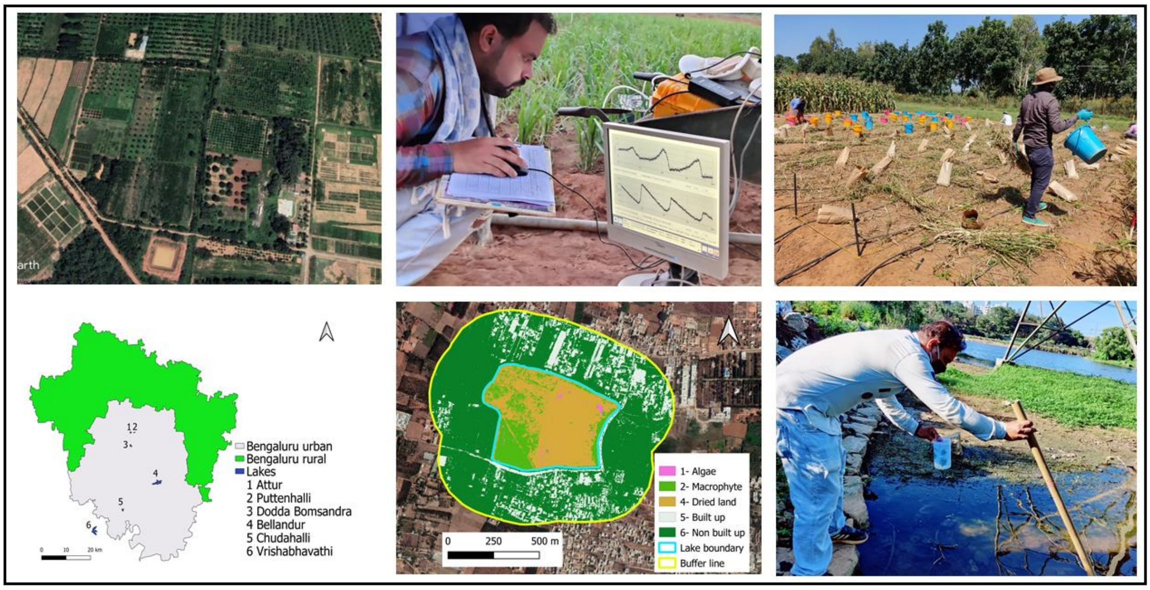
Plant growth, water quality, carbon and nutrient flows in rural-urban cropping systems of Bengaluru, India



Suman Kumar Sourav

Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics

Faculty of Organic Agricultural Science

University of Kassel

Witzenhausen

Plant growth, water quality, carbon and nutrient flows in rural-urban cropping systems of Bengaluru, India

Dissertation for the acquisition of the academic degree

of Doktor der Agrarwissenschaften (Dr. agr.)

Submitted to the

Faculty of Organic Agricultural Science

Organic Plant Production and Agroecosystems in the Tropics and Subtropics

University of Kassel

Suman Kumar Sourav

2023

Date of Defense: 15.03.2024

Table of contents

List of tables

List of figures

Acknowledgements

My deep thanks go to Prof. Dr. Andreas Buerkert for accepting me as his PhD student and supervising and supporting me throughout my study. I am highly indebted to Dr. Thanh Thi Nguyen, Dr. Mariko Ingold, and Dr. Martin Wiehle whose scholarly advice and encouragement were instrumental in shaping this PhD thesis. I also extend my gratitude to Apl. Prof. Dr. Christine Wachendorf, Prof. Dr. Judy Simon and Prof. Dr. Stephan Peth for their insightful comments on chapters 2 and 3, and I am grateful to Dr. Martin Wiehle for his encouragement during this study.

I gratefully acknowledge the support of the Deutsche Forschungsgemeinschaft (DFG) for providing the funding that made this PhD possible.

I feel incredibly blessed to have received an abundance of warmth, tolerance, and support from all members of the Organic Plant Production and Agroecosystem in the Tropics and Subtropics and Animal Husbandry in the Tropics and Subtropics departments during my stay in Germany. Special thanks are extended to Dr. Ellen Hoffmann, Ms. Katja Höck, and Ms. Sonja Klinger for consistently finding solutions to my complex issues. Without the patience and technical assistance of Eva Wiegard, Claudia Thieme-Fricke, and Andrea Mock, this PhD would not have been possible. In both academic discussions and cultural exchanges, I have greatly benefited from my PhD colleagues, who have become not only good friends but also like family: MD Shahin Alam, Dr. Deogratias Agbotui, Phyu Thaw Tun, Katherina Hemmler, Kira Fastner, and Abed Al Kareem Yehya. I extend my heartfelt thanks to Dr. Thanh Thi Nguyen and Dr. Prem Jose Vazhacharickal, who were always available to offer their assistance.

The data collection was made possible through the collaboration of Gandhi Krishi Vignan Kendra (GKVK), University of Agricultural Sciences, Bengaluru, which provided the necessary land and labor for conducting our field experiments.

Finally, I would like to express my heartfelt appreciation to my bedridden father, Jai Krishna Choudhary, and my supportive mother, Sukla Rani Choudhary, for their unwavering love and support throughout my entire PhD journey. I am deeply indebted to the encouragement and support from my elder sisters, Moni and

Monu Didi, and my younger sisters, Sumi, Chhoti, and Etu. A special appreciation goes to my brother-in-law, Anshu Ji, and my youngest sister, Etu, for their unwavering support to our parents in my absence.

English summary

The global urban population is expected to reach 5.2 billion by 2030 and by mid-2023 approximately 4.6 billion out of more than 8 billion population were living in towns or cities. This represents approximately 57% of the total global population and is set to reach 60% by 2030. India's urban population is expected to reach 607 million by 2030 and by mid-2030 40% of the total population will be living in urban areas. Growing urban population has multi-sectoral and dimensional implications in the rural, peri-urban, and urban ecosystem. Specifically, farming communities in the peri-urban and rural areas have got larger markets to supply the growing demand of food by the urban population. Consequently, farmers started practicing intensive cultivation on their farmlands. On the other hand, unplanned urbanization has led to major pollution of water bodies along rural-urban gradients due to release of sewage and industrial wastewater. Therefore, this thesis aimed at analyzing the effect of management intensification on soil carbon dioxide emission (CO_2) as well as consequences of urbanization around lakes on their ecosystem services in the southern Indian megacity of Bengaluru.

Study 1 focused on the effects of urbanization on management intensities exemplified by three levels (low, medium and high) of nitrogen (N) fertilizer application which eventually alters soil physical, chemical, and biological properties. To this end a two two-factorial split plot experiments were set up with maize (*Zea mays* L.), finger millet (*Eleusine coracana* Gaertn.), and lablab (*Lablab purpureus* L. Sweet) under rainfed and irrigated conditions, as well as the vegetables cabbage (*Brassica oleracea* var. *capitata*), eggplant (*Solanum melongena* L.), and tomato (*Solanum lycopersicum* L.) or chili (*Capsicum annuum* L.) under irrigated condition. CO_2 emissions were measured by using a Los Gatos Research (LGR) multi-gas analyzer in the morning and afternoon hours for each crop at all N treatments. CO_2 emission rates during afternoon hours were significantly higher (2-128%) than during morning hours. High N fertilizer treatment induced by 56.4% higher CO_2 emission compared to low N in rainfed field while in irrigated field the difference amounted to 12.1%. Crop specific CO_2 emission within a season were independent of N fertilization. The results indicate that the management intensification increases CO_2 emissions in the highly weathered Nitisols in Bengaluru. This also poses risks of polluting surface and

ground waters due to excessive leaching of N. The eutrophication of lakes, reservoirs, and ponds resulting from the accumulation of nitrogen, primarily derived from fertilizers as a non-point source of pollution, can result in elevated fish mortality and the proliferation of algal blooms. This can have adverse consequences on the role of aquaculture in supporting food security and rural incomes in numerous developing nations.

Study 2 was conducted to assess the consequences of urbanization in a 300 m buffer area of lake boundaries along the rural-urban gradient of Bengaluru. To gain insights into the dynamics of the lake ecosystems we analyzed land-cover changes (inside and in the buffer area) from 2002 to 2022 of six lakes of which two lakes each were selected per urbanization level in the northern and southern transect of the city. Supervised maximum likelihood Land Use Land Cover (LULC) classifications were conducted on 168 freely available, RGB Google Earth (GE) images to distinguish between macrophytes, algae, water, and dried land inside the lake, as well as built-up and non-built-up in the buffer area. The results indicated that macrophytes and algae were inversely correlated during the study period. While rainfall correlated positively with the wet surface area (sum of macrophytes, algae and water) in comparatively dry lakes, temperature was negatively correlated with wet surface area except for the perennial lakes Chudahalli and Vrishabhavathi. The built-up area was not consistently correlated with the wet surface area likely because of the effects of the sewage network connection, water blockage at the inlets/outlets or siltation in the lakes.

Thus, agricultural intensification, a process that is strongly interlinked with increased rates of urbanization can have major negative effects on agroecosystems and the remaining natural patches in urban settings. Longer-term interdisciplinary research involving social-ecological surveys and field inventories is necessary for this endeavor. These findings will serve to alert both farmers and policymakers about the ramifications of unplanned and unregulated urban expansion along the urban-rural continuum in Bengaluru and comparable rural-urban environments across Asia, particularly with regard to peri-urban agricultural practices and lake ecosystems.

Zusammenfassung

Bis 2030 werden voraussichtlich 5,2 Milliarden Menschen in Städten leben. Bereits Mitte 2023 lebten etwa 4,6 Milliarden von mehr als 8 Milliarden Menschen in Städten. Dies entspricht etwa 57 % der gesamten Weltbevölkerung und wird bis 2030 auf 60 % ansteigen. Auch in Indien wird die Stadtbevölkerung bis 2030 voraussichtlich 607 Millionen erreichen, und damit werden 40 % der Gesamtbevölkerung in städtischen Gebieten leben. Die wachsende Stadtbevölkerung hat multisektorale und -dimensionale Auswirkungen auf das ländliche, stadtnahe und städtische Ökosystem. Insbesondere die landwirtschaftlichen Gemeinschaften in den stadtnahen und ländlichen Gebieten haben größere Märkte, um die wachsende Nachfrage der Stadtbevölkerung nach Lebensmitteln zu decken. Infolgedessen haben die Landwirte begonnen, ihr Land intensiv zu bewirtschaften. Andererseits hat die ungeplante Verstädterung zu einer starken Verschmutzung der Gewässer entlang des Land-Stadt-Gradienten geführt, da landwirtschaftliche Abwässer und Industrieabwässer in die Gewässer eingeleitet werden. Ziel dieser Arbeit war es daher, die Auswirkungen der Bewirtschaftungsintensivierung auf die Kohlendioxidemissionen (CO_2) des Bodens sowie die Folgen der Verstädterung in der Umgebung von Seen auf deren Ökosystemleistungen in der südindischen Megastadt Bengaluru zu untersuchen.

Studie 1 konzentrierte sich auf die Auswirkungen der Verstädterung und Bewirtschaftungsintensität am Beispiel von drei Stickstoff (N)-Düngungsstufen (niedrig, mittel und hoch), die möglicherweise auch Einfluss auf die physikalischen, chemischen und biologischen Eigenschaften des Bodens haben. Zu diesem Zweck wurden zwei zweifaktorielle Split-Plot-Versuche unter Regen- und Bewässerungsbedingungen mit Mais (*Zea mays* L.), Fingerhirse (*Eleusine coracana* Gaertn.) und Lablab (*Lablab purpureus* L.) unter Regen- und Bewässerungsbedingungen sowie die Gemüsearten Kohl (*Brassica oleracea* var. *capitata*), Aubergine *(Solanum melongena* L.) und Tomate (*Solanum lycopersicum* L.) oder Chili (*Capsicum annuum* L.) unter Bewässerungsbedingungen durchgeführt. Die CO_2-Emissionen wurden mit einem Multigasanalysator von Los Gatos Research (LGR) in den Morgen- und Nachmittagsstunden für jede Kultur bei jeder N-Behandlung unter Bewässerungs-

und Regenwasserbedingungen gemessen. Die CO_2-Emissionsraten waren in den Nachmittagsstunden 2-128% höher als in den Morgenstunden. Eine Behandlung mit hoher N-Gabe führte zu 56,4 % höheren CO_2-Emissionen im Vergleich zu einer Behandlung mit niedriger N-Gabe im Regenfeld, während unter Bewässerung der Unterschied 12,1 % betrug. Die kulturspezifischen CO_2-Emissionen innerhalb einer Saison waren unabhängig von der N-Düngung.

