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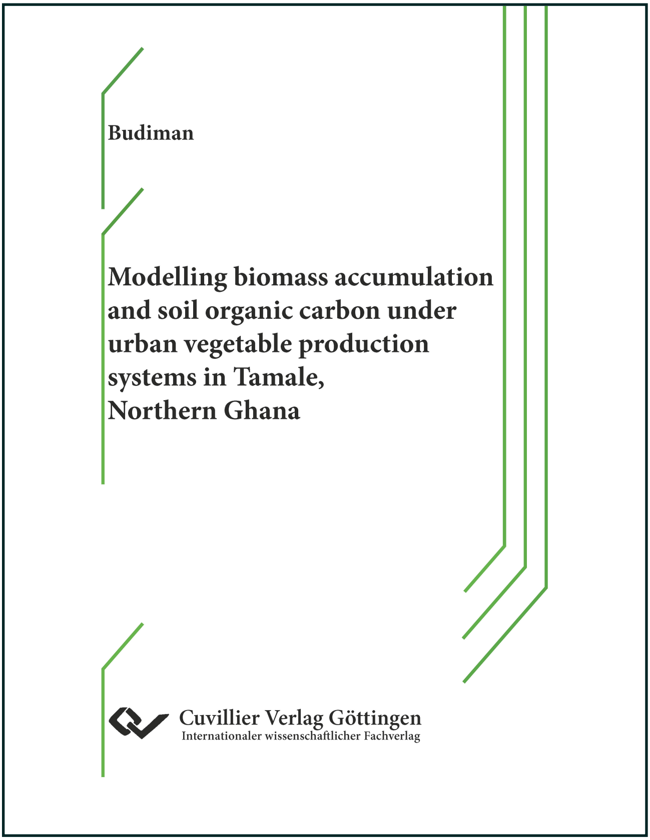

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## Summary

To develop sustainable urban and peri-urban agriculture (UPA) systems with high water and nutrient use efficiency and to promote food security on nutrient poor soils of West Africa under intensive rural-urban transformation and climate change, the Denitrification-Decomposition (DNDC) model can help to understand carbon (C) and nitrogen (N) turnover resulting from the complex interaction between soil, climate, management practices, and plant growth in vegetable production systems. To achieve those purposes, this study modelled biomass accumulation of the locally important vegetables amaranth (*Amaranthus cruentus*), lettuce (*Lactuca sativa L.*), jute mallow (*Corchorus olitorius* L.), and roselle (*Hibiscus sabdariffa* L.), and soil organic carbon (SOC) dynamics in response to a different level of N-fertilization, clean and waste water irrigation quantities, and biochar addition under current and future climate change scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) in Tamale, Northern Ghana. Crop modelling was preceded by a series of the DNDC model evaluation processes, that is calibration, validation, and analysis of uncertainty and its contributing factors, using field data of soil, climate, and crop growth from experimental plots in Tamale.

The studies described in Chapter 2 and Chapter 3 of this thesis confirm that the DNDC model performed well in simulating biomass accumulation of all vegetables and SOC under different input intensities with acceptable tolerance (α 5%) as reflected by the root mean square error (RMSE), relative error (E), and the correlation (r) values. However, DNDC modelling was limited to conditions without pest and disease incidence and was unable to simulate the impacts of biochar addition to SOC. For up-scaling the DNDC model in simulating vegetable biomass accumulation and the effects of SOC in West Africa, soil (pH and SOC) parameters need to be parameterized carefully due to spatial-temporal variation of these parameters and their contributing to the uncertainty of model outputs. Based on the simulation using the DNDC model under different management practices and projected climate change scenarios (baseline and RCPs), we propose transformative management practices combining N-fertilization and high nutrient loaded-waste water irrigation to stabilize marketable yield of all studied leafy vegetables without detrimental effects on soil fertility.

## Zusammenfassung

Um die nachhaltige Wasser- und Nährstoffnutzungseffizienz in stadtnahen Gemüseanbausystemen Westafrikas zu erhöhen und die Ernährungssicherheit in nährstoffarmen Böden unter intensiver Land-Stadt-Transformation und Klimawandel zu fördern, kann das DNDC-Modell beim Verständnis der Kohlenstoff (C)- und Stickstoff (N)-Umsätze helfen. Diese spiegeln die komplexen Wechselwirkung zwischen Boden, Klima, Bewirtschaftungspraktiken und Pflanzenwachstum wideren. Um diese Ziele zu erreichen, modellierte die vorliegende Studie die Biomasseakkumulation der lokal wichtigen Gemüsearten Amaranth (*Amaranthus cruentus*), Salat (*Lactuca sativa* L.), Malve (*Corchorus olitorius* L.) und Roselle (*Hibiscus sabdariffa* L.). sowie die SOC-Dynamik als Reaktion auf ein unterschiedliches Niveau der N-Düngung, der Bewässerungsmengen mit Trink und Abwasser sowie der Zugabe von Pflanzenkohle unter aktuellen und zukünftigen Klimawandelszenarien (RCP 2.6, RCP 4.5 und RCP 8.5). Vor der Modellierung erfolgten umfangreiche Bewertungsprozesse des DNDC-Modells, insbesondere seine Kalibrierung, Validierung und eine Analyse der Unsicherheit in Abhängigkeit von Felddaten zu Boden, Klima und Pflanzenwachstum aus Versuchsflächen in Tamale.

