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CHARACTERIZING NITROGEN LOSS AND GREENHOUSE GAS FLUX ACROSS AN INTENSIFICATION GRADIENT IN DIVERSIFIED VEGETABLE SYSTEMS

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DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Agriculture, Food and Environment
at the University of Kentucky

By

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ABSTRACT OF DISSERTATION

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The area of vegetable production is growing rapidly world-wide, as are efforts to increase production on existing lands in these labor- and input-intensive systems. Yet information on nutrient losses, greenhouse gas emissions, and input efficiency is lacking. Sustainable intensification of these systems requires knowing how to optimize nutrient and water inputs to improve yields while minimizing negative environmental consequences. This work characterizes soil nitrogen (N) dynamics, nitrate (NO_3^-) leaching, greenhouse gas emissions, and crop yield in five diversified vegetable systems spanning a gradient of intensification that is characterized by inputs, tillage and rotational fallow periods. The study systems included a low input organic system (LI), a mechanized, medium scale organic system (CSA), an organic movable high tunnel system (MOV), a conventional system (CONV) and an organic stationary high tunnel system (HT). In a three-year vegetable crop rotation with three systems (LI, HT and CONV), key N loss pathways varied by system; marked N_2O and CO_2 losses were observed in the LI system and NO_3^- leaching was greatest in the CONV system. Yield-scaled global warming potential (GWP) was greater in the LI system compared to HT and CONV, driven by greater greenhouse gas flux and lower yields in the LI system. The field data from CONV system were used to calibrate the Root Zone Water Quality Model version 2 (RZWQM2) and HT and LI vegetable systems were used to validate the model. RZWQM2 simulated soil NO_3^--N content reasonably well in crops grown on bare ground and open field (e.g. beet, collard, bean). Despite use of simultaneous heat and water (SHAW) option in RZWQM2 to incorporate the use of plastic mulch, we were not able to successfully simulate NO_3^--N data. The model simulated cumulative N_2O emissions from the CONV vegetable system reasonably well, while the model overestimated N_2O emissions in HT and LI systems.

KEYWORDS: Sustainable Intensification, Vegetables, Nitrogen Dynamics, N_2O and CO_2 Emissions, Organic Farming, RZWQM2

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11/20/2018

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DEDICATION

To *my Family*

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CHAPTER 1. **INTRODUCTION**

1.1 Sustainable intensification in vegetable systems

Meeting society's growing need for food while minimizing harm to the natural resource base upon which food production depends has been characterized as the collective "grand challenge" for agriculture (Foley et al., 2011). There is broad understanding that this challenge must be met largely on existing agricultural lands, and through managing natural resources more efficiently than they are currently (FAO, 2011; Tilman et al., 2011). Sustainable intensification invokes environmental goals such as optimizing the use of external inputs (Matson et al., 1997; Pretty 1997, 2008), increasing rates of internal nutrient recycling, decreasing nutrient loss (Gliessman, 2007), and closing yield gaps (Mueller et al., 2012; Pradhan et al., 2015; Wezel et al., 2015). To date, intensification efforts have focused largely on staple grain systems, but efforts to sustainably intensify fruit and vegetable production systems are particularly timely due to a suite of economic and environmental factors.

Similar to all sectors of crop and livestock production, global vegetable production has increased substantially in the past 50 years, with rising population growth and intensification of agricultural production systems (FAOSTAT, 2018). The five-fold increase observed in global vegetable yields since 1961 is a function of both increasing production area and increasing productivity on existing lands in production. This increase is largely due to conversion of lands from staple grain production to high-value specialty crops, particularly in small-holder farming areas experiencing declining grain prices (Weinberger and Lumpkin, 2007). The dual trends of diversification into vegetable production and intensifying production systems has been particularly strong in Asia, where highly intensive, protected agricultural production systems (e.g. plastic-covered greenhouse systems) have grown exponentially since 1980 (Norse et al., 2014). In the U.S., the number of vegetable farms has consistently increased, and although vegetable farms are typically smaller in production area, the total average value of produce sales per unit area is greater than average grain crop farms.

As such, production of vegetables and other high value specialty crops have created pathways for farmers to enter or remain in agriculture worldwide, with commensurate increase in global vegetable yields and area under specialty crop production. Weinberger and Lumpkin (2007) dubbed this trend “a silent horticultural revolution.” Certainly, there are significant benefits to increased production of nutritious, high value crops for farmers and the global food system. However, vegetable production systems span a gradient of production intensity, from very low external input, to arguably among the highest in water, nutrient, and agrochemical application. Such diversity in production practices does not lend to uniform management practices or consistent recommendations to sustainably intensify these expanding production systems.

Traditionally, vegetable production often involves repeated tillage, bare soil, and significant use of fertilizers, pesticides, and water. In the long-term, these practices can reduce productivity and profitability of a production system. As such, there is a growing need for production practices and management techniques that can increase or at least stabilize productivity and profitability while increasing the efficiency of inputs while minimizing environmental impacts (Wells et al., 2000).

Sustainable intensification has been proposed to increase crop yield with minimal loss of biodiversity, nutrients, soil, and greenhouse gas emissions. Further, the sustainability of the production systems should also be associated with temporal and spatial stability of yield as it relates to changes key soil properties (Schrama et al., 2018). Agricultural intensification and the resulting increases in yields have mainly been attributed to intensive irrigation practices, agrochemical inputs and intensive tillage. Due to problems of environmental degradation and perceived public health risk, there is growing interest in alternative farming systems including organic (no synthetic fertilizer and pesticide use) and low-input farming systems, which are being explored as ways to improve overall soil health, agricultural sustainability, and environmental quality (Poudel et al., 2002). However, more study of alternative production systems is needed to understand how input use and production practices in these systems affect environmental factors (Clark and Tilman, 2017). In the sections below, the literature regarding particular aspects of agricultural intensification are reviewed, including nutrient and irrigation use, use of fallow periods, and their effects on yield.

1.1.1 *Fertilizers*

Fertilizer use in vegetable crops is routine. For example, 98 percent of tomato production area was fertilized in the US in 2010 at the rate of 160 kg N ha^{-1} (USDA NASS, 2011). This is relatively high rate in comparison to other agricultural systems (e.g. small grains, forages, etc.) in the U.S. However, it pales in comparison to excessive rates applied in horticultural systems in input-intensive regions in the world. For example, N fertilizer use has been documented to be as high as 1000 kg ha^{-1} in covered vegetable areas of China (Zhu et al., 2005; Ju et al., 2007). Although increased N fertilization rates within a certain range have been shown to directly correlate to increases in crop yields in certain crop families (e.g. cole crops, Congreves et al., 2015), the effect of increased fertilizer rates may be negated by the greater influence of climate (temperature and precipitation) on crop yield. A recent study by Cui et al. (2018) demonstrated a 7.8-9.5 Mg ha^{-1} increase in grain yield with enhanced management practice, while at the same time reducing N fertilizer application (kg N per unit area) by 8.5-15.6 %. Further, a 23-35 % decrease in reactive N losses (N_2O emission, NH_3 volatilization, NO_3^- leaching) and 19-29 % reduction in greenhouse gas emission were achieved (Cui et al., 2018). The efficiency of fertilizer uptake by crop plants, particularly N fertilizers, and the environmental fate of fertilizer losses vary by the nature of the fertilizer. Mineral N fertilizer is commonly applied in mineral (inorganic) form as urea and solutions of urea and ammonium nitrate, with urea being most readily volatilized as ammonia (Battye et al., 1994). The use of "complete" fertilizer (containing N-P-K) is also common in vegetable production (Blatt and McRae, 1988), with the N component of these fertilizers generally consisting of urea and ammoniacal N.

In low-input and organic systems there is greater reliance on organic N sources, such as manures, composts, and byproducts of animal and plant processing industries (Gaskell and Smith, 2007). These are used in combination with crop rotations that often include annual and perennial cover crops or forages. Internal N cycling in these systems more closely mimic natural systems (Dawson et al., 2008). Compost, a source of plant nutrients, is also commonly used in organic and conventional vegetable production systems. In organic production systems, compost use is typically augmented with organic fertilizers during peak production and late season at periods of peak crop N demand (Gaskell and Smith, 2007). However, the uncertainty of nutrient content and availability in these biological amendments can lead to over or under-fertilization, build up and leaching of nutrients, or lack of synchrony between nutrient supply and plant uptake (Drinkwater and Snapp, 2007). It is necessary to understand how organic inputs and their management influence the temporal dynamics of soil inorganic N availability in the context of the farming system to balance the essential soil functions of providing crop fertility while reducing N losses to the environment (Norris and Congreves, 2018).

1.1.2 *Irrigation*

Vegetables are often irrigated. Surface and sub-surface drip irrigation has been increasingly used to irrigate vegetable crops around the world. Relative to other methods of irrigation such as flood, furrow or sprinkler irrigation systems, drip irrigation has greater water use efficiency than other water application methods (Darwish et al., 2003). Drip irrigation has been consistently shown to increase crop yield and water use efficiency in vegetable production systems (e.g. Singadhupe et al., 2003; Yaghi et al., 2013). Drip irrigation provides water directly to the plant root zone, and when coupled with practices that supply water in small quantity but frequent application, generally produces higher ratios of yield per unit area and yield per unit volume of water than typical surface or sprinkler systems (Darwish et al., 2003). In rain-protected agriculture systems, including high tunnels, all water is supplied via irrigation. Drip irrigation is the recommended irrigation method in these systems. Although all crop water is supplied via irrigation, the use of water is often reduced compared to irrigated open field production due to evapotranspiration loss (Fernandez et al., 2007). Some of the greatest growth in vegetable production systems has been in the use of such protected culture systems which include the use of greenhouses and polyethylene tunnels (e.g. high tunnels, hoop houses) in which vegetables are grown in-ground in a semi-controlled environment. Growth in horticultural crops produced in protected culture rose by 44% from 2009 to 2014 (USDA NASS, 2014). This pales in comparison to the adoption of protected agriculture in China, which accounts for 90% of global greenhouse structures (Chang et al., 2013) through rapid intensification of the agriculture sector since the 1980's (Norse and Ju, 2015). Yield in the protected agriculture can be twice as high as that over open culture (Chang et al., 2013). High tunnels are also commonly used to produce high value crops. With proper planning and management techniques, high tunnels can optimize yields, increase fruit quality, and provide season extension opportunities for high-value vegetable crops (O'Connell et al., 2012). Generally, high tunnels provide the opportunity for earlier crop planting and earlier harvest compared to open field conditions. O'Connell et al. (2012) reported similar yield in the first year and 33 % more tomato yield in the second year in high tunnels compared to open field conditions.

1.1.3 *Crop rotation and managed fallow periods*

Crop rotation is a key strategy to control environmental stresses and improve crop performance in conventional and organic vegetable systems. However, the need for biological inputs to replace synthetic inputs, and an emphasis on soil organic matter management in organic production drive organic growers to adopt major changes compared to their conventional counterparts. Higher cover crop diversity, frequent cover crop rotation, use of legume crops, and intercropping are more common in low input and organic farming. The increased complexity and diversity of crop rotations are likely to provide strong environmental benefits and enhanced ecosystem services (Barbieri et al., 2017), although more study of how the elements of rotation, tillage, cover crop use, and fertilizers/amendments interact is needed.

Cover crops, such as annual grasses or legumes, are often included between vegetable crops to prevent erosion, provide organic matter and nutrients for subsequent crops and minimize leaching (Thorup-Kristensen et al., 2003; Robacer et al., 2016). Although cover crops are not able to provide enough total N for a high N-demanding vegetable crop, or mineralize in synchrony with plant N demand (Drinkwater and Snapp, 2007) they may still increase the net economic returns (Muramoto et al., 2011) by trapping N otherwise lost. In temperate regions, cool season cover crops are most common, and are planted in the late summer or early fall, after harvest of warm season vegetables. They are terminated in the subsequent spring prior to planting. They may also be used in other temporal windows in the rotation vegetable systems. For example short-season summer cover crops provide weed suppression and nutrients for fall-planted vegetable crops (Creamer and Baldwin, 2000).

The interaction between cover crops (managed fallow) and the subsequent crop fertility regime affects the nature and magnitude of nutrient input losses in agroecosystems. Shelton et al. (2018) quantified N loss via leaching, NH_3 volatilization, N_2O emissions, and N retention in plant and soil pools of corn agroecosystems in Kentucky. Cover crop species and fertilization schemes affect N loss and availability in corn systems and dominant N loss pathways varied by season. NO_3^--N leaching was the primary loss pathway during the cover crop growing season, especially in treatments using leguminous monocultures (hairy vetch only), while N loss via N_2O-N and NH_3-N emissions was dominant during the corn growing season. Nitrogen contribution of legume-grass cover crop mixture into fertilizer application rates may reduce N loss without sacrificing yield (Han et al., 2017).

Pasture-crop rotations, which utilize a multiple year period of grazed pasture fallow followed by crop production, are popular in Argentina, Brazil, and Uruguay (Garcia-Prechac et al., 2004) and have significant effects on soil properties. Soil aggregate stability increases quickly by including pasture in the rotation with crops, due to the combination of a) the absence of tillage operation during the pasture cycle; (b) the dense and fibrous grass root systems that promote aggregation (Haynes et al., 1991). The combined use of cropping and pasture in rotation results in reduced soil erosion compared to continuous cropping (Garcia-Prechac et al., 2004). Agricultural soils benefit from the re-introducing perennial grasses and legumes into the crop field by gaining organic matter and strengthening their capacity for long-term productivity and environmental resiliency (Franzluebers et al., 2014). Crop-pasture rotation systems, as reported by Franzluebbers et al. (2014) exist in the US in some integrated livestock and crop production systems. Perennial forages in pasture add organic matter to soil, provide soil C sequestration, improve nutrient cycling, and support biological diversity.

1.1.4 *Effect of intensification on yields*

Intensification packages such as drip irrigation and plastic mulch have been generally found to increase crop yield while increasing water use efficiency. Singadhupe et al. (2003) reported 3.7-12.5% increases in tomato fruit yield, 31-37% water savings, and 8-11% increase in N uptake by plants by using drip irrigation system in tomato crops. Similar results have been found in potato (Zhang et al., 2017), and a suite of other crops. Intensification packages in vegetable systems can involve significant nutrient, water, plastic, and pesticide inputs. The net effects of these efforts have increased yields and decreased labor, improved nutrient and water use (Steffaneli et al., 2010), and reduced N losses to the environment, even when viewed relative to other intensified production systems, such as row crop agriculture systems (Goulding, 2000). Yield improvements through careful and efficient management of crop nutrients and water, precision farming, less intensive tillage could reduce future greenhouse gas emissions rather than clearing the lands for crop production (Burney et al., 2010).

The effects of intensification on crop yields has also been framed in the context of farm management philosophies or certifications. Specifically, organic and conventional systems have been compared as proxies for low and high intensity systems, respectively (e.g. Seufert et al., 2012). Examining the effect of these systems-level comparisons has been the subject of several recent meta-analyses of yield and ecosystems services in these systems. Relative yield stability (i.e., yield stability per unit yield produced) was higher in conventionally managed fields by 15% compared to organically managed fields (Knapp and van der Heijden, 2018). However, compared to conventional agriculture, organic agriculture generally had a positive effect on a range of environmental benefits, including above and belowground biodiversity, soil carbon stocks and soil quality. Similarly, de Ponti et al. (2012) reported 20% lower yield in organic systems compared to conventional systems. However, the difference in crop yield between organic systems and conventional systems were highly site specific; such as, in rain-fed legumes and perennials on weakly acidic to weakly alkaline soil, the yield difference was below 5 % (Seufert et al., 2012; Kniss et al., 2016). Kniss et al. (2016) also concluded that organic to conventional yield ratios vary widely among crops. In an analysis of organic yield data collected from over 10,000 organic farmers representing nearly 800,000 hectares of organic farmland in the United States, their results demonstrated that the organic yield average for all crops was 80% of conventional yield. Yield of organically produced cereal crops maize and barley was 65% and 76% of conventional yield, respectively. Organic squash, snap bean, sweet maize, and peach yields were not statistically different from conventional yields. Despite consistency in the literature indicating that crop yields in organic production are generally lower than conventional production, a meta-analysis of a global dataset by Crowder and Reganold (2015) suggested the price premiums for organic products may offset the lower yield with respect to net economic returns.

Recent meta-analyses (Garbach et al., 2016; Ponisio et al., 2015) identified organic systems as exemplars of systems that frequently experience significant gaps in actualized yield relative to potential yield (yield gaps). In these systems, relatively minor increases in inputs and subtle modifications of management practices can offer the potential of substantial yield increases, if these practices correct critically limiting production factors (Foley et al., 2011). Such yield gaps are most pronounced in low-input organic systems, attributed to the relatively low N concentration in biologically-based amendments. However, correcting yield gaps in organic systems in ways that minimize environmental impact may not strictly be a function of increasing inputs. Organic vegetable production may include very intensive practices, such as year-round cropping with lack of fallow periods, heavy irrigation and fertilization, and the use of protected agriculture systems such as plastic covered greenhouses or high tunnels. The simplification of these systems as binary components masks the diverse management practices and input intensity within any given system, be they organic or conventional.

Vegetable production systems are highly diversified, and the soil plant water balance, nutrient uptake and variability between vegetable crops within a system and among the production systems have been poorly addressed (Gary et al., 1998). The mechanisms and interaction of biotic and abiotic factors driving nutrient losses in vegetable production systems have yet to be fully elucidated. With this general framing of sustainable intensification in vegetable production systems in mind, this dissertation focuses on the N dynamics related to intensification in diversified vegetable production systems. In the sections below, the literature on N cycling in these systems from empirical studies and simulation modeling literature is reviewed.

1.2 Nitrogen dynamics in vegetable cropping systems

1.2.1 ***N cycling and retention***

The N cycle in agroecosystems includes assimilation, mineralization, immobilization, nitrification, denitrification, ammonia volatilization, nitrate leaching, runoff, and erosion processes (Neeteson and Carton, 2001). The N fertilizer applied to soil is lost through volatilization, denitrification, nitrification (Galloway et al., 2004). Although this work has strong focus on N cycling and fate, these processes are stoichiometrically linked to carbon (C) processes via microbially-mediated activities. As such, a brief discussion of the effect of N fertilizers on soil C stocks is warranted, particularly as it relates to sustaining soil fertility.

Excess synthetic fertilizer application in some intensive vegetable production systems has been linked to declines in soil inorganic carbon levels through soil acidification and reduction of calcium carbonates (Barak et al., 1997, Ju et al., 2007). Reduction in soil organic carbon has been hypothesized to occur via microbial priming by labile inputs leading to mineralization of old native organic carbon (McCarty and Meisinger, 1997). The soil organic matter pools and the C:N ratio in the biological amendment (such as compost and manures) influence the soil C dynamics and the net N mineralization. The long-term application of N fertilizer increases the slow pool proportion of soil organic carbon but decreases the passive pool proportion (Cong et al., 2014). Irrigation reduces carbon storage through soil respiration, but it may increase the soil C storage by increased crop biomass if incorporated in to soil (Zhou et al., 2016). Increases in soil C content have been attributed to manure (Chang et al., 2013), however these increases have often been observed in systems where manures have been applied at rates much higher than recommended (Chang et al., 2013; Norse and Ju, 2015), leading to potential manure associated-nutrient losses to the environment. In addition to the nature of the inputs, soil management practices such as crop rotation and tillage along with environmental factors such as temperature and irrigation affect the soil C and N mineralization and immobilization processes (Neeteson and Carton, 2001). Intensively cultivated vegetable crop production is characterized by high N-fertilizer application rates (Shennan et al., 1992). Sub-surface drip irrigation, inclusion of cover crops, less frequent and less intensive tillage, and crop rotation might be options to reduce N loss from the soil under vegetable production.

1.2.2 *N leaching in vegetable cropping system*

Crop lands have been shown to be key sources of N inputs to ground water. For example, in California, approximately 90 % of N flow to the ground water was linked to N leaching (Liptzin and Dahlgren, 2016). Nitrogen fertilization above 150-180 kg N ha^{-1} $year^{-1}$ typically increases leaching rates (Goulding, 2000). This rate is on the upper end of commercial vegetable production recommendations for sustainable nutrient management, but is not uncommon for many long-season crops (ID-36) (UK Cooperative Extension

Service, 2014). Globally, NO_3^- leaching has been demonstrated in areas of intensive vegetable production (Neeteson and Carton, 2001). For example, NO_3^--N concentrations leached from 1.2 m depth from fertilized vegetable fields in Oregon exceeded the EPA's standard of 10 mg L^{-1} for drinking water NO_3^--N (Feaga et al., 2009). Generally, N losses are pronounced in irrigated intensive vegetable production, as dissolved inorganic N moves with free water through the soil profile. Improved irrigation systems such as drip irrigation help to improve N use efficiency (Darwish et al., 2003). For example, Singadhupe et al. (2003) reported 20- 40% of reduction in N loss in drip irrigation compared to furrow irrigation in tomato. Protected agriculture systems have also been touted for their ability to prevent NO_3^- leaching compared to open field vegetable production systems (Xu et al., 2016). However, much of this depends on irrigation and fertility management. Across systems, adaptive nutrient management (Zebarth et al., 1991), decreasing total fertilizer N, splitting N applications, and irrigation management preventing irrigation water from adding to existing soil water below the rooting zone have been suggested as strategies to reduce NO_3^- loading from irrigated vegetable production systems (Kraft and Stiles, 2003).

1.2.3 *Trace gas emissions*

Approximately 20 % of the global anthropogenic greenhouse gas emissions and 60 % of total nitrous oxide (N_2O) emission is attributed to agricultural activities (Lokupitiya and Paustian, 2006). Nitrous oxide has a global warming potential approximately 298 times that of carbon dioxide (CO_2) (Forster et al., 2007), and exponential increases in N_2O emissions have been reported with increasing soil mineral N content (e.g. Grassini and Cassman, 2012; Cui et al., 2013).

Intensive vegetable production systems may have high soil mineral N values, often attributed to relatively high N recommendation rates. Simply reducing N fertilization may offer opportunities to reduce N_2O. Deng et al. (2013) reported reducing N fertilizer by 25%, resulting in N_2O emission reduction of 31% without compromising yields. However, in addition to soil NO_3^- content, soil water content and soil temperature, and their interaction, are also major factors affecting N_2O emissions. Wet-dry regimes, also driving N_2O emissions, may be considerably different in these frequently irrigated systems than in cereal crops production system, which are typically unirrigated.