Die Ergebnisse zeigen, dass die Intensivierung der Bewirtschaftung die CO_2-Emissionen auf den stark verwitterten Nitisolen in Bengaluru erhöht. Dies birgt auch die Gefahr der Verschmutzung von Oberflächen- und Grundwasser durch übermäßige Auswaschung von Stickstoff. Die Eutrophierung von Seen, Stauseen und Teichen infolge der N-Akkumulation, der hauptsächlich aus Düngemitteln als diffuser Verschmutzungsquelle stammt, kann zu einem erhöhten Fischsterben und zur Ausbreitung von Algenblüten führen. Dies kann sich nachteilig auf die Rolle der Aquakultur bei der Unterstützung der Ernährungssicherheit und der ländlichen Einkommen in zahlreichen Entwicklungsländern auswirken.

Deshalb untersuchte **Studie 2** die Folgen der Verstädterung in der Pufferzone im Umkreis von 300 m von der Seegrenze entlang des Stadt-Land-Gefälles von Bengaluru. Um Einblicke in die Dynamik des Ökosystems der Seen zu gewinnen, analysierten wir die Veränderungen der Bodenbedeckung (innerhalb und im Pufferbereich) von 2002 bis 2022 bei sechs Seen, von denen zwei aus drei Intensitätsstufen des Stadt-Land-Gefälles im nördlichen und südlichen Transekt der Stadt ausgewählt wurden. Anhand von 168 frei verfügbaren RGB-Bildern von Google Earth (GE) wurden überwachte LULC-Klassifizierungen (Land Use/Land Cover) durchgeführt, um zwischen Makrophyten, Algen, Wasser und trockenem Land innerhalb des Sees sowie bebautem und unbebautem Land im Pufferbereich zu unterscheiden. Die Ergebnisse zeigten, dass Makrophyten und Algen während des Untersuchungszeitraums in umgekehrter Beziehung zueinanderstanden. Während der Niederschlag in den vergleichsweise trockenen Seen positiv mit der feuchten Oberfläche (Summe aus Makrophyten, Algen und Wasser) korrelierte, war die Temperatur mit Ausnahme der mehrjährigen Seen Chudahalli und Vrishabhavathi negativ mit der feuchten Oberfläche korreliert. Die bebaute Fläche war nicht durchgängig mit der feuchten Oberfläche korreliert, was wahrscheinlich auf die Auswirkungen des Anschlusses an das Abwassernetz, die

Verstopfung der Wasserein- und -auslässe oder die Verschlammung der Seen zurückzuführen ist.

Die Intensivierung der Landwirtschaft, ein Prozess, der eng mit der zunehmenden Verstädterung verbunden ist, kann also starke negative Auswirkungen auf die Agrarökosysteme und die verbleibenden natürlichen Flächen in städtischen Gebieten haben. Hierfür ist eine längerfristige interdisziplinäre Forschung mit sozialökologischen Erhebungen und Feldinventuren erforderlich. Diese Ergebnisse werden dazu dienen, sowohl Landwirte als auch politische Entscheidungsträger über die Auswirkungen der ungeplanten / unregulierten Stadterweiterung entlang des Stadt-Land-Kontinuums in Bengaluru und vergleichbarer ländlich-städtischer Umgebungen in Asien zu informieren, insbesondere im Hinblick auf landwirtschaftliche Praktiken am Stadtrand und die Seen-Ökosysteme.

Chapter 1

General introduction

1.1 Introduction

This thesis is structured in four chapters. Chapter 1 contains a general introduction which gives an overview of urbanization and its consequences in the S-Indian megacity of Bengaluru, the study background, objectives and hypotheses. Chapter 2 focusses on soil respiration under different N fertilization and irrigation regimes in Bengaluru. Chapter 3 assesses the consequences of urbanization and weather on lake ecosystems during the year 2002 to 2022 in Bengaluru. Chapter 4 contains a general discussion, conclusions and recommendations.

1.1.1 Urbanization

Urbanization, in its narrow sense, refers to the proportional increase of the population living in urban areas (Potts, 2009, 2012). The gradual increase in the population of urban areas is a characteristic feature of human history since the establishment of the first cities on the earth. However, defining the term “urban” is not straightforward. The definition of the urban population varies from one country to another. Some countries define it with respect to the administrative boundary of the urban area and others define it based on urban population size and density or on functional characteristics such as prevalence of non-agricultural economic activities (Brockerhoff, 2000). Some scholars have developed complex, multi-criteria scales or indices for measuring the urbanity of a particular settlement (Jones-Smith & Popkin, 2010; Cyril et al., 2013; Hoffmann et al., 2017). Agencies compiling global urban data such as the World Urbanization Prospects (UNDESA, 2019), use national definitions of urban, with all their inconsistencies. In India, the definition (as per the circular of the 2021 Census) of “urban” is based on the administrative boundaries that had been defined by the statute as well as a minimum population of 5,000 persons residing at a given place in which at least 75 % of the male working population are engaged in non-agricultural pursuits. Also density of the population should be at least 400 person per km^2. Sometimes, urban administrative boundaries include a large proportion of areas that are functionally rural and *vice versa*. Therefore, urban population figures need to be used with some caution (Smit, 2021).

Several attempts were made to define the geographical limits of cities in more consistent ways such as in “urban agglomerations” based on the spread of built-up area, in “metropolitan areas” or in “functional urban areas” based on the economic and social integrity of surrounding areas which are reflected by the patterns of commutation (UNDESA, 2018). However, there is a lack of clear differentiation between urban and rural areas, so the concept of “peri-urban” emerged from the often blurred boundaries between “urban” and “rural” (Iaquinta & Drescher, 2000).

Urbanization not just only refers to the increase in the proportion of urban population but also refers to “the change in size, density, and heterogeneity of cities”. Urbanization is accompanied frequently by certain factors such as rural-urban-rural migration, segregation, and industrialization (Vlahov & Galea, 2002). Following are some implications of urbanization:

1. Change in people’s lifestyle - this includes dietary change, less physical activity, consumerism
2. Change in the political ecosystem – rise of city based social movements and opposition parties.
3. Increase in disease burden – this includes infectious diseases, non-communicable diseases, and injuries.
4. Change in land use land cover (LULC) with intensified use of resources – decrease in agricultural land and expansion of built-up area with negative externalities on ecosystems and urban habitants.

1.1.2 Global South

The Global South, is nowadays used as a term for “Third World” or “developing countries”. The term Third World was coined in an article written by Alfred Sauvy in1952 to refer to non-aligned countries in the emerging Cold War to distinguish them from the capitalist West (the First World) and the communist East (the Second World) (Sauvy, 1952). Gradually the term South (or Global South) began to replace the earlier term Third World by the end of Cold War in 1990s (Tomlinson, 2003; Comaroff & Comaroff, 2011). The usage of Global South and

Global North does not mean a clear division of global regions. There are various dissimilarities within each category and similarities and interconnections between North and South can also be found. However, it is useful to have a certain term for countries that have clearly lower levels of economic growth and governance and higher informalities compared with the more industrialized economies in the global North (Smit, 2021). Miraftab and Kudva (2015) mentioned that the Global South “offers a useful frame of reference to acknowledge the colonial past and a more recent shared development history”. Similarly, in the words of Mabin (2014), cities in the Global South are “marked both by a political economy of insufficient resources to provide on average a decent life for all and by (post) colonial disabilities”.

1.1.3 Urbanization in the Global South

Regardless of how the term urban is defined, it is clear that the proportional population in urban areas is increasing. The United Nations estimated that the proportion of the global population living in urban areas had increased from about 30% to 56% during 1950 to 2020, and it is projected to increase to 68% by 2050 (UNDESA, 2019). Most urban population growth will occur in the Global South because of the more rapid pace of urbanization compared with the Global North. Also, new urban population growth is taking place in the Global South. The urban population in the Global South was estimated to be 3.002 billion in 2015 which accounted for 75% of the total global urban population of 3.981 billion (UNDESA, 2019). The global urban population is expected to increase by about 793 million from 2015 to 2025 and 94% of this increase will be contributed by the Global South (UNDESA, 2019).

It is important to note that the levels of urbanization and urban growth rate widely vary from one region to another. For example, the African continent has the lowest level of urbanization but the highest urban growth rate whereas the Latin American and Caribbean countries already are the most urbanized regions of the Global South at present with the lowest rate of urban population growth (Table 1.1).

Table 1.1 Regional urban growth trend in the Global South

Region	Proportion of people living in urban areas (mid-2020)	Annual urban growth rate (2020-2025)
Africa	43.5%	3.44%
Asia	51.1%	1.84%
Latin America and Carbbean	81.2%	1.15%

Source: https://population.un.org/wup/Download/

1.1.4 Drivers of urbanization in the Global South

Urbanization reflects a combination of the natural increase of the urban population, rural to urban migration, and reclassification of rural areas as urban due to peripheral absorption of rural areas into growing cities (UN-Habitat, 2013). In the Global South, the increase in the urban population results from the following phenomena (UN-Habitat, 2013):

a) *Natural population growth* – this constitutes 60% of the population growth due to lower urban mortality rates, and a young and fertile demography.
b) *Rural to urban migration* – this adds 20% growth to the urban population.
c) *Reclassification of rural areas as urban areas* – this contributes the remaining 20% of the population growth in urban areas.

Fox (2012) states that urbanization is a process driven by population dynamics along with technological and institutional change. Gu (2019) identified five driving forces of urbanization in developing countries which include industrialization, modernization, globalization, marketization, and administrative or institutional power.

1.1.4.1 Industrialization

Lewis (1954) argued that the economic development of a region is based on the expansion of modern industrial sectors, which pulls the abundant and cheap labor from the agricultural sector. Sridhar et al. (2012) attempted to understand whether it is pull (towards urban area) or push (forced to leave rural area) factors motivating the migrants to move to the cities in the context of India especially in the case of rapidly growing IT industry in the S-Indian megacity of Bengaluru. In this context, both pull and push factors are prominent in migration. The higher the level of education of the migrants, the greater the importance of pull factors, whereas at lower levels of education, push factors become more prominent for migration. Social status (caste), family size, gender and other social networks play an important role in pulling or pushing migrants towards urban areas.

1.1.4.2 Modernization

Many countries of the Global South have undergone rapid urbanization after World War II while countries of the Global North underwent a completely different process of urbanization (Gu, 2019). Bogue (1959) stressed that the purpose of moving towards better/modern places is mainly driven by people’s desire to improve their living conditions. On the other hand, places with unfavorable living conditions can become a push factor for people. Scholars developed three modernization theories which influence the process of urbanization in developing countries: The Rostovian take-off model, the post modernization theory, and the pluralistic modernity theory. Since 1950-1960s, promoting national modernization to meet the needs for urbanization became a prime importance for many countries of the Global South. However, less developed countries could not succeed in keeping balance between migration and modernization, and this resulted in overcrowded urban areas with urbanization lagging far behind. This phenomenon of urbanization is called “hyper-urbanization or over-urbanization” (Gu, 2019).

1.1.4.3 Globalization

Globalization is a process of interaction and integration among the working professionals, companies, and governments of different nations. The current process of urbanization is driven by international trade, global investment, and technological flows, all supported by information technology (IT). In this context, super-urban agglomerations or global city regions are being developed which are the places of interrelated economic activity and they are drivers of national and global economies (Scott and Storper, 2003). Bengaluru also experiences a similar conducive environment as a global IT hub. The combination of a few favorable enabling factors gave rise to a globally integrated ‘e-region’. Following are the enabling factors which were found in Bengaluru (Dittrich, 2007):

1. One of the India’s top leading locations of education and research. As per the All-India Survey on Higher Education during 2020-2021, Bengaluru

urban district tops the list of number of colleges in a district in India by housing 1058 colleges.

