPSS (Version 24, IBM Corporation, Armonk, NY, USA) using a one-way ANOVA to compare the soil parameter means of different agricultural practices within a soil layer, as well as between top- and subsoil of each type of agricultural use. Maps were generated with Quantum GIS (Las Palmas 2.18.12, QGIS Development Team 2012).

3.4.2 Results

In 2015 the alkaline sodic wastewater consisted of a mixture of brewery and slaughterhouse effluents. At the sampling time tannery effluents were not entering the wastewater channel as the factory had closed some months before. Wastewater had an average pH of 9.2 and well water of 8.2. Wastewater had an EC of 2300 µS cm^{-1} and concentrations of 2.3 mg Mg l^{-1}, 266 mg Ca l^{-1} and 532 mg Na l^{-1}. Significant differences in chemical soil quality parameters (pH, Na_{exc}, ESP) between management groups (irrigated and rainfed) were observed in the two soil horizons (Figure 3.2).

Rainfed fields had an average soil pH of 6.3 throughout the soil profiles which was significantly lower than that of fallow and irrigated fields ($P < 0.001$, $F_{0\text{-}20cm} = 100$, $F_{20\text{-}40cm} = 38.6$). The pH of the upper soil horizon of the irrigated and fallow fields was 8.5 and 8.2, respectively, while the subsoil in both had a pH of 7.8; the difference between top- and subsoil was only significant in the irrigated fields ($P < 0.005$, $F = 2.9$). Comparing Figure 3.2A and B, pH was generally lower in the subsoil with a maximum of 8.5. Furthermore, all centrally located plots in close proximity to the wastewater channel exhibited elevated pH levels. This was expected since these were the fields most intensively irrigated or unintentionally flooded in the case of the fallow fields.

In the topsoil Na_{exc} of fallow and irrigated fields averaged 248 mg kg^{-1}, in subsoil Na_{exc} averaged 365 mg kg^{-1}. Rainfed fields were characterised by 10 mg Na_{exc} kg^{-1} in the topsoil, which increased significantly to 215 mg kg^{-1} in the subsoil ($P < 0.005$, $F = 77.1$). In the topsoil of rainfed fields a significantly lower Na_{exc} content was observed compared to the other fields ($P < 0.001$, $F = 28.1$), while no difference was found in the subsoil of the different field types.

The topsoil of fields with high pH were also high in Na_{exc} concentration (Figure 3.2A and 2C). In contrast, subsoil Na_{exc} concentrations were distributed differently (Figure 3.2D): the subsoil was significantly more sodic ($P < 0.000$, $F = 20.8$) than the topsoil. Subsoils of rainfed fields close to the channel and in the south of the gardening area were highly loaded with Na, even though they had never been irrigated. The high Na concentrations were also reflected in the high ESP values of irrigated and fallow fields and increased with depth from 17.5 % to 26.5 %. A sharp ESP increase from 0.1 % to 21.4 % ($P < 0.005$, $F = 82.5$) from the top- to the subsoil was seen in rainfed fields, whereby rainfed topsoil also differed significantly from that of other fields ($P < 0.001$, $F = 34.4$, Figure 3.2E and F).

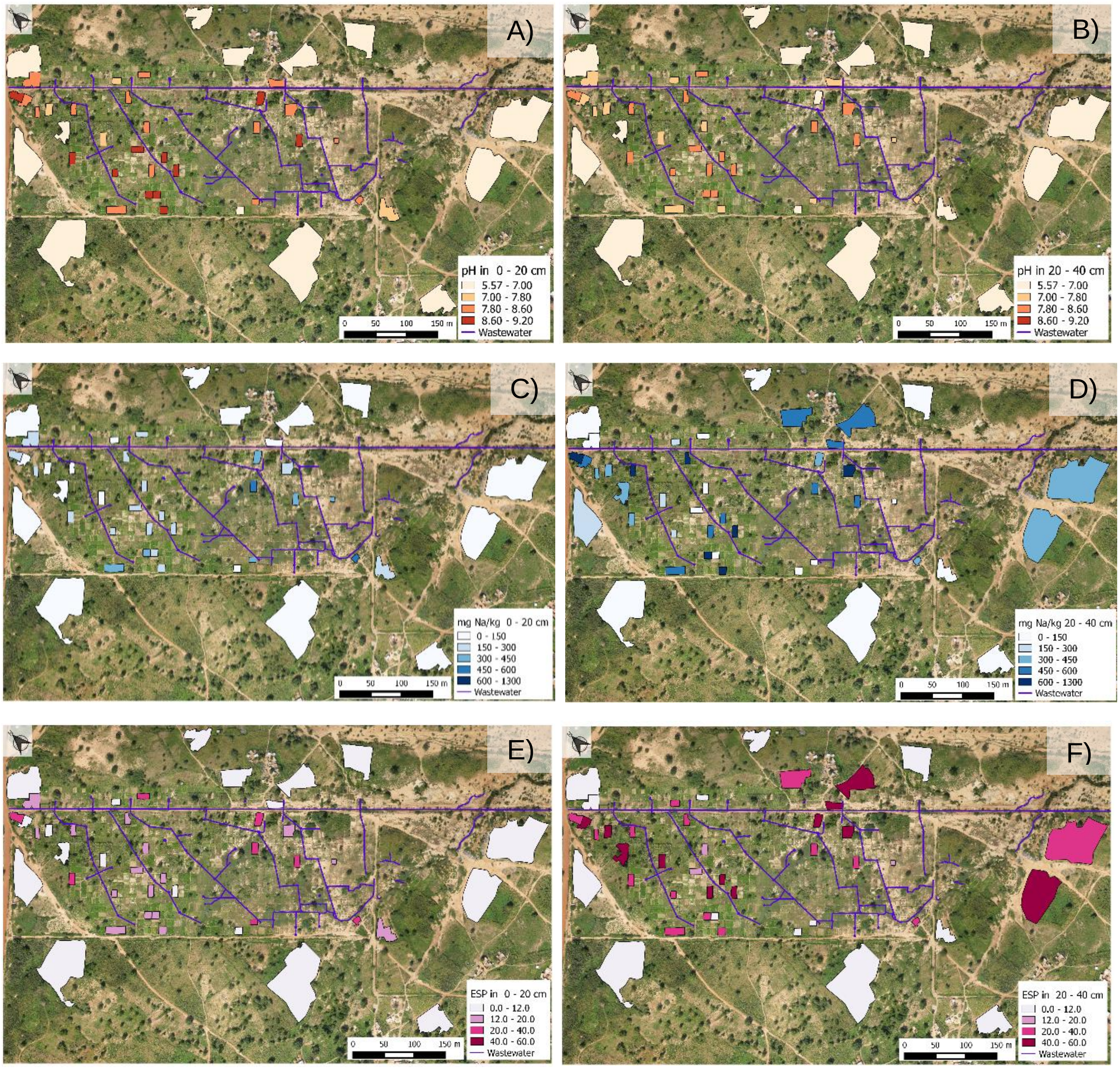

Figure 3.2. Kossodo urban farming area maps displaying measured levels of soil pH, exchangeable Na concentration and ESP at two depths: 0 - 20 cm (A; C, E) and 20 – 40 cm (B, D, F) in Ouagadougou, Burkina Faso (January 2015); Aerial photograph by Dr. J. Schlesinger.

Fields did not differ in EC, CEC, Mg and Ca concentrations between different agricultural practices within a soil layer and did not differ between top- and subsoil of each type of agricultural use. Overall, soil EC was low in all fields, with rainfed fields averaging 95 µS cm^{-1} throughout the soil profile. Irrigated and fallow fields had an average topsoil EC of 584 µS cm^{-1} and a EC of 344 µS cm^{-1} in the subsoils. Average soil CEC of 0 - 40 cm was 5.3 cmol kg^{-1}, exchangeable Mg concentration was 72 mg kg^{-1} and exchangeable Ca was 702 mg kg^{-1}.

3.4.3 Effects of crop rotation and length of irrigation period on soil properties

The interviews with Kossodo farmers revealed that the farming area can be characterised as an intensively managed system in which mineral fertiliser is used regularly, often in combination with manure and pesticides. Usually irrigation was done every second day by jerry cans. Farmers were unable to attend their plots daily, as most of them did not live nearby. Cropping regimes were grouped into irrigated crops (IR) including cultivation of spinach or “bulvaka” (*Corchorus olitorius* L.), whereas rainfed crops (RF) refers to maize, sorghum or millet cultivation. Non-utilised fields or fields on break were referred to as fallow (FA). To compare management effects on soil quality (Table 3.4), fields were ordered according to crop rotations and irrigation intensities as followed: i) Irrigated intensive cultivation for multiple years (IR-IR); ii) Irrigated cultivation altering with non-irrigated extensive cultivation such as one year of rainfed crops or fallow (IR-RF/FA, IR-IR-RF/FA); iii) Traditional rainfed agriculture including rotation of different crops (RF-RF); iiii) Fields that have remained fallow for at least three cropping cycles and will not be utilised in the foreseeable future (FA-FA or IR->FA).

Table 3.4. Means (±SD) of soil parameters of fields (n = 45) managed under different crop rotations (IR = irrigated, FA = fallow, RF = rainfed) and irrigation intensities, indicated by an arrow. Effects within the soil layer were calculated with ANOVA, followed by the Tukey-B post-hoc test. Letters indicate significant differences between means of different crop rotations.

Crop rotation	n	Irrigation intensity	Soil depth (cm)	pH	EC (µS cm^{-1})	CAC (cmol kg^{-1})	Na (mg kg^{-1})	ESP (%)
IR-IR	12	▼	0-20	8.4 (0.4) b	609 (173) b	6.2 (1.6)	249 (134) b	16 (7) b
			20-40	7.8 (0.6) b	381 (156) b	6.6 (3.8)	445 (277)	27 (14)
IR-IR-FA	3		0-20	8.3 (0.8) b	664 (307) b	5.4 (0.1)	190 (64) b	15 (5) b
			20-40	7.9 (0.5) b	362 (62) b	3.5 (1.9)	178 (93)	22 (6)
IR-RF/FA	8		0-20	8.3 (0.4) b	508 (150) b	6.2 (1.0)	235 (96) b	16 (6) b
			20-40	7.6 (0.4) b	305 (76) b	4.3 (1.9)	303 (254)	28 (22)
RF-RF	13		0-20	6.2 (0.5) a	102 (52) a	4.7 (0.9)	10 (9) a	1 (1) a
			20-40	6.3 (0.4) a	89 (67) a	4.2 (2.3)	215 (209)	21 (21)
IR->FA	5		0-20	8.1 (0.7) b	590 (141) b	6.1 (0.4)	264 (136) b	19 (11) b
			20-40	7.8 (0.6) b	339 (77) b	5.0 (1.0)	285 (254)	24 (22)
FA-FA	4		0-20	8.4 (0.5) b	616 (262) b	6.2 (2.0)	309 (99) b	22 (7) b
			20-40	7.9 (0.6) b	331 (133) b	6.0 (3.2)	488 (551)	26 (26)
F Value			0-20	34.7	17.8		11.6	14.8
			20-40	14.9	11.3			
P Value				< 0.001	< 0.001		< 0.001	< 0.001

Overall, gardening strategies varied only little as the municipality restricted the cultivation of wastewater-irrigated vegetables commonly eaten raw. Also, only few crops tolerated the high level of Na and the alkalinity of the irrigation water. As typical for an Amaranthaceae, spinach was observed by farmers to do better under Na and bicarbonate stress than *bulvaka*, which belongs to the Malvaceae. Spinach is able to accumulate excessive Na in leaves and petioles where it allows K to be replaced by Na (Lawlor and Milford 1973). Still, farmers reported that spinach seedlings suffered from sodic water application if sown too late after the end of the rainy season. During the dry season, wastewater is less diluted and is more likely to stress crops during the vulnerable germination phase. Thus, early sowing at the end of the rainy season is necessary. The longer the dry season lasts, the more plants suffer from exposure to concentrated wastewater. Farmers reported that until recently, it had been possible to postpone the final harvest of spinach plants until February or even to cultivate year-round. During the study period, however, spinach plants died after the third or fourth leaf-harvest in December. This, in combination with the soil parameter data and farmer statements that indicated that the soil surface had become progressively harder over the years, indicates that soil chemical and physical quality has degraded over the last ten years. Due to this degradation, an increasing number of farmers have decided or were forced to leave their plot fallow. In the case study, 5 out of 45 fields that had previously been intensively cultivated, were said to have undergone changes in soil conditions that rendered the field unusable by the farmer (IR->FA). Between 2010 and 2015, the number of fallow fields doubled (Figure 3.3), while the number of irrigated fields declined. Most fallow fields were located close to the waterlogged area demarcated in Figure 3.1, indicating the influence of stagnating groundwater and the seepage originating from the channel.