N_2O emissions in highly fertilized vegetable production systems are highest early in the season, immediately after the initial transplant, irrigation, and fertilization events. This effect is more pronounced when the soil is dry prior to the transplant and wetting event (Kusa et al., 2002; Sehy et al., 2003; He et al., 2007). The initial irrigation event upon transplanting may increase organic matter decomposition and N availability and accelerate soil nitrification and denitrification providing aerobic and anaerobic conditions for N_2O emission (Davidson et al., 1993; Sehy et al., 2003; He et al., 2007). Further, excessive and frequent irrigation in intensive systems may increase N loss. Dobbie and Smith (2003) found that the highest N_2O emissions occurred when soil water-filled pore space (WFPS) was greater than 60% in arable cropping systems. Similarly, Schaufler et al. (2010) reported a non-linear increase of N_2O and CO_2 emissions with increasing temperature, and positive correlation with soil water content. Higher temperature and lower soil water content may lead to lower N_2O emissions from N-fertilized agricultural soils (Xu et al., 2016). The total N_2O emissions from urea treated vegetable soil in the greenhouse were significantly lower than those from the open field soil. Further, N_2O emissions may be reduced to some extent by irrigation management. Tian et al. (2017) reported a 13.8 % reduction in N_2O emission with drip irrigation, and 7.7 % reduction with drip fertigation compared to flood irrigation using maize as a model crop.

Typically, greenhouse gas emission research in agriculture is not focused on vegetable cropping systems; especially linking management practices to greenhouse gas emissions. It is necessary to understand the contribution of vegetable production system to global greenhouse gas inventories, and to develop strategies to mitigate emissions in vegetable systems (Norris and Congreves, 2018). Further, the processes controlling CO_2 and N_2O emissions are highly influenced by spatially and temporally varying conditions such as temperature, soil water, and soil physical, chemical and biological properties, and these variations are unlikely to be adequately addressed on national level aggregate data (Lokupitiya, and Paustian, 2006). As such, site-specific data are needed to better understand these processes and recommendations for sustainable management.

1.3 Simulation modelling in vegetable production systems

Frequent field measurement to understand soil N and C processes over the long term is laborious and costly (Jiang et al., 2019). Process-based models allow to simulate soil N and C dynamics (Ma et al., 2012), and predict future N_2O emissions (Fang et al., 2015) and crop production (Uzoma et al., 2015; Jiang et al., 2019). Many process-based models have been developed to understand C and N processes in agro-ecosystems, although these have largely been designed for grain crop and forage systems. The process-based model helps to quantify N_2O emissions and N leaching from agricultural production systems and thereby providing important information for optimizing fertilizer use for producing crops (Deng et al., 2013). ExpertN (Engel and Priesack,1993) and VegSyst (Gallardo et al., 2011) are simulation models for N recommendation and N uptake simulation in vegetable systems, but these models lack the ability to simulate greenhouse gas emission and do not have widespread use. Many agro-ecosystem models are available and used to simulate soil water, soil N dynamics, greenhouse gas emissions, and crop yield. DNDC (Li et al., 1992), APSIM (McCown et al., 1996), Ecosys (Grant and Pattey,1999), DAYCENT (Parton et al., 1998; Del Grosso et al., 2000), RZWQM (Ahuja et al., 2000), FASSET (Olesen et al., 2002), NOE (Henault et al., 2005), and WNMM (Li et al., 2007) are the major simulation models used in agro-ecosystems.

RZWQM2 is an agro-ecosystem model, which simulates soil water content, soil temperature, soil N, N leaching, and crop yield (Ahuja et al., 2000). The agricultural management input options are crop and crop cultivar selection, planting date, manure and fertilizer application, tillage, irrigation, and pesticide application (Ma et al., 2011). Brooks–Corey equations are used to relate volumetric soil water content (θ) and soil suction head (h) (Ma et al., 2012). The potential evaporation and crop transpiration are described by the Shuttle-Wallace equation. Fang et al. (2014) incorporated the Simultaneous Heat and Water (SHAW) (Flerchinger and Saxton, 1989) model into RZWQM (Ahuja et al., 2000), and used it to simulate surface energy balance and canopy temperature along with crop growth and production in different climate and cropping seasons. More importantly, this model provides opportunity to simulate soil and plant processes under plastic culture (Fang et al., 2014), which is a common practice in vegetable system. RZWQM2 provides soil water content, root distribution, soil evaporation, soil transpiration, leaf area index, and plant height at each time step to

SHAW and then SHAW provides soil ice content, updated soil water content due to ice and freezing, and soil temperature to RZWQM (Fang et al., 2014). The RZWQM model has been used widely to simulate NO_3^- leaching (Yu et al., 2006; Gillette et al., 2018; Jiang et al., 2019). RZWQM has not been widely used in vegetable production systems, save a notable exception by Cameira et al. (2014), who used the model to study water and N budgets for organically and conventionally managed urban vegetable gardens. However, RZWQM2 has been used successfully to simulate N processes in number of other systems. Fang et al. (2015) combined the NOE model and DAYCENT model and incorporated them into RZWQM to simulate N_2O emissions, allowing other researchers to simulate N_2O emission (Gillette et al., 2017, 2018; Jiang et al., 2019). Wang et al. (2017) reported very negligible effect of tillage intensity on RZWQM2 simulated N_2O emission, which is in contradiction to the other field studies which reported increased N_2O emission with conventional tillage compared to no tillage (Sainju et al., 2012; Zurovec et al., 2017). Gillette et al. (2017) used the model to simulate crop production and N_2O emissions from conventional till and no-till at different N fertilization rates. Gillette et al. (2018) also used RZWQM to test N_2O emissions in a corn-soybean system with a winter rye cover crop. Similarly, Jiang et al. (2019) used RZWQM2 to study the effect of inorganic nitrogen (N) fertilization rates and timing, and water table management practices on N_2O and CO_2 emissions. Jiang et al. (2019) used RZWQM2 to simulate N_2O emission from a corn field and reported lower N_2O emission with split application of N fertilizer. RZWQM has been used to simulate NO_3^- leaching from soil in corn-soybean rotations (Gillette et al., 2018), and in wheat-maize double cropping system (Yu et al., 2006). Given the utility of RZWQM2 and the recent modifications to allow for simulating soil water and temperature in plastic mulches, additional modelling of vegetable systems using this newly released model version are particularly timely.

The mechanisms and interactions of biotic and abiotic factors driving N leaching, and N_2O emissions in vegetable production systems, have yet to be fully elucidated. The quantification of the N_2O and CO_2 emissions through field measurement or simulation modelling, and understanding the factors associated in a wide variety of production systems are necessary to formulate strategies that help mitigating those losses. Therefore, in this dissertation, my research objectives were to 1) relate crop yield to global warming potential (GWP) caused by N_2O and CO_2 losses in vegetable production systems 2) to simulate soil water, N_2O emission, soil NO_3^-N processes and crop yield in these systems; 3) to characterize inputs, crop N uptake, and leaching to compare vegetable production systems.

CHAPTER 2. **NITROGEN LOSS AND GREENHOUSE GAS FLUX ACROSS AN INTENSIFICATION GRADIENT IN DIVERSIFIED VEGETABLE ROTATIONS**

2.1 Introduction

Demand for increased food production is driving agricultural input intensification around the world (Tilman et al., 2011). Improved understanding of the interrelations between potential yield gains and environmental trade-offs would enable identification of areas where input-driven intensification could drive higher yields, while minimizing environmental impacts (Liu et al., 2018). To date, research on agricultural intensification has focused largely on staple grain systems. However, efforts to sustainably intensify fruit and vegetable production systems are particularly timely due to the rapid growth of vegetable production area, which has increased from 20.5 million ha in 1964 to 55.2 m ha in 2014 (FAOSTAT, 2018). In the U.S., the number of vegetable farms has consistently increased, and although vegetable farms are typically smaller in production area, total average value of produce sales per unit area is greater than average grain crop farms.

To date, agricultural intensification work in vegetable production systems has focused on use of irrigation, fertilizer, pest management practices, and decreasing fallow periods (Steffaneli et al. 2010). Fertilizer input rates in vegetable production systems are often greater than in other plant production systems. For example, in Salinas, California, a lettuce-broccoli rotation receives 300 to 550 kg N ha^{-1} yr^{-1} (Rosenstock and Tomich, 2016), and annual N fertilization may be as high as 1000 kg N ha^{-1} in covered vegetable areas of China (Ju et al., 2007; Zhu et al., 2005). Although increased N fertilization rates have been shown to directly correlate to increase in crop yields in certain crop families (e.g. cole crops), fertilizer N inputs above 150-180 kg N ha^{-1} $year^{-1}$ typically increase leaching rates (Goulding, 2000), and extensive NO_3^- leaching has been demonstrated in areas of widespread vegetable production. Adaptive nutrient management (Zebarth et al., 1991), decreasing total fertilizer N, splitting N applications, and irrigation management preventing irrigation water from adding to existing soil water below the rooting zone have been suggested as strategies to reduce NO_3^- loading from irrigated vegetable production systems (Kraft and Stiles, 2003).

In addition to NO_3^- leaching, work in agronomic systems has linked exponential increase in N_2O emissions to increased soil available N contents, and peaked after soil management activities, irrigation after fertilization events, and particularly N fertilizer inputs exceed crop N demand (Millar et al., 2018). Although vegetable systems may contain high levels of mineral N, wet-dry regimes may vary considerably in these frequently irrigated systems from cereal crops production system. As such, patterns observed in grain crop systems may not be directly applied to vegetable production systems.

Some of the greatest growth in vegetable production systems has been in the use of protected culture, including the use of greenhouses and polyethylene tunnels (e.g. high tunnels, hoop houses). In the U.S., production in protected agriculture systems increased by 44% from 2009 to 2014 (USDA NASS, 2014). In parts of East Asia and Europe, protected agriculture systems are common place, with the majority of vegetables, and to some extent fruits, produced under protective cover. Although yields may be increased, and foliar disease decrease due to lack of soil splash in these controlled environments, protected culture systems are prone to soil quality issues due to high input use and lack of flushing rains. For example, in protected culture areas of China, extremely high fertilizer use has been shown to cause degradation of soil and water quality, soil acidification, and soil salinization primarily due to NO_3^- accumulation (Ju et al., 2007, Guo et al., 2010) and low nitrogen use efficiency (Zhang et al., 2015).

Although some vegetable systems may be prone to input levels that may have undesirable environmental effects, vegetable production systems are diverse and variable in terms of production practices. There are many low input vegetable systems around the world in which intensification efforts may be sustainable and timely. For example, recent meta-analyses have found that yield gaps are most pronounced in low-input organic systems, particularly in systems with inadequate nutrient supply to the system, attributed to the relatively low nitrogen concentration in biologically-based amendments. Targeted and additional inputs may increase yields in the low input systems without substantive off-farm nutrient losses. Relatively minor increases in inputs and subtle modifications of management practices can offer the potential of substantial yield increases, if these practices correct critically limiting production factors (Foley et al., 2011). However, there are a number of factors affecting input use efficiency, yield increases, and soil and water quality impacts, and the mechanisms and interaction of biotic and abiotic factors driving losses in vegetable production systems have yet to be fully elucidated. Further, the interactive effect (and restrictive effect) of soil N, soil temperature, and soil moisture content on N_2O emissions varies not only between climates, but within a single climate, between agricultural ecosystems with different management practices (Xu et al., 2016). The objectives of this study were to 1) characterize soil mineral N pools and NO_3^- leaching, 2) quantify CO_2 and N_2O fluxes and 3) relate crop yield to global warming potential (GWP) caused by N_2O and CO_2 losses in three vegetable production systems.

2.2 Materials and Methods

2.2.1 *Research sites*

This three-year rotational study was initiated in early spring, 2014. Two sites in central Kentucky with Maury silt loam soil (a fine, mixed, active, mesic Typic Paleudalfs) were utilized, 1) The University of Kentucky Horticulture Research Farm (UK HRF) in Lexington, KY (37°58'29"N, 84°32'05"W), and 2) a local organic farm in Scott County, Kentucky (38°13'20"N, 84°30'38"W). Both farms are in the central Bluegrass region of Kentucky, with similar rainfall, temperature, and soil type (annual precipitation of 1209, 1475 and 1011 mm; average air temperature of 12 ºC, 13.3 ºC and 14.2 ºC in 2014, 2015 and 2016, respectively). Each system contained six replicate plots measuring 9 m x 1.5m. Initial soil conditions for each system are listed in Table 2.1.

2.2.2 *Cropping systems*

The three vegetable production systems were selected to represent a gradient of intensification, as characterized by duration of fallow periods, tillage intensity, and irrigation and nutrient inputs (Table 2.2). The Low Input Organic system (LI) consisted of an 8-year rotation beginning with five-year mixed grass/legume pasture that is rotationally grazed or cut for hay for grass-finished beef and calf production. After the five-year fallow period, the pasture was broken with deep inversion plowing, disking and surface rototilling to transition fields into a three-year rotation of annual crops. No supplemental fertilizer was added, and drip irrigation was used exclusively for sweet peppers (*Capsicum annum* L., ‘Aristotle’) produced using a plasticulture system. Table beets (*Beta vulgaris* L., ‘Red Ace’), collards (*Brassica oleracea* var medullosa L., ‘Champion’) and beans (*Phaseolus vulgaris* L., ‘Provider’) produced on bare ground received only natural rainfall, and no supplemental irrigation. For the past 15 years, the farm has grown diversified organic vegetables in the annual crop portion of the rotation, after transitioning from two generations of conventional tobacco production in a similar rotation. This experiment follows the three-year vegetable crop rotation.

The two more intensive systems (Conventional and High Tunnel) are representative of common commercial vegetable production systems, and were located at the UK HRF. The Conventional system (CONV) consisted of a winter wheat (*Triticum aestivum*) cover crop terminated with tillage in early spring (Table 2.2) followed by seasonal annual vegetable production (Table 2.3). Inputs included mineral fertilizers applied pre-plant and in-season, split-application via fertigation when required for the crop as per commercial vegetable production recommendations for the study region (UK Cooperative Extension Service, 2014). Crops were scouted weekly for insects and pathogens, and treated with prophylactic fungicides (sweet pepper and table beets) and insecticides (collards only) according to recommendations. All crops were drip irrigated in every 2-3 days interval in summer and 3-4 days interval in winter season depending on rainfall. All crops were drip irrigated.

The organic high tunnel system (HT) consisted of three, replicated unheated 9.1 m x 22 m steel structures with polyethylene film coating. As is typical for management of these structures, crops are grown in soil without supplemental heat or light, and are only passively ventilated through manual opening of doors and side curtains. High tunnel systems are "season extending" technologies used in specialty crop production, allowing for lengthening the growing season of warm-season crops by approximately one month each in the spring and fall, and allowing for cool-season vegetable production throughout the winter in the study region. Also typical to these systems, cover crops are not used, as these intensive production systems often are used for production of high value crops. The use of managed fallows not considered economically efficient unless they address a production issue, such as pathogen or pest management. Crop residues were removed from the system to minimize pathogen presence. Pre-plant fertilizer consisted of composted horse manure (C:N ratio 25:1) and granular organic fertilizer (Harmony 5-4-3, BioSystems, LLC, Blacksburg, VA) were incorporated into the soil before crop planting at a rate of 67 kg N ha^{-1}, and 45 kg N ha^{-1} respectively. Supplemental fertigation with liquid organic fertilizer (Brown's Fish Fertilizer 2-3-1, C.R. Brown Enterprises, Andrews, NC) was applied in-season only to the sweet pepper crop, at flowing and heavy fruit set (twice total) at the recommended rate constituting an additional 28 kg N ha^{-1} at each fertigation event. Water inputs in the HT system are via irrigation, as the plastic cover over the structure excluded all rainfall. All crops were drip irrigated in every 2-3 days interval in summer and 3-4 days interval in winter season. The crop rotation and timing of management activities are detailed in Table 2.3.

2.2.3 *Soil sampling*

Soils were sampled monthly at 0-15, 15-30, and 30-50 cm depths for mineral N (NH_4^+-N and NO_3^--N). On each sampling date, three cores were taken per plot at each depth, homogenized, and bulked for a single analysis per plot. Fresh soil samples were kept refrigerated (~ 4.4º C) until processing, passed through a 2 mm sieve and processed within 24 h of sampling. Soil mineral N was extracted from a 5 g subsample of fresh soil in 1M KCl (Rice et al., 1984) and analyzed by a microplate spectrophotometer (Epoch Model, BioTek Instruments, Inc., Winooski, VT), after NO_3^- was reduced using a cadmium reduction device (ParaTechs Co., Lexington, KY) (Crutchfield and Grove, 2011).

Ion exchange resin (IER) methods were used to assess net N mineralization via IER resin bags placed at the mid-depth point of the 0-15 cm and 15-30 cm depths (7.5 cm and 22.5 cm depths, respectively). NO_3^- leaching was assessed using IER lysimeters placed below the plant rooting zone (50 cm depths). A mixed bed resin was used in both resin bags and lysimeters (Purolite MB400, Bala Cynwyd, PA). IER bags were made from 1000 mm^2 knit swimwear fabric, filled with 1 teaspoon (5 ml size) of resin and sealed with a ~0.10 m-long cable tie. Resin bags were replaced monthly, at the time of soil sampling. After recovery, resin bags were rinsed of loose soil using DI water, resin mineral N extracted in 2M KCl, and analyzed by colorimetric analysis, as described above. IER lysimeters were constructed from PVC tubing after the method of Susfalk and Johnson (2002), using 2 teaspoonfuls of resin per lysimeter. Lysimeters were inserted carefully under soil that had not been disturbed through previous excavation by digging a horizontal installation trench approximately 50 cm perpendicular to the main vertical excavation trench. IER lysimeters were replaced every three months, and once recovered, disassembled, with resin mineral N extracted using the 2M KCl method described above.

Trace gas fluxes (N_2O, NH_3, CO_2, and CH_4) were measured weekly in 2014 and bi-weekly in 2015 and 2016 (excluding periods when the ground was frozen) using a FTIR-based field gas analyzer (Gasmet DX4040, Gasmet Technologies Oy, Helsinki, Finland). The static chamber method (Parkin and Venterea, 2010) was used, with rectangular stainless-steel chambers (16.35 cm x 52.70 cm x 15.24 cm) installed in each plot. Chambers were installed after planting of initial crops in the rotations, and kept in the soil for the duration of the three-year study, except during tillage operations. When pans were removed periodically, chambers were replaced at least 24 hours prior to sampling events. At the time of gas sampling, the gas analyzer was connected to the field chamber by affixing a matching rectangular gas pan connected to the analyzer, clamped tightly in place, and measured continuously for ten minutes. The gas fluxes were calculated by using the following equation (Iqbal et al., 2013):

$$(F) = \frac{\Delta C}{\Delta t}\,\frac{V}{A}\,\rho$$

Where F is the gas flux rate (mg m^{-2} h^{-1}), ΔC/Δt indicates the increase/decrease of gas concentration (C) in the chamber over time (t), V is the chamber volume (m^3), A is the chamber cross-sectional surface area (m^2), ρ denotes density of gas (kg m^{-3}) at 25°C. Cumulative gas fluxes were estimated by interpolating trapezoidal integration of flux versus time between sampling dates and calculating the area under the curve (Venterea et al., 2011).

Soil water potential was measured using granular matrix sensors (After December 2014) (Watermark, Irrometer Co., Riverside, CA) installed at three depths in the soil profile (10, 30, and 50 cm depths), with one sensor per depth and per plot. Watermark sensor data was transmitted continuously wirelessly to a data logger (Watermark Monitor 900M, Irrometer, Co., Riverside, CA), with readings taken each time water potential changed. Additional hand-made Tensiometers were constructed of 21.5 mm diameter plastic pipe with 22.2 mm diameter ceramic porous cups at lower end and installed at 10 cm, 30 cm, 50 cm and 70 cm depth in each plot. Tensiometer readings were taken weekly using a digital Tensimeter (Soil Measurement System, Tucson, AZ). The soil water potential data from watermark sensors and Tensiometers were converted to volumetric soil water content (m^3 m^{-3}) using the van Genuchten (1980) equation:

$$\theta = \theta r + \frac{\theta s - \theta r}{[1 + |\alpha h|^n]^m}$$

where θr = 0.067, θs = 0.45, α =0.02, n = 1.41, m = 1-1/n for silty loam for all soil depths (van Genuchten et al., 1991).

2.2.4 *Plant sampling*

Fresh vegetable yields were measured from the entire plot area from each plot. Sweet pepper fruit, collard leaves and beans were harvested at multiple times as the harvestable portion reached marketable stage, and table beets were harvested once, as roots reached marketable size. Plant biomass samples were collected from 2, 0.25 m^2 samples per plot at the end of the growing season, dried at 60^0 C until a constant mass was achieved. Dried samples were homogenized on a Wiley Mill and a subsample ground on a jar mill (U.S. Stoneware, East Palestine, OH). Crop plant samples were analyzed for C and N content via flame combustion (Flash EA 1112 elemental analyzer, CE Elantech Inc., Lakewood, CA).

2.2.5 *Statistical analysis*

Shapiro-Wilk's W-test was used to test for normality of data. CO_2 and N_2O flux data were log-transformed to meet normality conditions. Non-parametric Spearman rank correlations were conducted using JMP Pro 13.2 (SAS Institute, Cary, NC) for CO_2, N_2O fluxes with soil temperature and soil mineral N content.

2.3 Results

2.3.1 *Time series data*

2.3.1.1 Low input system

Soil mineral N (NH_4^+-N and NO_3^--N) and NO_3^- -N leaching rates (expressed by IER lysimeter data), were consistently greatest in the LI system at the start of the rotation, however Figure 2.1 shows that soil NH_4^+-N peaked at the end of the rotation. After this initial period of high soil mineral N content, values were low compared to the other systems and peaked seasonally at each sampling depth in late spring of each year, with annual peak values declining throughout the rotation. The highest soil mineral N contents at the surface layer (0-15 cm) were 64 kg ha^{-1} in May 2014, 55 kg ha^{-1} in April 2015, and 50 kg ha^{-1} in June 2016 (see Figure 2.1 for additional depths). Cumulative mineral N trapped in resin bags summed for the entirety of the rotation from 2014 to 2016 in LI system was 3274 μg g^{-1} resin for the 7.5 cm depth and 3492 μg g^{-1} for the 22.5 cm depth. Cumulative NO_3^- collected from lysimeters over the entire cropping period from 2014 to 2016 was 1826 μg g^{-1}. It is of note that NH_4^+-N content was greater than ~40 % of total mineral N during the beans portion of the rotation (2016), but was typically less than 12 % during the remainder of the rotation, excepting for seasonal peaks in the early spring. In both soil and resin bag samples, for most of the sampling dates throughout the rotation (Figure 2.1), soil and resin N values were lower in the LI system compared to the other systems, which received external fertilizer. Complementary IER data indicate the mineralization rates were low at these times as well, with monthly IER values < 200 μg g^{-1} resin. Soil volumetric water content was consistently driest in the sparsely irrigated LI system among the three systems.