2. Availability of large-scale knowledge based public sector industries and the associating numerous small-scale workshops to service them.
3. Production of a large number of English speaking, highly skilled, and relatively inexpensive young urban people who are ready to grab any opportunity in the global village.
4. Karnataka state government rolled out different facilitation schemes for the development of the IT industry. During 1992-2000, the Software Technology Park Scheme, the opening of the telecom sector, and the expansion of communication infrastructure played a significant facilitating role. Between 2001 to 2010, software exports grew 15 times in value. Many IT Multinational Companies (MNCs) started recognizing the potential of software developed in Bengaluru. After 2011, the Government focused on expanding the IT industries and promoting start-ups in different sectors.
5. Liberal environment for foreigners.
6. Salubrious climatic conditions as a conducive environment attracting innovative companies.

1.1.4.4 Marketization

With the flow of foreign direct investment (FDI) into new development areas, new global manufacturing system emerged (Gu, 2019). This established a worldwide manufacturing network, which has “super-manufacturing” and servicing abilities and takes of FDI and cheap domestic laborers from rural areas (Gu, 2019). From 2000 to 2023 the Indian government has attracted foreign investments with a total amount of 919 billion US$ of which 595 billion were received in the last 9 years. The Indian service sector received the highest FDI inflow during the financial year 2022-2023. Karnataka State was with 24% of the total FDI equity inflow during FY 2022-2023[1] second among all Indian states

1.1.4.5 Administrative/institutional power

Government policies play an important role in regulating and influencing the market by working closely with private enterprises. Tremendous efforts have been made by the respective governments to make cities like Bengaluru, Kuala

---

[1] https://www.investindia.gov.in/foreign-direct-investment

Lumpur, and Suzhou global high-tech centers (Gu, 2019). The Greater Bengaluru metropolitan area is governed by a municipal corporation called the Bruhat Bengaluru Mahanagara Palike (BBMP). In 2020, the Karnataka state government passed the BBMP bill to improve decentralization, ensure public participation, and address critical administrative and structural concerns in Bengaluru.

1.1.5 Consequences of urbanization

Cities like Bengaluru have brought remarkable changes in the life of their inhabitants by providing better health, education, and job opportunities. The city also plays a crucial role in the economic development of the state and in India. However, the following sections will discuss the effects of urbanization on social, economic, and environmental components.

1.1.5.1 Social impact of urbanization

Rural-urban migration has significantly affected the socio-dynamics of the urban and rural population in and around Bengaluru. Rural areas may lose from the out-migration of skilled residents and urban areas may get overcrowded which can result in an increase in slum areas (Sridhar et al., 2012). According to the 2011 Census of India, 19.6% of the population of 210 urban agglomerations in India live in slums (Sahasranaman and Bettencourt, 2021). Hereby the UN defines slums as “communities characterized by insecure residential status, poor structural quality of housing, overcrowding, and inadequate access to safe water, sanitation, and other infrastructure” (UN-Habitat, 2004). The poor ventilation, light or sanitation facilities in slum areas create detrimental effects on health and safety of the slum dwellers.

1.1.5.2 Economic impact of urbanization

Since the Industrial Revolution, the transformation of human society can be explained by the three terms industrialization, urbanization, and globalization (Chen et al., 2014). Industrialization directly contributes to economic growth, which further stimulates the process of urbanization in developed and newly industrialized economies through division of labor and development of non-agricultural sectors. Many statistics of developed economies reveal that urbanization is positively correlated with the Gross Domestic Product (GDP) per capita (Chenery and Taylor, 1968; Henderson, 2003). The general notion of economic growth is that it promotes the expansion of modern industries and increases the urban population. On the other hand, urbanization promotes economic growth. Therefore, many policies in countries of the Global South aim to foster urbanization, with the goal of boosting economic growth (Pugh, 1995; Hope, 1998; Friedmann, 2006).

The increasing rate of urbanization in low and non-industrialized countries questions the applicability of urban economic theory (Petrakos, 1989; Montgomery, 2008; Glaeser, 2014; Gollin, 2015). AT the same rate of urbanization Asia contains a larger number of explosive economies than Sub-Saharan Africa. On the other hand, developed economies seem to have A competitive advantage in perpetuating urbanization (Di Clemente, 2021).

1.1.5.3 Environmental impact of urbanization

Urban/city growth processes are closely linked with biophysical and ecological processes. The interrelationship between urbanization and environment is quite complex, thus researchers adopted separate modes of analysis for deciphering the forward and backward linkage between urbanization and the environment (McDonald, 2009). Health, sustainability, and resilience of an urban environment largely depend on the ability of a region to provide, regulate, and support ecosystem services (Mundoli et al., 2017; Guo et al., 2020; Evans et al., 2022). Hereby urban ecosystems act as hotspots for the links between humans and nature (He et al., 2021; Li et al., 2021) and create an enormous demand of ecosystem services. However, they also generate a substantial number of threats to the environment (Chen et al., 2022; Schirpke et al., 2022).

In countries of the Global South, urban areas often have only limited access to fresh water, sanitation, and waste disposal thereby reducing green spaces, and deteriorating public health (Trask, 2022). Under these conditions, peri-urban agriculture (PUA) has been proposed for harvesting rainwater and open land for integrating economic, social, and ecological interests. However, urban planners often take provisions to push agriculture away from cities due to negative externalities of farming activities such as noise, soil, and water pollution (Brinkley, 2012). On the other hand PUA provides direct access to food, animal feed, bioenergy, and medicine together with rainwater reservoirs, biodiversity and wild life habitats to urban areas (Power, 2010; Likitswat and Sahavacharin, 2023). As food demand is expected to increase due to growing population in urban areas, it is imperative to understand the role of urban environment and global agricultural production and ecosystem conservation (Wilhalm and Smith, 2018).

Rapidly growing megacity like Bengaluru have a major impact on ecosystems and their biodiversity. The high influx of migrants has led to the encroachment and pollution of water bodies, replacement of open areas, parks, and forest into high rise commercial, industrial and residential buildings (Nair, 2005; Sudhira et al., 2007; Nagendra and Gopal, 2010, 2011). Like many other Indian cities, urban growth in Bengaluru is much less directed by state policies or colonial legacies than in many other parts of the world. This has created an uneven and complex pattern, with accelerated and haphazard growth at the periphery (Schneider and Woodcock, 2008; Taubenböck et al. 2009). High land price and scarcity of land in the city center pushed new developments at the periphery (Sudhira et al., 2003; Shaw and Satish 2006). Urban expansion has also greatly transformed the land use patterns and institutional forms of governance of many peri-urban agricultural areas (Nair 2005; D’Souza and Nagendra 2011).

1.1.6 Background and justification of the study

In 1991, the Government of India passed major economic reforms with the aim of loosening overall governmental control and encouraging participation of entrepreneurs in India’s economic development. This led to the accelerated growth of the economy reaching 8 % per annum during the first decade of 21st century compared with an average annual growth rate of 3 % in the early 1980s. In the 11th Five Year Plan (2007-2012) urbanization was regarded as a positive factor for overall development (Bhagat, 2018). Consequently, Bengaluru became the principal administrative, cultural, commercial, industrial and knowledge capital of Karnataka State.

This development has put tremendous pressure on (peri-) urban agricultural land, water resources, and labor. Consequently, the cropping pattern in the rural-urban gradient has changed. Many farmers have been pushed to grow high value crops such as finger millet (*Eleusine coracana* (L.) Gaertn.,), tomato (*Solanum lycopersicum L.*), eggplant (*Solanum lycopersicum* L.), grape (*Vitis vinifera* L.), and cabbage (*Brassica oleracea*) instead of traditional low value staple crops. The water use efficiency of these crops are often high due to efficient drip irrigation and high value of produce per unit water consumed (Jain et al., 2019).

During the course of urbanization, farmers were continuously adapting their cultivation practices and management intensities in response to new challenges and opportunities brought by the development of urban markets and their demand structure (Swain & Teufel, 2017).

It has been previously shown that intensive management practices with continuous use of mineral fertilizers may lead to losses in soil organic carbon (SOC; Singh et al., 1999) and soil health (Anwar et al., 2005; Kumar et al. 2017, 2018). The direct effects of such practices include shifting decline in soil pH which can negatively affect soil micro-organisms (Chu et al. 2007; Enwall et al., 2007; Liu & Greaver, 2010). On the other hand, higher plant growth, enhanced rhizo-deposition, and increased recycling of plant residues into the soil are factors that stimulate the growth and activity of soil micro-organisms in fertilized soils (Salinas-Garcia et al., 1997; Lugato et al., 2006; Chu et al. 2007).

Excessive N application has also been linked with nitrate pollution of ground and surface water bodies. Nitrate-N can easily percolate below the root zone in agricultural soils and potentially contaminate ground and surface waters. When nitrate-N levels exceed allowable limits, they render groundwater unsuitable for drinking. In surface waters where nitrogen is a limiting factor, an excess of nitrate-N can stimulate phytoplankton productivity, leading to eutrophication. This, in turn, results in widespread hypoxia and anoxia, a loss of biodiversity, and the proliferation of harmful algal blooms, which can have detrimental effects on fisheries (Bartley et al., 2003; Gilbert et al., 2006; Howarth, 2008). At present major knowledge gaps exist about the effects of year-round crop growth on matter fluxes and volatilization of carbon (C) and nitrogen (N), and leaching of N, phosphorus (P), potassium (K), and sulphur (S) which may contribute to polluting water bodies of Bengaluru.

Unplanned expansion and intensification of Bengaluru has transformed the land-use patterns, and governance of wetland and water bodies. For centuries, thousands of water reservoirs surrounding the city were used for agriculture, fishing, drinking, cattle washing, and domestic needs (Buchanan, 1870). These water reservoirs were maintained by dams and channels along rainfed streams interconnecting several reservoirs throughout the region (Rice, 1897a, b). This network of wetlands supported a wide variety of birds, fishes, amphibians, reptiles, insects, and micro-organisms until the early 1990s (Krishna et al., 1996). In earlier days, lakes in Bengaluru were managed by the village communities clustered around them, but now the control over lakes are in the hands of various government departments with overlapping jurisdiction and responsibilities (Gowda and Sridhara, 2007; D'Souza and Nagendra, 2011). The majority of the lakes surround the city at its periphery. Rapid change in land use around the lakes and wetlands (D'Souza and Nagendra, 2011) disrupted the drainage networks, and polluted the wetlands through discharge of domestic and industrial wastes (ESG, 2009).

The alterations observed in the vicinity of the lake have had a significant impact on the indigenous species residing in these aquatic environments due to a reduction in available habitat niches, elevated nutrient levels, and simplified food chains. This has led to the loss of species and contributed to global conservation concerns (Pickett et al., 2011; Peralta et al., 2019). These changes call for an investigation on the effects of urbanization around lakes and the seasonal variation on lake dynamics using a time-series approach.

1.2 Research objectives and hypothesis

Given the above, this PhD study aims to explore the carbon and nutrient flow, and the dynamics of wetland ecosystems along the highly dynamic rural urban gradient of Bengaluru.

The specific objectives of this study were to:

a. Assess the effects of fertilizer management intensification on soil respiration (CO_2 emission) under complex crop rotation in the peri urban area of Bengaluru.
b. Assess seasonal and urban effects on lake ecosystem dynamics using Google Earth (GE) satellite images over the last two decades.

To achieve these objectives, the following hypotheses were tested:

a. High N fertilizer application enhances soil respiration.
b. Wetlands are polluted by increasing urbanization and seasonal weather variation.

1.3 Study site locations

To test these hypotheses, studies were conducted at different locations of Bengaluru. The local climate at this location is divided into two distinct seasons: the Indian Summer Monsoon (also called *“Kharif”* season from June to November) yielding an average annual rainfall of 873 mm (± SD 197 mm) while the dry season (*“Rabi”* season from December to May) receives rainfall in rare event (Buerkert et al., 2023). Study 1 was conducted within a two two-factorial cropping system experiment set up at the field station of the University of Agricultural Sciences Bangalore (UASB), GKVK Campus (Fig. 1.1). The detailed description of the field experiment is given in Chapter 2. Study 2 was conducted on six lakes of Bengaluru including three from a northbound and three from a southbound transect. The lakes were selected representing the urban, peri-urban and rural environments of the city (Figure 1.1).