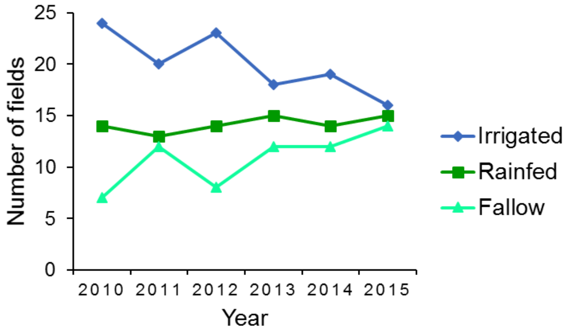

Figure 3.3. Number of urban fields in the Kossodo area (n = 45) under different agricultural management strategies (industrial wastewater irrigated, rainfed or fallow) between 2010 and 2015 in Ouagadougou, Burkina Faso.

Cultivation strategies were found to be unrelated to differences in soil parameters of different crop rotations and irrigation intensities (Table 3.4). Aside from the rainfed fields, all fields were alkaline, sodic and had elevated EC levels. Even though rainfed fields were mostly not located directly next to the channel or in occasionally inundated areas, rainfed subsoils accumulated Na, as discussed previously. Of interest was that the subsoil of rainfed areas was only influenced by the Na entering via subsurface flow, but was not affected by the pH or EC of the wastewater. Furthermore, the data indicate that, regardless of whether irrigated fields underwent a fallow or rainfed break of up to two years, the soil was still affected by wastewater after this period. Overall, the area faces a severe sodification problem, which cannot be ameliorated by limiting irrigation intensity nor by resting the land for one or two rainy seasons since groundwater seepage originating from the wastewater channel is likely to continually induce a re-contamination of the subsoil in the area.

3.5 Discussion

3.5.1 Literature comparison

Data about sodic wastewater effects on agricultural soils have been reported in a variety of units, which are sometimes not convertible. At least three standard methods for the evaluation of soil cations are used. Soil Na concentration can be measured using total or exchangeable values and, moreover, values can be reported in concentrations of the soil solution or per unit soil weight. In the absence of comparable reporting methods, one is often only able to compare treatment effects within a study but not between studies. Additionally, differences in soil and climatic conditions are of major importance when assessing cation variability in soil and water due to mobility, adsorption and dilution effects. Water and soil data were rarely given simultaneously and most literature neglected field history, subsoil conditions or farmers´ knowledge.

In our literature review, data was converted in comparable units whenever possible in order to provide an overview of soil sodification effects worldwide. In contrast to other studies, our case study focused on Na as a pollutant and attempted to provide a holistic understanding of the study area including water contaminant sources, the history of field management, analyses of top- and subsoil, as well as farmers’ knowledge.

3.5.2 Physical soil conditions

The reviewed literature and our case study underline the necessity of restricting Na concentrations in wastewater through proper treatment prior to discharge. Discharged sodic water, even if not used for irrigation, contaminates soils during floods alongside streams and channels and by subsurface water flow. Moreover, it should be emphasised that gaps in utilisation of sodic water in the crop rotation (e.g. one or two-year fallows) do not help in soil recovery (Table 3.4).

It is commonly known that sodicity leads to impermeability and waterlogging of topsoils (Hamilton et al. 2007), but the phenomenon is critical because this structural damage may become irreversible (Sou et al. 2013). Additionally, translocation of dispersed clays to the subsoil may occur, thereby generating a hardpan and resulting in a stagnation of sodic water such as in Kossodo. Here groundwater movement is likely flowing horizontally and downwards along the minor terrain slope of 1.3 % in a southerly direction, as indicated by the direction of channel flow (Figure 3.1). It is assumed that a waterlogged layer was created below the agricultural horizon of 20 cm as it is not rare in Lixisols (Driessen et al. 2000). Gleyic Lixisols were found, resulting from the shallow sodic water table. The major Na_{exc} increase in our study was limited to the 20 - 40 cm layer. Furthermore, it is assumed that capillary rise of sodic soil water could introduce Na to the topsoil and affect plant growth. Rainfed fields located more to the east and west were not affected as the path of least resistance was to the south.

In our 2015 study pH, EC and Na concentration in the wastewater were all higher than those from the same channel shown earlier by Sou et al. (2013). Unfortunately, it could not be determined whether the subsoil had already been contaminated after a two to three year utilisation of wastewater.

The results of Leal et al. (2009) showed a rather constant Na level throughout the soil profile even if Na levels were highest at 20 to 40 cm depth, which is comparable to our study. In the Brazil study Na loading of the soil had already occurred after an irrigation period < 1.5 years with treated wastewater containing just 120 mg Na l^{-1} - slightly above WHO's recommended threshold. The soil conditions were very similar to those of our study, supporting the conclusion that sodification processes are not limited to the soil surface given the high mobility of Na. Contrary to this elevated pH levels were only found near the channel and it is concluded that the bicarbonates in the wastewater are less mobile and were buffered or bound quickly after seeping through the channel walls and entering the subsoil.

3.5.3 Effects on agriculture

West African farmers often know about the deleterious effects of wastewater irrigation on their crops as reported by a case study in Nigeria (Binns et al. 2003) which was confirmed by the results of the interviews in our study. At Kossodo the daily change in the effluent mixture also led to shifts in odour and colour. On days when wastewater was noticeably of an elevated concentration, farmers tried to avoid irrigation and preferred to wait. However, if the wastewater remained concentrated or a certain unwanted effluent did not stop flowing, the farmer could then be faced with the dilemma of either letting his / her crops die of water shortage or irrigating, which risked enhancing the Na and alkalinity stress to the soil and plants, as well as skin irritations resulting from contact with the alkaline water.

In Ouagadougou the lacking availability of safe irrigation water in the constructed farming area may force farmers to cease their cultivation, leading some to return to cultivating their original site illegally (Ouedraogo 2010). Maconachie and Binns (2006) reported on the difficulty of gaining access to farmland in urban and peri-urban areas. Due to the increasing land prices associated with urbanization, arable peri-urban areas are rapidly being converted from cropland to urban uses (Schlesinger et al. 2015). After the construction of the industrial zone in the urban periphery of Ouagadougou, wastewater was introduced and agriculture intensified. After ten years, the soil had already sodic characteristics, leaving it in a degraded state. Degradation over a similar timespan has also been reported in cities of Pakistan (Simmons et al. 2010).

Widespread shifts in agricultural management regimes of peri-urban areas from staple food production towards wastewater-irrigated vegetable production (Huang et al. 2006) may cause significant changes in soil parameters, fertility decline (Maconachie and Binns 2006) and Na contamination (Hussain 2002). Irrigation with sodic water leads to a loss of arable land, which is a particular cause for concern in the tropics, where soils are less fertile by nature. This may contribute to an increased dependence of food imports and a loss of work, trade and income opportunities.

3.6 Conclusions

Comparing soil cation concentrations between different studies is rather difficult, as there are no standard analytical methods. Nevertheless, several studies coincided in that irrigation with industrial wastewater at a sodicity exceeding 100 mg l^{-1} leads to detrimental effects for soil and plants over time. Therefore, laws are needed that prohibit the discharge of sodic wastewater. Water treatments need to reduce Na concentrations of accessible effluents. These need to be accessible “low-tech” solutions of greater reliability than counting on the dilution effects of natural water bodies. Pollutants in wastewater are especially concentrated during the dry season in semi-arid regions. Furthermore, soil productivity is endangered by sodic water, not only from the irrigation of agricultural areas but also by horizontal subsurface flows delivering sodic soil water originating from wastewater channels.

To better understand the effects of wastewater on agrarian fields, research should always include subsoil sampling as well as soil sampling of the surrounding area, since Na is mobile and contamination might be unapparent. Overall, wastewater with > 100 mg Na l^{-1} should not be utilized by farmers in semi-arid regions, as it will likely lead to permanent soil degradation, thereby endangering the productivity of farmland.

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Chapter 4

Gypsum amendment to soil and plants affected by sodic alkaline industrial wastewater irrigation in urban agriculture of Ouagadougou, Burkina Faso

4.1 Abstract

Low quality water such as sodic alkaline industrial wastewater is often used to irrigate crops in intensively managed urban gardening systems in the semi-arid tropics to help meet the fresh food demands of a rapidly increasing city population. An on-farm experiment was established to examine the effects of sodium (Na) and bicarbonate (HCO_3^-) loaded industrial wastewater on soil and crops on the one hand, and to determine melioration effects on soil condition and plant development on the other hand. To ameliorate the sodified soil, fine powdered gypsum ($CaSO_4$) as soil amendment was applied onto the upper soil (0 - 20 cm) before sowing of crops. Depending on soil pH and exchangeable sodium percentage (ESP), which reflected the level of soil degradation (SDL), two different amounts of gypsum were applied: 6.8 t ha^{-1} in moderate and 10 t ha^{-1} in high SDL plots. Subsequently rainfed maize (*Zea mays* L.) and irrigated spinach (*Spinacia oleracea* L.) under two irrigation water qualities (clean and wastewater) were cultivated. Chemical and physical soil parameters, as well as plant root density (RLD), crop yield and nutrient content were determined. The results showed that gypsum application reduced soil pH on average below 8 and reduced ESP below 18 %. Furthermore, gypsum treated soils showed a significant reduction of sodium absorption rate (SAR) from 14.0 to 7.9 and aggregate stability was increased from 44.2 % to 51.2 %, which in return diminished Na content in plant tissues up to 80 % and significantly increased RLD of maize. Overall, Calcium (Ca) addition through the gypsum amendment changed the soil cation balance by increasing the Ca:Mg ratio from 3.5 to 7.8, which likely influenced the complex interactions between competing cations at the exchange surfaces of the soil and cation uptake by plant roots.