CO_2 fluxes were seasonally-dependent and significantly correlated to soil temperature (Table 2.4). The greatest CO_2 flux rates were observed in mid-summer each year, on 2 July 2014 (950 mg m^{-2} hr^{-1}), 22 June 2015 (732 mg m^{-2} hr^{-1}) and 10 August 2016 (732 mg m^{-2} hr^{-1}) (Figure 2.1). CO_2 fluxes were negligible from November to early April each year. Similarly, N_2O fluxes were seasonally-influenced, with peak rates typically occurring after rainfall or irrigation events, early in summer as soils warmed and after tillage events. Peak daily N_2O fluxes occurred on 11 June 2014 (522 μg N m^{-2} hr^{-1}), 29 June 2015 (393 μg N m^{-2} hr^{-1}), and 8 June 2016 (58 μg N m^{-2} hr^{-1}). N_2O emissions were not strongly correlated with soil mineral N, soil temperature, or soil water content values. As with soil mineral N content, fluxes and peak fluxes declined over the three-year rotation.

2.3.1.2 Conventional system

Soil mineral N content in the CONV system was seasonally-dependent, with peak values at the beginning of the cropping season (Figure 2.2). Peak values declined over the duration of the rotation, concomitant with decreasing quantities of fertilizer applied for the crops in the rotation. The greatest soil mineral N contents were 170 kg ha^{-1} in May 2014, 51 kg ha^{-1} in June 2015, and 26 kg ha^{-1} in June 2016. Cumulative mineral N collected in resin bags from 2014 to 2016 was 6539 μg g^{-1} at 7.5 cm and 8975 μg g^{-1} at 22.5 cm depths. Cumulative NO_3^--N collected in lysimeters was 2326 μg g^{-1}. As in the LI system, the relative percentage of NH_4^+-N in total mineral N (NH_4^+-N + NO_3^--N) was greater than 30% of the overall mineral N composition in soil and resin bag samples at the majority of the sampling dates throughout the rotation (Figure 2.2).

Soil moisture content in the CONV system exhibited some drying at the 10-cm-depth, but was generally consistently near saturation for the silt loam soil type [Saturation = 0.45 $cm^3 cm^{-3}$ (van Genuchten et al., 1991)]. This relatively high soil water content is reflective of precipitation and regular irrigation inputs consistent with commercial vegetable production recommendations (UK Cooperative Extension Service, 2014).

CO_2 fluxes in the CONV system were seasonally-dependent, and were correlated to soil temperature (Table 2.4) although the correlation was weaker than in the other two systems. The greatest CO_2 fluxes were observed in mid-summer each year, with the greatest fluxes on 23rd June 2014 (428 mg m^{-2} hr^{-1}), 6 July 2015 (511 mg m^{-2} hr^{-1}) and 10 August 2016 (478 mg m^{-2} hr^{-1}). CO_2 fluxes were negligible from November to early April in 2014, and low but with occasional fluxes during the same period in 2015, likely due to warmer soil temperatures and more moderate temperatures in winter of 2015. N_2O fluxes were seasonally-influenced, with peak rates typically occurring early in the cropping season, coinciding with pre-plant tillage and fertilizer incorporation. N_2O fluxes in the CONV system were the lowest of the three systems, with daily peak values occurring on 31 May 2014 (65 µg m^{-2} hr^{-1}), 22 April 2015 (145 µg m^{-2} hr^{-1}), and 8 June 2016 (144 µg m^{-2} hr^{-1}). It is notable that after peak N_2O events, low and negative fluxes were observed.

2.3.1.3 High tunnel system

Soil mineral N content remained consistently higher in the HT system than in the other studied systems throughout the experiment, particularly at the 30-50 cm depth. Similar to the other systems, mineral N decreased over the duration of the rotation. The greatest soil mineral N contents were observed after fertilization events in May 2014 (147 kg ha^{-1}), September 2014 (198 kg ha^{-1}), June 2015 (91 Kg ha^{-1}), and June 2016 (57 kg ha^{-}

^{1}) (Figure 2.3). Cumulative mineral N adsorbed in resin bags for the entirety of the rotation was 2754 μg g^{-1} for the 7.5 cm depth, and 3841 μg g^{-1} for 22.5 cm depth. Cumulative lysimeter NO_3^- was 2161 μg g^{-1}.

Soil water content in the HT system fluctuated between saturation and 75% of field capacity during active crop production periods. Soil water content is solely representative of irrigation inputs, as rainfall is excluded in this system. When fallow, soils were not irrigated and exhibited soil water content as low as ~ 0.20 cm^3 cm^{-3} for the 2 week – 3 month fallow periods (Figure 2.3).

Peak CO_2 fluxes in the HT system were comparatively lower than the other systems, and occurred ~1 month earlier than the open field systems. CO_2 flux was well correlated with soil temperature (Table 2.4). Peak CO_2 flux rates occurred on 23 June 2014 (274 mg m^{-2} hr^{-1}, 8 May 2015 (313 mg m^{-2} hr^{-1}), and 8 June 2016 (303 mg m^{-2} hr^{-1}). CO_2 fluxes rates were consistently higher in the HT system than the open field systems during winter, and correlated to higher soil temperatures in the HT structures. Similarly, N_2O emissions were greater than in the other systems during winter, although fluxes were still low, even given the relatively high mineral N content throughout the soil profile. Peak annual N_2O flux coincided with tillage and incorporation of pre-plant fertilizer. Peak N_2O fluxes occurred on 26 June 2014 (95 µg m^{-2} hr^{-1}), 29 July 2015 (257 µg m^{-2} hr^{-1}) and 8 June 2016 (153 µg m^{-2} hr^{-1}).

2.3.2 *Cumulative CO_2 and N_2O fluxes*

CO_2 flux for the entire length of the rotation was greatest in the LI system (12.85 $\pm$ 0.12 ton CO_2-C ha^{-1}), followed by the CONV system (8.45 $\pm$ 0.31 ton CO_2-C ha^{-1}), and the HT system (8.26 $\pm$ 0.34 ton CO_2-C ha^{-1}). N_2O flux was the entire length of the rotation was greatest in the LI system (5.67 kg N_2O-N ha^{-1} $\pm$ 0.70), followed by the HT system (4.52 kg N_2O-N ha^{-1} $\pm$ 0.97), and the CONV system (2.81 kg N_2O-N ha^{-1} $\pm$ 0.31). Trends in flux data presented according to the global warming potential (GWP, ton CO_2 equivalent ha^{-1}) demonstrate that the cumulative differences between systems across the rotation are driven by differences in the first 1.5 y in the rotation (Figure 2.4a).

2.3.3 *Yield and yield scaled GWP*

Crop yields were consistently lowest in the LI system (Figure 2.4b). Yields were similar between the CONV and HT systems. Yield-scaled GWP, a relative measure of yield to cumulative GWP for the rotation, demonstrated consistently greater GWP per unit of yield in the LI system, driven both by greater fluxes as well as lower yields for each crop (Figure 2.4c).

2.4 Discussion

2.4.1 *Soil mineral N*

Soil mineral N peak annual values decreased throughout the rotation in all systems. This is likely an artifact of the crop rotation, which was patterned after the LI system. The rotation was farmer-designed and included crops with consistently strong market demand in the study region, grown in order of decreasing nutrient demand. Vegetable crop rotations are highly variable, based on adaptive management informed by factors such as environmental conditions and markets (Dury et al., 2012). Further, organic vegetable farmers frequently view crop selection and rotation design as a multi-criteria decision framework, optimizing for nutrient demand, pest management, and markets (Mohler and Johnson, 2009; Nair and Delate, 2016). Utilizing standard fertilizer recommendations in the HT and CONV systems, nutrient inputs declined throughout the crop sequence, likely affecting mineral N values as well as N loss pathways. Despite decreasing inputs, HT soils maintained consistently greater levels of mineral N in the top 30 cm layers, likely due to lack of leaching rains in this system (Zikeli et al., 2017), consistent with literature in both conventional and organic HT systems (Shi et al., 2009).

Resin mineral N pools have not been found to consistently correlate well with soil mineral N content, or driving abiotic parameters. Particularly in surface soil layers, some literature has found good correlation of resin N to soil water content (Binkley et al., 1983), mineral N (Kramer et al., 2006), and soil temperature (Johnson et al., 2005). Our results are consistent with data finding no consistent correlation between resin N and soil mineral N pools (Hanselman et al., 2004, Johnson et al., 2005) or soil water content (Allaire-Leung et al., 2001). Further, resin N content revealed less variability within and between systems than soil samples. This may indicate that in this application, resin N was a less sensitive methodology in detecting changes in soil mineral N pools than soil sampling. We did single KCl extraction as described in methods, but a research has reported insufficient nutrient desorption from the single extraction and suggested a series of KCl extractions compared to single extraction (Kolberg et al., 1999).

The greatest NO_3^- leaching measured via IER resin lysimeters were observed in the CONV system. These losses mainly occurred after planting of crops as the small seedlings were unable to capture the applied initial fertilizer. Fertilizer inputs in this system were from inorganic fertilizer sources, and applied according to recommended best practices for commercial vegetable production in the study region (UK Cooperative Extension Service, 2014). Lowering fertilizer inputs in vegetable production systems to reduce nutrient losses has not been focused upon to the degree that it has been in agronomic systems (Quan et al., 2015). However, with the increase in vegetable production acreage world-wide and its environmental impact becoming more apparent, there is a growing body of literature indicating that recommended fertilizer rates for vegetable production may be reduced and still not negatively affect yield while leaching rates can be reduced (Zhang et al., 2017). Relatively high leaching rates from CONV system indicate that additional research on fertilizer rates and timing; amount and frequency of irrigation in the study region may be warranted to sustainably intensify CONV vegetable production.

2.4.2 *Soil water content measurements*

Tensiometers and watermark sensors were compared in this study in order to assess the variability and reliability of watermark sensors to tensiometric methods. Watermark sensors are typically used as low-cost instrumentation for irrigation monitoring that can be deployed year-round, including during low temperature conditions when the water in tensiometers may freeze and render them unusable. During the main growing season, watermark sensors demonstrated greater sensitivity to changes in soil moisture content than the tensiometers did in moister soil conditions, presumably when the conductivity across the sensor was better due to the intact ion bridge (Thompson et al., 2007). During dry and unirrigated fallow conditions, the tensiometers performed at a lower range of water content than the watermark sensors, which began to fail at 0.18 cm^3 cm^{-3}. Overall, soil water content data were not well correlated between the watermark sensors and tensiometer data, and watermark data were more variable.

2.4.3 *Trace gases*

CO_2 fluxes were found to be strongly correlated with temperature in all systems, although peak values varied by system (Table 2.4). Higher correlation between CO_2 flux and temperature in LI system (R^2 = 0.80) value might be related to the higher total soil C in the LI system as well as the composition of soil C (Benbi et al., 2014), which may be comprised of carbon substrate with greater availability for organic matter decomposition. This is notable, as the three systems differed substantially in tillage regime, fallow management, and inputs. Except for the initially large fluxes in the LI system at the beginning of the rotation after inversion tillage and breaking of the pasture fallow, annual CO_2 peaks were not substantively different from CONV after two years. This may indicate that within annual vegetable production systems, CO_2 flux may vary more between climates and soil types than by management within a given region.

N_2O fluxes were not well correlated to any single abiotic factor, but did peak seasonally in the mid-late summer in all systems, with mid-season peaks after organic or synthetic N fertilizer application and tillage events in all systems. In particular, N_2O fluxes were not well correlated with soil mineral N content. This is notable, in particular, in the HT system, which maintained consistently greater soil mineral N content in the top 30 cm soil layers, compared to two other systems but did not exhibit greater N_2O peaks or cumulative flux. We hypothesize this may be due to the relatively consistent water content and decreased frequency of wet-dry cycles in the HT system, thereby reducing the high magnitude N_2O fluxes measured after rainfall or high-volume application of water (Jamali et al., 2016). Along with this, reduced N_2O fluxes might be due to overriding effect of dry soil conditions during fallow period in the HT even though high temperature and high soil N was observed (Xu et al., 2016). The interactive effect of changed temperature and soil moisture content on N_2O emissions varies with different agro-ecosystems with different agricultural management. Decreased N_2O emissions might be attributed to an overriding effect of dry soil moisture conditions on N_2O emissions in N-fertilized vegetable soil even though enough soil N substrate was present (Xu et al., 2016). The greatest N_2O flux peaks and cumulative values were observed in the LI system, particularly after incorporation of the pasture residue. Tillage in pastures has been shown to increase the mineralization of organic N that produces N_2O by both nitrification and denitrification. Furthermore, irrigation at the time of planting elevates N_2O emissions (Estavillo et al., 2002; Pinto et al., 2004). It is notable in our results that throughout the LI rotation soil mineral N content was considerably less than the other systems, but the initial total N and total C were highest in LI (Table 2.1). CO_2 flux was well correlated with N_2O flux in LI system. Carbon dioxide emissions are also used as an indicator of microbial activity or respiration in soil (Parkin et al., 1996).The higher N_2O fluxes in our study might be correlated with higher soil C content in the LI system. Denitrification is one biological process producing N_2O, that requires an electron donor such as carbon (Loick et al., 2017) and is stimulated by higher soil organic matter in this compared to the other two systems (Cheng et al., 2017).

2.4.4 *Harvested crop yields*

The HT system, an intensively-managed, organic production system, did not experience a “yield gap” when compared to the CONV system, a common issue in organic production systems (e.g. Seufert et al., 2012; de Ponti et al., 2012). The difference in yield of some crops between the HT and CONV systems may be explained in part by differences in crop sensitivities to the inputs or environmental factors. The HT system exhibited greater sweet pepper yield than the CONV system. This crop benefits from the protective cover of the structure in decreasing fungi-foliar disease incidence (Powell et al., 2014). The CONV system had greater bean yield, which may be due to flower drop in HT due to higher daily max temperatures (Monterroso and Wien, 1990) in the summer. Yields in the LI system were highly variable across the rotation, with two of the crops experiencing near crop-failures (table beets and collards). It is important to note that this study occurred in one field of a highly diversified LI farm. In these extensive systems, variability in a given location or crop is buffered on the farm-scale by practices such as crop and variety diversification, successional planting, and production on an extensive scale with lower yields on a per unit area (Liebman and Davis, 2000). As such, the data presented here reflect field-scale observations, and not whole farming system productivity.

2.4.5 *Sustainable intensification of horticultural systems*

Yield-scaled GWP is used as one integrated measure to relate yield to environmental impact per unit output (Schellenberg et al., 2012). Due to low yields in some crops (as discussed above), and high fluxes after the pasture fallow incorporation, the LI system had much greater GWP per unit yield in each crop in the rotation. The comparatively intensive and CONV systems did not differ greatly. It is of note that this calculated measure of system impact per unit output does not account for “footprint” of inputs in the associated systems that are critically linked to the sustainability of the production system inputs, such as energy embodied in inputs, irrigation water usage, etc. Further, this approach does not relate to future yield levels or resiliency via changes in the soil resources, such as soil organic matter, salinity, or reduced biological activity due to decreases in fallow periods.

However, our yield data are consistent with others that show that lower-input organic farming systems may be good candidates for sustainable intensification (Garbach et al., 2016; Ponisio et al., 2015). Relatively minor increases in irrigation at critical times, more efficacious weed management, or small applications of fertilizer at critical crop phenological stages may have strong influence on yields.

2.5 Conclusion

This study quantified the CO_2 and N_2O fluxes from a suite of diversified vegetable systems representing a gradient of input and management intensification. Key loss pathways in the low input (LI) system were via greenhouse gas fluxes, whereas in the conventional system (CONV) they were via leaching. Despite higher soil mineral N content in the high tunnel (HT), N_2O fluxes were not higher compared to low input (LI) system. Yield-scaled GWP was greater in the LI system compared to CONV and HT system, driven both by greater fluxes and lower yields. From the perspective of sustainable intensification in these three systems, our study suggests CONV systems may benefit from reduced fertilizer inputs in combination with irrigation management to minimize downward directed hydraulic gradients particularly just after planting of crops; LI systems may benefit from targeted additional fertilizer and irrigation inputs. This work supports literature indicating the need to examine long-term soil impacts in HT systems over longer timelines.

2.6 Tables and figures

Table 2.1 Initial soil conditions at study depths of three study agroecosystems.

Agricultural System	**Soil Depth (cm)**	**Soil pH**	**Soluble Salts (mmhos m^{-1})**	**Total N (%)**	**P (Kg ha^{-1})**	**K (Kg ha^{-1})**	**Total C (%)**	**POX C (mg kg^{-1} of soil)**	**Soil NO_3^--N kg ha^{-1}**
Low Input Organic (LI)	0-15	5.4±0.05	18±0.8	0.16±0.010	580±19	196±14	1.75±0.05	317±19	61±7
	15-30	5.4±0.02	13±1.5	0.11±0.005	668±33	170±12	1.31±0.05	133±18	39±5
	30-50	5.3±0.04	10±0.8	0.07±0.004	828±48	163±12	0.87±0.05	63±40	27±2
Conventional (CONV)	0-15	5.3±0.07	16±3.1	0.07±0.020	153±9	473±28	1.10±0.03	63±17	45±8
	15-30	5.2±0.08	13±1.1	0.08±0.003	134±6	399±10	1.09±0.03	64±12	28±2
	15-30	5.2±0.01	9±0.4	0.07±0.005	92±9	357±14	0.83±0.06	43±22	19±1
Organic High Tunnel (HT)	0-15	6.1±0.25	30±8.0	0.13±0.030	254±58	388±61	1.56±0.28	329±40	76±14
	15-30	5.9±0.17	27±6.2	0.13±0.010	237±40	358±13	1.48±0.09	117±8	19±3
	30-50	5.7±0.12	16±1.1	0.09±0.010	173±17	313±54	1.12±0.06	207±156	19±1

Table 2.2 Management characterization of three study agroecosystems, as characterized by cropping system duration, and tillage, nutrient and irrigation input intensities.

Agricultural System	**Cash Crop Production (typical months/year)**	**Tillage Frequency (approx. depth in m)**	**Nutrient Input Regime**	**Irrigation Method**
Low Input Organic (LI)	8-9	Semi-annual soil preparation with primary inversion tillage (0.30 m), Secondary soil preparation with disc (0.20 m). In-season weed control via sweep cultivation (0.15 m).	Five-year fallow prior to cropping cycle, annual cool-season cover crop between cash crops.	Drip irrigation in plasticulture beds applied at the time of planting. Bare ground crops depended only on precipitation.
Conventional (CONV)	8-9	Semi-annual soil preparation with a soil spader (historically inversion tillage, 30 cm), secondary soil preparation with disc (0.20 m). In season weed control via sweep cultivation (0.10 m).	Annual cool-season cover crop between cash crops, Synthetic fertilizer applied pre-plant and split-application via fertigation in long-season crops.	Drip-irrigated.
Organic High Tunnel (HT)	12	Quarterly secondary tillage with rototiller (0.20 m). In season weed control via surface cultivation (0.05 m) with hand tools.	Semi-annual compost application, pre-plant granular organic fertilizer (pelletized poultry litter-based).	Drip-irrigated.

Table 2.3 Crop timing and fertilizer rates in three study agroecosystems. Timing of the crop rotation is detailed by planting date (PD) to final termination date (TD) by primary tillage or crop removal.

System		Crop Rotation				
		2014		2015-2016		2016
		Sweet pepper (*Capsicum annum* L., 'Aristotle')	Head lettuce (*Letuca sativa*, 'Dov')	Table beets (*Beta Vulgaris*, 'Red Ace')	Collards (*Brassica oleracea var. medullosa*, 'Champion')	Beans (*Phaseolus vulgaris*, 'Provider')
Low Input Organic (LI)	PD to TD	14 May – 9 Sept	--	8 June – 3 Sept	11 Oct – 23 March	28 May – 4 Aug
Conventional (CONV)	PD to TD	20 May – 1 Aug	--	24 April – 7 Aug	19 Aug – 26 Feb	7 May – 26 July
	Fertilizer	78 kg N ha^{-1} at planting on 20 May; split application of 9 kg N ha^{-1} on 29 May, 8 June, 16 June, 20 June, 27 June, 9 July	--	56 kg N ha^{-1} at planting on 24 April	56 kg N ha^{-1} at planting on 19 Aug; split application of 9 kg N ha^{-1} on 8 Sept, 15 Sept, 22 Sept, 28 Sept, 2 Oct	56 kg N ha^{-1} at planting on 16 May
Organic High Tunnel (HT)	PD to TD	22 April – 29 July	15 Sept – 21 Nov	12 March – 12 June	25 Sept – 26 Feb	28 April – 8 July
	Fertilizer	Horse manure compost equiv. to 24 ton ha^{-1}, 45 kg N ha^{-1} of pelleted organic fertilizer (5-4-3) at planting	Same as for Sweet pepper	Same as for Sweet pepper	Same as for Sweet pepper	Same as for Sweet pepper

Table 2.4 Spearman rank correlation values for N_2O flux and soil mineral nitrogen (NO_3^--N and NH_4^+-N) and soil temperature, and carbon dioxide flux and soil temperature in three study vegetable production systems.