Die in Kapitel 2 und Kapitel 3 beschriebenen Modellierungsstudien bestätigen, dass das DNDC-Modell die Simulation der Biomasseakkumulation aller Gemüsesorten und des Bodenkohlenstoffgehaltes (SOC) unter verschiedenen Inputintensitäten mit akzeptabler Toleranz (α 5 %) vornehmen konnte, was sich n niedrigen Werten für den Relativen Fehler (Root Mean Square Error, RMSE) und hohen Korrelationswerten (r) widerspiegelte (E). Allerdings war die DNDC-Modellierung auf Bedingungen ohne Schädlings- und Krankheitsinzidenz beschränkt. Das DNDC-Modell erlaubt es auch nicht, die Auswirkungen der Zugabe von Pflanzenkohle auf den Bodenkohlenstoffgehalt zu simulieren. Für die

Hochskalierung des DNDC-Modells zur Simulation der Akkumulation pflanzlicher Biomasse und des SOC in Westafrika müssen wichtige Boden- (pH-Wert und SOC) aufgrund ihrer räumlich-zeitlichen Variation sorgfältig parametrisiert werden. Auf der Grundlage der durch das DNDC-Modell unter verschiedenen Bewirtschaftungspraktiken und prognostizierten Klimawandelszenarien (Basislinie und RCPs) simulierten Ergebnisse schlagen wir transformative Bewirtschaftungspraktiken vor, die N-Düngung und nährstoffreiche Abwasserbewässerung kombinieren, um einen marktfähigen Ertrag der untersuchten Blattgemüsearten zu ermöglichen ohne negative Auswirkungen auf die Bodenfruchtbarkeit.

# Chapter 1

## General introduction

### 1.1 Urbanization, climate change, and food security in West Africa

For the last decade West Africa's agriculture is experiencing intensive transformation from subsistence-based to increasingly market-oriented land use systems. During 1950-2015, Africa's urban population increased from 27 million to 567 million and it is projected to reach 1.5 billion by 2050 (Walther, 2021). The growing population in the urban areas has perpetuated a high demand for food, which is met by imports from other regions leading to an over-reliance on foreign supply, which impacts food prices and availability (Stage et al., 2009; Cockx et al., 2019). Given that during this period West Africa has experienced little growth in extra-farm job opportunities (Fay & Opal, 2000; Fox, 2012), many of its urban dwellers remain impoverished with limited access to nutritious food (Tevara, 2023).

From an ecological perspective, rapid and unplanned urbanization has led, like in other parts of the world, to the destruction of natural habitats, deforestation, and soil degradation, which negatively affected ecosystem services such as water regulation, pollination, and nutrient recycling, adversely impacting food production (Assennato et al., 2022; Ofoezie et al., 2022). Furthermore, climate change is amplifying water stress and extreme temperature, which increase uncertainty of food production (Rosenzweig et al., 2014). In conclusion, urbanization and climate change have negatively affected food security in West Africa which requires urgent attention to improve people's access to food, while promoting sustainable land use.

## 1.2 Promoting sustainable urban and peri-urban agriculture: Towards enhanced food security

Urban and peri-urban agriculture (UPA) contributes to nutrition security by fostering access to quality food, as it provides up to 40% of the demand for food by urban dwellers in developing countries (Smit et al., 1996; Koscica, 2014; Sangwan & Tasciotti, 2023). It therefore also plays a key role for urban provision of food and related income, although it occupies and only small area of land (Dossa et al., 2011; Sangwan & Tasciotti, 2023).

Since the late 1970, UPA has become more intensive resulting in the use of external resources such as high application rates of mineral fertilizers and pesticides. This has had negative effects on local ecosystems (Bryld, 2003). In contrast to the widespread nutrient mining in rural production systems leading to progressing soil degradation, UPA in West Africa is characterized by insecure land titles, intensive irrigation, and an often poor coupling of crop and livestock production (Diogo et al., 2010; Drechsel & Dongus, 2010; Bellwood-Howard et al., 2018).

In seasonally semi-arid climates such as prevalent in the West African Sahel, the availability of irrigation water is a major determinant of intensive crop production. In UPA production systems, the use of waste water irrigation is widespread, given the rare water supply from streams, wells, lakes/rivers, and pipelines (Tuffour et al., 2023). To meet market demands for a variety of food and to diversify cropping cycles, most farmers in West Africa’s UPA optimize their income in the wet season by growing a range of crops together in mixed cropping arrangements. In Northern Ghana, in contrast, during the dry season, less than 60% of the farm lands were cultivated and growers concentrate on leafy vegetables such as lettuce (*Lactuca sativa L.*), cabbage (*Brassica oleracea L.*), roselle (*Hibiscus sabdariffa* L.), jute mallow (*Corchorus olitorius* L.) and amaranth (*Amaranthus cruentus*; Bellwood-Howard et al., 2018).