4.2 Introduction

West African cities are facing rapid urbanisation as in Ouagadougou, the capital city of Burkina Faso, with an average annual growth rate of 9.2 % contributing to a likely doubling of the urban population of Burkina Faso by 2025 (UN-Habitat 2014). This change results in an increased demand by old and new citizens for fresh agricultural products. This can be partly fulfilled by urban and peri-urban agriculture (UPA). As the dry season extends over eight months, crop irrigation of UPA farmers heavily relies on well water, wastewater channels or dams (Kiba et al. 2012). Beside positive nutritional effects of wastewater on crops, possible negative effects of urban wastewaters used for crop irrigation such as contamination with pathogens (Diogo et al. 2013; Amoah et al. 2005) or heavy metals (Binns et al. 2003) are well known. Rarely documented is the effect of sodic alkaline industrial wastewater, as it is used in urban farms in Burkina Faso, on soil degradation and crop development. With the prolonged irrigation with

HCO_3^- and Na loaded water, alkalization and sodification of the soil takes place, as was reported by Sou et al. (2013). The multi-year use of sodic alkaline wastewater destroys soil structure and lets clay particles of the soil disperse. As a consequence field and air capacity is decreased (Bernstein 1975) and soil organic matter, which is in many cases already very low in the tropics, disperses and the soil solution with the dissolved carbon moves upwards by capillary rise and accumulates as a black layer also referred to as “Black alkali” (Brady and Well 2002). The problems for plant growth on sodic soils (pH > 8.2, EC < 4000 µS cm^{-1}) are much less described than for saline soils (pH > 8.2, EC > 4000 µS cm^{-1}, (Abrol et al. 1988)), but are known to lead to osmotic stress and deficits in nutrient uptake. The high presence of exchangeable Na (Na_{exc}) leads to a replacement of cations such as Ca and magnesium (Mg) at the exchange complex (Bernstein 1975) with a potential subsequent precipitation of Ca and Mg as plant unavailable carbonates (Abrol et al. 1988). Besides the plant nutritional problems, the physical damage of the soil can reduce root growth (Magistad 1945) and was reported to hinder seed germination in oat seedlings (Gao et al. 2014), but such sodification and alkalinisation effects on plants are little explored at the field scale.

In contrast much research has been done on reclaiming fields with gypsum ($CaSO_4$) application to enhance crop production on soils with problems of alkalinisation, sodification and clay dispersion. As a soil amendment gypsum is well known to reverse negative effects of alkaline soils by reducing the soil pH as well as the ESP and thereby increasing crop yields (Oster 1982; Sekhon and Bajwa 1993; Bronick and Lal 2005). Gypsum derived Ca substitutes Na at the exchange complex of soil particles and the generated sodium sulphate (Na_2SO_4) dissolves in the soil solution, which can then be leached to deeper soil layers (Rengasamy et al. 1986). The flocculation of the dispersed clay particles results in improved soil structure by loosening the compacted soil, improving the infiltration rate, impeding erosion (Yu et al. 2003), as well as preventing and lowering crusting (Amezketa et al. 2005). The addition of Ca can further bind soil organic matter and improve aggregate stability, water holding capacity and overall increase crop yields (Stamford et al. 2003).

Research gaps exist on how to reclaim degraded soils under sub-Sahelian conditions such as of intensive UPA in West Africa. The aim of this study therefore was to determine the effects of gypsum application on soil properties and plant growth of one sodium intolerant and one sodium tolerant crop by reducing pH and ESP below the critical values of 8 and 15 %, respectively.

4.3 Materials and Methods

4.3.1 Study area

The study was conducted under UPA conditions in Ouagadougou, the capital city of Burkina Faso. The location belongs to the sub-Sahelian zone where the unimodal rainy season lasts from May to September. Annual precipitation was 820 mm in 2015.

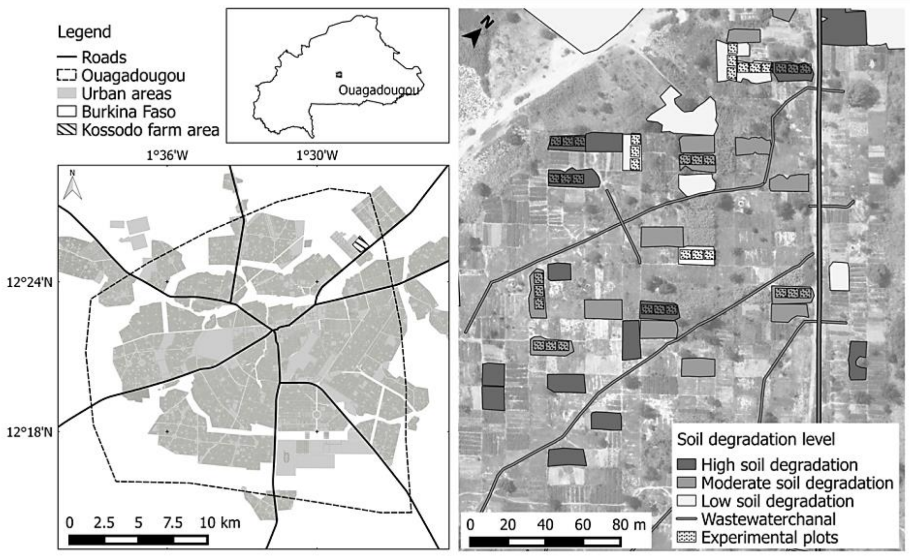

Figure 4.1. Map of urban Ouagadougou (left) and of the Kossodo research site showing differences in soil degradation levels and selected plots for the experiment in 2015, Aerial photograph by Dr. J. Schlesinger.

At Kossodo, during dry season, irrigation of urban vegetable gardens was done by utilisation of wastewater from the city´s industrial zone (Figure 4.1). The open-space farming area was created in 2006, allotting 20 ha of arable land into small plots of 100 to 150 m².

4.3.2 Experimental design

After a preliminary survey including interviews (n = 45), group discussions, vegetation mapping and soil sampling (n = 45), 12 farmers and their fields were selected for an on-farm experiment based on the criteria of availability, soil pH and EC, homogeneity and similar management history of each field, and absence of water logging during the rainy season.

Based on cultivation practices of the preceding cropping seasons, 12 fields were grouped into three soil degradation levels (SDL, Table 4.2), with each level comprising four repetitions (Figure 4.1). Fields of low SDL were defined by rainfed cultivation during the previous seasons and reflecting the traditional extensive cultivation system. Fields of medium SDL comprised soils with an increased deflocculation of clay particles due to irregular use of sodic alkaline wastewater for irrigation during the previous years. The high SDL comprised fields with a continuous and intensive use of sodic alkaline irrigation water during the last decade.

Each field was subsequently divided into three plots of 5 m x 6 m size. In fields of medium and high SDL, gypsum was applied in one plot per field. Plots with medium degraded soils were treated with 6.8 t ha^{-1} of gypsum and plots of high degraded soils received 10 t ha^{-1}. Doses were set according to Ilyas (1997) and Richter (2005) although somewhat higher than the calculated gypsum requirements (Rasouli et al. 2013), to compensate for low infiltration rates due to a crusted top soil conditions. Gypsum (85 % purity, granule size < 1 mm) was applied in two rates, once after the first rainfalls in 2015 and the second rate one week later. The fine powder was incorporated into the upper 20 cm of the soil.

For the experiment two crops were cultivated: (1) maize (*Zea mays* L., local variety “Barka”) that was cultivated during the rainy season in 2015 without irrigation and (2) spinach (*Spinacia oleracea* L.) that was cultivated during the dry season in 2015/16 under two different irrigation regimes. For maize cultivation two treatments were examined: no gypsum (-G, control) and gypsum (+G). In the period between the first gypsum application and the harvest of maize total rainfall was 630 mm. Spinach cultivation was conducted under three treatments: clean water irrigation with gypsum amendment (CW+G), clean water irrigation without gypsum amendment (CW-G) and sodic alkaline wastewater irrigation (WW-G). Spinach was seeded at the end of October 2015, and marketable leaves were harvested three times (39, 60 and 81 days after sowing). Irrigation was done three times per week with 12 l m^{-2} each time (total irrigation 416.2 l m^{-2}).

4.3.3 Data collection

Water samples

Samples of clean water and wastewater were analysed for total nitrogen (N), total chemical oxygen demand (COD), total phosphors (P), chlorine (Cl), potassium (K), Mg, and Na (Table 4.1). Samples were taken from the channel or the water basin into sterile glass bottles four times during spinach cropping. Total P, Mg, Cl, COD and total N were measured with a Spectrophotometer (Automatic wavelength selection photometer 7100, Palintest Ltd, Gateshead, UK). Sodium and K were measured by flame photometry (Aanalyst 300, Perkin Elmer Inc., Hopkinton, MA, USA). Before each irrigation event, pH and EC of irrigation water were measured.

Table 4.1. Ranges of chemical properties of clean and industrial wastewater used for spinach irrigation at the UPA site of Kossodo in Ouagadougou, Burkina Faso in 2015.

Parameter (Unit)		Clean water	Wastewater
pH		7.9 - 9.2	8.6 - 9.2
EC	(µS cm^{-1})	120 - 393	2200 - 2320
SAR	(mmol $l^{-1})^{0.5}$	0.5 - 1.0	8.8 - 9.0
Na	(mg l^{-1})	7 - 26	461 - 545
Ca		8 - 46	256 - 274
K		5.2 - 18.9	49.2 - 54.3
Mg		1 - 7	1 - 10
Cl		3 - 29	2 - 35
Total N		0.4 - 3.6	3.0 - 8.6
Total P		0 - 0.7	16.1 - 19.5
Total COD		0 - 45	820 - 890

Soil analyses

To determine the effects of gypsum on chemical and physical soil properties, four soil samples per plot were collected and mixed to a composite sample and analysed before gypsum application, after maize cultivation (October 2015) and after the final spinach harvest (January 2016). Soil samples were analysed for pH measured in a soil-water solution of 1:2.5 and EC in a soil-water solution of 1:2. Exchangeable cations (Na, K, Mg and Ca), effective cation exchange capacity (CEC) and P were determined after silver thiourea (0.01M Ag) extraction by using an atomic absorption spectrometer (900TH, Perkin Elmer Inc., Hopkinton, MA, USA) and a flame photometer (Corning 400, Coring Ltd., Halstead, UK) was used to determine Na and K. Available P was analysed by the P Olsen method, as 83.3 % of the samples had a pH above 7.5. C and N was analysed by dry combustion (Vario MAX CHN, Elementar Analysensysteme GmbH, Langenselbold, Germany). Texture was analysed for two soil horizons, from 0 to 10 cm and 10 to 20 cm by laser diffraction with an Analysette 22 MicroTec plus including a wet dispersion unit (Fritsch GmbH, Idar-Oberstein, Germany).

SAR and ESP were calculated according to FAO (Abrol et al. 1988) and Scheffer/Schachtschabel (Blume et al. 2016).

To determine soil aggregate stability of the upper soil layer (0 - 20 cm), three undisturbed soil samples per plot were taken after the third harvest of spinach and analysed with a wet sieving apparatus (Eijkelkamp Soil & Water, Giesbeek, Netherlands). The samples were processed as described by Ouattara et al. (2008), but only one sieve with a mash size of 0.25 mm was used and samples were shaken for 5 min. Results were corrected for sand content (Seybold and Herrick 2001), so that sand-free water stable aggregates of 0.25 - 2 mm size were given in percent.