Environmental Variables	**N_2O**		
	Low Input Organic	**Conventional**	**High Tunnel**
Soil mineral N (0-15 cm)	r = 0.30	r = 0.08	r = 0.20
Soil mineral N (15-30 cm)	r = 0.14	r = 0.02	r = 0.32
Soil mineral N (30-50 cm)	r = 0.28	r = 0.12	r = 0.13
CO_2	r = 0.46	r = 0.26	r = 0.16
Soil temperature (^oC, 10 cm)	r = 0.35	r = 0.07	r = 0.15
	CO_2		
	r = 0.80	r = 0.55	r = 0.55

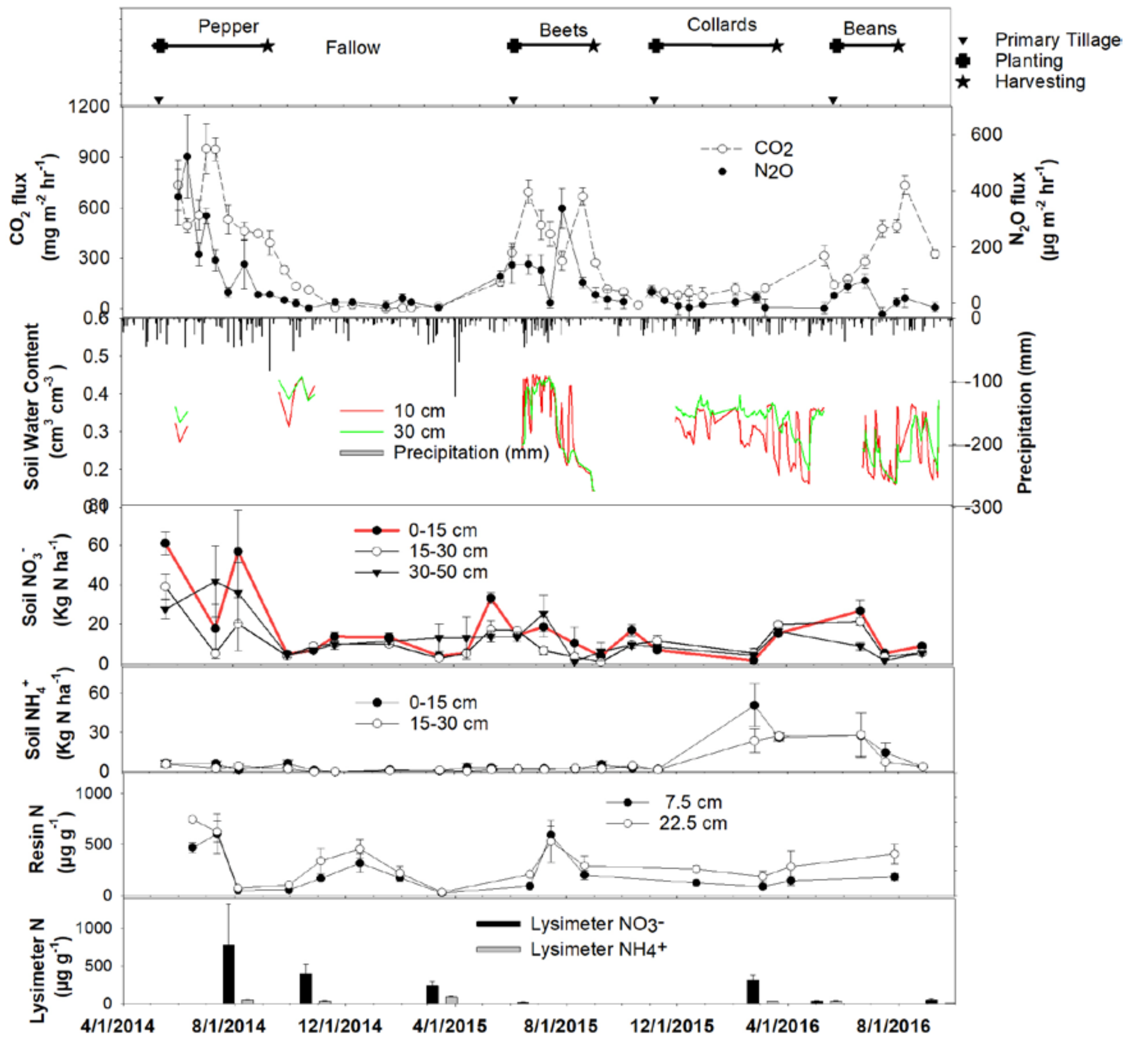


Figure 2.1 Time series data from the Low Input (LI) system from 2014 – 2016, including CO_2 and N_2O flux, soil water content and precipitation, and soil NH_4^+-N and NO_3^--N, total mineral N extracted from ion exchange resin bags, and leaching measured via ion exchange resin lysimeters.

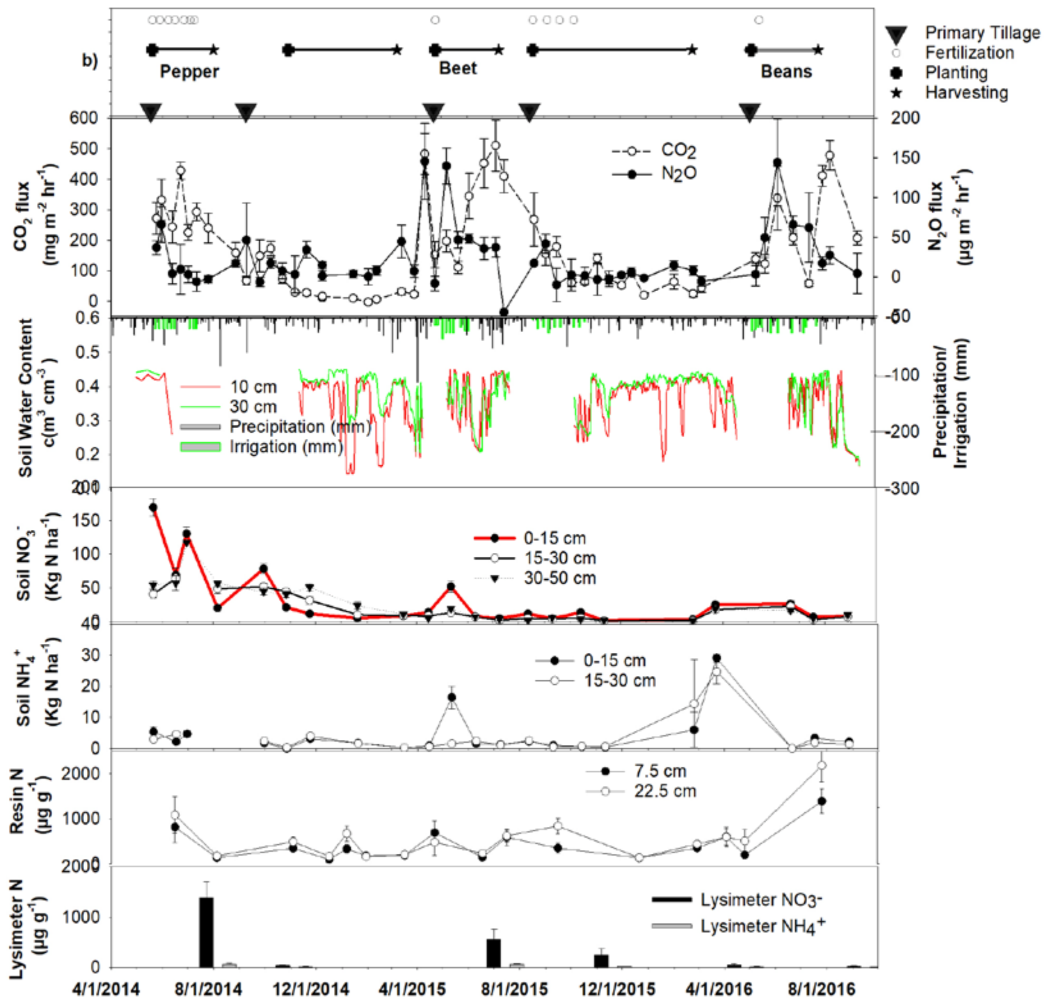


Figure 2.2 Time series data from the Conventional (CONV) system from 2014 – 2016, including CO_2 and N_2O flux, soil water content and precipitation, and soil NH_4^+-N and NO_3^--N, total mineral N extracted from ion exchange resin bags, and leaching measured via ion exchange resin lysimeters.

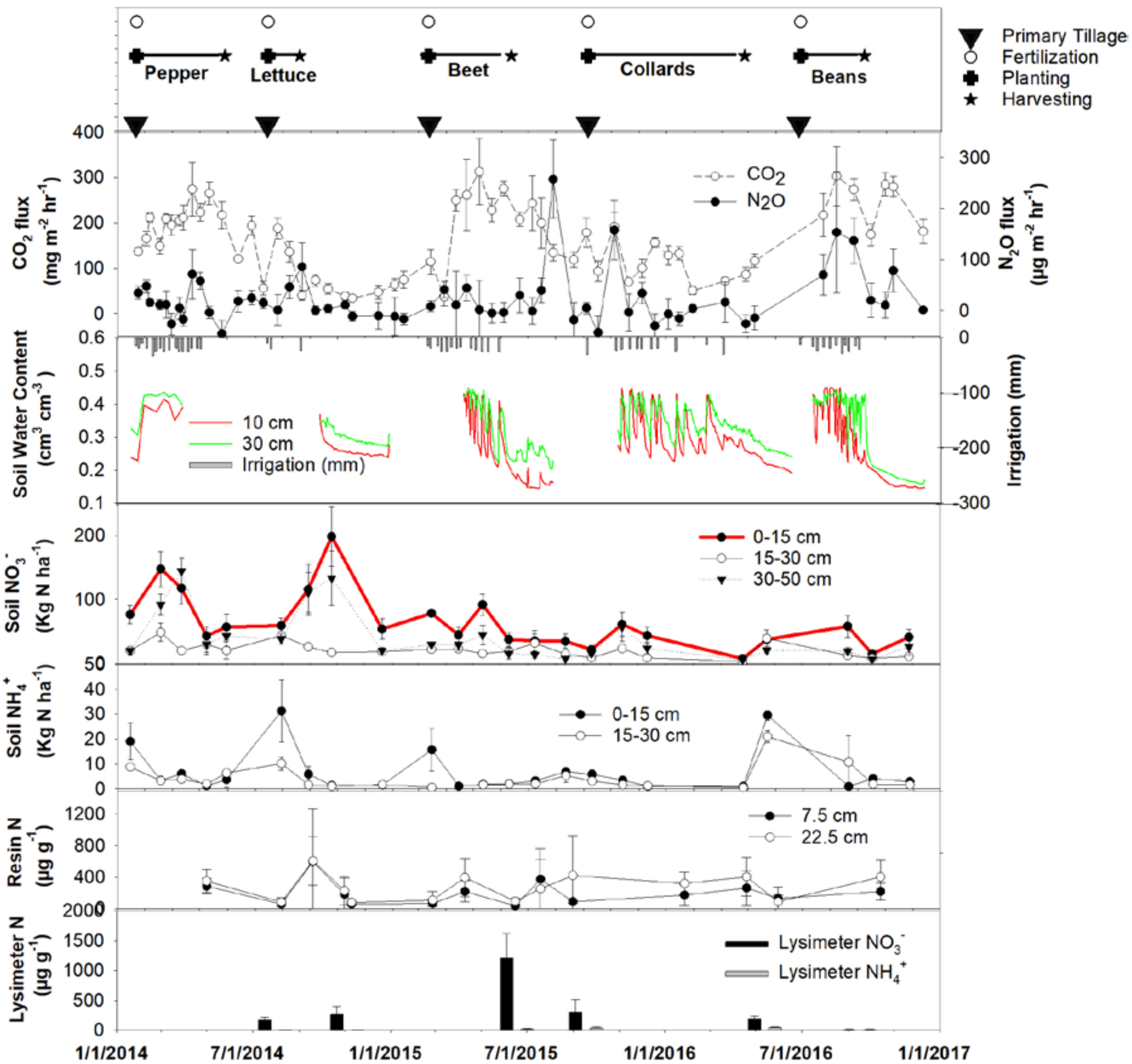
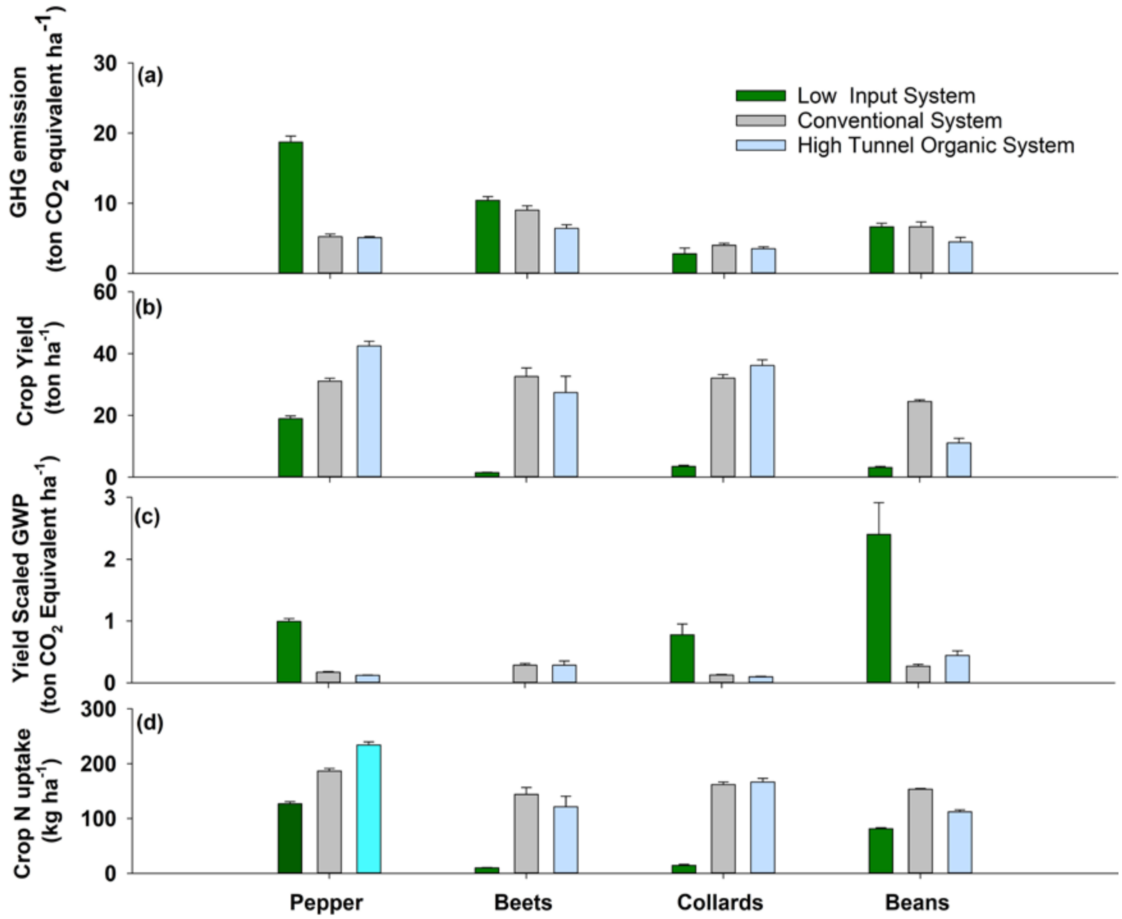


Figure 2.3 Time series data from the High Input Organic (HT) system from 2014 – 2016, including CO_2 and N_2O flux, soil water content and precipitation, and soil NH_4^+-N and NO_3^--N, total mineral N extracted from ion exchange resin bags, and leaching measured via ion exchange resin lysimeters.



*Yield Scaled GWP of LI beets (7.2 ±0.6) not included in graph for better view.

Figure 2.4 Systems-level comparison of (a) Cumulative greenhouse gas (GHG) emission, (b) Crop yield, (c) Yield-scaled global warming potential (GWP), and (d) Crop N uptake in the 2014-2016 crop rotation.

CHAPTER 3. **USING RZWQM2 TO SIMULATE NITROGEN DYNAMICS AND NITROUS OXIDE EMISSIONS IN VEGETABLE PRODUDUCTION SYSTEMS**

3.1 Introduction

Vegetable production area has increased consistently in the U.S, from 1949 to 2014 (USDA NASS, 2014). Although production area is expanding, the body of literature on the effect of vegetable production on soil processes, greenhouse gas emissions, and nutrient leaching is limited (Zhang et al., 2018). This is due, in part, to highly variable production practices due to variability in crop choice, input and management intensity, and the adoption of diverse conservation practices (Rezaei Rashti et al., 2015). Inorganic fertilizers, cover crops, manure, and compost are sources of N, necessary for crop production. However, increased N application significantly contributes to air and water pollution and global warming (Galloway et al., 2004).

Agricultural soils contribute approximately 60% to total anthropogenic emissions of N_2O (Lokupitiya and Paustian, 2006), a potent greenhouse gas with global warming potential 298 times greater than CO_2 (IPCC, 2014). Primary source of N pollution to groundwater and water bodies is from agricultural soils applied with N fertilizers (Tilman et al., 2011). Although smaller in production area relative to staple grain crops, vegetable production systems are often fertilized with higher rate of N fertilizer (Rosenstock and Tomich, 2016) and most often irrigated. These inputs are likely driving the increased N_2O emissions and NO_3^- leaching losses that have been reported from vegetable production systems (Liptzin and Dahlgren, 2016; Xu et al., 2016).

High temporal and spatial variability of fluxes in gases such as N_2O fluxes (Fang et al., 2015) makes it difficult to quantify emissions across variable agricultural production systems. Further, process-based models allow an opportunity to simulate soil N and C dynamics (Ma et al., 2012), predict N_2O emissions (Fang et al., 2015) and crop production (Jiang et al., 2019; Uzoma et al., 2015). However, the majority of process-based models have been developed for grain crop and pasture-based systems, and many do not incorporate production methods and technologies common in vegetable production.

For example, the use of plastic mulches is one of the components of intensive production of vegetable crops, which continues to grow worldwide (Lament, 1993). Drip irrigation in conjunction with plastic mulch reduces evaporation from mulched soil and decreases irrigation requirements. Drip irrigation has been increasingly used to irrigate vegetable crops globally and reported to have greater water use efficiency compared to flood, furrow or sprinkler irrigation methods (Darwish et al., 2003). Vegetable production in protected agriculture systems, in which covered structures exclude rainfall are also increasingly common world-wide. In the US, the use of high tunnels, which are passively heated and ventilated structures with crops grown in-ground production is also increasing (USDA NASS, 2014). These semi-controlled environments are protected from rainfall and typically have higher temperatures than the open field, allowing for extension of the growing season of warm season crops and production throughout the winter season in many temperate climates. However, these temperature and moisture regimes differ substantially from the open field. In such protected structures, as with many of the vegetable production technologies and practices mentioned above affect soil temperature and soil water dynamics, which are major drivers of soil N dynamics and other agroecosystem processes. Many of these technologies and production practices are difficult to simulate in process-based models developed for open field grain or forage systems.

Root Zone Water Quality Model 2 (RZWQM2) is a comprehensive ecosystem model that simulates soil water, temperature, N and C dynamics and crop yield (Ahuja et al., 2000). RZWQM2 has been extensively applied to better understand soil water, soil N and C dynamics, N leaching, and crop yield in agronomic crop production systems such as corn, wheat, and soybean (Ma et al., 2007; Malone et al., 2007; Yu et al., 2006). RZWQM2 has not been widely used in vegetable production systems, save a notable exception by Cameira et al. (2014), who used the model to study water and N budgets for organically and conventionally managed urban vegetable gardens. However, recent additions to the model by Fang et al. (2014) incorporated the Simultaneous Heat and Water (SHAW) (Flerchinger and Saxton, 1989) model in to RZWQM. The updated RZWQM2 can be used to simulate soil water and temperature under plastic mulch, a common vegetable production technique. Drip irrigation is also supported by the model, as are a number of vegetable crops, making RZWQM2 an ideal candidate for evaluating for its ability to simulate a wide variety of vegetable production systems.

RZWQM2 require detailed input data for weather, soil physical, chemical and hydraulic information, and agronomic management to run the model (Malone et al., 2004; Gillette et al., 2018). Provided with this information and appropriately calibrated and validated, RZWQM has been used widely to simulate NO_3^- leaching (Yu et al., 2006; Gillette et al., 2018; Jiang et al., 2019). Further, Fang et al. (2015) combined the nitrous oxide emission (NOE) model and DAYCENT model and incorporated them into RZWQM to simulate N_2O emissions, and then it has been used to simulate N_2O emission by other researchers (Gillette et al., 2017, 2018; Jiang et al., 2019). As such, RZWQM2 is a strong process-based model to help researchers better understand the soil water, N dynamics and N leaching across the complex array of crop management, fertilizer use, crop rotation, and tillage frequency characteristic of vegetable production systems. The objective of this study was to simulate soil water, N_2O emission, soil NO_3^--N processes, and crop yield in diversified vegetable rotations that include a variety of common vegetable production practices.

3.2 Materials and methods

3.2.1 *Research sites*

This three-year rotational study was initiated in early spring 2014 in two sites in central Kentucky with Maury silt loam soil (a fine, mixed, active, mesic Typic Paleudalfs). Each system contained six replicate plots. Details about research sites for this chapter was utilized from previous chapter. Initial soil conditions for each system are listed in Table 2.1.

3.2.2 *Cropping systems description*

The three vegetable production systems utilized in this study were characterized by fallow periods, tillage intensity, and irrigation and nutrient inputs. They are presented in Table 2.3. Additional management and input descriptions are provided in Shrestha et al. (2018). The Conventional system (CONV) consisted of a winter wheat (*Triticum aestivum* L.) cover crop during winter 2014, planted in late fall and terminated with tillage in early spring (Table 2.3), followed by vegetables.

The Organic High Tunnel system (HT) consisted of three, replicated unheated 9.1 m x 22 m greenhouse structures. Horse manure compost and granular organic fertilizer

(Harmony 5-4-3, BioSystems, LLC, Blacksburg, VA) were incorporated into soil at a rate of 67 kg N ha^{-1} before planting each crop. Details about amount and timing of fertilizer application are presented in Table 2.3. All crops were drip irrigated.

The Low Input Organic system (LI) consisted of a long-term rotation of a five-year mixed grass/legume pasture followed by a three-year rotation of annual crops. No supplemental fertilizer was added, and drip irrigation was used exclusively for pepper. Irrigation was applied only if precipitation was insufficient at critical stages of crop development. Both the HT and LI systems were certified organic under the US National Organic Program Guidelines (USDA, 2018).