In this region, where native soil fertility is low, given the prevalence of highly weathered Arenosols and Ferralsols, the application of mineral fertilizers is particularly intensive. To fill knowledge gaps on the effects of agricultural intensification on soil fertility and crop production in UPA systems, this study was therefore conducted in Tamale, the third largest city of Ghana after Accra and Kumasi.

### 1.3 Crop modelling for transformative adaptation of UPA systems

In the search for adaptation strategies to climate change, crop modelling can be instrumental in understanding and extrapolating experimental results towards developing more sustainable UPA systems in West Africa (Bouman et al., 1996; Boote et al., 2010; Balogun et al., 2022; Farrell et al., 2023). Crop models are able to predict which practices are likely to result in maximum yields and enhanced environmental sustainability by simulating different scenarios (Magwaza et al., 2022; Zaffaroni & Bevacqua, 2022; Fu et al., 2023). As climatic conditions shift, crop models can also help to select climate-resilient crops and adaptive management practices (Carr et al., 2022). In relation to mitigation strategies, such models allow the identification of soil management strategies to improve water and nutrient use efficiencies (Amouzou et al., 2018). Thus, crop modelling research can help understand the scope of transformative adaptation in a particular UPA system by increasing its resiliency to climate change's impacts while promoting food security and environmental sustainability.

However, research on crop modelling is frequently limited by the model's capability to cope with local complexity addressing the interaction between climate and soil conditions, farmers' management, varietal response to soil fertility differences and input levels. Hereby recent research has highlighted the paucity and quality of reliable data available for the accurate calibration and verification of crop models, particularly in countries of sub-Saharan Africa (Boote et al., 1996; Di Paola et al., 2016; Kephe et al., 2021). These limitations must be taken into account when selecting appropriate models for specific research questions.

### 1.4 The DNDC model: Challenges and opportunities

The denitrification-decomposition (DNDC) model, a process-based biogeochemical model, was initially developed to simulate nitrous oxide ($N_2O$), carbon dioxide ($CO_2$), and dinitrogen ($N_2$) emissions from agricultural soils (Li et al., 1992). After 20 years of improvements, this model can simulate many the processes involved in the biogeochemical cycles of carbon (C) and nitrogen (N) in various ecosystems for studying sustainable land use management and greenhouse gas (GHG) emissions (Gilhespy et al., 2014). The current version of the DNDC model requires climate, soil physical properties, vegetation, and anthropogenic activity as model inputs to drive three interacting sub-models (soil climate, plant growth, and decomposition) to predict soil environmental variables. The modelled soil environmental variables drive nitrification, denitrification, and fermentation sub-models to simulate NO, $N_2O$, $N_2$, $NH_3$, and $CH_4$ fluxes (Li, 2000).

As with other crop models, applying the DNDC model in a new area is associated with challenges to calibrate and validate it in order to increase the model's confidence in predicting the output according to the desired scenario. For this purpose, a field experiment is needed to generate the minimum required data. In West Africa, existing studies are limited to determining $N_2O$ emissions in natural savannahs such as in Burkina Faso (Grote et al., 2009). However, the DNDC model has also been reported to successfully simulate more components of C and N turnover in various cropping systems of many countries (Giltrap et al., 2010). Results of a recent survey study among model users worldwide stated that the DNDC model offered a user-friendly graphical interface, a comprehensive library of the crops and soil types, and detailed daily outputs (Gilhespy et al., 2014), making it likely to also be successfully applied to transformative adaptation of UPA systems in West Africa.

## 1.5 Research objectives

Given the above-mentioned knowledge gaps, my PhD research focused on modelling growth and C and N emissions of locally important leafy vegetables (amaranth, lettuce, jute mallow, and roselle) cultivated in a two-year vegetable rotation experiment in Tamale, N-Ghana, West Africa. The main objective of my study was to monitor and model vegetable production and key soil fertility parameters thereby increasing our knowledge about how to foster food security in urban areas of West African cities in the wake of climate change effects on agriculture. The specific objectives of my Ph.D. study therefore were:

1. To validate the DNDC model against measured biomass accumulation, N uptake, and soil organic carbon (SOC) stocks data for different management practices,
2. To determine the uncertainty of DNDC-simulated vegetable biomass accumulation and SOC,
3. To identify the factors contributing most to the DNDC-simulated biomass accumulation and SOC uncertainty,
4. To understand the DNDC-simulated biomass accumulation and SOC dynamics at each management practices under future climate scenarios.

The results were hoped to contribute to predict the effects of sustainable management strategies on vegetable production in the study region.

## 1.6 Study area

Within the Urban Food$^{Plus}$ project, in the framework of which my study was conducted, experimental plots were established on a typical UPA production site in Tamale, Northern