Plant samples

Fresh matter (FM) and dry matter (DM) yields of both crops were determined. For maize five subplots and for spinach six subplots with each six plant pockets were harvested. Plant samples were analysed for N, C, P, Mg, Na and K concentrations, N and C were analysed by dry combustion. To determine Mg, P, K and Na in plants, an ash solution was prepared from which P was analysed colorimetrically with a spectrophotometer (U-2000, Hitachi Ltd., Tokyo, Japan) by the P-yellow-method (Lange and Vejdêlek 1980), K and Na were measured with a flame photometer (BWB-XP, BWB Technologies Ltd., Newbury UK) and Mg with an atomic absorption spectrometer (906AA, GBC Scientific Equipment, Braeside, Australia).

The effects of gypsum on the development of maize and spinach plant roots was assessed by taking five soil samples per plot using soil sampling rings of 3.2 cm diameter and 10 cm height. Soil samples were mixed afterwards to one composite sample per plot. Roots were extracted through washing and sieving (mesh size 1.94 mm) and afterwards scanned with Epson Perfection V700 (Epson Deutschland GmbH, Meerbusch, Germany) in combination with a WinRHIZO software (Regent Instruments Inc., Ville de Québec, QC, Canada) followed by the calculation of root length density (RLD).

4.3.4 Statistical analysis

The difference between the preconditions of experimental fields using SDL as a fixed factor was tested by ANOVA. Treatment effects on soil and plant properties for the different SDLs of the experiment were tested by using a nested ANOVA with gypsum treatment (-G and +G) and water quality (CW and WW) as fixed factors and field as a random factor using R statistics software (R Development Core Team 2015) with additional functions provided by the R package lmerTest (Kuznetsova et al. 2015). Correlations between all soil and plant parameters were tested by calculating one-way Pearson correlation coefficients with SPSS (Version 24, IBM Corp., Armonk, NY, USA).

Data were visualised with the help of SPSS and Excel 2013 (Microsoft Corp., Redmond, WA, USA) and maps were generated with Quantum GIS (Chugiak 2.4.0., QGIS Development Team 2012).

4.4 Results

4.4.1 Soil parameters

Initial soil properties measured in dry season

The soil was classified as a Lixisol (FAO 2014) with a bulk density at 0 - 20 cm of 1.42 g cm^{-3}. The dominant clay mineral was kaolinite (Sou et al. 2013) and cations dominated by Ca. The pH of lower soil layers (20 - 40 cm), analysed during a pre-soil survey, was between 5.6 and 8.5 and average EC was 319 µS cm^{-1}. The topsoil (0 - 20 cm) of the experimental fields showed a clayey silt texture (Eckelmann et al. 2006). Unamended plots were significantly higher in pH and Na affected parameters (EC, SAR, ESP, and Na_{exc}) along the SDL (ANOVA, Table 4.2).

Table 4.2. Means (±SD) of soil chemical parameters of fields with low, moderate and high soil degradation level (SDL) prior to gypsum application at the urban farming Kossodo area of Ouagadougou, Burkina Faso in the dry season (May 2015).

Parameter	(Unit)	Low SDL		Moderate SDL		High SDL		F statistics	
		n = 12		n = 12		n = 12		F value	P value
pH		7.4	(0.5)	8.2	(0.2)	8.5	(0.2)	**23.7**	**< 0.001**
EC	(µS cm $^{-1}$)	275.2	(174.1)	502.1	(81.7)	581.8	(128.1)	**12.89**	**< 0.01**
SAR	(mmol l^{-1})$^{0.5}$	5.1	(2.9)	12.1	(1.6)	13.4	(2.2)	**43.24**	**< 0.001**
ESP	(%)	11.9	(4.9)	24.7	(2.9)	25.8	(3.6)	**87.24**	**< 0.001**
CEC	(cmol kg^{-1})	4.6	(1.0)	4.9	(0.7)	4.9	(0.6)	0.20	0.82
Ca	- - - (mg kg^{-1}) - - -	393.8	(69.4)	331.7	(83.0)	313.4	(108.4)	0.90	0.44
Na		129.9	(72.4)	278.8	(37.7)	293.1	(61.0)	**16.38**	**< 0.001**
K		215.7	(116.3)	205.3	(47.3)	301.1	(78.6)	2.45	0.14
Mg		57.0	(15.6)	48.8	(16.6)	37.3	(19.9)	1.92	0.20
N		0.5	(0.2)	0.6	(0.1)	0.5	(0.2)	0.22	0.81
P Olsen		19.3	(9.0)	25.1	(8.4)	19.7	(9.5)	0.75	0.50

Short term effects of gypsum application on soil parameters

Gypsum application reduced pH, SAR, ESP and Na_{exc} and increased EC and exchangeable Ca significantly (nested ANOVA, Table 4.3). The soil pH of gypsum treated plots was neutralised to values of 7.2 (SD ± 0.37). Furthermore, gypsum application to moderate and highly degraded soils led to the ESP decrease of below 15 %. Average of Na_{exc} in untreated plots of high SDL was twice as high as in gypsum treatments, whereas Na_{exc} in degraded soils reached up to 271.3 mg kg $^{-1}$. The EC in gypsum treated plots reached up to 1343.3 µS cm^{-1}. Generally, exchangeable Ca was low with a maximum of 731.4 mg kg^{-1} and exchangeable Mg was above 32 g kg^{-1} in all treatments.

Table 4.3. Means (±SD) of parameters of the three soil degradation levels (SDL) with (+G) or without gypsum (-G) application after the harvest of rainfed maize. Significance of gypsum effects was calculated with a nested ANOVA, arrows indicate direction of the main effect (Eff.).

		Low SDL	Moderate SDL		High SDL		Gypsum		
Parameter	(Unit)	-G (n = 12)	-G (n = 8)	+G (n = 4)	-G (n = 8)	+G (n = 4)	Eff.	F value	P value
pH		7.2 (0.6)	7.8 (0.3)	7.2 (0.3)	8.1 (0.3)	7.2 (0.2)	↓	**33.2**	**< 0.001**
EC	(µS cm^{-1})	224 (115)	327 (109)	566 (269)	404 (75)	790 (324)	↑	**16.5**	**< 0.01**
SAR	(mmol l^{-1})$^{0.5}$	3.7 (2.5)	6.3 (2.6)	4.1 (2.7)	8.8 (2.1)	3.6 (1.2)	↓	**13.9**	**< 0.01**
ESP	(%)	9.4 (5.6)	14.8 (5.0)	10.4 (6.3)	20.8 (4.7)	9.2 (2.6)	↓	**12.1**	**< 0.01**
Ca	- - - (mg kg^{-1}) - - -	411 (71)	427 (93)	519 (48)	359 (109)	551 (118)	↑	**8.7**	**< 0.05**
Na		92 (59)	170 (68)	116 (76)	204 (46)	105 (40)	↓	**12.7**	**< 0.01**
K		138 (54)	164 (17)	149 (35)	196 (52)	159 (40)	↓	2.14	0.17
Mg		65.7 (17)	73.7 (22)	54.7 (8)	36.8 (6)	40.1 (2)		1.66	0.22
N		586 (149)	674 (115)	696 (71)	455 (91)	596 (100)	↑	2.89	0.11
P Olsen		18.5 (11.1)	16.1 (11.2)	13.9 (5.7)	29.2 (12)	18.4 (8.9)	↓	1.68	0.22

The ratio of Ca:Mg was significantly higher in gypsum treatments than in unamended control plots (nested ANOVA, $P < 0.01$) and reached in medium SDL and high SDL values above 5. The ratio was with 11.8 highest in plots that received the highest doses of gypsum. Exchangeable soil K varied between 67 and 262 mg kg^{-1}. As gypsum led to a Na_{exc} reduction, it increased the K:Na ratio (nested ANOVA, $P < 0.02$). Overall, gypsum application did not affect exchangeable CEC, which remained low with a maximum of 6.5.

Effects of gypsum application on soil parameters under wastewater and clean water irrigation

Clean water irrigation as well as gypsum treatments decreased the soil pH (Table 4.4). Irrespective of irrigation water quality, the application of gypsum led to a significant decrease in pH, SAR, K and to an increased Ca content. In contrast, no significant gypsum effects were found for soils' ESP or Na, EC, Mg, N and P concentration. Aggregate stability increased significantly in soils with gypsum application compared to plots without gypsum (nested ANOVA, $P < 0.05$). Gypsum treatment increased significantly the Ca:Mg ratio to an average of 7.8 (nested ANOVA, $P < 0.01$), whereas the Mg:K ration was significantly reduced by clean water irrigation (nested ANOVA, $P < 0.01$).

Table 4.4. Mean value (±SD) of soil parameters of different soil degradation levels (SDL) after spinach cultivation in 2016 treated and irrigated with clean water (CW-G), gypsum and clean water (CW+G) and wastewater (WW-G). Treatment effects within SDL were calculated with nested ANOVA, arrows indicate direction of the effect (Eff.).

		Low SDL		Moderate SDL			High SDL			Gypsum			Clean Water		
Parameter	(Unit)	CW-G	WW-G	CW-G	CW+G	WW-G	CW-G	CW+G	WW-G	Eff.	F value	P value	Eff.	F value	P value
		n=8	n=4	n=4	n=4	n=4	n=4	n=4	n=4						
pH		7.1 (0.6)	8.5 (0.1)	7.6 (0.2)	7.0 (0.3)	8.6 (0.2)	8.2 (0.6)	7.2 (0.2)	8.4 (0.7)	↓	**19.7**	**< 0.001**	↓	4.0	0.07
EC	(µS/cm^{-1})	305.2 (143.0)	615.0 (54.4)	460.0 (153.3)	799.0 (333.1)	805.8 (169.3)	586.5 (231.3)	784.3 (302.4)	886.8 (64.7)	↓	1.0	0.34	↓	**6.6**	**0.02**
SAR		9.4 (3.4)	7.5 (4.1)	9.2 (1.8)	7.5 (2.7)	10.5 (3.0)	11.1 (1.6)	7.9 (1.5)	14.0 (1.6)	↓	**13.3**	**< 0.01**	↓	3.7	0.08
ESP	(%)	18.4 (5.0)	12.9 (7.1)	19.1 (3.3)	17.8 (7.7)	18.5 (5.4)	19.6 (3.9)	17.4 (3.3)	22.6 (2.8)	↓	1.4	0.25		0.3	0.62
Ca	- - - (mg kg^{-1}) - - -	367.7 (96.0)	320.6 (67.6)	424.8 (74.8)	617.7 (88.7)	357.7 (102.4)	394.8 (100.6)	770.5 (280.2)	311.1 (63.7)	↑	**38.6**	**< 0.001**	↑	1.6	0.23
Na		227.6 (58.0)	175.3 (89.5)	255.8 (66.1)	227.6 (76.0)	253.5 (65.9)	290.3 (70.6)	266.7 (70.1)	322.4 (44.9)	↓	1.7	0.21		0.3	0.62
K		352.4 (114.4)	430.1 (35.9)	432.0 (143.0)	307.9 (56.6)	463.3 (100.5)	442.8 (98.9)	359.7 (45.2)	522.0 (98.0)	↓	**13.5**	**< 0.01**	↓	1.8	0.20
Mg		71.4 (21.0)	67.1 (19.0)	93.9 (32.7)	62.0 (8.5)	65.3 (15.8)	70.8 (26.9)	52.0 (7.8)	53.8 (13.7)	↓	2.6	0.13	↑	**5.2**	**0.04**
N		913.5 (164.8)	891.0 (227.8)	1084.2 (370.4)	869.0 (95.0)	958.8 (263.8)	673.1 (252.4)	804.5 (96.3)	648.6 (197.2)		0.0	0.97		0.3	0.62
P Olsen		27.8 (16.2)	44.8 (19.6)	56.6 (16.4)	53.6 (10.2)	47.1 (6.5)	52.7 (10.3)	44.8 (13.9)	48.8 (24.5)		0.1	0.76	↑	1.5	0.25