3.2.3 *Measured data*

Soil, plant and N_2O flux sampling methods are presented in detail in Shrestha et al. (2018). Briefly, soils were sampled monthly at 0-15 cm, 15-30, and 30-50 cm depths for mineral N (NH_4^+ and NO_3^-) from six replicate plots. On each sampling date, three cores were taken per plot at each depth, homogenized, and bulked for a single analysis per plot. N_2O flux was sampled bi-weekly (excluding periods when the ground was frozen) using a FTIR-based field gas analyzer (Gasmet DX4040, Gasmet Technologies Oy, Helsinki, Finland). The static chamber method (Parkin and Venterea, 2010) was used, with rectangular stainless-steel chambers (16.4 cm x 52.7 cm x 15.2 cm) installed in each plot. Gas fluxes were calculated by using the following equation (Iqbal, 2013):

$$(F) = \frac{\Delta C}{\Delta t}\frac{V}{A}\rho$$

Where F is the gas flux rate (mg m^{-2} h^{-1}), ΔC/Δt indicates the increase/decrease of gas concentration (C) in the chamber over time (t), V is the chamber volume (m^3), A is the chamber cross-sectional surface area (m^2), ρ denotes the gas density at 25°C.

Cumulative gas fluxes were estimated by interpolating trapezoidal integration of flux versus time between sampling dates and calculating the area under the curve (Venterea et al., 2011).

Soil water potential was measured using granular matrix (Watermark) sensors (Irrometer Co., Riverside, CA) installed at three depths in the soil profile (10, 30, and 50 cm depths), with one sensor per depth, for a total of three per plot. Watermark sensor data was transmitted continuously via wireless transmitters to a data logger (Watermark Monitor 900M, Irrometer, Co., Riverside, CA), with readings logged each time when the water potential changed. Soil temperature was measured at the time of N_2O flux measurement with digital soil thermometer inserting at of 10 cm depth from soil surface.

Fresh vegetable yields were measured from the entire plot area of 13.5 m^2 from each of the plots. Pepper fruits, collard leaves and green beans were harvested at multiple times as the harvestable portion reached marketable stage, and table beets were harvested once, as roots reached marketable size. Plant C and N content were analyzed from a subsample plant material collected from each plot at the final biomass harvest. Final biomass samples were dried at 60 ºC until a constant mass was achieved, homogenized on a Wiley Mill (Thomas Scientific, Swedesboro, NJ), and a subsample ground on a roller mill (C.Z-22072, U.S. Stoneware, East Palestine, OH). One plant sample from each plot for each crop was analyzed for percent C and N on an elemental analyzer (Thermo Scientific FlashSmart, CE Elantech, Lakewood, NJ).

3.2.4 *Model description*

RZWQM2 is a one-dimensional agricultural system model, which simulates mineralization and immobilization of crop residues, mineralization of soil N, volatilization, nitrification, and denitrification (Ahuja et al, 2000). Soil water content, nutrient leaching and crop yield are also simulated. The agricultural management input options are crop and crop cultivar selection, planting date, manure and fertilizer application, tillage, irrigation and pesticide application (Ma et al., 2012). Brooks–Corey equations are used to relate volumetric soil water content (θ) and soil suction head (h) (Ma et al., 2012). The potential evaporation and crop transpiration are described by the Shuttle-Wallace equation. Fang et al. (2014) incorporated the simultaneous Heat and Water (SHAW) (Flerchinger and Saxton, 1989) model into RZWQM (Ahuja et al., 2000), and used to simulate surface energy balance and canopy temperature along with crop growth and production in different climate and cropping seasons. RZ-SHAW model was able to quantify the effect of crop growth on the energy balance under different agronomic management practices. RZWQM2 provides soil water content, root distribution, soil evaporation, soil transpiration, leaf area index, and plant height at each time step to SHAW and then SHAW provides soil ice content, updated soil water content due to ice and freezing, and soil temperature to RZWQM (Fang et al., 2014). RZWQM2 provides soil evaporation (AE), which is used by SHAW to compute the energy balance of the surface soil layer by forcing water vapor flux from the soil surface, and therefore latent heat flux, to equal the soil evaporation (Fang et al., 2014). Soil heat flow and temperature in the soil matrix, considering convective heat transfer by liquid and latent heat transfer by vapor for freezing soil is given by

$$\mathbf{C_s}\frac{\partial \mathbf{T}}{\partial \mathbf{t}} - \boldsymbol{\rho}_\mathbf{i}\mathbf{L_f}\frac{\partial \boldsymbol{\theta}_\mathbf{i}}{\partial \mathbf{t}} = \frac{\partial}{\partial \mathbf{z}}\left[\mathbf{K}_{\mathbf{t(s)}}\frac{\partial \mathbf{T}}{\partial \mathbf{z}}\right] - \boldsymbol{\rho}_\iota \mathbf{c}_\iota \frac{\partial \mathbf{q}_\iota \mathbf{T}}{\partial \mathbf{z}} - \mathbf{L_v}\left(\frac{\partial \mathbf{q_v}}{\partial \mathbf{z}} + \frac{\partial \boldsymbol{\rho}_\mathbf{v}}{\partial \mathbf{t}}\right)$$

where Cs and T are volumetric heat capacity (J kg^{-1} K^{-1}) and temperature (°C) of the soil, ρ_i is density of ice (kg m^{-3}), θ_i is volumetric ice content (m^3m^{-3}), $K_{t(s)}$ is soil thermal conductivity (W $m^{-1}K^{-1}$), ρ_l is density of water, c_l is specific heat capacity of water (J kg^{-1} K^{-1}), θ_i is liquid water flux (m s^{-1}), q_v is water vapor flux (kg m^{-2} s^{-1}), L_f is latent heat of fusion (335,000 J kg^{-1}) and ρ_v is vapor density (kg m^{-3}) within the soil (Fang et al., 2014).

The N_2O emission algorithm in RZWQM2, as described in Fang et al. (2015), was partly taken from the DAYCENT model (Parton et al., 1998; Del Grosso et al., 2000) and Nitrous Oxide Emission (NOE) model (Henault et al., 2005). N_2O emission from nitrification (N_2O_nit) is calculated as following (Del Grosso et al., 2000) and presented below:

$$N2O_{nit}=Fr_{N2O\text{-}nit}\times F_{SW_{nit}}\,R_{nit}$$

$$F_{SW\_nit}=\frac{0.4\ WFPS\ \text{-}1.04}{WFPS+1.04}$$

where $Fr_{N2O\text{-}Nit}$ is the fraction of nitrification for N_2O emissions, and 0.02 was used as the default value in DAYCENT (Del Grosso et al., 2000; Parton et al., 2001); F_{SWnit} is the soil water factor for the oxygen availability effect on N_2O emission during nitrification (Khalil et al., 2004) taken from the NOE model.

N_2O emission from denitrification (N_2O_{den}) is calculated as following (Del Grosso et al., 2000):

$$N2O_{den}=Fr_{N2O\text{-}den}\times R_{den}$$

$$Fr_{N2O\text{-}den}=\frac{1}{1+R_{NO\text{-}N2O}+R_{NO\text{-}N2O}}$$

$$R_{NO\text{-}N2O} = 4 + \frac{9\ \tan^{-1}\{0.75\pi\ (10\ D\text{-}1.86)\}}{\pi}$$

$$R_{N2\text{-}N2O} = \max\ \{0.16\ k1, k1\ \exp\ (\frac{-0.8\ [NO3]}{[CO2]})\}\ \max\ (0.1, 0.015\ WFPS\ 100\text{-}0.320)$$

$$k1 = \max\ (1.5, 358.4\text{-}350\ D)$$

where $Fr_{N2O\text{-}den}$ is the fraction of denitrification for N_2O emissions; $R_{NO\text{-}N2O}$ is the ratio of NO to N_2O; $R_{N2\text{-}N2O}$ is the ratio of N_2 to N_2O; $[NO_3]$ is soil NO_3^--N; D is gas diffusivity in soil (Davidson and Trumbore, 1995); WFPS is water filled pore space.

3.2.5 *Model input, calibration and validation*

Weather input data for the CONV and LI systems, including daily minimum and maximum air temperature, wind speed and direction, shortwave radiation and relative humidity were entered as daily summary data local to the research sites (KYMESONET, 2018). Daily precipitation data for LI was taken from a Georgetown-Scott County Regional Airport, Scott county (8 km from research site) downloaded from NOAA (NOAA, 2018). For the HT system, daily maximum, minimum temperature and relative humidity values were summarized from data loggers measuring on 15-minute intervals, mounted 2 m high in the center of the structures (WatchDog B102, Spectrum Technologies, Aurora, IL). The calculation of daily solar radiation inside tunnels was taken from VegSyst V2 model (Gallardo et al., 2016) and calculated as the product of solar radiation outside and tunnel plastic roof transmissivity:

$$SR_{in} = SR_{out} \times \tau$$

τ for double layer polyethylene sheet for high tunnel = 0.7 (Biernbaum, 2013)

where SR_{in} is the incoming solar radiation, SR_{out} is the outgoing solar radiation, and τ is the transmissivity of polyethylene sheet cover on high tunnel. RZ-SHAW model was used for pepper in 2014 in all three system and only in CONV collard, as these crops were grown under black plastic mulch (Plastic emissivity - 0.95, albedo - 0.05 and transmissivity - 0.86), RZWQM2 was used for the other crops.

Model simulations were done for each crop separately. For pepper, the model was started on April 1st, 2014 and ended on 10th September 2014 in all systems. Final soil C, N pools from the pepper were used to initialize the model for the following crops. Model simulation for cover crop in CONV, lettuce in HT and fallow in the LI system was started on 11th September 2014. Starting date for model run for beet, collard and bean were 1st March 2015, 16th August 2015 and 1st March 2016 in all systems. The cumulative N_2O emissions were calculated for each crop season separately. Soil bulk density was measured from field samples (Table 3.1), while soil texture data and soil water content at 1/3 and 15 bar of soil (Table 3.1) were obtained from USDA NRCS Web soil survey (Web Soil Survey, 2018), and calibrated in CONV system (Table 3.1). Saturated hydraulic conductivity, soil water content at 1/3 bar and 15 bar for the 50 cm depth were calibrated in relation to the measured soil water content in the CONV system; and then followed by calibration at 30 cm and 10 cm soil depth. Initial values for fast and slow residue pools; slow, medium and fast soil humus pools; and microbial pools were calculated based on measured soil carbon data (Table 3.1) by conducting a “warm up” run (to get stable soil residue and microbial pool) for 10 years under current weather and management practices for the CONV and HT system. Initial carbon pool for the LI system were obtained by running the grass module to mimic the pasture production system (Feng et al., 2015). Model default values were used for soil chemistry data. Crop parameters were calibrated with the measured yield component data from CONV system and validated by HT and LI system. For the pepper crop, the crop parameters were obtained from DSSAT pepper variety ‘Capistrano’, as plant height, leaf structure and fruit type were similar to pepper variety ‘Aristotle’. For bean, dry bean variety ‘Andean Habit 1’ was chosen, as plant characteristics were close to variety ‘Provider’. For the table beet, the DSSAT sugar beet var ‘SVRR1142E’ was chosen and we modified the crop parameters G2 leaf expansion rate during stage 3 to 130 cm^2 cm^{-2} day^{-1}, G3 Root tuber growth rate to 14.5 g m^{-2} day^{-1} and plant biomass at half of maximum height to 9.07 g $plant^{-1}$ (Tei et al., 1996). The DSSAT cabbage variety ‘990001 Tastie 4’parameter was modified to simulate the collard crop. The specific leaf area of cultivar under standard growth conditions (SLAVR) was modified to 80 cm^2 g^{-1} (Uzun and Kar, 2004) and maximum size of full leaf (three leaves) (SIZLF) was measured, 350 cm^2. The HT system included an additional crop in the rotation, due to the year-round production capacity of the system. The DSSAT cabbage crop parameters; SLAVR modified to 100 cm^2 g^{-1} (Tei et al., 1996) and SIZLF modified to 250 cm^2, as measured to simulate a lettuce crop. The model performance in simulating the soil water, soil NO_3^-, N_2O emissions and crop biomass was evaluated by root mean square error (RMSE) and coefficient of determination (R^2).

3.3 Results and discussion

3.3.1 *Soil temperature*

RZWQM2 simulated soil temperature was compared with the measured values (Table 3.2). In all cropping systems, RZWQM2 underestimated the soil temperature for all crops except for peppers, which were grown under black plastic mulch. In the CONV system, RZWQM2 underestimated average soil temperature (Figure 3.1 (d)) by 3, 2.3, 0.2 and 1.5 °C during the cover crop, beet, collard and bean growing seasons, respectively. In the HT system, RZWQM2 underestimated average soil temperature by 7.6, 3.6, 3.8 and 2.5 °C during lettuce, beet, collard and bean growing season, and shown in Figure 3.2(d). Similarly, the average soil temperatures were underestimated by 4.3, 0.9, 4.4 and 3.3 °C during fallow, beet, collard and bean growing seasons, respectively in LI system. The underestimation might be related to timing of temperature measurement; as soil temperatures were measured during the day time, while the model simulated the temperature values as an average of daily temperature (Jiang et al., 2019). The R^2 and RMSE values ranged from 0.43-0.86 and 1.22-3.68 °C in CONV; 0.63-0.86 and 1.26-3.15 °C in HT; 0.24-0.93 and 1.93-3.55 °C in LI system (Table 3.2).

3.3.2 *Soil water content*

The simulated soil water content in three different layers (15 cm, 30 cm and 50 cm) were evaluated using measured values for CONV, HT and LI systems (Table 3.3). The simulated water contents in different soil layers showed reasonably good agreement with measured soil water (Table 3.3). The model overestimated the soil water content values at 10 cm and 30 cm during pepper and collard green growing season in all systems and values were close to the measured value at the layer 50 cm. It should be noted that pepper and collard were grown in a raised bed, while other crops were grown in a flat bed. In the CONV system, RZWQM2 was able to simulate soil water well during pepper, and beet growing seasons, but collard and bean were not well simulated at 30 cm depth (Figure 3.1). RZWQM2 was able to simulate soil water content well in the HT system except for the collard growing season (Figure 3.2), where the R^2 values were lower than 0.33 for all soil layers. RZWQM2 was able to simulate the soil water in the LI system well (Figure 3.3), as R^2 values are more than 0.65 in all cases except for bean growing season (Table 3.3). The lower agreement between the simulated and measured soil water values in the CONV and LI systems might be related to additional water uptake by weeds, which were neither simulated nor measured. R^2 values may be lower during the overwinter grown collard in the CONV and HT systems, as the soil water sensors used tend to record lower soil water content values during freezing soil conditions.

3.3.3 *Soil nitrate content*

The simulated soil NO_3^--N content in three different layers (0-15 cm, 15-30 cm and 30-50 cm) were compared using measured values for CONV, HT, and LI systems (Table 3.4). During the pepper growing season, RZWQM2 underestimated the soil NO_3^--N content in all systems in all three soil layers. In the CONV system, the model was able to simulate soil NO_3^--N well during the cover crop, beet and bean growing seasons (Figure 3.4(a), 3.4(b), 3.4(c)), showing the R^2 values ranging from 0.38 to 0.97 (Table 3.4). However, there was not good agreement between simulated values and the measured values during pepper and collard growing season in the CONV system. It should be noted that the pepper and collard in the CONV system were grown under black plastic mulch in an approximately 15 cm high raised beds spaced ~ 1m apart, with the field consisting of a series of such plastic-covered raised beds. Initial fertilizer was broadcast evenly over the field prior to raising the beds. However, subsequent fertilizer was applied with drip irrigation during the growing season, which narrowed the fertilizer application to the soil water pattern dispersed by the drip irrigation. The model simulated soil NO_3^--N well during the cover crop, beet, and bean portion of the rotation, where the crops were planted in flat bed and the row-to-row distance was small (Table 3.4). The largest difference between RZWQM2 simulated and field measured soil NO_3^--N values were in CONV pepper, a system in which the standard best management practice in the growing region is to split the fertilizer application between pre-plant and in-season fertigation. In this practice, 2/3 of the fertilizer is applied during the growing season weekly (though this may be more frequent) at a commercially-recommended rate. The measured values were taken from samples within the middle 50% of the bed, which may have a greater concentration of NO_3^--N than the edges of the bed. From our results, we could say that the model simulated soil NO_3^--N well in beet and bean in all systems, which were grown in flat bed conditions and in which the row to row distances were lower than pepper and collard.

In the HT system, soil NO_3^--N values in the 0-15 cm layer were poorly simulated throughout the rotation (Figure 3.5a), with R^2 values below 0.29 (Table 3.4). This might be attributed to the high denitrification N loss and N immobilization, despite high simulated mineralization (Table 3.7). However, the model was able to simulate the soil NO_3^--N reasonably well at 15-30 cm soil layer (Figure 3.5b). The model did not do well ($R^2 < 0.03$) in simulating soil NO_3^--N content in the 30-50 cm layer during pepper, lettuce and beans growing season. The inability of the RZWQM2 model to simulate the soil NO_3^{-}-N content in the upper 15 cm of soil in the high tunnel grown vegetable system might be associated with the source of fertilizer used, tillage intensity, soil temperature and moisture regime. In the HT system, only organic fertilizer and horse manure compost were used to fertilize the vegetable crops in all cropping seasons. A small tiller which turns over only the top 10 cm of soil, was used; concurrently, almost all fertilizer applied to crops remains in the top 10 cm. As some researchers reported, N decomposition, denitrification, and nitrification processes are not straightforward in organic manure applied soil (Chen et al., 2013), and resulted in differences in timing and the amount of simulated and observed soil NO_3^{-}-N under high tunnels. RZWQM2 simulated results showed continuous N mineralization and denitrification process during the fallow period in HT system, that simulated loss (the major contribution being from denitrification), and resulted in decreased simulated soil NO_3^{-}-N concentration present in soil during fallow period. Cassman and Munns (1980) reported that there is significant interactive effect of soil water and temperature on N mineralization. Sharp decline in net N mineralization occurs between 0.3 and 2-bar and thereafter it decreases gradually over the 2- to 10-bar range at all temperatures (Cassman and Munns, 1980). Reduced soil microbial activity could be expected in fallow periods without irrigation in the high tunnels (Knewtson et al., 2012), which are protected from rainfall, and are only irrigated during the crop growing period. Despite having higher soil temperature in the tunnel, a driver of microbial activities in soil, is overridden by the reduced organic decomposition when moisture is a limiting factor (Knewtson et al., 2012). Nitrate leaching was also significantly reduced from greenhouse grown vegetables in elevated temperature conditions, which led to higher NO_3^- concentrations in greenhouse condition than in open field conditions.

In the LI system, simulated soil NO_3^--N values in the surface layer (0-15 cm) were not in good agreement with the observed values throughout the rotation, with R^2 values below 0.10 and RMSE values ranging between 4.59 to 31.82 kg ha^{-1} during crop growing seasons (Table 3.4). However, the simulated 15-30 cm soil NO_3^--N content were in good agreement with the measured values, except for the bean growing season. The simulated soil NO_3^--N content values at 30-50 cm depth were in excellent agreement with the measured values showing the R^2 values more than 0.70 for all crops except collard (R^2 = 0.18) and pepper and, RMSE values ranging between 2.09 – 4.24 kg ha^{-1} (Table 3.4).

3.3.4 ***Nitrous oxide emissions***

The measured and simulated cumulative N_2O-N emissions during each cropping season in CONV, HT and LI system are presented in Table 3.5 and daily N_2O fluxes are shown in Figure 3.4(d) for CONV, Figure 3.5(d) for HT and Figure 3.6(d) for LI system. In the CONV system, RZWQM2 simulated the cumulative N_2O-N emission well from 2014 to 2016, while the model generally overestimated fluxes in HT system and underestimated fluxes in LI system the total N_2O-N emission throughout the crop rotation.

In the CONV system, observed cumulative N_2O-N emissions were 0.25, 0.29, 1.10, 0.25, and 0.93 kg N_2O-N ha^{-1} during pepper, cover crop, beet, collard and bean growing season, while the simulated N_2O-N emissions were 0.74,0.10, 0.67, 0.62 and 0.68 0.96 kg N_2O-N ha^{-1} during pepper, cover crop, beet, collard and bean growing season (Table 3.5). For the CONV system, RZWQM2 reliably simulated the N_2O emissions, showing the R^2 values 0.36 to 0.78 except for cover crop and RMSE values between 0.90 to 6.83 g N_2O-N ha^{-1} day^{-1}. RZWQM2 overestimated the emission during the pepper and collard growing season while underestimating emission during cover crop, beet and bean growing season. It should be noted that the pepper and collard were grown under plastic mulch. The model was able to reliably simulate the peaks of N_2O emission in the CONV system (Figure 3.4(d)) but simulated higher fluxes than measured just after the tillage and incorporation of fertilizer after pepper planting. The better simulation of magnitude and timing of soil NO_3^--N and N_2O fluxes in the CONV system might be related to the source of N, and the spatial pattern of synthetic N fertilizer application. Fang et al. (2015) and Gillette et al. (2017) also reported good agreement between RZWQM2 simulated and measured N_2O emissions from synthetic N fertilizer field with/without tillage. In the CONV system, the overestimation of N_2O during the pepper (which were grown under plastic mulch) growing season might be related to the overestimation of soil temperature. Kim et al. (2014) also reported greater simulated N_2O emissions than measured values with radish grown under plastic mulch and fertilized with 50-150 kg N ha^{-1}.

In the HT system, the measured cumulative N_2O-N emissions were 0.59, 0.39, 0.69, 1.20 and 1.59 kg N_2O-N ha^{-1}, whereas simulated values were 2.11,0.45, 0.71, 1.42 and 3.03 kg N_2O-N ha^{-1}, during the pepper, cover crop, beet, collard and bean growing season (Table 3.5). In the HT systems, RZWQM2 simulated cumulative N_2O-N emissions were close to measured values during the lettuce, beet and collard growing season, but overestimated the cumulative N_2O-N emission during the pepper and bean portions of the rotation. This overestimation of the N_2O-N emission in high tunnels might be related to the simulation of higher peaks just after fertilizer application. In general, simulations underestimated the soil NO_3^--N content but overestimated soil N_2O emissions. There are various practices that may not be well simulated in RZWQM2 that contribute to this discrepancy. First, high tunnels are structures that exclude rainfall from the growing environment. As such, water for crops was provided exclusively by irrigation; soil temperature and moisture dynamics vary from the open field conditions in which the model was developed and is typically used. Irrigation inputs were applied via drip irrigation, as discussed above. Finally, this system utilized compost applications prior to crop planting, which may mineralize at rates greater than predicted in the simulation. The net effects of these discrepancies resulted in a variation in timing of denitrification and nitrification and other N processes between simulated and observed conditions in high tunnels. These issues are demonstrated in simulation results such as those shown in Figure 3.5(d), which show N_2O peaks on August 11th, 2014 and August 20th, 2015, that were larger than the measured values, and which contributed largely to the cumulative fluxes in the HT system. RZWQM2 simulated higher N_2O emissions in the HT system, but lower N_2O emissions in the HT were observed in our work. Most of the literatures showed that N_2O fluxes increased exponentially with increasing soil moisture, temperature and NO_3^- content and decreases with reduced soil moisture content (Dobbie et al., 1999). The algorithms for N_2O emission, adopted by Fang et al. (2015) to incorporate into RZWQM2 model, are based on soil water content, soil temperature, and soil N content. The interactive effect of changed temperature and soil moisture content on N_2O emissions varies with different agro-ecosystems with different agricultural management. Decreased N_2O emissions indicated might be attributed to an overriding effect of dry soil moisture conditions on N_2O emissions in N-fertilized vegetable soil even though enough soil N substrate was present (Xu et al., 2016). Warmer and drier conditions, as in high tunnels, could affect both the population abundance and community structure of nitrifiers and denitrifiers in the vegetable soil (Xu et al., 2016).