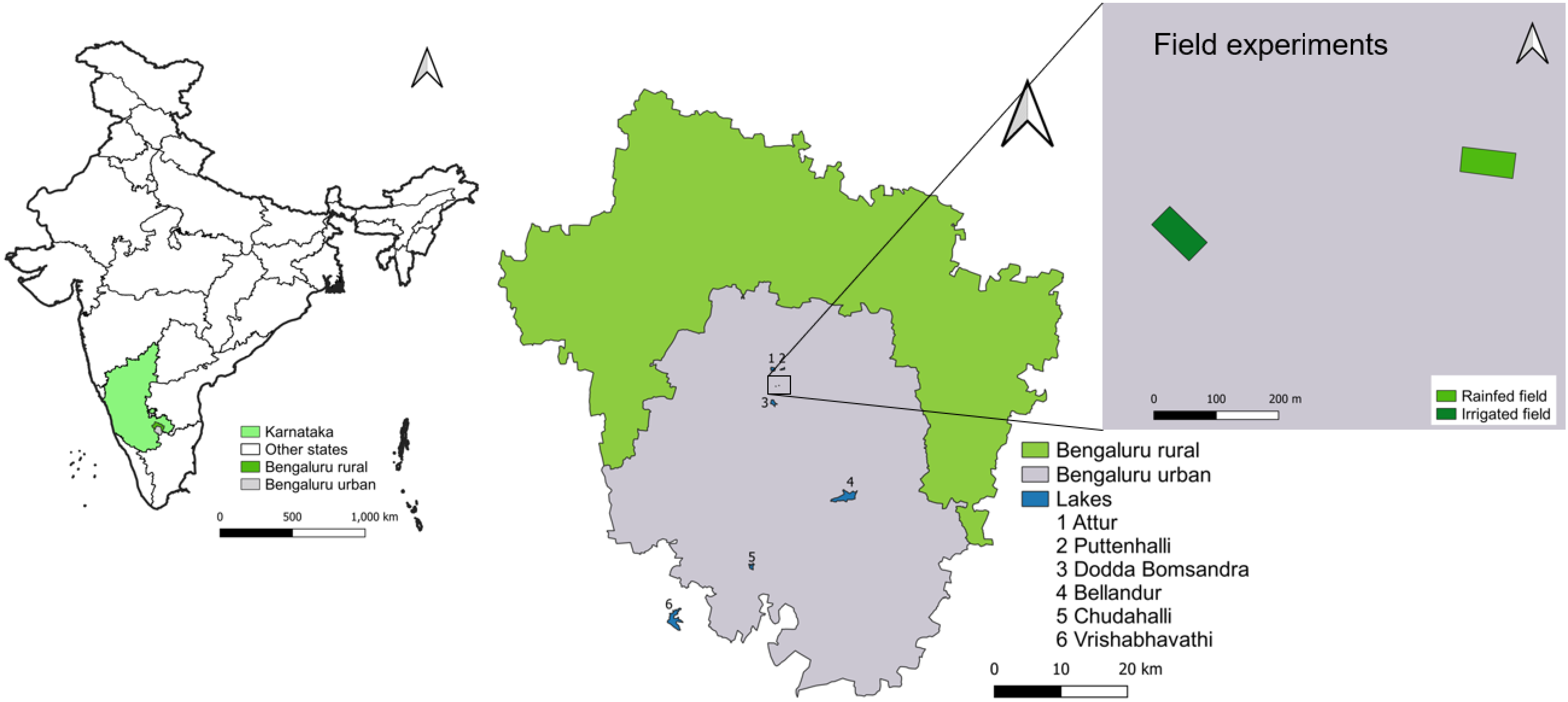


Figure 1.1 Map of India (on the left side) showing the location of lakes and field experiments (on the right side) in Bengaluru, Karnataka, S-India.

Chapter 2

Soil respiration under different N fertilization and irrigation regimes in Bengaluru, S-India[1]

2.1 Abstract

Rapid urbanization in many countries of the Global South has led to intensification of urban and peri-urban agriculture (UPA) whose effects on the soils' physical, chemical, and microbial properties have been hardly studied. We therefore investigated the effects of different intensity levels, exemplified by three rates of mineral nitrogen (N) addition and irrigation on CO_2 emissions in typical crops during the wet (*Kharif*) and dry (*Rabi*) season on a Nitisol in Bengaluru, S-India. Respiration data were collected from 2017 to 2021 in two two-factorial split-plot experiments conducted under rainfed and irrigated conditions. Test crops were maize (*Zea mays* L.), finger millet (*Eleusine coracana* Gaertn.), and lablab (*Lablab purpureus* L. Sweet) under rainfed and irrigated conditions, as well as the vegetables cabbage (*Brassica oleracea* var. capitata), eggplant (*Solanum melongena* L.), and tomato (*Solanum lycopersicum* L.) or chili (*Capsicum annuum* L.). Carbon dioxide (CO_2) emissions were determined using a Los Gatos Research (LGR) multi-gas analyzer whereby under our study conditions CH_4, NH_3 and N_2O were negligible. Measurements were conducted from 7:00 am to 11:30 am and repeated from 12:30 pm to 6:00 pm. Irrespective of irrigation, season, crops and N fertilizer level, CO_2 emission rates during afternoon hours were significantly higher (2-128%) than during morning hours. In the irrigated field diurnal emission differences between afternoon and morning hours ranged from 0.04 – 1.61 kg CO_2-C ha^{-1} hr^{-1} while in the rainfed field they averaged 0.20 – 1.78 kg CO_2-C ha^{-1} hr^{-1}. Irrespective of crops, in the rainfed field CO_2 emissions in high N plots were 56.4% larger than in low N plots whereas in the irrigated field they were only 12.1% larger. The results of a linear mixed model analysis indicated that N fertilization enhanced CO_2 emissions whereby these effects were highest in rainfed crops. Soil moisture enhanced emissions in rainfed crops but

---

[1] The content of this chapter has been published in a different format as "Sourav, S.K., Subbarayappa, C.T., Hanumanthappa, D.C. et al. Soil respiration under different N fertilization and irrigation regimes in Bengaluru, S-India. *Nutr Cycl Agroecosyst* (2023). https://doi.org/10.1007/s10705-023-10311-y"

decreased them under irrigation where crop-specific CO_2 emissions within a season were independent of N application. Soil temperature at 5 cm depth enhanced CO_2 emissions in both fields. Overall, higher N and soil temperature enhanced CO_2 fluxes whereas effects of soil moisture depended on irrigation.

Keywords: CO_2 emission, intensification, linear mixed model, seasonal soil respiration

2.2 Introduction

Worldwide agroecosystems around rapidly growing cities are greatly affected by rural-urban transformation as farmers continuously adapt their crop choices and management intensities in response to the growing competition for land, labor, and water as well as the opportunities of large and close-by urban markets (Swain and Teufel 2017). This leads to intensified crop cultivation which may affect the soils' physical, chemical, and biological properties whose response to the regime-shifts imposed remains poorly studied (Elmqvist et al. 2013; Steinhübel and von Cramon-Taubadel 2020). This is particularly the case for poorly buffered tropical soils of the Global South. Jain et al. (2019) reported that farmers in many peri-urban areas of India have changed their cropping patterns focusing on high-priced horticultural or local specialty crops such as grape (*Vitis vinifera* L.) and finger millet (*Eleusine coracana* Gaertn.). Such crops yield higher revenue per unit of water consumed and are often cultivated year round under drip irrigation. Short duration crops are intensely rotated whereby a major knowledge gap exists on the effects of irrigation and fertilization on CO_2 emissions (Buerkert et al. 2021).

Agriculture is a significant contributor to greenhouse gas (GHG) emissions (Heimsch et al. 2021; Lynch et al. 2021) whereby the majority of studies agree that CO_2 contributes the largest proportion of GHG emissions from soils and its flux rates are more than hundred times larger than those of N_2O, CH_4 and other gases which is, however, partly compensated for by higher GHG effects of the latter (Ruser et al. 2006; Chen et al. 2010; Abalos et al. 2014; Negassa et al. 2015). CO_2 emissions from soils heavily depend on its water content and N status (Darwish et al. 2006; Abalos et al. 2014) and it is also known that crop rotation in combination with irrigation and fertilizer application lead to changes in soil C and

N dynamics by altering plant primary production, nutrient uptake, and recycled plant residues (Snyder et al. 2009; Weiler et al. 2018; Oldfield et al. 2019; Araya et al. 2021).

From a subtropical *Pinus* plantation in southeastern China Iqbal et al. (2008) reported that CO_2 emissions depended on soil temperature and water-filled pore space (WFPS). Tang et al. (2005) and Gaumont-Guay et al. (2006) determined that 70% of the diurnal variation of soil CO_2 fluxes were determined by soil temperature, which was similar to results of Manka'abusi et al. (2020) for CO_2, N_2O, and NH_3 in Quagadougou (Burkina Faso) and Tamale (northern Ghana). In the same study, cropping cycles and seasons also affected CO_2 emissions whereby CO_2 emissions under amaranth (*Amaranthus* L.) were significantly higher (20-83%) than those of other crops in the cycle (lettuce - *Lactuca sativa* L., jute mallow - *Corchorus olitorius* L. and carrot - *Daucus carota subsp. sativus*) across all treatments. It was also observed that mean CO_2 emissions for lettuce and carrot were significantly lower (11-66%) during the cold and dry season compared with the rainy period.

In Bengaluru rural-urban transition has led to altered cropping patterns (Patil et al. 2019), depletion of ground water sources (Kulkarni et al. 2021), intensification of N fertilizer application (Prasad et al. 2019), and a shift from rainfed agriculture to irrigated systems (Prasad et al. 2016). Under the monsoonal climate conditions of S-India with frequent drought spells irrigation plays an important role in enhancing crop yield, but little is known about changes in soil respiration as a consequence of system intensification exemplified by rising N levels and irrigation on the prevailing heavily leached tropical soils.

To fill this knowledge gap, we therefore have investigated CO_2 emissions from soils (soil respiration) in complex rotation systems to (i) assess diurnal changes in CO_2 emissions across different seasons, (ii) record the effects of N fertilization on CO_2 emissions, and (iii) determine crop specific irrigation effects on CO_2 fluxes. We hypothesized that (1) CO_2 emissions during afternoon hours are significantly higher than during morning hours, (2) N application enhanced CO_2 fluxes, and (3) under irrigated conditions CO_2 emissions were similar for all crops.

2.3 Materials and methods

2.3.1 Site overview and experimental design

Two two-factorial cropping experiments were established on the premises of University of Agricultural Sciences, Gandhi Krishi Vignan Kendra (GKVK) Campus, Bengaluru (UASB), Karnataka State, S-India with cultivated crop in a 3-part rotation and N fertilizer levels as fixed factors. At a distance of 500 m both experiments were established on deeply leached sandy Kandic Paleustalfs (US Soil Taxonomy) or Dystric Nitisols (World Reference Base) with identical treatments and crop rotations, but a different randomization. One field completely depended on rainwater and thus carried the Rainfed Experiment (RE; 13° 5'19.05"N, 77°34'16.11"E, 927 m asl). The other field had provision of irrigation water and therefore was an Irrigated Experiment (IE; 13° 5'15.32"N, 77°33'59.71"E, 930 m asl; Figure 2.1). The RE field had a history of arable cropping of finger millet (*Eleusine coracana* Gaertn.) for more than five years, while the IE was newly established after clear-cutting a >10-year old *Eucalyptus* plantation. This site was cleaned from all plant debris (tree stumps, roots, and branches) and ploughed followed by disking and several months of fallow prior to cultivation (Buerkert et al. 2023). The local climate in Bengaluru with a mean annual rainfall of 943 mm (Navya 2021) is divided into two distinct periods: the wet season from June to November and the dry season from December to May.