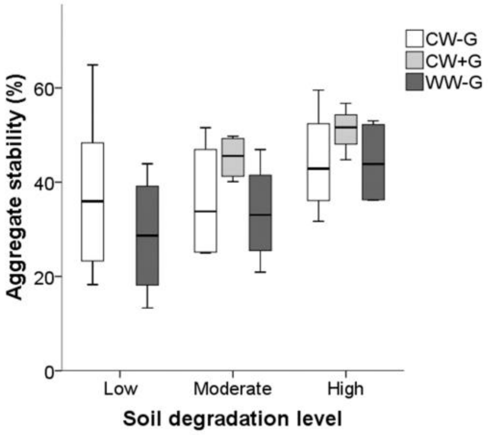

Figure 4.2. Aggregate stability of soil treated with clean water (CW-G), gypsum and clean water (CW+G) and wastewater (WW-G) for different soil degradation levels.

Seasonal effects

Independent of the treatment, the rainy season reduced Na affected parameters such as pH, ESP, SAR and Na_{exc} (Figure 4.3) compared to data prior to the experiment. Overall, average Na_{exc} in soil after the rainy season did not exceed 230 mg kg^{-1} (Table 4.3). Comparing soil Na from the dry season 2015 with the dry season 2016, results were similar.

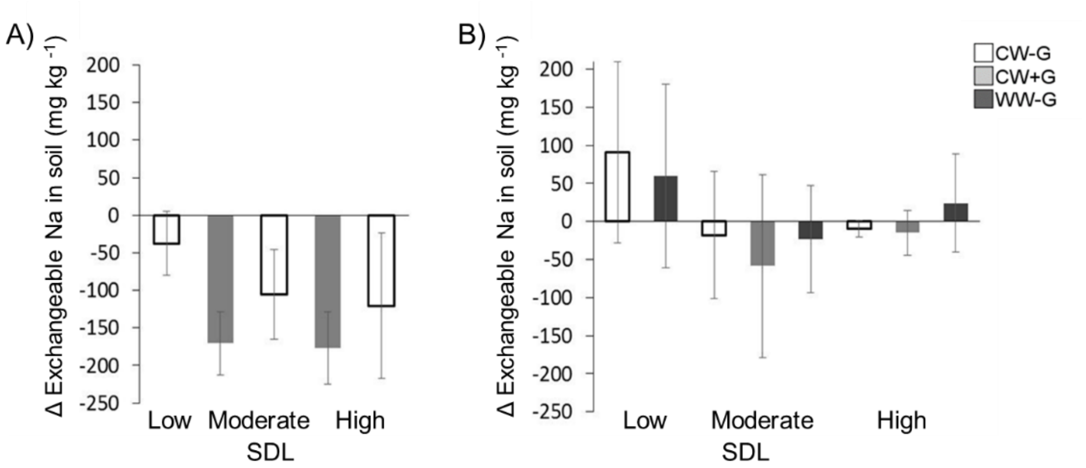

Figure 4.3. Seasonal changes of exchangeable Na in the topsoil prior to the experiment (dry season 2015) and after A) rainfed maize (rainy season) and B) irrigated spinach (dry season 2016) in the treatments with clean water irrigation (CW-G), gypsum application and clean water irrigation (CW+G), wastewater irrigation (WW-G) of a field experiment at Kossodo, Ouagadougou, Burkina Faso. Error bars indicate standard deviation.

4.4.2. Results of plant performance

Maize cultivation in the rainy season of 2015

Total yield of maize, including the parameters maize straw and maize grain, did not differ significantly between the three soil degradation levels and gypsum treatment. Variation of yield was high, especially in untreated plots in high SDL, where yields of above ground biomass varied between 10.9 and 32.3 t FM ha^{-2} (Figure 4.4A). However, maize RLD decreased with increasing SDL as it was negatively affected by increasing pH (nested ANOVA, $P < 0.05$) and was significantly higher in gypsum treated fields than in untreated plots (nested ANOVA, $P < 0.01$; Figure 4.4B).

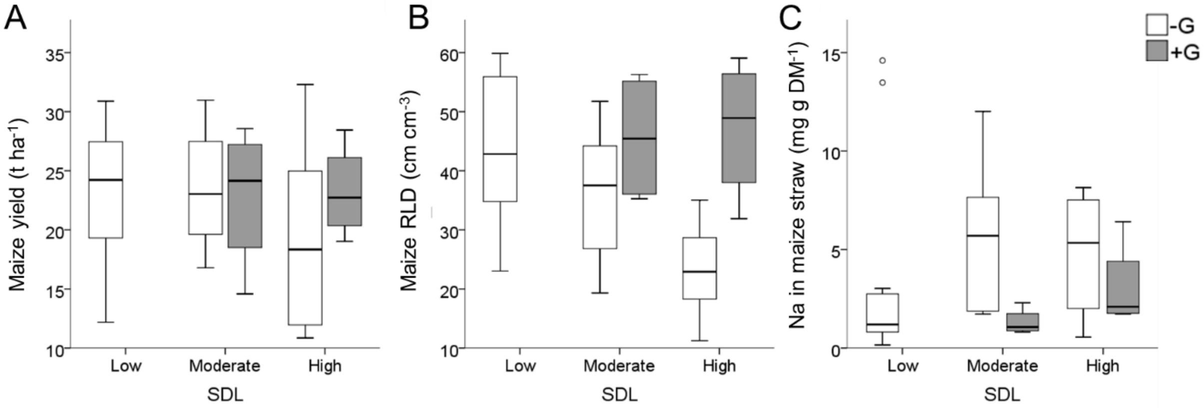

Figure 4.4. Effects of gypsum application (+G) on maize yield (A), maize root length density (RLD, B) and Na content in maize straw (C) cultivated on soils of low, moderate and high degradation level (SDL) at the urban vegetable field site of Kossodo, Ouagadougou (Burkina Faso) during the rainy season 2015.

However, Na concentration in maize straw was significantly reduced in plants that were cultivated on gypsum treated fields (nested ANOVA, $P < 0.05$; Figure 4.4C). Except for the Na concentration in maize straw, no significant treatment-related differences were found in maize nutrient concentrations. Average maize straw nutrient values were P with 2.44 mg g DM^{-1}, Mg with 1.21 mg g DM^{-1}, K with 3.74 mg g DM^{-1} and total N with 7.59 mg g DM^{-1}.

Spinach cultivation during the dry season in 2015/16

The second harvest yielded highest with an overall average of 4.49 t FM ha^{-1}. Cumulative yields ranged from 1.33 t FM ha^{-1} to 25.48 t FM ha^{-1} (Figure 4.5A). Root length density showed significant gypsum treatment effect (nested ANOVA, $P < 0.05$, Figure 4.5B).

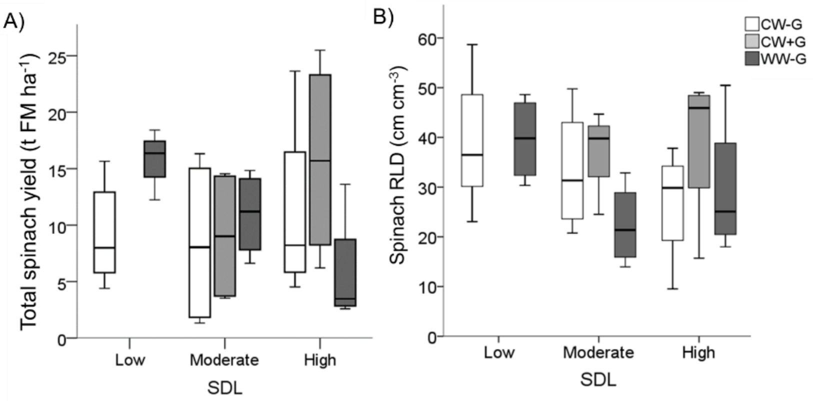

Figure 4.5. A) Cumulated spinach harvest and B) Spinach root length density in plots of different soil degradation levels (SDL) under the treatments: clean water irrigation (CW-G), gypsum amendment and clean water irrigation (CW+G) and wastewater irrigation (WW-G).

Spinach fresh matter yield (FM) was highly variable within the study plots and was unaffected by soil degradation level, gypsum application or irrigation water quality.

However, Na content of spinach plants was significantly reduced due to clean water irrigation (nested ANOVA, $P < 0.001$) and this positive effect could be boosted by additional gypsum incorporation into the soil (nested ANOVA, $P < 0.001$; Figure 4.6A). Furthermore, irrigation with clean water led to an increase in the K and P concentration of spinach plants with gypsum. Spinach K content was significantly higher in clean water treatments (nested ANOVA, $P < 0.001$) and gypsum treatment (nested ANOVA, $P < 0.001$; Figure 4.6B). A significant increase was also found in biomass P of spinach grown with clean water irrigation (nested ANOVA, $P < 0.001$; Figure 4.6D). Overall, no correlation of spinach yield with soil parameters or with plant nutrient concentrations was found. Only RLD was negatively correlated with soil Na ($r = -0.46$, $P < 0.001$) and RLD was positively correlated with spinach K ($r = 0.4$, $P < 0.02$). Spinach K content was negatively correlated to Na ($r = -0.9$, $P < 0.001$) and positively to P ($r = 0.54$, $P < 0.001$).

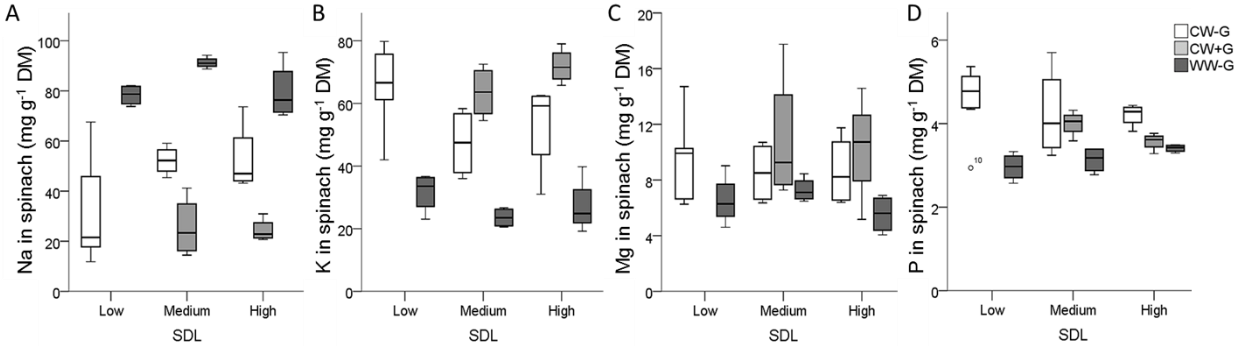

Figure 4.6. A) Na, B) K, C) Mg and D) P concentration of spinach plants grown in different soil degradation level (SDL) and different treatments (irrigated with clean water (CW-G), gypsum amendment and clean water irrigated (CW+G), wastewater irrigated (WW-G)) in a vegetable field experiment at Kossodo, Ouagadougou, Burkina Faso.