In the LI system (Table 3.5), the measured N_2O-N emissions were 2.73, 0.13, 1.38, 0.98 and 0.39 kg N_2O-N ha^{-1}, whereas the RZWQM2 simulated values were 0.36, 0.12, 0.22, 0.41 and 0.14 kg N_2O-N ha^{-1} during the pepper, cover crop, beet, collard and bean growing seasons, respectively (Table 3.5). RZWQM2 underestimated the cumulative N_2O-N emission for all crop in the LI system. The plots in the LI system were converted from rotational grazing pasture into crop fields to grow vegetable in 2014. At the start of the crop in 2014, we observed large peaks of N_2O flux but that decreased in subsequent years. The model could not simulate the large peaks at the starting of the planting season in 2014. The first month after pepper planting was the major contributor to the overall observed emission in LI system, which contributed 25 % of observed cumulative emission during entire cropping period from 2014 to 2016. Pinto et al. (2004) reported high N_2O flux after tillage operations followed by rapid reduction in perennial grasslands. The RZWQM2 model estimated the N_2O emission based on the existing soil N content and the soil water content. The role of crop residue on N_2O emission is complex and is not taken into account by RZWQM2. The addition of the crop residue not only supply the N for N_2O production, it also enhanced oxygen depletion by stimulating microbial respiration and promoted anaerobic conditions for denitrification and N_2O production (Chen et al., 2013). In a laboratory study by Kravchenko et al. (2017), gravimetric soil water content of the plant residue (separated from soil-residue mixture) exceeded gravimetric soil water content of soil from soil residue mixture by a factor of 4-10, accelerated N_2O emission. Deng et al. (2013) reported the significantly increased N_2O emission from soil from vegetable production systems after addition of the organic matter. In LI, the simulated N_2O emissions were lower than the measured values. The simulated N leaching from LI vegetables were higher than from the other two systems. The major simulated N leaching loss in LI systems were contributed by the fallow period and the collard growing period. Elevated N leaching was reported by Evanylo et al. (2008) during winter when soil is without an actively growing crop and precipitation exceeds evaporation. Simulation results also showed the 60 and 74 kg ha^{-1} of mineralized N during the fallow period and collard in LI system. The higher N leaching from the crop field converted from pasture might be attributed to underestimating mineralized N from residues and higher infiltration rate (Evanylo et al., 2008).

3.3.5 *Crop yield and biomass*

The measured and simulated crop yield on dry matter basis in CONV, HT and LI systems are shown in Table 3.6. RZWQM2 was reliably able to estimate the pepper, beet and bean yield in all systems. Collard yield were overestimated, as we did not sample total plant biomass at each green leaf harvesting, rather only harvestable yield, whereas the model included all the leaves on the plant. Measured beet yields were low due to weed pressure in LI system. Collard yields were low due to low seasonal temperatures during the collard growing season, which was expected and is well simulated by RZWQM2. Green bean yields were overestimated by RZWQM2 in the LI system compared to the measured yield, which may be due to model not accounting for N uptake by weeds during bean growing season.

3.3.6 *Model simulated outputs through the soil profile*

The simulated soil N mineralization, immobilization as well as denitrification, runoff, seepage and emission losses of N from the 100 cm soil profile from each crop growing season from CONV, HT and LI system are presented in Table 3.7. In LI system, The N simulated seepage losses were higher during the fallow period and crop growth failure during beets (due to weed pressure) and collards (due to very low temperature during early growth). This shows the lack of growth of plant not only results in loss of crop yield, but also leads to the losses of N from the field.

3.4 Conclusion

RZWQM2 was selected for this purpose due to recent modifications to accommodate vegetable production and for its widespread use in simulating soil N and C processes, and provision to simulate soil water and temperature under plastic mulch. Our results suggest that RZWQM2 may effectively simulate soil temperature, soil water and N dynamics and vegetable yields grown for crops grown on bare ground (e.g. beet, collard and bean). RZWQM2 underestimated the soil temperature for all crops except for pepper, which were grown under black plastic mulch. RZWQM2 simulated soil NO_3^--N content reasonably well during beet, collard and bean growing seasons in CONV and LI systems, but could not simulate well during pepper crops which were grown under plastic mulch. RZWQM2 simulated cumulative N_2O emission from 2014 to 2016 reasonably well compared to field measured values in the CONV system, while the model overestimated it in the HT system and underestimated it in the LI system. Crop yields were simulated well in all systems. RZWQM2 simulated soil water content well in CONV, HT, and LI vegetable systems. Although vegetable systems are very complex in terms of the crop use, fertilizer use, crop rotation, tillage frequency, the use of a well calibrated model helps researchers better understand the soil N dynamics and leaching.

3.5 Tables and figures

Table 3.1 Measured soil bulk density (BD) and texture and calibrated saturated hydraulic conductivity (Ksat), saturation (θs), 1/3 bar ($\theta_{1/3}$), 15 bar (θ_{15}) and residual (θr) soil water content

					Uncalibrated			Calibrated				
Soil depth (cm)	BD (g cm^{-3})	Sand %	Silt %	Clay %	Ksat cm hr^{-1}	$\theta_{1/3}$ (cm^3 cm^{-3})	θ_{15}	Ksat cm hr^{-1}	$\theta_{1/3}$ (cm^3 cm^{-3})	θ_{15}	**θ_s** (cm^3 cm^{-3})	θr
0-15	1.41	7	76	17	0.68	0.285	0.135	0.48	0.305	0.125	0.46	0.015
15-30	1.43	7	76	17	0.68	0.295	0.153	0.48	0.305	0.133	0.46	0.015
30-50	1.45	6	65	29	0.15	0.321	0.204	0.15	0.312	0.174	0.45	0.04
50-70	1.45	6	65	29	0.15	0.318	0.215	0.15	0.312	0.215	0.45	0.04
70-100	1.47	6	62	32	0.15	0.325	0.225	0.15	0.324	0.225	0.44	0.04

Table 3.2 Measured and simulated daily average temperature, R^2 and RMSE values of soil temperature (ST) in Conventional (CONV), High Tunnel Organic (HT), and Low Input (LI) system during 2014-2016.

Cropping system	Crops	Mes soil temperature (°C)	Sim soil temperature (°C)	RMSE (°C)	R^2
CONV	Pepper	24.2	26.5	1.22	0.43
	Cover crops	7.0	4.0	3.68	0.81
	Beets	17.3	15.0	2.49	0.85
	Collards	14.2	14.0	3.27	0.86
	Beans	21.1	19.6	2.85	0.60
HT	Pepper	21.1	21.2	1.26	0.86
	Lettuce	11.2	3.6	3.02	0.84
	Beets	15.1	11.5	2.90	0.78
	Collards	15.7	11.9	2.83	0.81
	Beans	22.7	20.2	3.15	0.63
LI	Pepper	26.0	27.6	2.35	0.24
	Fallow	7.9	3.6	3.21	0.93
	Beets	19.2	18.3	1.93	0.92
	Collards	15.4	11.0	3.03	0.76
	Beans	23.0	19.7	3.55	0.49

*Mes = Measured, Sim = Simulated, RMSE = Root Mean Square Error

Table 3.3 Measured and simulated average, R^2 and RMSE values of volumetric soil water content in Conventional (CONV), High Tunnel Organic (HT), and Low Input (LI) system during 2014-2016.

Cropping system	Crops	10 cm				30 cm				50 cm			
		Mes	Sim	RMSE	R^2	Mes	Sim	RMSE	R^2	Mes	Sim	RMSE	R^2
		$cm^3\ cm^{-3}$				$cm^3\ cm^{-3}$				$cm^3\ cm^{-3}$			
CONV	Pepper	0.39	0.43	0.08	0.44	0.41	0.44	0.03	0.83	0.43	0.43	0.01	0.71
	Cover crops												
	Beets	0.36	0.41	0.05	0.6	0.37	0.42	0.05	0.57	0.41	0.41	0.04	0.16
	Collards	0.37	0.42	0.02	0.18	0.39	0.43	0.01	0.14	0.41	0.42	0.01	0.4
	Beans	0.37	0.35	0.04	0.33	0.4	0.36	0.05	0.07	0.42	0.36	0.02	0.18
HT	Pepper	0.37	0.41	0.01	0.74	0.41	0.41	0.03	0.41	0.41	0.4	0.02	0.57
	Lettuce	0.26	0.2	0.02	0.62	0.3	0.22	0.01	0.87	0.34	0.26	0.001	0.91
	Beets	0.24	0.3	0.05	0.77	0.29	0.31	0.04	0.81	0.34	0.33	0.02	0.89
	Collards	0.31	0.36	0.06	0.12	0.35	0.36	0.04	0.17	0.38	0.36	0.04	0.18
	Beans	0.25	0.24	0.04	0.74	0.29	0.26	0.04	0.74	0.31	0.29	0.03	0.66
LI	Pepper	0.3	0.35		1	0.35	0.36		1	0.38	0.37		1
	Fallow												
	Beets	0.36	0.33	0.05	0.7	0.35	0.36	0.04	0.81	0.38	0.37	0.04	0.65
	Collards	0.29	0.35	0.03	0.84	0.32	0.37	0.02	0.92	0.35	0.38	0.03	0.86
	Beans	0.27	0.26	0.06	0.36	0.28	0.29	0.05	0.33	0.31	0.31	0.06	0.46

*Mes = Measured, Sim = Simulated, RMSE = Root Mean Square Error

Table 3.4 Measured and simulated average, R^2 and RMSE values of soil NO_3^--N content in Conventional (CONV), High Tunnel Organic (HT), and Low Input (LI) system during 2014-2016.

Cropping System	Crops	0-15 cm				15-30 cm				30-50 cm			
		Mes	Sim	RMSE	R^2	Mes	Sim	RMSE	R^2	Mes	Sim	RMSE	R^2
		kg N ha^{-1}				kg N ha^{-1}				kg N ha^{-1}			
CONV	Pepper	107	13	89.19	0.34	67	10	37.50	0.54	76	10	43.13	0.27
	Cover crops	29	13	9.48	0.95	34	12	17.64	0.38	40	10	10.92	0.44
	Beets	16	5	3.31	0.97	7	5	2.87	0.54	8	5	6.44	0.17
	Collards	5	6	6.22	0.09	3	10	2.31	0.16	3	5	1.75	0.38
	Beans	16	9	10.25	0.39	12	5	7.21	0.55	12	4	2.92	0.85
HT	Pepper	88	24	48.73	0.06	28	10	11.09	0.38	66	10	59.06	0.03
	Lettuce	107	20	78.85	0.09	26	4	4.93	0.90	76	1	54.93	0.00
	Beets	54	50	24.12	0.26	21	5	7.27	0.00	26	3	10.28	0.46
	Collards	33	65	27.76	0.13	11	31	3.60	0.87	25	21	15.47	0.64
	Beans	38	75	20.27	0.12	17	24	17.27	0.05	18	21	9.74	0.00
LI	Pepper	45	6	31.82	0.10	21	16	5.10	0.95	35	20	4.24	0.84
	Fallow	10	4	4.59	0.29	8	8	1.40	0.84	8	13	2.09	0.71
	Beets	22	13	18.31	0.07	9	10	7.21	0.10	13	9	3.77	0.80
	Collards	7	19	8.06	0.02	7	15	3.54	0.66	7	12	2.45	0.18
	Beans	14	12	11.35	0.07	13	5	10.85	0.03	8	5	3.51	0.77

*Mes = Measured, Sim = Simulated, RMSE = Root Mean Square Error

Table 3.5 Measured and simulated cumulative N_2O-N flux during each crop period, R^2 and RMSE values in Conventional (CONV), High Tunnel Organic (HT), and Low Input (LI) system during 2014-2016.

Cropping system	**Crops**	**Measured cumulative kg N ha^{-1}**	**Simulated cumulative kg N ha^{-1}**	**RMSE g N_2O -N ha^{-1} day^{-1}**	**R^2**
CONV	Pepper	0.25	0.74	2.45	0.60
	Cover crops	0.29	0.10	1.78	0.01
	Beets	1.10	0.67	6.83	0.36
	Collards	0.25	0.62	0.90	0.78
	Beans	0.93	0.68	4.54	0.63
HT	Pepper	0.59	2.11	4.09	0.04
	Lettuce	0.39	0.45	4.54	0.04
	Beets	0.69	0.71	11.17	0.14
	Collards	1.20	1.42	2.93	0.84
	Beans	1.59	3.03	8.03	0.31
LI	Pepper	2.73	0.36	23.80	0.29
	Fallow	0.13	0.12	1.00	0.10
	Beets	1.38	0.22	19.74	0.20
	Collards	0.98	0.41	2.25	0.01
	Beans	0.39	0.14	3.30	0.07

*RMSE = Root Mean Square Error

Table 3.6 Measured and simulated crop yield during the cropping season 2014-2016.

	Crops	Yield (Dry matter kg ha^{-1}) Measured	Simulated
CONV	Pepper	4128	4398
	Beet	5805	6884
	Collards	3599	6892
	Beans	2739	3336
HT	Pepper	5944	6403
	Beet	4936	4810
	Collards	4488	3839
	Beans	1220	1230
LI	Pepper	2669	4871
	Beet	487	312
	Collards	469	192
	Beans	576	2073

Table 3.7 Simulated soil N processes and loss pathways from 100 cm soil profile in three vegetable systems

	Crops	Mineralization	Immobilization	Denitrification	N Runoff	N Seepage	N_2O Emission	N_xO Emission	Plant N uptake
				kg N ha^{-1}					
CONV	Pepper	173	3	168	3	30	18	3	134
	Cover crops	45	0	29	0	19	4	1	24
	Beets	66	3	43	6	23	5	1	69
	Collards	109	7	51	0	26	9	5	163
	Beans	150	3	53	1	16	7	2	146
HT	Pepper	358	18	77	2	11	10	4	265
	Lettuce	144	25	115	0	1	10	4	108
	Beets	291	23	50	0	6	4	1	91
	Collards	194	27	57	0	22	8	2	175
	Beans	349	22	38	0	9	6	3	109
LI	Pepper	181	17	32	0	59	3	1	168
	Fallow	60	5	12	0	70	1	0	0
	Beets	69	3	12	1	36	2	1	26
	Collards	74	10	12	0	69	2	1	2
	Beans	124	3	7	1	11	2	1	131

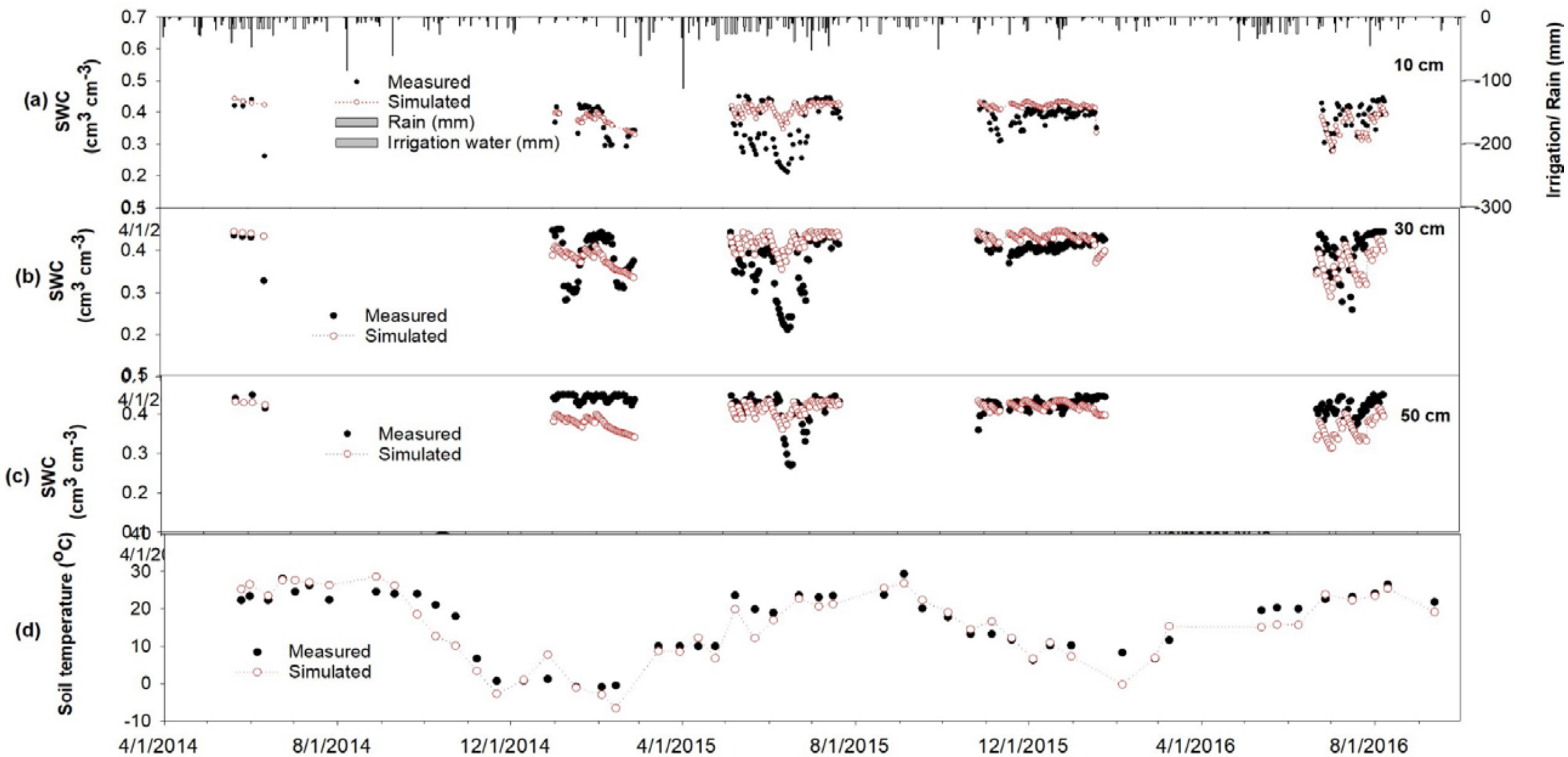


Figure 3.1 Measured and simulated soil water content at (a) 10 cm (b) 30 cm and (c) 50 cm and (d) soil temperature at 10 cm in Conventional System (CONV) during the year 2014-2016.

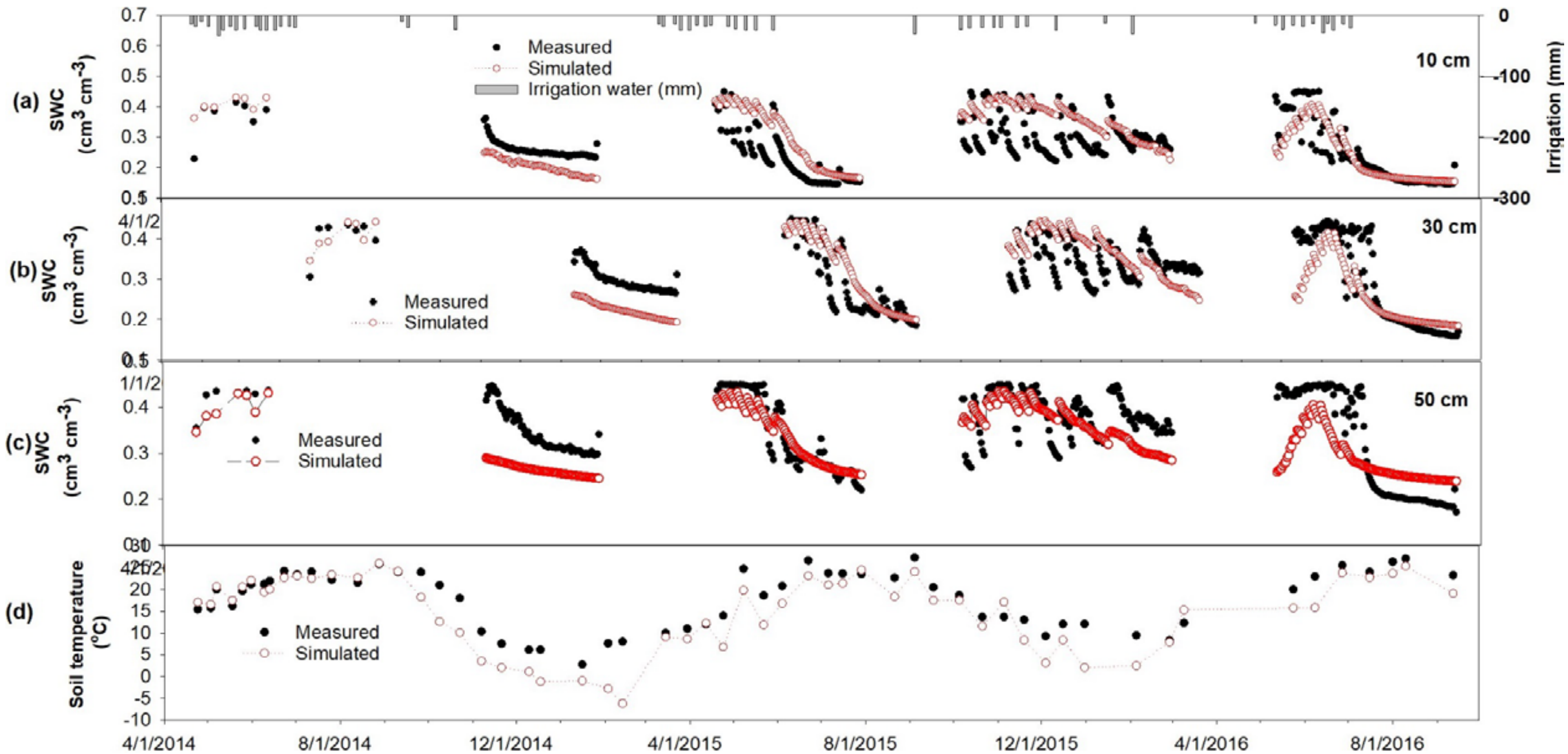


Figure 3.2 Measured and simulated soil water content at (a) 10 cm (b) 30 cm and (c) 50 cm and (d) soil temperature at 10 cm in High Tunnel Organic System (HT) during the year 2014-2016.