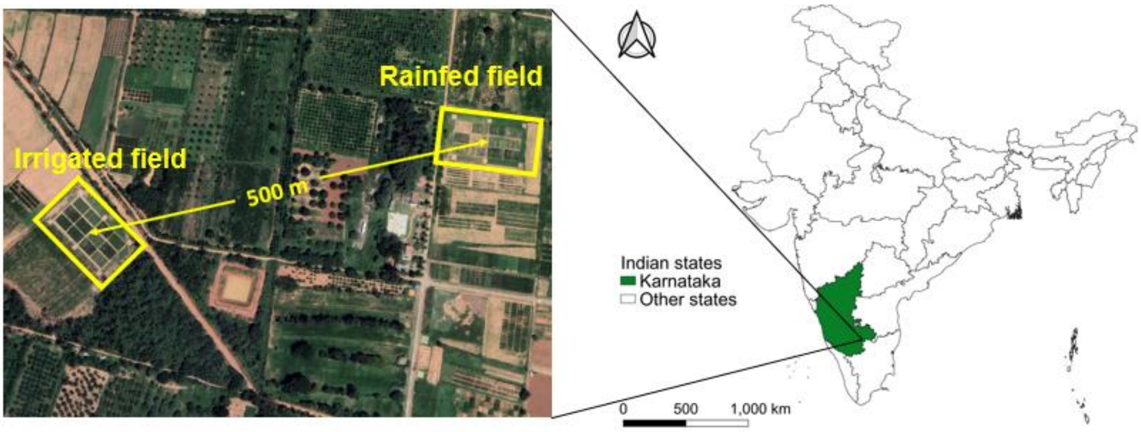


Figure 2.1 Location of the two experimental fields at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India. Google Earth, Oct 2017.

The layout of both experiments comprised 12 main plots (three crops replicated four times) in each field. Each main plot contains three subplots (12 m x 6 m) with randomly allocated a low, medium, and high N fertilizer rate (Figure 2.2). High N stands for the officially recommended N application dose for the corresponding crop, whereas medium N was defined as 50% of high N. The low N treatment consisted initially of 1/3rd of the recommended N which was reduced to zero from the 2018 wet season onwards (see appendix Table A 2.1). During the wet seasons crops rotated in both experiments were maize (*Zea mays* L., cv. Hema), lablab (*Lablab purpureus* L. Sweet, cv. HA3), and finger millet (cv. ML-365). In the dry season only IE was planted with cabbage (*Brassica oleracea* var. capitata, cv. Unnati), eggplant (*Solanum melongena* L., cv. Ankur), tomato (*Solanum lycopersicum* L., cv. NS-501) from 2017 to 2019, and chili (*Capsicum annum* L., cv. Demon) from 2020 to 2022 (Table 2.1).

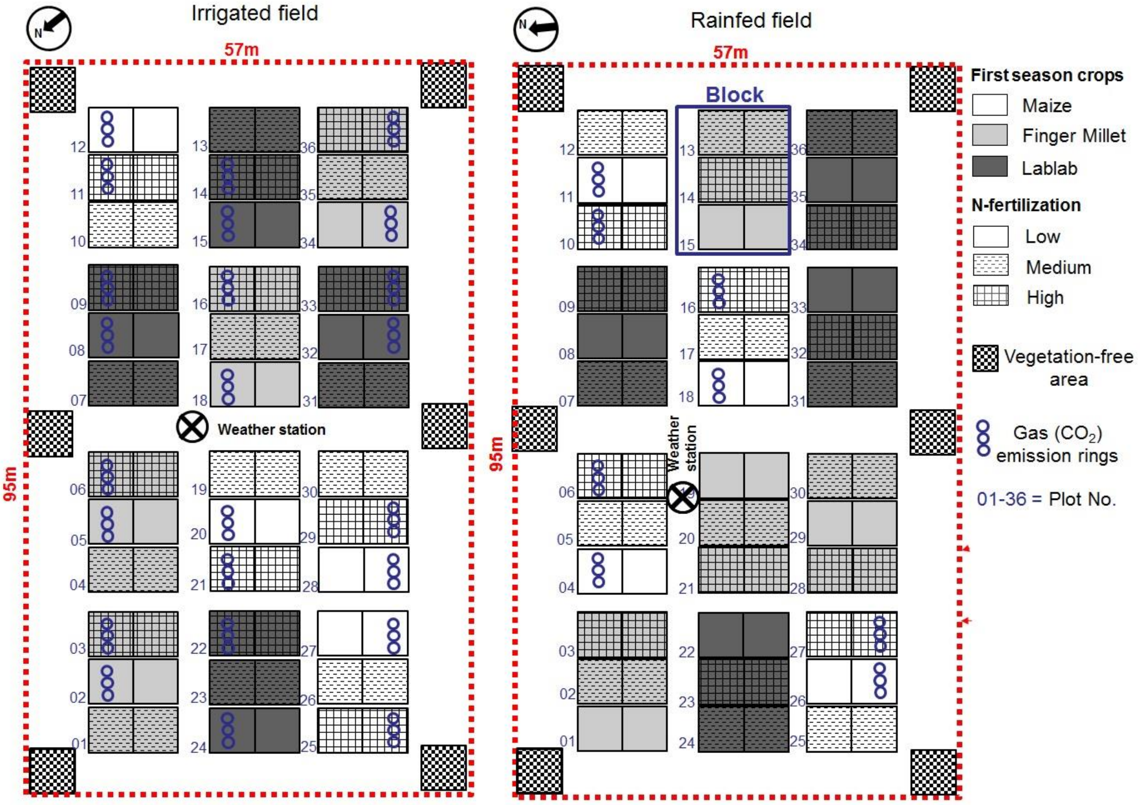


Figure 2.2 Layout of the two cropping system experiments at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India (Buerkert et al. 2021).

Table 2.1 Crop rotation in the two cropping system experiments at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India

Years	Seasons	Rainfed			Irrigated		
2016	Dry	-	-	-	-	-	-
	Wet	Maize	F. millet	Lablab	Maize	F. millet	Lablab
2017	Dry	-	-	-	Cabbage	Eggplant	Tomato
	Wet	F. millet	Lablab	Maize	F. millet	Lablab	Maize
2018	Dry	-	-	-	Eggplant	Tomato	Cabbage
	Wet	Lablab	Maize	F. millet	Lablab	Maize	F. millet
2019	Dry	-	-	-	Tomato	Cabbage	Eggplant
	Wet	Maize	F. millet	Lablab	Maize	F. millet	Lablab
2020	Dry	-	-	-	Cabbage	Eggplant	Chili
	Wet	F. millet	Lablab	Maize	F. millet	Lablab	Maize
2021	Dry	-	-	-	Eggplant	Chili	Cabbage
	Wet	Lablab	Maize	F. millet	Lablab	Maize	F. millet

Urea (46% N) was used as a N source and was complemented by a broadcast application of phosphorus (P) as single super phosphate (SSP; 3.1% P) and potassium (K) as muriate of potash (MOP; 41.5% K). Nitrogen was split-applied with 50% during sowing and the remaining amount 30 days after sowing (DAS; see appendix Table A 2.1).

Rainfall and air temperature data at the experimental locations were recorded from 10th June 2016 until 10th May 2022 at 15 min intervals by an automatic HOBO weather station (Onset Comp. Corp., Bourne, MA, USA). Annual rainfall in the driest year 2018 was only 728 mm, whereas 2021 received 1212 mm. Mean minimum and maximum air temperatures in the wet season were 18°C and 28°C, respectively, whereas in the dry season they were 19°C and 32°C (see appendix Figure A 2.1).

2.3.2 Soil sampling and analysis

Soil samples were collected at the beginning, in the middle, and after the experimental period (Table 2.2). To this end, in each high and low N plot, ten cores of 4.2 cm diameter were randomly collected at 0-15 cm depth, mixed, air-dried, and sieved to 2 mm. Dry-matter and organic matter were determined according to VDLUFA (1997). Soil pH was determined in a 0.01 M $CaCl_2$ solution with a freshly calibrated pH electrode (WTW pH3110, Xylem Analytics Germany Sales GmbH & Co. KG, Weilheim, Germany). To measure total soil C and N, a

VarioMax CHN-Analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany) was used.

Table 2.2 Soil carbon (C), nitrogen (N), and pH of the two experimental sites (Irrigated Experiment, IE and Rainfed Experiment, RE) at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India.

	2016				2019				2021			
	RE		IE		RE		IE		RE		IE	
Mean	Low N	High N	Low N	High N	Low N	High N	Low N	High N	Low N	High N	Low N	High N
C (%)	0.5	0.5	0.8	0.9	0.4	0.5	0.8	0.8	0.4	0.5	0.8	0.8
N (%)	0.04	0.04	0.07	0.07	0.04	0.05	0.07	0.08	0.04	0.05	0.08	0.08
pH	4.5	4.5	5.0	5.2	4.4	4.2	6.9	6.8	4.2	4.2	6.4	6.4

2.3.3 *In situ* gas emission measurements

CO_2 emission data were collected from the wet season 2016 to the dry season 2021 for which total above-ground biomass data are available at Buerkert et al. (2023). Measurements were conducted using a closed-chamber system connected to a multi-gas analyzer by a 1.5 m long PVC pipe of diameter 0.005 m. An INNOVA 1312 Photoacoustic Multi-gas Monitor (CO_2, N_2O, CH_4, NH_3 and H_2O; Luma Sense Technologies A/S, Ballerup, Denmark) was used from 2016 until dry season 2019 and thereafter replaced by a Los Gatos Research (LGR) Multi-gas Analyzer (CO_2, CH_4, NH_3 and H_2O; ABB Inc., San Jose, CA, USA) for higher accuracy and data density. To this end, three rings of 0.075 m height and 0.29 m diameter were installed at the beginning of the cropping season in plant rows by pushing the rings 0.05 m deep into the soil, 1 m away from the bunds. The area inside the rings/collars was cleaned from plant debris and weed plants one day before measurement without disturbing the soil. In every season, CO_2 emissions were determined before and after the first and second N application. The one-day measurement before fertilizer application was used as the baseline emission. After N application, emissions were determined for up to three days in the morning (7:00-11:30 am) and afternoon hours (12:30 pm to 6:00 pm) together with air temperature and relative humidity as well as soil temperature (0-0.05 m and 0.10 m depth) and volumetric water content (0.1 m depth) inside the gas emission chambers. In each ring, emissions were recorded for 4 minutes at a frequency of 1 minute with Innova and of 10 seconds with LGR. One minute of refreshing time was used for flushing out accumulated gas inside Innova/LGR to avoid any carry over effects between measurements.

Under the tropical environmental conditions and management practices on the deeply weathered, well aerated soils of our study, emissions of NH_3 and N_2O were negligible in 65% of all measurements. This created an improper distribution of the gas emission data for both gases among the crops and treatments. CH_4 emissions were always small and negative. Therefore, we excluded these parameters from further analysis and for this study used only CO_2 emission data.

During four years, each crop in the rotation was covered at least once in each plot (2017-2019). In the RE, gas emissions were determined for only one crop per season, starting with millet. CO_2 emission measurements started in the dry season 2017 and ended in 2021. Wet season measurements were taken between 2017 to 2020.

2.3.4 Statistical analysis

All raw data were synchronized with the respective time stamps in STATA 15 software (StataCorp, 2017). Subsequently, data were loaded in R 4.2.0 software (R Core Team 2022) to calculate gas fluxes using the linear model of the “gasfluxes” package (Fuss 2020). CO_2 flux rates were calculated by subtracting initial chamber concentrations from final concentrations and dividing the difference by the time period for which gas emission was measured. Data were tested for normality and non-normal data were discarded for each ring’s measurement in a season of a crop at respective fertilizer application time. The mean difference between two independent groups was analyzed by one-way analysis of variance (ANOVA) adjusted with the Bonferroni procedure in STATA 15. A repeated measures mixed linear (ML) model analysis was used in STATA 15 to investigate the effects of N application, soil temperature, and soil moisture on CO_2 flux rates. Fixed effects were N rate, soil temperature, soil moisture, and their interaction, while crops were considered as random. The equation was determined using backward stepwise regression in which least significant variables were dropped one after another until no insignificant variables remained.