4.5 Discussion

4.5.1 Soil heterogeneity

Chemical soil properties in common rainfed cropping systems in West Africa are well known to be very heterogeneous (Buerkert et al. 1995; Mowo et al. 2011). This was also observed in the preconditions of the selected fields of our experiment, with high variations of available macronutrients such as Ca and P. In rural areas the heterogeneity of the soils is known to result from natural and management processes such as termite activities, soil erosion and deposition, as well as selective application of organic amendments and soil preparation (Buerkert et al. 1995). Soil heterogeneity in UPA is additionally influenced by different agricultural strategies of farmers on plots often smaller than 100 m². In our experiment the effect of industrial wastewater use increased the soil heterogeneity due to the change of water composition over time and due to differences in farmers' activities and willingness to intensify their plots by irrigating with wastewater. Still a pH of 7.4, an EC of 275 µS cm^{-1} and an ESP of 11.9 (Table 4.2) was considered as typical for arable soils in the UPA of Ouagadougou.

4.5.2 Plant development under normal agricultural practice

Maize yields were generally low due to an unusual rain shortage during the stage of maize corn development in September 2015 and a Mg deficit was noticed in all treatments (Marschner 2012). As expected, typical wastewater use in Kossodo, increased the Na influenced parameters of the top soil significantly and thus led to structural deficits of the soil, with a crusty structure and poor aeration (Bernstein 1975; Marschner 2012; Sou et al. 2013). Nevertheless, it could not be proven that physical soil structure was one of the driving forces for the reduced plant growth, as aggregate stability was slightly higher in higher SDL (Figure 4.2). Of the measured parameters, only the higher pH and lower ESP seemed to be responsible for weak maize growth, as yield tended to decrease by increasing SDL. Normally soil K, as it was significantly increased due to former wastewater application in high SDL, should increase the maize yield, but the negative effect of high pH and Na content diminished this fertilizer effect. The increase of soil Na led to a reduced soil K and lower K uptake by plants and even a leaking of plant K content through plasma membrane channels (Shabala and Cuin 2008; Wang et al. 2013). On the other hand K may have blocked the Mg uptake or the transport from the plant roots into the upper part of the plant (Gransee and Führs 2013; Guo et al. 2016). Unfortunately, no correlation of soil and plant concentrations with maize K concentration was found.

A surplus of Na may reduce P availability as it bounds to calcium phosphate (Richter 2005; Marschner 2012) especially for maize as a P inefficient plant (Richter 2005), but soil parameters showed that sufficient P for maize growth was available, so that similar to Mowos (2011) findings the variations in available soil P should not affect maize yield.

Spinach did not show any differences in yield between SDL if irrigated with clean water (Figure 4.5). As a Na tolerant plant, spinach is one of the rare crops that can grow during the dry season under saline-sodic conditions. The Amaranthaceae can adjust to the osmotic stress by replacing K with Na in the plant tissue to maintain leaf turgor under sodicity stress. The excessive Na is accumulated in leaves and petioles (Lawlor and Milford 1973). This, and the addition of nutrients through wastewater, explain the increased spinach yield in wastewater treatments of low SDL. Thus, not the total Na concentration affects yield of salt tolerant plants, but the K:Na ratio (Shabala and Cuin 2008; Shabala and Pottosin 2010). Unfortunately, our data did not show if K was a growth limiting factor, but spinach likely suffered from high Na concentrations, even if the EC tolerance limit of 2.000 µS cm^{-1} reported in Shannon and Grieve (1998) was not reached.

4.5.3 Effect of gypsum treatment on soil properties

The aim of decreasing the site`s soil pH with gypsum application to below 8, as well as decreasing the ESP and therefore improving soil conditions was reached. Still mean values of the final ESP in gypsum treatments remained above our target of 15 %. Comparing Na content of before and after the experiment, Na_{exc} was barely decreased by gypsum and clean water application (Figure 4.3).

There are three likely causes for this: First, the total rainfall and irrigation of 1046 mm during seven months of the experiment, may not have been sufficient to leach sodium given high evaporation rates, which can reach up to 2000 mm a^{-1} (World Bank 2009). Secondly, the downwards increasing soil clay content hinders leaching and provokes water stagnation so that the relatively high doses of gypsum applied were not well distributed throughout the soil profile, as the increased Ca values in gypsum treatments indicate (Table 4.4). Surprisingly, Na_{exc} of clean water irrigated plots in low SDL increased, which leads to the third possible explanation that Na must have been introduced from deeper layers or by unexpected groundwater flows. Evidence for this is that farmers occasionally blocked the wastewater channels to irrigate their fields. Sodification occurred in fields where water temporary stagnated in the soil, whereas in others the gypsum reclamation effect may still have been on-going, as leaching of Na will continue during the next rainy season.

Besides the fact that gypsum did not have the expected effect on Na concentrations in the soil and plant growth, soil condition did improve, as aggregate stability increased by 12 % and 7 % in moderate and high SDL plots, respectively. Also, farmers reported that the soil structure was improved and it was easier to plough.

4.5.4 Effect of gypsum treatment on plant development

Maize growth, especially of roots, was increased as the likely consequence of lower soil pH and decreased ESP in gypsum plots compared to untreated plots, even if gypsum was probably not sufficiently washed through the soil profile. Similar results were reported by Favarotto et al. (2008) where unleached gypsum treatments still reduced negative effects of Na on plant growth and led to similar yields as in the control plots.

Unfortunately, yield data did not show significant gypsum effects. One factor preventing treatment effects on maize growth could have been a cation imbalance due to the high Ca content in gypsum, even though no treatment effects in Na, Mg, P and K content of maize were found. Generally, a high Ca:Mg ratio results in a replacement of Mg by Ca at the exchange complex of the soil and leads to leaching and unavailability of Mg for plants (Shainberg et al. 1989; Landon 1991). In Favaretto (2008), Ca:Mg ratio increased up to 3.2 due to gypsum application, but did not affect maize growth, as Mg concentration was still absorbable by the plant. The results of our experiment showed that in treated and untreated maize a latent Mg deficiency was noted as Mg content in straw was 1.21 mg g DM^{-1}. Low Mg uptake can lead to reduced yield and root growth (Gransee and Führs 2013) and may have occurred even if exchangeable soil Mg was apparently sufficient during plant growth with more than 30 mg kg^{-1}. Further no significant difference in Mg concentrations of plants were found between treatments, so that the higher Ca availability in gypsum-amended plots may not have aggravated the latent Mg deficit in maize plants (maize nutrient contents listed in 4.4.2).

Spinach yield instead was slightly increased in gypsum treatments, but still varied widely and gypsum treatment effects were diminished due to the positive nutritional effect of wastewater. The decreased pH and the increased Ca improved K plant availability and improved K-Na selectivity of roots possibly by blocking non-selective cation channels (Shabala 2000; Qadir and Schubert 2002). In contrast to maize, spinach was not facing Mg deficits, as Mg concentration was highest in gypsum treated plots, even though Mg in soil was reduced by gypsum.

4.6 Conclusions

In the first year after application gypsum treatment of our saline-sodic soil enhanced maize root growth and decreased Na concentration in the shoots of maize and spinach reflecting changes in key soil parameters such as ESP and pH. Yield of both crops was barely improved by gypsum treatment, as leaching of Na in soil was not yet completed. Further research including long term measurements and physical soil parameters would be necessary to verify these results.

4.7 Acknowledgements

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Chapter 5

General discussion, conclusions and recommendations

5.1 Pathogenic contamination of urban cultivated lettuce in West Africa

The results of this thesis revealed that irrigation with water from different types of polluted water bodies may result in diverse problems. Our first study indicated that all sources of irrigation water in Ouagadougou, wells, rivers and channels were contaminated with pathogens above “health based targets” (WHO 2006), resulting in a contamination of urban cultivated vegetable. Traditionally food in West Africa is cooked and not eaten raw. Still, salad is nowadays a popular dish and the baseline survey of the Urban Food$^{\text{Plus}}$ Project indicated that lettuce consumption and production was high not only in Ouagadougou, but that it was also frequently consumed in smaller cities such as Tamale (Ghana, Bellwood-Howard et al. 2015).

The study on lettuce was performed at the beginning of the rainy season. Although Amadou et al. (2014) did not find seasonal differences in contamination rates of lettuce in Bobo Dioulasso, Burkina Faso, repeated sampling in different seasons could add to the knowledge about contamination of lettuce, as water quality is strongly affected by the amount of precipitation. Our results of coliform loads in water were similar to water analyses done by fermentation in Ouagadougou during the dry season (Akponikpè et al. 2011), but lower than in a study from Accra, Ghana, where channel water was used for irrigation (Owusu-Ansah et al. 2017).

In Abidjan, the largest city of Ivory Coast, lettuce is also a popular food. However, faecal coliform load of lettuce sold in the market, as counted on violet red bile lactose agar (Coulibaly-Kalpy et al. 2017), was lower than that found in our study. Despite the relatively low sample number, the presented results of lettuce microbial contamination underline the problem of water sanitation. The indicated post-harvest handling of washing lettuce with tap water can reduce health risks. Therefore, the need for awareness of how to deal with low quality irrigation water is substantial. Contrary to Qadir et al. (2010) who stated that actors in the trade chain were unaware of contamination due to irrigation and wash water, our results indicated that producers and traders (Figure 5.1) were aware of the risks and were also willing to change management practices to reduce pathogens on lettuce. To offer the cleanest possible products, well or tap water was used to wash with a preference for the cleaner water source if available. Overall, governments implementation of the WHO’s “Guidelines for the safe use of wastewater, excreta and greywater” (WHO 2006), as well as investments in sanitation infrastructure are needed to prevent the risks of diarrhoeal diseases.

Figure 5.1. Lettuce trade chain from field to market: A) well water for irrigation, B) washing in the field, C) transport to the market, D) storage on the market, E) selling in a street shop in Ouagadougou, Burkina Faso (in 2014).

The wide range of pathogen loads in irrigation water indicates that water quality throughout Ouagadougou was very diverse. Pathogens, for example, might be introduced to well water by a single manure application and persist for several weeks (Wright 1989; Baudart et al. 2000; Winfield and Groisman 2003). The wide range of pathogenic load on lettuces was probably related to different abiotic factors, which could not be captured during the study. The natural bacterial growth is enhanced in warm humid climates, whereas the antagonistic effect of sunlight can deactivate and kill susceptible pathogens. Additional cross-contamination especially from lettuce to lettuce through washing water, was likely and calls for the utilisation of detergents, as documented by Amoah et al. (2007).

Despite the risk of contamination, the use of wastewater as irrigation water and nutrient source is important to local farmers. Health risk reduction is possible with adequate post-harvest handling or with on-farm water treatment strategies such as on-field filter systems (Kätzl et al. 2015; Werner et al. 2018).