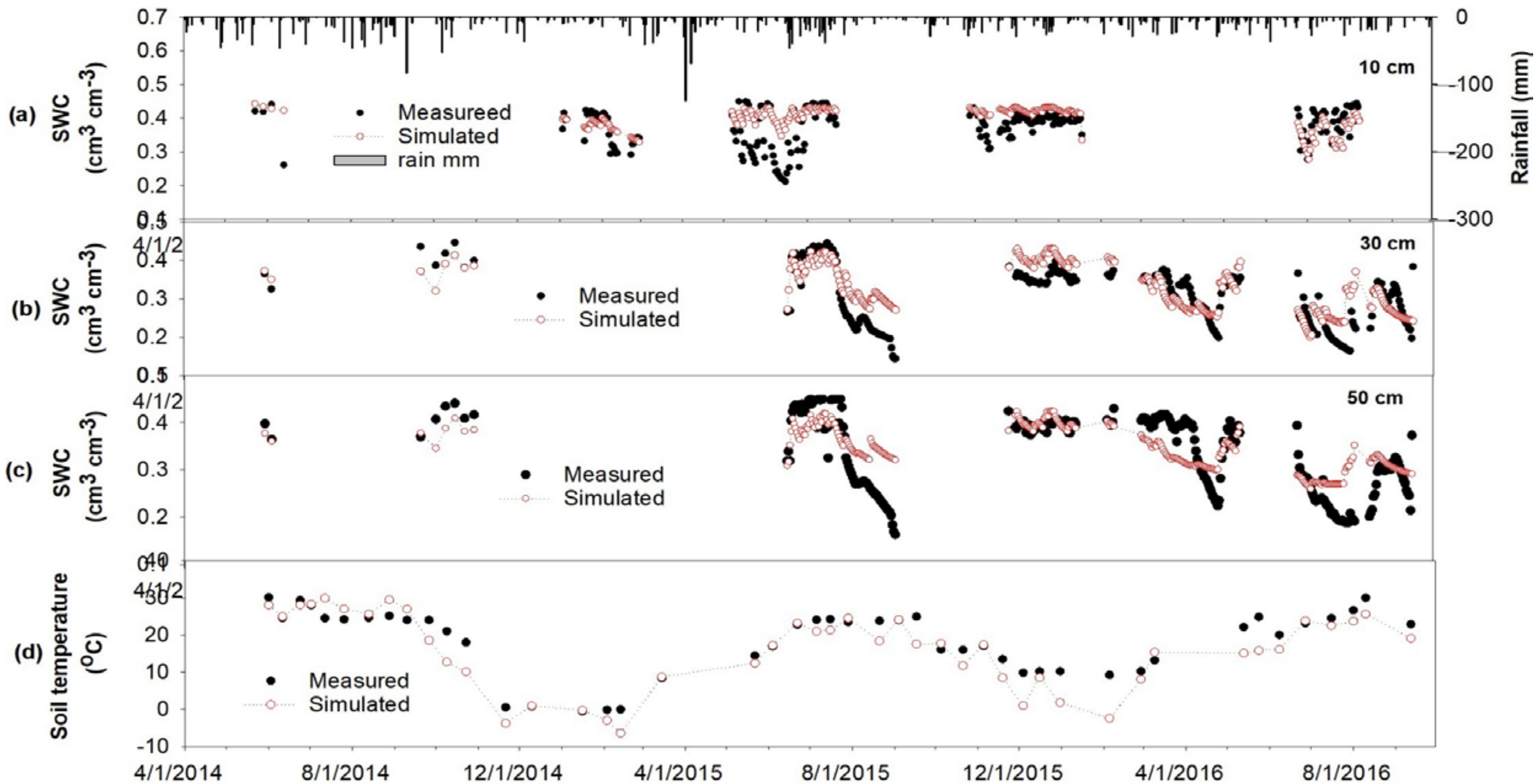


Figure 3.3 Measured and simulated soil water content at (a) 10 cm (b) 30 cm and (c) 50 cm and (d) soil temperature at 10 cm in Low Input System (LI) during the year 2014-2016.

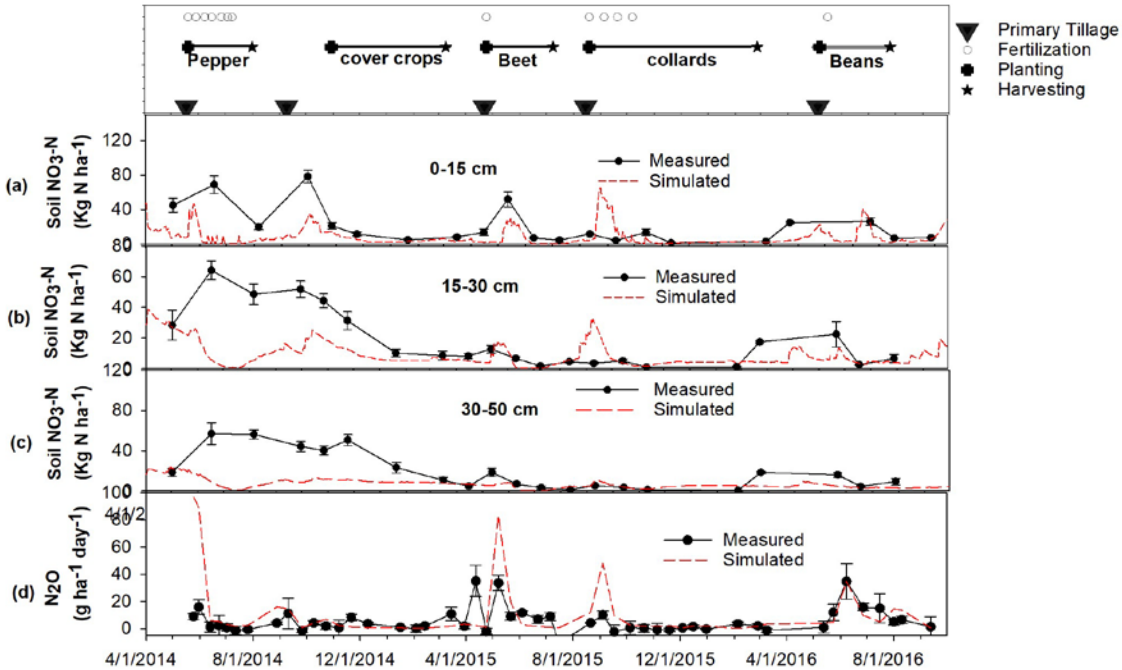


Figure 3.4 Measured and simulated soil NO_3^--N in layer (a) 0-15 cm (b) 15-30 cm (c) 30-50 cm and (d) N_2O emission in the Conventional System (CONV) during the year 2014-2016.

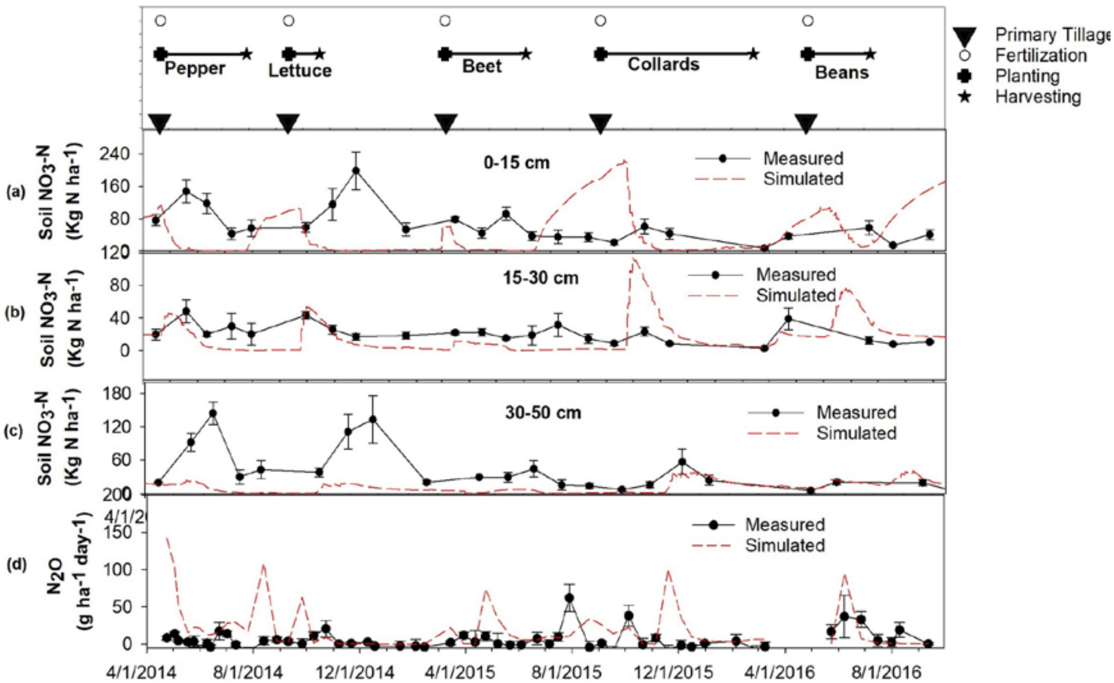


Figure 3.5 Measured and simulated soil NO_3^--N in layer (a) 0-15 cm (b) 15-30 cm (c) 30-50 cm and (d) N_2O emission in the High Tunnel Organic System (HT) during the year 2014-2016.

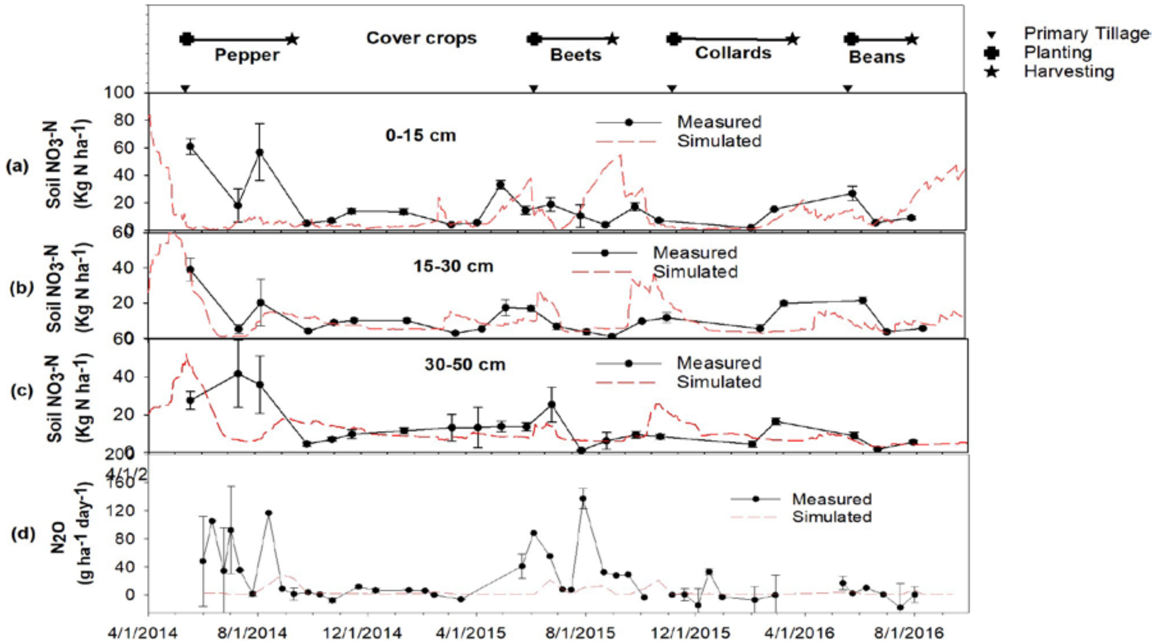


Figure 3.6 Measured and simulated soil NO_3^{-}-N in layer (a) 0-15 cm (b) 15-30 cm (c) 30-50 cm and (d) N_2O emission in Low Input System (LI) during the year 2014-2016.

CHAPTER 4. CHARACTERIZING THE SUSTAINABILITY OF INTENSIFICATION IN VEGETABLE SYSTEMS

4.1 Introduction

Sustainable intensification, and related concepts, are increasingly being advocated as frameworks to reconcile needs for increasing agricultural yields with maintaining environmental integrity (Wezel et al., 2015). Agricultural input efficiency (AIE) has been proposed as a holistic metric to evaluate agriculture's environmental impact relative to yields (e.g. Robertson and Swinton, 2005; Clark and Tilman, 2017). Measured as the amount of food produced per unit of input, AIE has utility in evaluating the point at which when additional inputs do not equate to additional yields, and subsequently are linked to impacts on the environment (Clark and Tilman, 2017). AIE has been used as a unifying concept for discussions linking input:output efficiencies to the broader impacts of agriculture on the environment, including energy use, land use, nutrient impact on waterways, and greenhouse gas emissions (Clark and Tilman, 2017). Among these, nitrogen (N) losses from agricultural systems to the environment have been considered the most problematic (e.g. Robertson and Swinton, 2005). The nitrogen use efficiency (NUE) of a cropping system can be increased by achieving greater N uptake efficiency from applied N and reducing the amount of N lost from soil organic and inorganic N pools (Cassman et al., 2002).

Sustainable agriculture-oriented vegetable production systems, whether managed according to an environmentally-minded certification (e.g. USDA organic, etc.) or utilizing conservation-minded best practices are managed with explicit intention to minimize environmental impact while optimizing yields. However, evaluating NUE, and AIE more generally in such alternative systems is lacking (Clark and Tilman, 2017).

Historically system comparisons have been binary, pitting conventional vs. organic (e.g. Seufert et al., 2012), or greenhouse vs. open field (Clark and Tilman, 2017). However, specific production practices related to the intensity of production systems are highly variable, even among sustainable and organic vegetable production systems.

A finer-scale understanding of how organic inputs and their management in the context of the farming system influences the temporal dynamics of soil inorganic N availability is needed to balance the essential soil functions of providing crop fertility while reducing N losses to the environment (Norris and Congreves, 2018).This work aims to characterize AIE, specifically NUE and the N dynamics driving uptake and losses, across a gradient of sustainable vegetable production systems utilized in the mid-southern region of the US. Intensification in these systems is characterized by fertilization, water use, tillage, and use of fallow periods. Such data offer the opportunity to evaluate the "trade-offs" between specific environmental impacts and yield, utilizing model crops produced in the spring, summer, and fall.

4.2 Materials and methods

Three model crops, representing typical crops grown seasonally in the region, were studied for three years in each of five production systems, beginning in early spring, 2014 (Table 4.1). The five systems spanned two sites in central Kentucky with Maury silt loam soil (a fine, mixed, active, mesic Typic Paleudalfs); 1) The University of Kentucky Horticulture Research Farm (UK HRF) in Lexington, KY (37°58'29"N, 84°32'05"W); 2) a local organic farm in Scott County, Kentucky (38°13'20"N, 84°30'38"W). Both farms are in the central Bluegrass region of Kentucky, with similar rainfall, temperature, and soil type (annual precipitation of 1209, 1475 and 1011 mm; average air temperature of 12 ºC, 13.3 ºC and 14.2 ºC in 2014, 2015 and 2016, respectively). Each system contained three replicate plots measuring 9 m x 0.75m.

4.2.1 *Cropping systems*

The five vegetable production systems were selected to represent a gradient of intensification, as characterized by duration of fallow periods, tillage intensity, irrigation, and fertilization (Figure 4.1). General management aspects of each of these systems are described below.

4.2.1.1 Low input system (LI)

The LI system is based on an 8-year rotation consisting of a five-year period of mixed grass/legume pasture that is rotationally grazed or cut for hay for grass-finished beef and calf production. After the five-year fallow period, the pasture was broken with deep inversion plowing, disking and surface rototilling to transition fields into a three-year rotation of annual crops. No supplemental fertilizer was added, and drip irrigation was provided only for the pepper crop. Crops produced on bare ground received only natural rainfall and no supplemental irrigation. Tillage and fertilizer for model crops are detailed in Table 4.1. For the past 15 years, the farm has grown diversified organic vegetables in the annual crop portion of the rotation, after transitioning from two generations of conventional tobacco production in a similar rotation. This system is representative of a low external input commercial organic vegetable farming system, and is a working partner farm marketing a diversity of organic vegetable crops and animal products through local market channels.

4.2.1.2 Community supported agriculture system (CSA)

The CSA system is characterized by the seasonal production of vegetable crops with inclusion of cover crops once per year in rotation. The rotation involves production of over 40 different vegetable crops, grown in a rotation based on alternation of botanical families. Vegetable crops were supplied with 25 ton ha^{-1} compost one time per year, in the Fall, typically followed by a cool season (Winter) cover crop. A granular, manure-based organic fertilizer (Nature Safe 10-2-8, Darling Ingredients, Irvine, TX) applied at the time of planting to bring the crop fertility to the commercial production recommended fertilizer rate (UK Cooperative Extension Service, 2014) using a nutrient budget approach which accounts for roughly for the nutrient contribution of the compost additions and legume cover crop. All crops were irrigated with sub-surface drip irrigation. All crops were drip irrigated in every 2-3 days interval in summer and 3-4 days interval in winter season depending on rainfall. Annual primary tillage using a rotary spader (Imants, ImantsUSA, Perkiomenville, PA) was used to incorporate cover crop residue and prepare fields, followed by frequent shallow cultivation utilizing ground-driven rolling basket weeders or finger weeders for weed control. Tillage and fertilization for model crops are detailed in Table 4.1. This system is representative of a medium-scale, input- and mechanization-intensive commercial organic vegetable farming operation utilizing best management practices for open-field organic production. This is a working demonstration and education farm on the UK Horticulture Research Farm site, marketing a diversity of organic vegetable crops primarily through a community supported agriculture program.

4.2.1.3 Movable high tunnel system (MOV)

Movable high tunnels are full size (9.1 m x 22 m) passive solar greenhouses made of steel framing with a polyethylene film coating that are moved once per year (see High Tunnel system for additional description). MOV structures were rotated through a series of three positions such that crops are grown under the cover of the structure for one year continuously, then the structures were moved, and cropped area is planted into legume and cereal cover crops for two years. After 2 years, tunnels moved back to previous place to grow organic vegetable crops. In the MOV system, 24 ton ha^{-1} horse manure compost and 45 kg N ha^{-1} of pelleted organic fertilizer (Harmony 5-4-3, BioSystems, LLC, Blacksburg, VA) were applied in to soil before planting each crop. Irrigation in the MOV system was via drip irrigation, as the plastic cover over the structure excluded all rainfall. All crops were drip irrigated in every 2-3 days interval in summer and 3-4 days interval in winter season. Tillage and fertilization for model crops are detailed in Table 4.1. This system is representative of an alternative production system for organic high tunnel production focused on maintaining soil health and reducing disease incidence in these typically production-intensive systems.

4.2.1.4 Conventional system (CONV)

The CONV system consisted of a winter wheat (*Triticum aestivum*) cover crop terminated by mowing and tillage in early spring utilizing a rotary spader, followed by seasonal annual vegetable production. Fertilization included complete, balanced mineral fertilizers (Miller 19-19-19, Miller Chemical and Fertilizer, Hanover, PA) applied pre-plant and in-season, split-application of calcium nitrate fertilizer (13-0-0, PureCal, Master Plant-Prod Inc., Brampton, ON) via fertigation when required for the crop as per commercial vegetable production recommendations for the study region (UK Cooperative Extension Service, 2014). All crops were drip irrigated in every 2-3 days interval in summer and 3-4 days interval in winter season depending on rainfall. Tillage and fertilization for model crops are detailed in Table 4.1. This system is representative of an input-intensive conventional vegetable production system utilizing best management practices.

4.2.1.5 High tunnel system (HT)

The HT consisted of three, replicated static unheated 9.1 m x 22 m steel structures with polyethylene film covering. As is typical for management of these structures, crops are grown in soil without supplemental heat or light, and are only passively ventilated through manual opening of doors and side curtains. High tunnel systems are “season extending” technologies used in specialty crop production, allowing for lengthening the growing season of warm-season crops by approximately one month each in the spring and fall, and allowing for production of cool-season vegetables throughout the winter in the study region. Also typical to these systems, cover crops were not used, as these intensive production systems often are used to produce of high value crops at times when market premiums are captured through early or late season production. As such, fallow periods are not considered economically efficient unless they address a production issue, such as pathogen or pest management. All crop residues were removed from the system to minimize pathogen presence. In the HT system, 24 ton ha^{-1} horse manure compost (Wet mass) and 45 kg N ha^{-1} of pelleted organic fertilizer (Harmony 5-4-3, BioSystems, LLC, Blacksburg, VA) was applied to soil before planting each crop. Supplemental fertigation with liquid organic fertilizer (Brown’s Fish Fertilizer 2-3-1, C.R. Brown

Enterprises, Andrews, NC) was applied in-season only to the sweet pepper crop, at flowering and heavy fruit set (twice total) at the recommended rate constituting an additional 28 kg N ha^{-1} at each fertigation event. Irrigation in the HT system was via drip irrigation, as the plastic cover over the structure excluded all rainfall. All crops were drip irrigated in every 2-3 days interval in summer and 3-4 days interval in winter season. Tillage and fertilizer inputs for model crops are detailed in Table 4.1. The system is representative of year-round, organic high tunnel production systems that are input- and production-intensive.

4.2.2 ***Model crops and management***

Model crops were selected based upon crops that would be representative of production practices in each model system (Table 4.1). As this project takes a systems approach, timing of production varies slightly between systems, particularly between the open field systems (LI, CSA and CONV) and the protected agriculture systems (MOV and HT). Model crops were selected representing spring, summer, and fall production; table beet (*Beta vulgaris* L., 'Red Ace'), sweet pepper (*Capsicum annum* L., 'Aristotle') and collard greens (*Brassica oleracea* L. *var. medullosa*, 'Champion'), respectively. Three plots measuring 13.5 m^2 each were randomly assigned within crop rows in each of the systems. Rows were located in fields consisting of diversified vegetables in the LI and CSA systems, with adjacent rows in plants of the same botanical family and/or management regime. Fields in the CONV system were monocultures of the model crop. Rows in the HT and MOV systems were within diversified tunnel systems consisting of varies of crops being grown for season extension purposes. Model crops were in different fields/rows each year, following the rotation scheme representative of each system.