2.4 Results

2.4.1 Mean CO_2-emissions

The soil temperature at a depth of 5 cm in the rainfed field averaged 29.2±4.0 °C, compared to 27.4±4.1 °C in the irrigated field. Rainfed soil exhibited a moisture content of 11.5±4.3 %, whereas the irrigated soil measured 19.8±7.6 %. Inside the chamber, relative humidity reached 67.2±13.9 % in the rainfed area and 64.6±16.7 % in the irrigated one. CO_2-emissions before and after fertilizer application in the IE (Figure 2.3) and RE (Figure 2.4) varied widely across time.

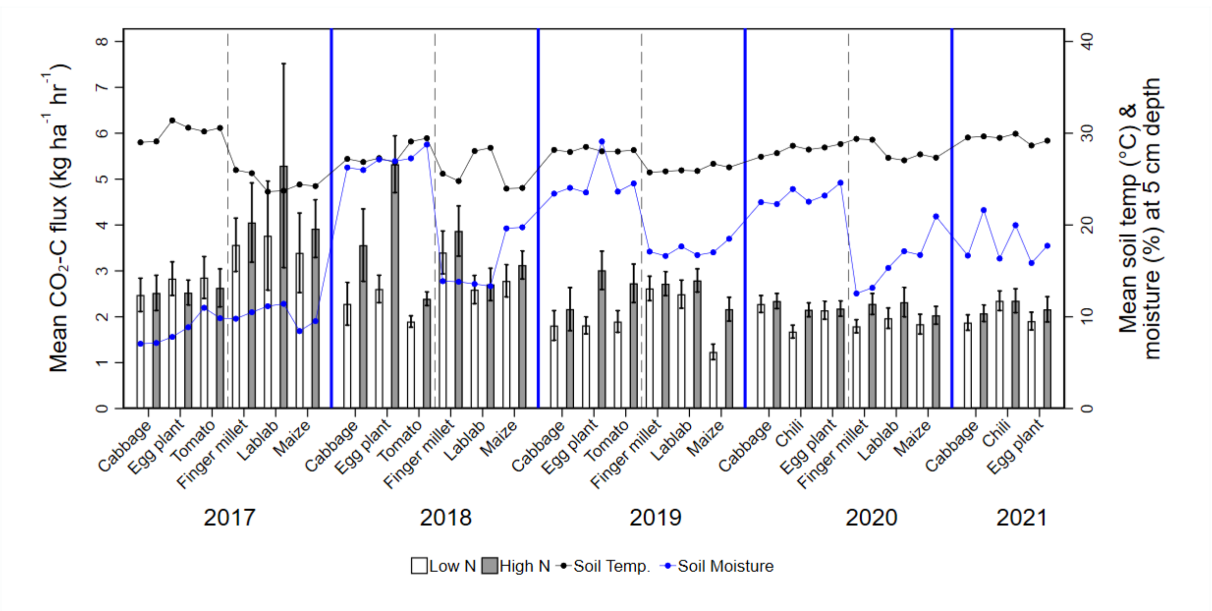


Figure 2.3 Mean CO_2-C emissions of irrigated crops before and after different levels of N application under the soil moisture and temperature conditions at GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India.

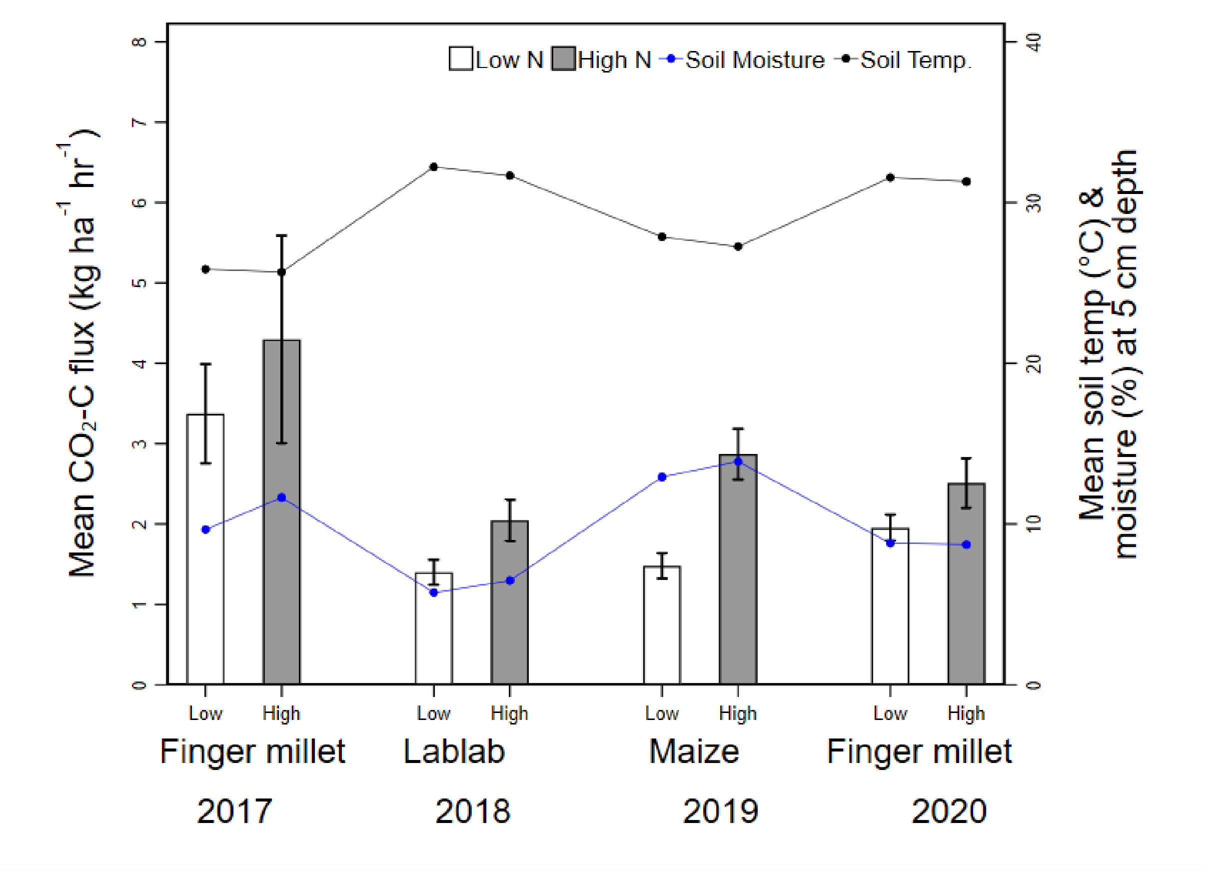


Figure 2.4 Mean CO_2-C emissions of rainfed crops under different N application, soil moisture, and temperature conditions at GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India.

2.4.2 Diurnal variation in CO_2 emissions

Across all crops, treatments, and both fields, CO_2 emissions averaged 1.97 ± 1.0 kg C ha^{-1} hr^{-1} in the morning (7:00 to 11:30 am) and 2.73 ± 1.5 kg C ha^{-1} hr^{-1} in the afternoon (12:30 to 06:00 pm). Regardless of crops and treatments, CO_2 emissions during afternoon hours were 46.1% and 8.7% higher than during morning hours in the RE and IE ($p<0.001$), respectively. Diurnal variations of CO_2 emission in low and high N plots of the RE and IE were high (Table 2.3) but the differences between afternoon and morning hours were always positive. Differences of diurnal CO_2 emissions across crops were not consistent with regards to N application.

Table 2.3 Diurnal variation of CO_2 emission within low and high N plots in different crops of a rainfed and irrigated experiment (RE and IE) at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India

Field type	**Crop**	**Difference of CO_2-C emissions (%) (Afternoon-Morning)**	
		Low N plots	**High N plots**
Rainfed	Finger millet	32.4***	11.0
Rainfed	Lablab	15.7	31.3**
Rainfed	Maize	128.4***	101.5***
Irrigated	Cabbage	41.5***	36.8***
Irrigated	Chili	12.2*	9.8
Irrigated	Egg plant	52.7***	36.9***
Irrigated	Tomato	27.5***	21.5***
Irrigated	Finger millet	33.7***	48.1***
Irrigated	Lablab	33.9*	72.0***
Irrigated	Maize	1.8	26.8***

***,**,* Significance at $p < 0.01$, 0.05 & 0.10, respectively

2.4.3 Fertilization effects on CO_2-C emissions for wet and dry season crops

Nitrogen application significantly ($p<0.05$) affected CO_2 emissions in all wet season crops of the RE and IE, as well as dry season crops in the IE. Mean CO_2 fluxes ranged from 1.5 to 3.0 kg C ha^{-1} hr^{-1} (Table 2.4). High N plots had significantly higher CO_2 emission than low N plots across all crops and seasons in both experiments. The difference between high and low N plots' CO_2 emissions (across crops) during the wet season in the IE was 56.4% (0.93 kg C ha^{-1} hr^{-1}) whereas it was 12.1% (0.28 kg C ha^{-1} hr^{-1}) in the IE. Similarly, during the dry season the difference was 8.0% (0.17 kg CO_2-C ha^{-1} hr^{-1}). Analyzed crop-wise, the differences in CO_2 emissions between low and high N plots in irrigated field were between 0.3 to 0.4 kg C ha^{-1} hr^{-1}, except for eggplant which had 1.0 kg C ha^{-1} hr^{-1}. On the other hand, rainfed finger millet and lablab had CO_2 flux differences of 0.5 and 0.6 kg C ha^{-1} hr^{-1}, respectively, whereas maize had 1.0 kg C ha^{-1} hr^{-1}. The amount of urea fertilizer applied in dry season during 2019 - 2021 was 15.0 % higher than during the wet season. Also, MOP application was 14.8% and SSP 31.8% higher than during the wet season while total dry matter yield in the dry season averaged only 43.0% of the wet season dry matter. Soil moisture content affected CO_2 emissions positively under rainfed condition but negatively under irrigation.

Table 2.4 Comparison of mean CO_2–C emissions from different crops in the irrigated and rainfed field experiment (RE and IE) at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India.

Field type	**Crop**	**Mean CO_2 flux (kg C ha^{-1} hr^{-1})**		**Significance (P)**
		Low N plots	**High N plots**	
Rainfed	Finger millet	2.0 (74)	2.5 (68)	0.003
Rainfed	Lablab	1.4 (34)	2.0 (40)	0.001
Rainfed	Maize	1.5 (83)	2.9 (89)	0.001
Irrigated	Cabbage	2.1 (230)	2.5 (251)	0.003
Irrigated	Chili	2.0 (130)	2.3 (145)	0.008
Irrigated	Egg plant	2.3 (292)	3.3 (314)	0.001
Irrigated	Tomato	2.1 (144)	2.5 (158)	0.001
Irrigated	Finger millet	2.5 (243)	2.8 (243)	0.039
Irrigated	Lablab	2.7 (250)	3.0 (252)	0.045
Irrigated	Maize	2.0 (250)	2.4 (266)	0.002

2.4.4 Crop specific CO_2 emissions under irrigation

To analyze the effects of growing crops on CO_2 emissions, we focused on the IE because its plots were intensively cultivated throughout the year. Plots of dry season crops cabbage, chili, eggplant, and tomato had CO_2 emission rates between 1.8 – 2.5 kg C ha^{-1} hr^{-1} (Table 2.3). On the other hand, plots with wet season crops finger millet, lablab and maize had emission rates between 2.3 - 3.0 kg C ha^{-1} hr^{-1} with a confidence interval of 0.95. Mean CO_2 emissions within a season did not significantly vary between crops. However, across seasons lablab plots had significantly higher CO_2 emissions than those of cabbage, chili, eggplant and tomato while emission rates in maize and finger millet plots were significantly higher than those of cabbage, chili, and eggplant (Figure 5).