Methods to analyse pathogenic contamination of lettuce

To identify traders' impact on the lettuce contamination level from the farm to the consumer, total coliform and *E. coli* loads were selected as an indicator. Unfortunately, no universal indicator for health studies related to wastewater exists (Sou 2009). Total coliforms include faecal and non-faecal bacteria such as *Citrobacter, Enterobacter, Escherichia, Hafnia, Serratia, Yersinia* and *Klebsiella* (Mara and Horan 2003), which were used to monitor the overall microbial quality of lettuce, irrigation and wash water. If samples were tested positive for total coliform, the analyses of faecal coliform such as *E. coli* were added to determine the risks of diarrhoeal diseases. Due to laborious analytical procedures and absence of well-equipped microbial laboratory facilities, it was decided to focus only on total coliforms during the additional experiment. The results of this experiment combined with the results from the field allowed to demonstrate the situation on-farm as well as to highlight possibilities for improvement of the status quo.

The standard method of counting total coliform and *E. Coli* on the culture media Chromocult ES agar (Merck KGaA, Darmstadt, Germany) was chosen, as commonly used to detect faecal contaminations in fresh food by Burkina Faso's national laboratories. Alternatively, the microplate method of most probable number (MPN) could have been used, but was rejected as it was more expensive and the necessary ingredients were not easy to acquire in Burkina Faso. Unfortunately, caution must be applied when comparing both methods, as MPN is based on a statistical calculation and results in higher but correlating values than in plate counts, as observed by Prats et al. (2008).

Salmonella ssp. was analysed by a standard procedure (ISO: 6579:2002) in the national laboratory and was identifiable up to the species level with the API 20E strips. Unfortunately, to analyse one sample took two weeks. Where different species of *Salmonella* were found, the number of repetitions had to be increased for confirmation. Conversely, one could identify cross-contamination of *Salmonella* in water or on lettuce, in cases where different species were found. Unfortunately, this costly and time-consuming analyses was, due to lack of facilities, only done to confirm the presence of *Salmonella*.

5.2 Sodic alkaline wastewater and pathways of soil contamination

A literature review of Muyen (2011) criticised that no long term monitoring of Na accumulation through the soil profile was available for most studies of irrigation with sodic water. The aim of our study therefore was to fill the research gap concerning soil quality changes with Na-rich wastewater throughout the soil profile. We also wanted to study the effects of cropping history by comparing soil and water data from 2006 and 2015 in the Kossodo area. The presented literature review in chapter 3 was conducted with a focus on semi-arid and tropical conditions. Studies in which soil and water data were given simultaneously were preferred. All data was converted into comparable units. Where ESP or SAR were not given, these missing values were added if sufficient parameters for calculation were available, and compared to the soil of gardens in the industrial area of Kossodo, Ouagadougou. Here wastewater was used to irrigate, which increased soil pH and Na above the international standards (Weber and Juanico 2004; WHO 2006), leading to problems for soils and crops (Pedrero et al. 2010). The hazards of HCO_3^- and Na reportedly occurred already shortly after the establishment of the horticulture area in Kossodo, nearly ten years ago (Sou et al. 2013). The pH documented by Sou was on average 8.6 in the years from 2006 to 2008, which caused soil deflocculation. Our data, measured in 2015, indicated that soil pH had increased up to 9.2. Differences between the results might be partly due to seasonal or methodological effects, but values still indicated an increased alkalinity hazard. In addition, changes in the composition of industrial effluents occurred, as for instance the tannery was closed in 2014. This might have led to a concentration of sodic beverage industrial effluents, reflected by increasing Na concentration of the wastewater from 326 mg l^{-1} to 532 mg l^{-1}, in 2008 and 2015 respectively. Before industrial wastewater was discharged into the channel, it passed a microphyte sewage treatment plant owned by the National Office for Water and Sanitation (ONEA). After the first sedimentation phase, a biological purification under aerobic conditions should have taken place. Whether the treatment plant functioned properly is questionable. Probably, the 30 days water residence time just allows solids to settle, before being discharged. In any case, the treatment plant is not able to reduce neither pH nor Na concentration of the wastewater. In 2015, after our experiment, the beverage industry started to add an acid to their wastewater. This was done to neutralise the pH, but unfortunately the company did not employ a feedback loop, resulting in a wide range of pH values for the effluents. The Na concentration of wastewater was not affected by this treatment and remained high.

Treatment plants in Burkina Faso mostly do not implement chemical water treatment, such as adjusted acids (with H_2SO_4 or HCl) to reduce the pH of wastewater. In modern treatment plants neutralisation of wastewater is commonly done, usually at the end of the water treatment to not interrupt the bacterial based processes during the biological phase (Draxler 2007).

Contrary to this, Na is rarely eliminated and rather increased during wastewater treatment, as it is used during chemical phase to remove Ca and Mg (Spellman 2014) and to precipitate heavy metals (Patwardhan 2017). Reports about sodium reduction in wastewater are very scarce. Hussain (2013) investigated a low cost, coagulation based method of wastewater treatment, in which the initial Na concentration of 120 mg l^{-1} was reduced to 3.5 mg l^{-1} by the addition of aluminium sulphate ($Al_2(SO_4)_3$) followed by filtration through charcoal.

Negative effects of wastewater were not only introduced as a result of irrigation, but also by the sheer existence of the wastewater channel. The readily soluble Na was introduced to the soil of the farming area by different pathways (Figure 5.2):

Irrigation with sodic water firstly increases soil Na concentration of the upper soil, which leaches into the subsoil. Secondly, seepage water seemed to saturate the subsoil around the channel, whereby Na was introduced and further transported by the movement of the groundwater. Soil water is likely to move horizontally due to the accumulated clay in the elevation horizon (Bt) of the subsoil (Driessen et al. 2000; Bockheim 2014), preventing leaching.

Other relevant ways of Na addition to the soil were the frequently monitored flooding incidents. Due to blocking of the channel, by the farmers or by accident, overland flow with sodic wastewater occurred and water stagnated in the low floodplains. At the beginning of the dry season this was even desired by the farmers, as it reduced their irrigation workload. They prepared dug outs which were located at the end of the channel branches, close to their fields. For irrigation purposes, the main channel was blocked by sticks near the junction of the channel branch, so that water flows into the cultivated area. Even after the rainy season, wastewater was still used to enhance, rather than to limit plant growth. Due to high evaporation rates, a rapid concentration and accumulation of the Na occurred and increased with each irrigation or flooding event. Besides this, channel branches and dug outs were not constructed with a concrete stream bed as the main channel, and this likely has enhanced seepage to the subsoil.

During the rainy season, the channel inundates part of the agricultural and fallow fields. Areas with regular flooding events were proved to suffer from higher Na concentrations in the top- and subsoil, where we found gleyic properties in the soil profile resulting from periodical oxygen deficits due to water stagnation. The second study further indicated, that unirrigated fields with a distance of more than 200 m can still be affected by subsoil sodification, which must have resulted from vertical movement of sodic water.

Overall, it was evident that Na contamination of the topsoil was related to irrigation and flooding, whereas subsoil Na hazard were most likely induced by relocation of Na from soil water.

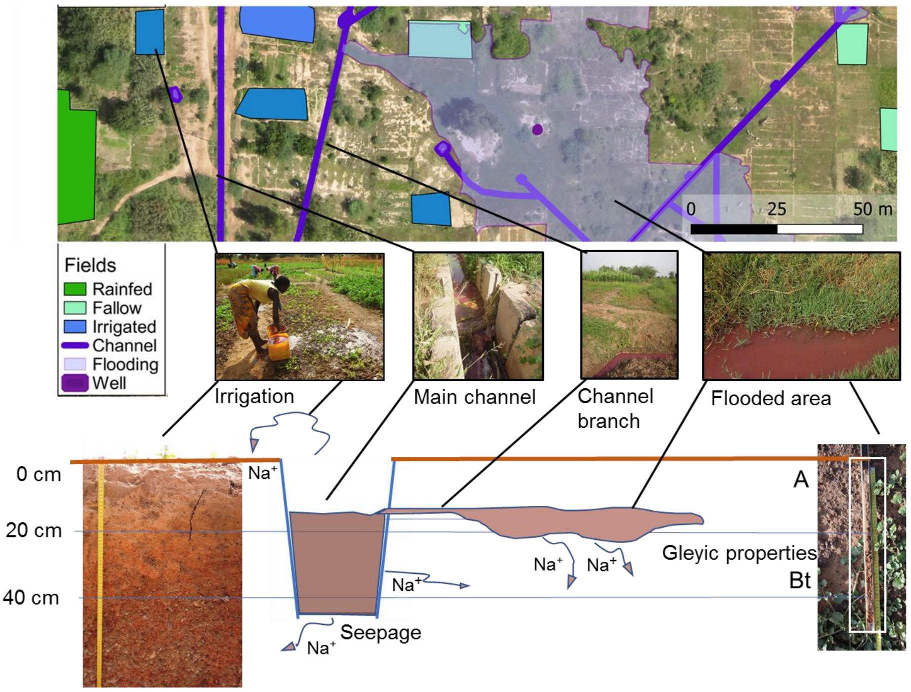


Figure 5.2. Pathways of soil sodification due to a sodic wastewater channel in irrigated urban agricultural area of Kossodo, in Ouagadougou the capital city of Burkina Faso.

5.3 Agricultural strategies to cope with wastewater induced soil sodicity

Crop production in the industrial area Kossodo was limited by the Na hazard and farmers tried to adapt by the use of the following simple strategies:

i) Selection of sodium tolerant crops such as spinach and *bulvaka*
ii) Avoidance of contaminated areas
iii) Implementation of a cultivation break
iiii) Seeding crops at the end of rainy season

Crop selection was very limited and many crops started to wilt in December, likely due to increased Na stress in the dry season. Avoidance and fallow strategies lead to reduced productivity and are not efficient for farmers. Early sowing avoids Na stress for seedlings, but reduces the chance of late dry season harvests, when returns are highest (Drechsel et al. 2006).

To test a melioration strategy, gypsum was amended in the on-farm experiment (Figure 5.3). This standard method to reduce Na hazards of soil (Oster 1982; Sekhon and Bajwa 1993; Yu et al. 2003; Amezketa et al. 2005; Bronick and Lal 2005) was selected because fine gypsum powder is readily soluble and commonly available at a reasonable price.

Pre-selection of the experimental field was done in January 2015, as part of the soil survey which resulted in the Kossodo case study. The selection criteria for the experimental field were i) homogeneity of farmers field, ii) no water stagnation iii) farmers willingness to take part in the experiment, as well as iiii) short distance between the selected fields, to facilitate the supply for clean water treatments.

Using the same fields as in the soil survey was unfortunately not possible as the initially randomly selected fields did not fit the experimental design. Therefore, subsoil sampling of the chosen fields was lacking, which might have helped to better explain yield effects and would have increased the value of the experiment.