4.2.3 *Soil sampling*

Soils were sampled monthly at 0-15, 15-30, and 30-50 cm depths for mineral N (NH_4^+ and NO_3^-). On each sampling date, three cores were taken per plot at each depth, homogenized, and bulked for a single analysis per plot. Fresh soil samples were kept refrigerated (~ 4.4º C) until processing, passed through a 2 mm sieve and processed within 24 h of sampling. Soil mineral N was extracted from a 5 g subsample of fresh soil in 20 ml of 1M KCl (Rice et al., 1984) and analyzed via microplate spectrophotometer (Epoch, BioTek Instruments, Inc., Winooski, VT), after NO_3^- was reduced using a cadmium reduction device (ParaTechs Co., Lexington, KY) (Crutchfield and Grove, 2011). Nitrate leaching was assessed using ion exchange resin (IER) lysimeters placed below the plant rooting zone (50 cm depth). IER lysimeters were constructed from PVC tubing after the method of Susfalk and Johnson (2002), using 2 teaspoonfuls of resin per lysimeter. IER lysimeters were replaced every three months, and once recovered, disassembled, with resin mineral N extracted using 100 ml of 2M KCl in the method as described above.

4.2.4 *Yield and plant biomass sampling*

Fresh vegetable yields for each system were measured from the entire plot area from each plot. Yields represent marketable yield for each system, which includes all direct market quality yields for the LI and CSA systems, and combined USDA grade 1 and 2 for each crop in the MOV, HT and CONV systems. Sweet pepper fruit, collard leaves and beans were harvested at multiple times as the harvestable portion reached marketable stage, and table beets were harvested once, as roots reached marketable size. Plant biomass samples were collected from 2, 0.25 m^2 samples per plot at the end of the growing season, dried at 60^0 C until a constant mass was achieved. Dried samples were homogenized on a Wiley Mill and a subsample ground on a jar mill (U.S. Stoneware, East Palestine, OH). Crop plant samples were analyzed for C and N content via elemental analysis (Flash EA 1112, CE Elantech Inc., Lakewood, CA).

4.3 Results and discussion

4.3.1 *Fresh vegetable yield*

The average fresh beet, pepper fruit and collard leaves yield from 2014 to 2016 in all five systems are presented in Table 4.2. Yields were consistently higher in the MOV system, and lowest in the LI system across all crops. The movable tunnels were moved every year, so the crops in the MOV system benefitted from the additional N supply by the cover crops compared to the HT system. CSA and CONV yields were not markedly different for any crop. Beet yields may have been low in the LI system due to low stand density, or poor germination due to lack of irrigation, compared to the other study systems, as well as higher weed pressure. Pepper yields may have been depressed in the LI system due to weed pressure as well. Collard greens were also consistently planted later in the LI system than in other systems, as is typical for the management of this production system. In this system, management preference is for extensive production with minimal input per unit area, with overall farm yields buffered by large cropping areas and great crop diversity to buffer low yields or a crop failure. Overall, high tunnel yields were greater due to improved crop quality grown under the protective structures, as well as higher planting density common in these systems.

4.3.2 *N leaching*

The average (of three growing season of a crop) NO_3^--N leaching per lysimeter from 2014 to 2015 are presented in Figure 4.2. Among the crops, the greatest mean NO_3^--N leaching values were observed during the spring beet crop, ranging from the smallest values in the MOV system (3.3 mg NO_3^--N per lysimeter) to a nearly four-fold increase in greatest values in the CSA system (12.8 mg NO_3^--N per lysimeter). It should be noted that these are numerical comparisons, as these characterization data have not been compared statistically. During the summer pepper crop, the greatest leaching loss were observed in the CONV system (7.7 mg NO_3^--N per lysimeter) and smallest in the HT system (1.5 mg NO_3^--N per lysimeter). During the fall collard crop, the greatest NO_3^--N leaching values were observed in the CSA system (10.5 mg NO_3^--N per lysimeter) and MOV system (6.7 mg NO_3^--N per lysimeter). Surprisingly, 4.5 mg NO_3^--N per lysimeter was observed in LI system, although no additional fertilizer or compost were applied to the pepper crops. The pepper crop was consistently in fields that were in the first year of vegetable production after the five-year pasture fallow, and experienced high levels of N mineralization with the decomposition of the incorporated fallow. Leaching in the fall collard crop were highest in the CSA, which may be due to bare ground production of collards in this system, while in the CONV system, collards were grown with plastic mulch. Generally, the leaching were lower in crops produced under protected structures (MOV and HT systems), in spite of greater soil mineral N content in these systems (Table 4.3). When compared among the open field systems, the higher leaching in CSA system might be attributed the higher N fertilizer application, in which crops were fertilized with 25 ton ha^{-1} of compost and supplemented by organic fertilizers.

4.3.3 ***Soil mineral N content***

Mean soil NO_3^--N at 0-15, 15-30 and 30-50 cm soil layer for each crop and system are presented in Table 4.3. Mean values were calculated from monthly samples, and averaged across the growing season for each model crop to characterize relative N availability in the model systems. Soil surface layer (0-15 cm) values were greatest in all crops and systems. Average soil NO_3^--N content in the 0-15 cm soil layer for the cool season beet and collard crops was below 31 kg N ha^{-1} in the open field systems, whereas values in the covered MOV and HT systems were more than 60 kg N ha^{-1}. Average soil NO_3^--N content in the 15-30 cm and the 30-50 cm soil layers followed similar trends as the 0-15 cm layer.

Average soil NO_3^--N was generally greater in the pepper crop than in the beet or collard crops, which may be attributed to greater total fertilization in each system to meet crop demand. In all systems except for the LI system, the pepper crop received split application of fertilizer, with several fertigation events throughout the season. The additional fertilizer applications maintained greater soil NO_3^--N throughout the growing season, compared to pre-plant only fertilizer application in other crops.

In the beet and collards crops, the average soil NO_3^--N content in all layers was greater in the tunnel systems (HT and MOV) compared to open field systems (CONV, CSA and LI). In the pepper crop, the LI, MOV, and HT systems had greater soil average soil NO_3^--N content in all layers. The elevated NO_3^--N content in the LI systems in this crop may be explained by the timing of the pepper in the crop rotation in the LI system. Crops with high nutrient demand, such as pepper, are typically grown in the first year of the crop portion of the eight-year rotation, immediately after incorporating the five-year pasture fallow.

4.3.4 ***N uptake relative to fertilization***

Total plant N uptake was calculated from the combined N content from the yield, aboveground, and belowground plant biomass fractions. Total N inputs were calculated from external fertilizer and compost N inputs for each system (Table 4.1). Compost N inputs were calculated from an estimated mineralization rate of 50% of the applied compost in the year of application (Leikam and Lamond, 2003). In the LI system, there were no external N fertilization, and so a value of 0 was applied. Average crop N uptake and N fertilizer applied in each system for each crop is presented in Table 4.4.

In the LI system, N uptake was greater than N applied for all crops, due to the zero value used for the quantity of N applied. This method accounts for only external inputs in this evaluation of efficiency, and is not reflective of total N inputs to the system. In the LI system, pepper uptake was greater than that of beet or collards. In the CSA system, N applied was consistently greater than crop N uptake. This may indicate that in the CSA system, in which fertility levels are guided by commercial vegetable production recommendations, there may be opportunities for reducing fertilization without sacrificing yields. In the MOV system, uptake was greater than N applied, driven by high yields relative to N fertilization. It should be noted that the two-year cover crop rotation prior to production in the MOV systems contributed to the relatively high yields in this system. Cover crop inputs are not accounted for using this method. In the CONV system, crop N uptake was greater than N applied in the beet and pepper crops and was nearly balanced in the collard crop. In the HT system, beet crop N uptake was greater than the quantity of N applied, whereas the uptake and application quantities were nearly balanced in the pepper and collard crops. Variability in crop N uptake values and the ratio of N uptake: N applied is largely a function of variability in crop yield from year-to-year. Many factors contribute to yield variability, including weather, crop management, and weed control, to name a few.

4.4 Conclusion

Overall the parameters evaluated in this study allow for relative comparisons of productivity, inputs, and efficiencies between the five study systems. The LI system demonstrated low yields relative to the other systems, and had high soil mineral N content and leaching in the first year after the incorporation of the pasture fallow. Soil mineral N content and leaching decrease in subsequent years of the vegetable crop rotation. The CSA system maintained yields and soil NO^{-}_{3}-N content consistent with the CONV commercial vegetable system. However, N inputs were in excess of crop N uptake for all model crops in the CSA system, and leaching were high during the beet and pepper crops, which were grown in the open field. The CONV system maintained N levels via fertigation of synthetic fertilizers and use of plastic mulches. Leaching values were particularly high in the beet crop, in which plastic mulches were not used and the spring season in which the crop was grown is typically cool with abundant rainfall. Crop N uptake in the CONV system was generally greater or equal to the quantity of N applied. In both high tunnel systems (HT and MOV), soil NO_3^--N was high throughout the soil profile. Yield was greatest in the MOV system when compared to the other five systems, likely due to the two-year cover crop rotation prior to production under the MOV structures. Yields in the HT system were also greater than the open field systems.

These results demonstrate that there are no clear categorical ranking of systems as characterized by input use, rotational fallow, nutrient losses, or yields. However, these results may provide opportunities for evaluating the efficiency of fertilizer inputs to yields. Such analyses are important metrics for assessing the sustainability of intensification efforts in agricultural systems.

4.5 Tables and figures

Table 4.1 Fertility and irrigation management for model crops in the five study systems.

System	Table Beets (*Beta vulgaris* L., 'Red Ace')	Sweet Pepper (*Capsicum annum* L., 'Aristotle')	Collards (*Brassica oleracea* L. *var. medullosa*, 'Champion')
Timing	Spring crop (2014, 2015 and 2016)	Summer crop (2014, 2015 and 2016)	Fall crop (2014 and 2015)
Plant Spacing	5 cm between plants in double rows per 50 cm bed, with 1 m between bed midpoints.	45 cm between plants in double rows per 75 cm bed, with 2 m between bed midpoints.	45 cm between plants in double rows per 75 cm bed, with 2 m between bed midpoints.
Low Input Organic (LI)	No compost or fertilizer No irrigation (rainfall only)	No compost or fertilizer Drip irrigation Black plastic mulch	No compost or fertilizer No irrigation (rainfall only)
Community Supported Agriculture (CSA)	25 ton ha^{-1} compost. 57 kg N ha^{-1} (2014), 67 kg N ha^{-1} (2015 and 2016) of organic fertilizers Sub-surface drip irrigation No mulch flat	25 ton ha^{-1} compost. 57 kg N ha^{-1} (2014), 100 N kg ha^{-1} (2015 and 2016) of organic fertilizers 33 kg N ha^{-1} of sodium nitrate (16-0-0) fertigation Sub-surface drip irrigation Black plastic mulch	25 ton ha^{-1} compost. 57 kg N ha^{-1} (2014), 67 kg N ha^{-1} (2015 and 2016) of organic fertilizers Sub-surface drip irrigation No mulch

Table 4.1 continued……………..

Movable High Tunnel system (MOV)	24 ton ha^{-1} horse manure compost 45 kg N ha^{-1} of pelleted organic fertilizer Drip irrigation Rainfall protection	24 ton ha^{-1} horse manure compost 45 kg N ha^{-1} of pelleted organic fertilizer 28 kg N ha^{-1} fertigation with liquid fish fertilizer Drip irrigation Rainfall protection	24 ton ha^{-1} horse manure compost 45 kg N ha^{-1} of pelleted organic fertilizer Drip irrigation Rainfall protection
Conventional system (CONV)	56 Kg N ha^{-1} balanced fertilizer at planting Drip irrigation	78 Kg N ha^{-1} balanced fertilizer at planting 60 kg N ha^{-1} calcium nitrate fertigation in split Drip irrigation Black plastic mulch	56 Kg N ha^{-1} balanced fertilizer at planting 60 kg N ha^{-1} calcium nitrate fertigation in split Drip irrigation Black plastic mulch
High Tunnel (HT)	24 ton ha^{-1} horse manure compost 45 kg N ha^{-1} of pelleted organic fertilizer Drip irrigation Rainfall protection	24 ton ha^{-1} horse manure compost 45 kg N ha^{-1} of pelleted organic fertilizer 28 kg N ha^{-1} fertigation with liquid fish fertilizer Drip irrigation Rainfall protection	24 ton ha^{-1} horse manure compost 45 kg N ha^{-1} of pelleted organic fertilizer Drip irrigation Rainfall protection

Table 4.2 Mean marketable (USDA grades 1&2) fresh yield of pepper, beet and collard from 2014, 2015 and 2016 in the five study systems.

System	Fresh crop yield (kg ha^{-1})		
	Beet	Pepper	Collard
LI	9,686±2350	19,637±806	3,524±356
CSA	30,681±2491	35,395±4427	25,819±1286
MOV	54,224±3972	56,130±3341	47,843±3634
CONV	28,933±4219	30,860±985	32,076±1126
HT	35,223±3642	44,936±3197	36,145±1864

Table 4.3 The averages soil NO_3^--N during pepper, beet and collard growing season from 2014, 2015, and 2016 in low input, community supported agriculture, movable high tunnel, conventional and high tunnel system

		Average soil NO_3^--N (kg N ha^{-1})		
Soil layer (cm)	System	Beet	Pepper	Collard
0-15	LI	24 ± 1	66 ± 8	19 ± 4
	CSA	31 ± 5	41 ± 7	7 ± 1
	MOV	74 ± 6	67 ± 13	72 ± 21
	CONV	23 ±3	44 ± 7	12 ± 3
	HT	61 ± 5	72 ± 10	63 ± 10
15-30	LI	16 ± 0	25 ± 4	13 ± 2
	CSA	14 ± 2	16 ± 2	15 ± 6
	MOV	29 ± 5	15 ± 2	32 ± 13
	CONV	14 ± 1	22 ± 3	5 ± 1
	HT	21 ± 2	31 ± 8	19 ± 6
30-50	LI	14 ± 0	43 ± 6	14 ± 2
	CSA	16 ± 1	21 ± 5	7 ± 2
	MOV	38 ± 5	54 ± 11	48 ± 13
	CONV	10 ± 1	27 ± 4	4 ± 0
	HT	32 ± 3	53 ± 8	53 ± 10

Table 4.4 The Average crop N uptake and N fertilizer applied in five systems.

System	Beet		Pepper		Collard	
	N uptake (kg N ha^{-1})	N applied (kg N ha^{-1})	N uptake (kg N ha^{-1})	N applied (kg N ha^{-1})	N uptake (kg N ha^{-1})	N applied (kg N ha^{-1})
LI	41±10	0	107±2	0	13±1	0
CSA	115±9	167	164±16	200	74±3	167
MOV	171±8	145	240±12	201	179±13	145
CONV	100±22	56	148±3	138	120±4	116
HT	116±16	145	199±11	201	135±7	145

	Extensive Organic	Medium-Scale Organic	Movable Organic High Tunnel	Conventional	Stationary Organic High Tunnel
					
Production	Seasonal*	Seasonal*	Year-round	Seasonal*	Year-round
Fallow Periods	5 year forage-based fallow, with rotational grazing	Annual cover crop once per year	Annual cover crop twice per year	Annual cover crop once per year	None
Tillage Frequency	None (fallow) -> Intensive semi-annual primary and secondary (horticulture)	Annual primary tillage, bed shaping, frequent shallow cultivation for weed control	Semi-annual primary tillage, additional semi-annual secondary tillage, frequent cultivation for weed control	Semi-annual primary and secondary tillage	Quarterly secondary tillage, frequent cultivation for weed control
Nutrient inputs	Fallow, cover crop, minimal compost	Cover crop, compost, granular manure-based fertilizer	Cover crop, compost, granular manure based fertilizer	Cover crop, synthetic fertilizer	Compost, granular manure-based fertilizer
Intensification	Low →				High

Figure 4.1 Overview of five model farming systems representing a gradient of intensification, as characterized by timing of production and fallow periods, tillage frequency, and nutrient inputs.

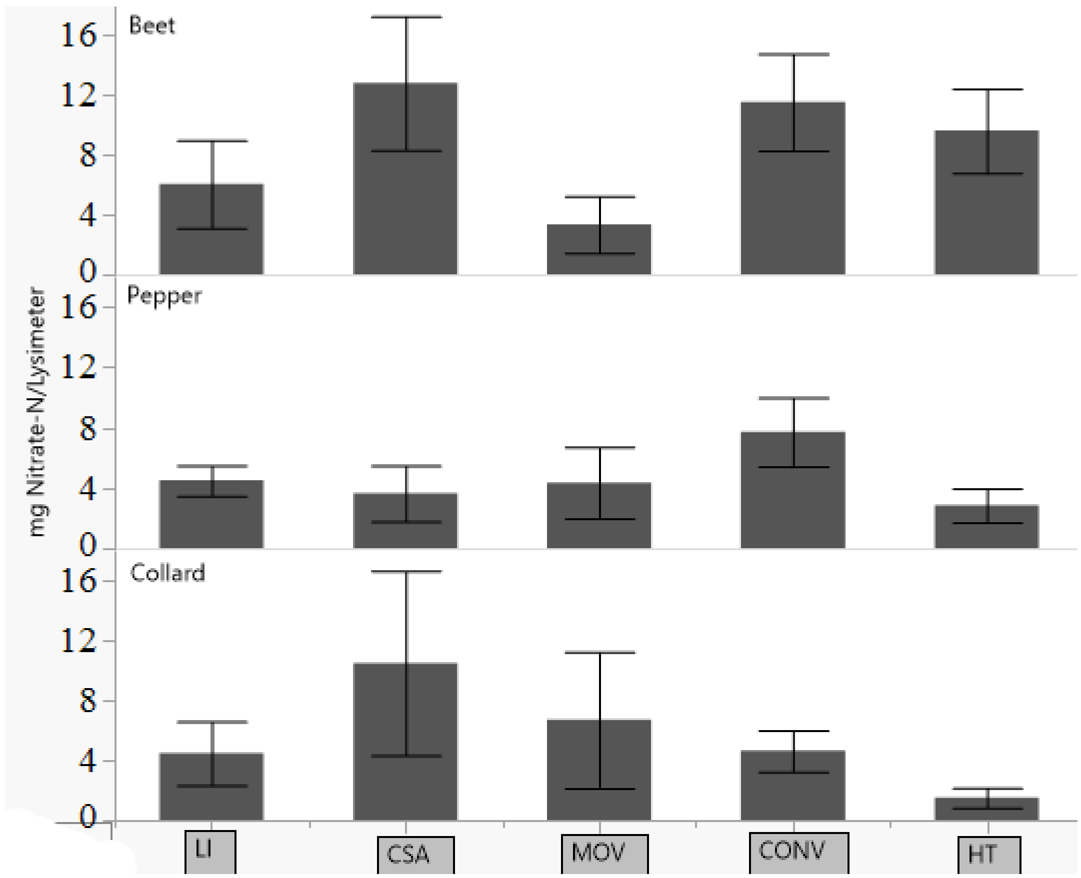


Figure 4.2 Mean NO_3-N per lysimeter values in model crops in the five study systems from 2014, 2015 and 2016

CHAPTER 5. **CONCLUSIONS**

Chapters 2 and 3 of this dissertation quantified the soil mineral N dynamics, CO_2 and N_2O fluxes and characterize NO_3^- leaching from three different vegetable production systems viz. low input organic system (LI), conventional system (CONV) and high tunnel organic system (HT). Along with this, we calculated yield-scaled global warming potential (GWP) for three vegetable production systems. Key loss pathways in the low input (LI) system were via greenhouse gas fluxes, whereas in the conventional system (CONV) they were via leaching. Although HT was expected to produce higher gas fluxes due to greater soil mineral N content, this was not observed, although the peak timing and basal flux patterns differed from the open field systems. Yield-scaled GWP was greater in the LI system compared to CONV and HT system, driven both by greater fluxes as well as lower yields. From the perspective of sustainable intensification in these three systems, our study suggests CONV systems may benefit from reduced fertilizer inputs in combination with irrigation management to minimize downward directed hydraulic gradients particularly just after planting of crops; LI systems may benefit from targeted additional fertilizer and irrigation inputs; and this work supports literature indicating the need to examine long-term soil impacts in HT systems over longer timelines. These results indicated that the soil mineral N content and N_2O emission varied with vegetable production systems with varied management practices. The N losses were high in LI, although the total yield was not higher. Increasing the crop N uptake in LI system by effectively managing weeds and targeted and timely irrigation might decrease the N_2O losses and N leaching, which was pronounced at the starting of cropping period.

However, such losses may be difficult to manage due to the nature of fallow conversion to vegetable production.

In addition to this, RZWQM2 model was used to simulate soil water, N_2O emission, soil NO_3^--N processes and crop yield in diversified vegetable rotations representing a gradient of production intensities. RZWQM2 simulated soil NO_3^--N content reasonably well during beet, collard and bean growing seasons in CONV and LI system, but could not simulate well during pepper crops which were grown under plastic mulch. RZWQM2 simulated cumulative N_2O emission from 2014 to 2016 was reasonably well compared to field measured values in CONV system, while the model overestimated in HT system and underestimated in LI system the cumulative N_2O emission. Crop yield and soil water content were simulated well in all systems. Overall, this work contributes to key gaps in the literature characterizing environmental processes contributing to evolution of sustainable intensification in vegetable production system. The limitations in our study is lacking detail physiological crop growth parameters of model crops for better simulation.

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Professional Positions

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Publications

- Shrestha, D. 2013. Indigenous vegetables of Nepal for biodiversity and food security. International Journal of Biodiversity and Conservation, 5(3), 98-108.

- Shrestha, D., A. Srivastava, S.M. Shakya, J. Khadka and B.S Acharya. 2012. Use of compost supplemented human urine in sweet pepper (*Capsicum annuum* L.) production. Scientia Horticulture, 153:8-12.

- Khadka, J. and D. Shrestha. 2012. Plant dry matter production and partitioning of sour lime saplings fertilized with human urine. Nepalese Horticulture, 8:29-34.

Honors and Awards

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