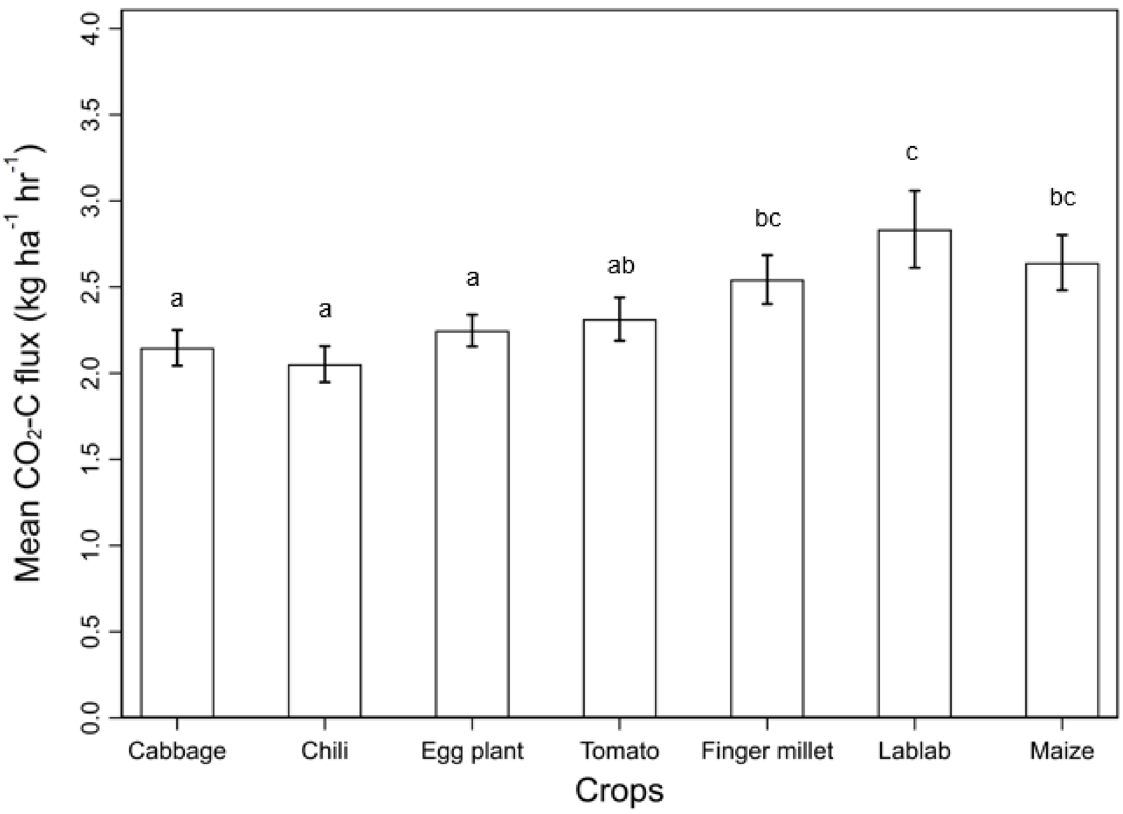


Figure 2.5 Crop specific mean CO_2–C emissions in an irrigated crop rotation experiment at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India. Mean CO_2 emissions of both low and high N plots for each crop across years yielded different numbers of replications for each crop: cabbage (5), eggplant (5), tomato (3), chili (2), finger millet (4), lablab (4), and maize (4). Vertical bars indicate +/- one standard error of the mean.

2.4.5 Mixed effects of treatment-application, soil temperature, soil moisture, and crops on CO_2 emissions

We also analyzed treatment level, soil moisture, and soil temperature as fixed effect parameters while crops were considered as a random effect parameter (Table 2.5). Random parameter did not significantly affect the fixed parameters as the variance inflation factor (VIF) for each independent variable in the regression model was close to 1. This indicates that crops had no significant effect on CO_2 emissions. Effects of N application on CO_2 emissions were lowest in dry season crops and highest in rainfed wet season crops. Soil moisture had different effects in irrigated and rainfed plots: in IE it was negatively correlated with CO_2 emissions while in RE it enhanced CO_2 emissions. Effects of soil temperature on CO_2

emissions were highest in rainfed wet season crops and lowest in irrigated dry season crops.

Table 2.5 Mixed model coefficients of fixed effect parameters and estimates of random parameters on CO_2 emissions (kg C ha^{-1} hr^{-1}) in a rainfed and irrigated crop rotation experiment at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India.

	Dry season	**Wet season**	
	Irrigated	**Rainfed**	**Irrigated**
Fixed effect	Coefficients	Coefficients	Coefficients
Treatment level (0- low, 1- high)	0.280***	0.974***	0.419***
Soil moisture (%)	-0.012***	0.062***	-0.023***
Soil temperature at 5 cm (°C)	0.044***	0.069***	0.068***
Random effect	Estimate	Estimate	Estimate
Crops (crop Id)	0.002	2.81e-18	2.61e-14

*** Significance at $p < 0.01$

2.5 Discussion

2.5.1 Soil temperature and moisture increases CO_2 emissions

Agriculture along the rural-urban gradients in the S-Indian megacity of Bengaluru with its 12 Mio inhabitants is characterized by the intensive use of agricultural inputs, continuous cropping, and increasingly year-round irrigation despite notorious water scarcity. Our experiments aimed at mimicking cultivation patterns in this transformative environment. It is well known that soil temperature and moisture greatly influence a soil's C and N mineralization rates (Sierra 1997; Rey et al. 2005). Under non-limiting moisture conditions higher temperature enhances microbial metabolism which leads to higher C and N decomposition by increasing microbial respiration (Lloyd and Taylor 1994; Rey et al. 2005; Allison et al. 2010). Davidson and Janssens (2006) stated that a significant proportion of labile soil organic carbon is subject to temperature sensitive decomposition, while other fractions remain stable under environmental constraints, which often mask temperature effects on soil organic matter (SOM) decomposition. In our study differences in mean soil temperature to 5 cm depth between afternoon and morning hours in rainfed and irrigated fields were 4.1°C and 5.9°C, respectively. The temperature difference was higher in the IE than the RE, most likely due to the cooling effect of irrigation water applied during morning hours. In the RE, overall CO_2 emission rates during afternoon hours were 46% higher than during morning hours while in the IE CO_2 emissions during afternoon hours were 40% higher than during morning hours in the wet season. The lower diurnal variation of emissions in the irrigated field may be due to the limiting effects of higher soil moisture on CO_2 emission during the wet season. Peng et al. (2011) reported in their study that soil moisture became a limiting factor for CO_2 emission during the growing season (July-September) within a similar moisture content (2-22%) and temperature (20-40°C) range.

2.5.2 N fertilization increases CO_2 emissions

At low soil C such as in our study higher N is known to stimulate soil microbial activity which in turn increases SOC mineralization thereby emitting more CO_2 (Häring et al. 2017). Another mechanism by which higher N fertilization increases CO_2 emissions is the sequestration of higher carbon (C) inputs from increased crop growth (Adviento-Borbe et al. 2007). In our study irrespective of irrigation, CO_2 emissions in all crops significantly increased with N application. However, the relative increase in CO_2 emissions of wet season crops from low N plots was greater in rainfed plots than in irrigated plots. The mean CO_2 emission in rainfed high N plots was 56.4% higher than in low N plots. In the IE the same set of wet season crops grown on high N plots had only 12.1% higher CO_2 emissions than those in low N controls.

Development of root and shoot growth in plants also induces increase in CO_2 emissions (Magill et al. 1997). On our experimental plots, high N plots had significantly higher aboveground plant biomass than low N plots (Moran-Rodas et al. 2022; Buerkert et al. 2023). Higher CO_2 emissions from the high N plots aligns with the results of previous studies. Correlations between dry matter yield and CO_2 emissions were $r = 0.37$ ($P= 0.018$). Under irrigation crop specific CO_2 emissions are unrelated to N fertilization.

Over the entire experimental period, crop types within a season didn’t affect CO_2 emissions under different soil C, N, temperature, and moisture conditions. Differences in CO_2 emissions among different crop species may also be due to differences in root respiration of these crops. In this context, it has been shown that plant root respiration may contribute 10-90% of the total soil CO_2 emissions (Rochette et al. 1999; Hanson et al. 2000). In our study the wet season crop lablab had higher mean CO_2 emissions than maize and finger millet. Being a legume, lablab has comparatively higher energy demands than cereals and vegetable crops which is positively correlated with root respiration (Rao and Ito 1998).

CO_2 emissions of all crops in wet season averaged 2.6 kg C ha^{-1} hr^{-1}, whereas in dry season it was 2.2 kg C ha^{-1} hr^{-1} (Figure 2.3). This difference in seasonal CO_2 emissions may be attributed to a lower soil moisture content (17%) and higher biomass production during the wet season and residual effects of higher N rates applied in the dry season (22%). Among all grown crops in our experiment, maize was the most sensitive in terms of biomass production to limited N and produced higher biomass than other crops. The combined effect of lower biomass production and higher soil moisture content in dry season may have led to residual N at the onset of the following wet season.

2.5.3 Combined effects of N fertilization, soil moisture, and soil temperature on CO_2 emissions

The magnitude of N fertilization effect was highest in rainfed crops whereby high N plots had 2-5 times higher biomass production than plots without N (Buerkert et al. 2023). In the IE the high N treatment led to an only 20-30% higher biomass compared with zero N plots. N fertilization induces microbial activity and root respiration in the plants and the findings of this study agree with the results of previous studies (Sainju et al. 2008; Peng et al. 2011). Soil moisture affected CO_2 emission differently depending on irrigation. In the RE field, soil moisture positively correlated with CO_2 emissions but negatively in the IE field. Usually, irrigation or rain in dry soil increases C mineralization and root respiration, resulting in higher CO_2 flux rates (Curtin et al. 2000; Abalos et al. 2014). Hashimoto and Komatsu (2006) reported that soil moisture has a parabolic relationship with soil surface CO_2 emissions and controls the diffusivity of the CO_2 along air filled pores. Similarly, in the IE higher soil moisture content might be hindering the diffusion of CO_2 to the atmosphere, which was, however, not measured. Temperature plays an important role in decomposing soil organic matter (SOM). In our study, soil temperature (up to 5 cm depth) affected the CO_2 emission equally in IE and RE fields during the wet season but had slightly lower effect during the dry season (Table 2.5). In the latter season diurnal soil temperature differences were greater than in the wet season but on the other hand soil moisture content was comparatively higher due to continuous irrigation. Thus, the higher soil moisture content may have masked the temperature effects during the dry season.

2.6 Conclusions

This study confirmed that on the deeply weathered Nitisols of S-India N application leads to higher CO_2 emissions whereby the magnitude of C losses depends on soil moisture. The effects of N application on C losses were considerably higher under rainfed than under irrigated conditions. Soil moisture content affected CO_2 emissions positively under rainfed but negatively under irrigated conditions. There was no indication of crop effects on CO_2 emissions but wet crops had significantly higher CO_2 emission under irrigation which was likely due to residual effects of irrigated dry season crops. This calls for further research on the interactions between soil moisture and CO_2 emissions under more controlled conditions.

Chapter 3

Urbanization's effect on the lake ecosystem dynamics in Bengaluru, South India, 2002-2022

3.1 Abstract

Land use transformation in the rapidly growing megacity of Bengaluru in South India has greatly influenced its lake ecosystems. To gain insights into the dynamics of lake ecosystems along an urban-rural gradient, we analyzed lake-cover changes (along with a 300m buffer zone) of six lakes from 2002 to 2022. The lakes studied were Bellandur and Dodda Bommasandra (urban), Attur and Puttenhalli (peri-urban), and Chudahalli and Vrishabhavathi (rural). Supervised maximum likelihood Land Use/Land Cover (LULC) classifications were conducted on 168 freely available, RGB Google Earth (GE) images to distinguish between macrophytes, algae, water, and dried land inside the lakes, and built-up and non built-up area in the buffer zone. Antagonistic relationships between macrophytes and algae were observed at all locations. Rainfall was positively correlated with the wet surface area (that is macrophytes, algae, and water) in comparatively dry lakes. Similarly, air temperature was negatively correlated with the wet surface area except for the Vrishabhavathi Lake. However, the built-up area in the buffer zone did not show a consistent correlation with the wet surface area, most likely because of sewage connections of certain lakes with distant urban areas.