It was found that gypsum treatments reduced soil pH, but not Na concentrations. Still, gypsum application led to a significantly lower plant Na concentration. Normally, increasing sodicity results in a cation uptake competition by plant roots (Gransee and Führs 2013) and to passive root uptake of Na (Kramer et al. 1977; Gao et al. 2014), which is followed by yield depressions due to the unavailability of other nutrients such as K and Mg. Probably, the addition of Ca improved the K availability for plants and improved K-Na selectivity of roots by blocking non-selective cation channels (Shabala 2000; Qadir and Schubert 2002). Results proved that maize root development in topsoil was improved in gypsum treated plots, even though gypsum was not leached. As root samples were taken only at 0 – 10 cm depth and yield was not correlated with root growth, it is very likely that roots only developed better in the topsoil. The reduced ESP resulted from the reduction in the Na:Ca ratio due to increasing Ca content.

Attempts to identify correlations between case study results from January 2015 with yield results of the experiment lasting from May 2015 to January 2016 failed. The analysed parameters for neither top- nor subsoil explained yield variations between or within fields. As the area was very heterogeneous at a very small scale, data interpolation was difficult.

Overall, results of the on-farm experiment in combination with the outcome of the soil survey indicated a severe problem of sodicity distributed throughout the soil profile.

This may have been the reason why a single application did not lead to the desired yield improvement. It is likely that the duration of the experiment was insufficient and effects could be determined after another rainy season. The subsoil can not be meliorated as long as the channel water continues to be contaminated, as Na will be repeatedly reapplied. Further research should also include the measurement of physical soil characteristics, such as infiltration rate, which was not done due to technical difficulties.

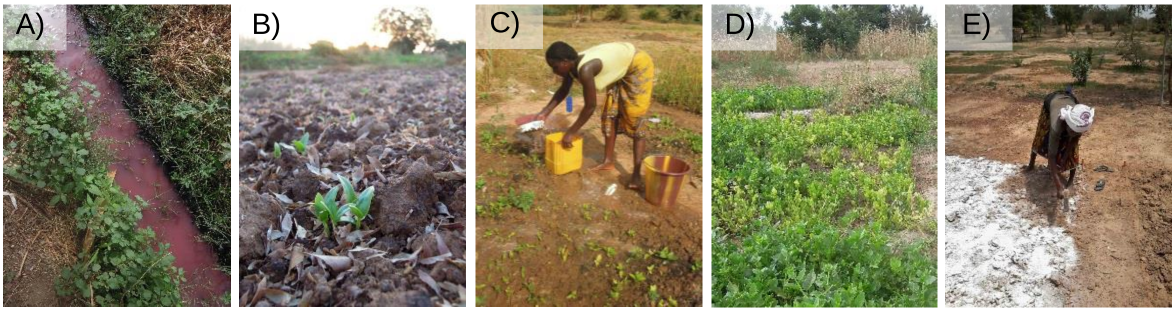


Figure 5.3. Irrigated spinach cultivation with alkaline sodic industrial wastewater: A) industrial wastewater channel, B) emerging spinach seedling, C) spinach irrigation D) spinach facing sodium stress, E) gypsum application in experimental plot.

5.4 Effect on soil life

To understand the effects of soil sodicity on soil fauna, altogether 120 topsoil samples (12 cm diameter, three replicates per plot) were collected during the gypsum experiment (October and December 2015) to document the abundance of collembola and mites. Unfortunately, no treatment effects were found. The collembola abundance was low in maize (4.06, SD 4.12, n = 60) and nearly zero in spinach (n = 60). In addition, a low abundance of soil mites was recorded in the rainy season in maize, on average 52.11 (SD 62.01) and zero in spinach.

A study by Stenchly et al. (2017) revealed that soil-dwelling arthropods showed the same abundance on neutral and alkaline soils, whereas the abundance of mobile arthropods, such as Hymenoptera, Diptera and Auchenorrhyncha abundance was reduced in plots with increased salinity. These authors concluded that soil-dwelling arthropods were tolerant to the change of soil parameters, but that mobile above-ground arthropods, including beneficial predators and pollinators tend to rapidly change their habitat in the small-scale vegetable systems dominating in UPA systems of West Africa.

5.5 Shift of urban agricultural system

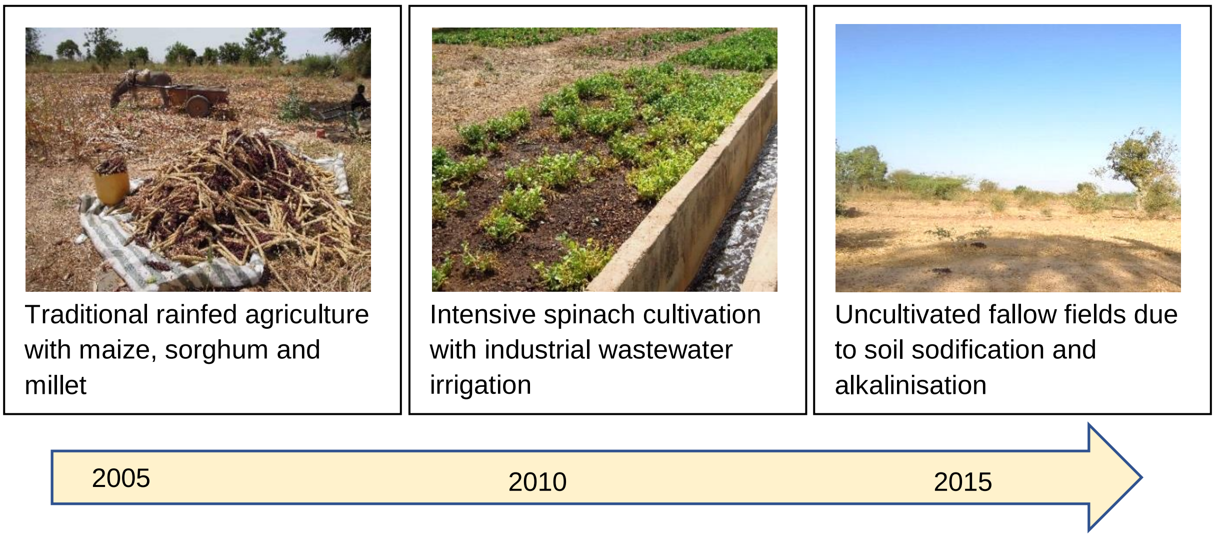
The resettlement of farmers from unofficial urban farming areas to the official gardens in Kossodo was reportedly done to avoid pollution of the produce (Korbéogo 2017). Our first study supports the argument of faecal contamination of vegetables in the open-space farms along the water channels. However, the industrial zone is unfortunately not suitable as a compensating gardening area, as shown in chapter 3 and 4. Contamination risks have shifted from health risk due to microbiological loads on the agricultural produce to an environmental pollution by inorganic compounds of industrial wastewater as well as to a loss in agricultural productivity. Viancelli et al. (2015) indicated that inactivation of *E.coli* and *Salmonella* spp. begins only at a pH of 9 to 9.5, so that also pathogenic risks will not be reduced as the pH of Kossodo's wastewater was 9.2.

The negatively affected soil quality reduced yields and farmers income opportunities. Even though this was known by authorities, the problems were trivialised by the governmental water institute (Figure 5.4). Also, the industrial water users did not show interest to tackle the problem, no sampling of the beverage effluents was possible during the two and a half years of data collection.

Figure 5.4. Sign of the governmental water institute, L'Office National de l'Eau et de l'Assainissement (ONEA), allowing the use of industrial wastewater in Kossodo, Ouagadougou (Burkina Faso).

Further, no extension officer was available to support farmers and no farmer association was created to cope with the problems. Ouedraogo (2010) stated that farmers were only interested in immediate returns on their labour investment. Indeed, farmers need to get a return, but are also aware of the need of sustainable soil management, to ensure future yields. Further, Na stressed spinach leaves are not marketable.

Overall, a rapid shift of the agro-ecosystems was documented (Figure 5.5). Before the establishment of the garden area, farming was done extensively for more than 50 years. The intensification by cropping irrigated vegetables with wastewater started in 2006. At Kossodo at first all kinds of vegetables were grown, later it was prohibited to grow raw edible vegetables and further only Na tolerant crops were to be chosen. Finally, cultivation declined over years.



Traditional rainfed agriculture with maize, sorghum and millet

Intensive spinach cultivation with industrial wastewater irrigation

Uncultivated fallow fields due to soil sodification and alkalinisation

Figure 5.5. Shift of the agro-ecosystems from extensive to wastewater irrigated crop production, resulting in a loss of farmland in the Kossodo industrial area of Ouagadougou, Burkina Faso.

Continuous irrigation was one factor increasing Na concentration of the soil, but some local Na accumulations would most likely have also occurred without farmers using the water. The seepage and flooding from the wastewater channel were important factors for sodifiing the area, which negatively affects productivity resulting in a reduced land value (Hussain 2002).

5.6 Conclusions and recommendations

In urban vegetable production of Ouagadougou the irrigation water sources were contaminated either by pathogens, inorganic pollutants or both. Lettuce irrigated with well water was similarly contaminated by *E. coli* and *Salmonella* spp. as if irrigated with wastewater polluted channel water. The contamination increased along the trade chain but could be reduced by washing lettuce with tap water. Our lettuce study indicated the importance of post-harvest handling of the fresh produce and highlights a simple strategy to reduce health risks without the utilization of detergents.

Our study gave an overview of the possible contamination status of lettuce on the way to the market and highlights the importance of wash water quality. Additional analyses of wash water before and after the washing, would give further information about how much water is needed and how often wash water has to be changed. As this is likely to depend on contamination load of the lettuce, one should test lettuce with different degrees of contamination. Further it is likely that cross-contamination occurred which did not originate from the wash water.

The problem of inorganic pollutants can not be easily eliminated by utilization of tap water, as wastewater contaminates soil and diminishes vegetable yields.

Our study indicated that irrigation with sodic water induced Na accumulation in top- and subsoils, whereby flooding and seepage from wastewater channel were likely to further increase the Na hazard, especially for the subsoil. Therefore, soil water movements seemed to be of major importance. To gain a better understanding of Na distribution in subsoil a hydrological profile would be needed, including analysis of chemical compositions of soil and water, as well as physical parameters.

No literature was available on irrigation with sodic waters, that took soil water movements and subsoil properties into account. In the industrial area of Ouagadougou, not only urban gardens but also the surrounding areas were sodified, even though they had never been irrigated.

Overall, compliance with WHO Na threshold of 100 mg Na l^{-1} especially in semi-arid regions is necessary to prevent the deterioration of farmland.

Improving a sodic soil by incorporation of gypsum was successful in reducing soil pH and partly improving rooting conditions. Still, such a soil needs to be free of stagnating properties to allow leaching of Na. Otherwise, a recontamination will quickly occur and crop development will be hindered. For further experiments it would be necessary to map top- and subsoil properties. The soil survey identified important factors triggering Na accumulation throughout the whole area, as well as indicating the necessity of terminating sodic wastewater utilization and treatment of water before discharging and subsequent agricultural use.

Gypsum as a soil amendment only helps to reduce Na concentration of the soil. It is not a strategy to reduce Na effects on soil properties if Na is continuously present. Once irrigation with sodic alkaline water is stopped gypsum treatment in combination with clean water irrigation and rain, will likely reduce soil Na over the time. The speed with which this occurs will depend on aggregate stability, penetration resistance or infiltration rates of the soil. Industries that cause the discharge of such alkaline wastewaters have to be included into research projects and Na should be reduced before discharge of the water.

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Affidavit

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