Keywords: Google Earth images, Lake Vegetation, Rural-urban gradient, Urban wetland

3.2 Introduction

In 2023 of the currently eight billion on our planet approximately 4.6 billion, or 57% are considered “urban” as they live in towns or cities. The latter figures are likely to surge by nearly 600 million by 2030, culminating in a total of 5.2 billion, or approximately 60%. Following this trend, India’s urban population is expected to reach 607 million by 2030, with 40% of the Indian population living in urban areas by mid-2030 (UN, 2019).

As urban areas continue to grow, the water bodies in urban areas undergo severe transformations due to the discharge of urban wastewater and pollutants (Martínez-Arroyo & Jáuregui, 2000; Naselli-Flores, 2008; He et al., 2011). In Bengaluru referred to as India's "Silicon Valley" or the "City of Lakes" urbanization has significantly altered the structure of the urban and peri-urban landscapes (Ramachandra & Aithal, 2019; Sen & Nagendra, 2021). The pace of urbanization was driven by economic liberalization in the early 1990s, coinciding with the advent and rapid growth of the information technology (IT) and related industries (Sudhira et al., 2003). Bharadwaj et al. (2022) identified that 37.8% of Bengaluru's growth occurred as edge expansion, a peculiar pattern of outward growth of cities in many countries of the Global South (Chakraborty, 2022). Hereby, Bengaluru is one of Asia's fastest-growing megacities with currently around 13 million inhabitants, nearly doubling the populace from 2002 (UN, 2022). It lies 920 m above sea level in the southern part of the Deccan Plateau, which is typically formed of sheets of massive granite rocks lying under a thin surface layer of soil.

The lakes in Bengaluru are primarily man-made, interconnected through storm water drains which carry excess water from higher to lower elevations. Over time, these lakes have provided various ecological services and supported local livelihoods (McDonald et al., 2011; Nagendra et al., 2013). In the past, agrarian communities clustered around the lakes, relying on them as a source of irrigation water, fertilizer from silts scraped from the lakebed, grass or fodder, drinking and cleaning water, and fishing. Present-day, the lakes are mostly used by urban communities for recreational purposes such as walking, boating, yoga, bird watching, and cultural events (Sen & Nagendra, 2021). Beyond the direct benefits provided by the lakes, there are some indirect benefits to the surrounding environment such as flood control (Dittrich, 2007), groundwater recharge (Sudhira & Nagendra, 2013), wastewater treatment (Ramachandra et al., 2016a), lower ambient temperature (Parikh et al., 2015), and biodiversity conservation (Hettiarachchi, 2014).

Over the last decades the water demand by Bengaluru's population has increased exorbitantly, yet the integration of the water bodies into the city supply and reuse remains inadequate (Unnikrishnan et al., 2017). As a result, private borewells have been drilled up to a depth of 400 m, and additionally a 100 km long trench was built to extract the politically conflicted water resources of the Cauvery-Arkavathy river basins to meet the rising water demand of the city (Ramachandra et al., 2016b; Ramachandra & Aithal, 2016). The water commons of the city are becoming part of the public health concerns given a severe contamination of surface and underground water (Goldman, 2011). Ramachandra et al. (2016a) reported that 98% of lakes in Bengaluru are encroached, disrupting their interconnectivity. Furthermore, 90% of the lakes have been polluted by untreated sewage, industrial effluents, and the dumping of solid wastes and building debris. Varalakshmi and Ganeshamurthy (2012) claimed that more than half of the city's lakes were highly polluted. Despite this pollution, local farmers use these lakes to collect fodders for their cattle, and extract contaminated irrigation water to irrigate their fields. This can lead to the accumulation of toxins in the soil, lower the yield of crops, generate health issues, and cause marketing difficulties for local products (Varalakshmi & Ganeshamurthy, 2012).

In wetlands aquatic macrophytes have several ecological functions (Carpenter & Lodge, 1986). They aid in the sequestration of organic carbon and nutrients, stabilization of sediments and shorelines (Søndergaard, 2010), and can be used as indicators of water quality (Brucet, 2013). In Bengaluru, a quarter of the lakes are fully covered by macrophytes, a phenomenon attributable to the rapid growth of exotic invasive species indicating lake degradation (Verma et al., 2003). Depending on the season the macrophyte cover in the wetlands of Bengaluru is dominated by a mixture of floating water hyacinth (*Eichhornia crassipes* (Mart.) Solms) and rooted alligator weed (*Alternanthera philoxeroides* (Mart.) Griseb.), nut grass (*Cyperus rotundus* L.), and narrow leaf cuttail (*Typha angustifolia* L.) along with *Chlorella* algae and a *Cyanophycea* bacterial population (Bhat et al., 2017; Ramachandra et al., 2017; Mahapatra et al., 2018). The mixture of macrophytes and bacterial-algal communities of phytoplanktons play an important role in these lake ecosystems as they contribute to water purification (Ramachandra et al., 2003; Ramachandra et al., 2014; Mahapatra et al., 2018; Ramachandra et al., 2018). With the rapid spatial growth of macrophyte cover, the algal activity is lowered significantly which can lead to higher oxygen demand for lake ecosystems (Ramachandra et al., 2017; Mahapatra et al., 2018).

Advances in remote sensing approaches and increasing availability of images with high spectral and temporal resolution have allowed to understand spatio-temporal variation in lake dimensions and cover as a consequence of urbanization (Ramachandra & Kumar, 2008; Gautam et al., 2015; Bareuther et al., 2020). The latter authors also reported that lake cover dynamics are more driven by seasonal monsoon-related factors than by differences in their waste water-related nutrient status.

In view of the above, this study aims to add a new dimension to the prevailing literature by investigating the effects of seasonality and urbanization within a 300m buffer zone on lake ecosystem dynamics by using freely available Google Earth (GE) satellite images from 2002 to 2022. We hereby want to determine the effect of urbanization on wetland environments. Specifically, we aim to (i) determine seasonal and temporal dynamics of vegetation, and (ii) detect the proportion of built-up areas surrounding different lake types and siltation-derived dried-up lake shores along an urban-rural gradient of Bengaluru.

3.3 Materials and Methods

3.3.1 Study locations

Bengaluru on the southern Indian Deccan Plateau has a mild climate throughout the year with temperatures ranging from 18°C to 38°C during the monsoonal summer and 12°C to 25°C during the dry winter (Ramachandra & Aithal, 2019). Average annual precipitation is 900mm, with the majority occurring between June and September (Ravindrababu et al., 2010). Along an urban-rural gradient defined according to Hoffmann et al. (2017) we selected six lakes with a buffer distance of 300m from the lake boundary to determine typical urbanization effects on lake encroachment (Figure 3.1).

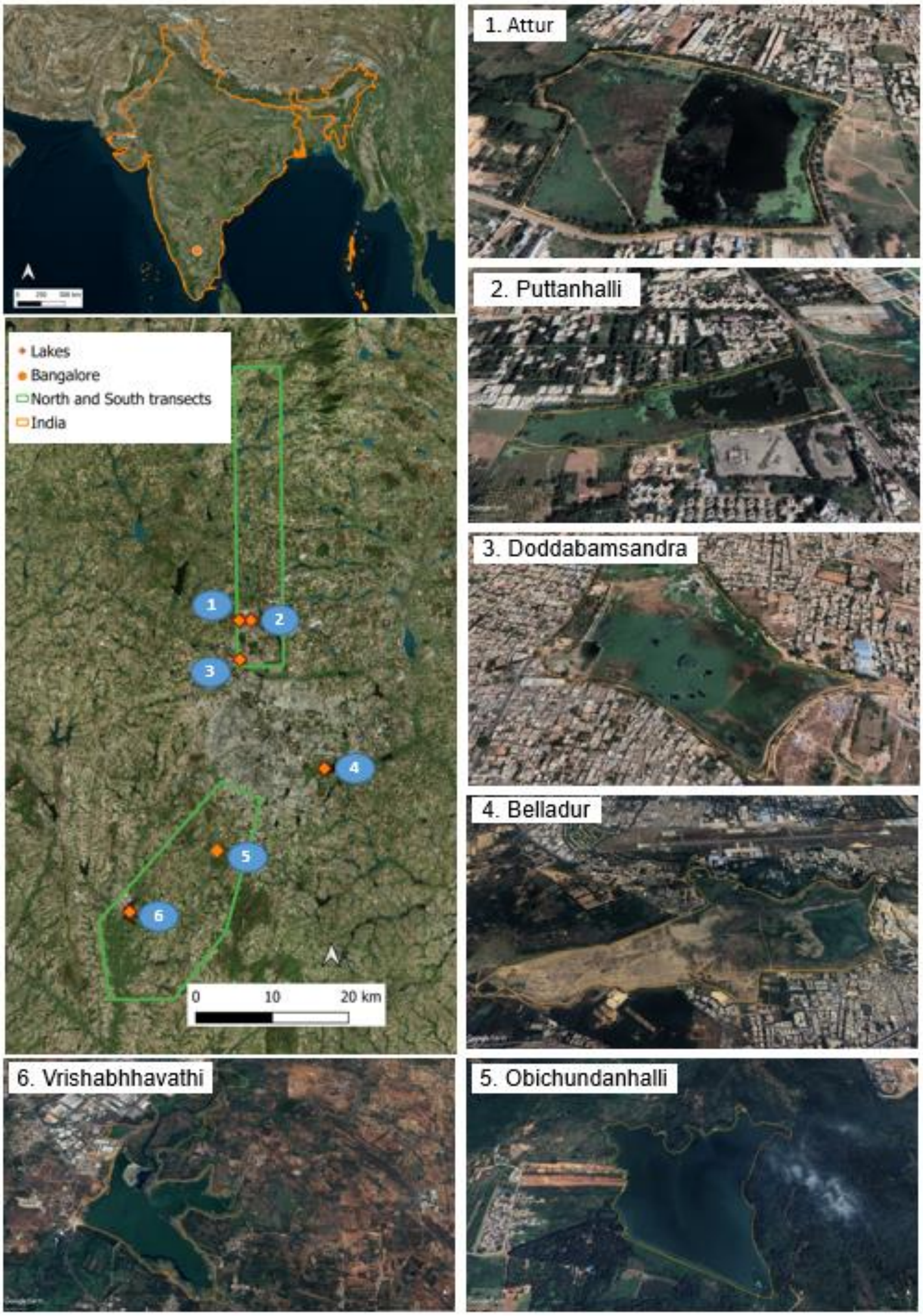


Figure 3.1 Study locations in the Bengaluru area of S-India. The 2022/2023 satellite images of the six lakes (Sources: Google Earth Pro 7.1 and base map in QGIS, retrieved on 23.02.2023)

3.3.2 Data collection

A total of 168 images of the six selected lakes from 2002-2022 were downloaded from GE Pro 7.1 whereby incomplete, blurred, and cloud-covered images were excluded (Table 3.1). The six lakes were divided into the three strata “urban”, “peri-urban”, and “rural” following Hoffmann et al. (2017). In each image, a set of ‘virtual’ Ground Truthing Points (GTPs) was determined to allow for training and accuracy assessment of image classifications (Step 3, under section “Classification of GE Images”).

Table 3.1 List of satellite images collected from Google Earth Pro 7.1 in Bengaluru, S-India

Name of lakes	Strata (1 rural, 2 peri-urban and 3 urban)	Number of images	Period available
Attur	2	29	2004-2021
Bellandur	3	38	2002-2022
Chundahalli	1	26	2004-2022
Dodda Bommasandra	3	28	2002-2021
Puttenahalli	2	33	2004-2020
Vrishabhavathi	1	14	2004-2019
Total of images		**168**	

3.3.3 Image classification

Step 1: Georeferencing and definition of lake boundaries and buffer zones

The downloaded images were georeferenced using the Georeferer tool in Quantum Geographic Information System (QGIS) 3.30.1 whereby at least four clearly defined control points were selected such as road intersections, corners of a major building, or sharp edge(s) of the lakes. We used the same control points to georeference all images of the same lake to ensure that all images of a lake are placed at the same location in the geographical coordinate system. Boundaries of the lake were manually drawn by using the “Add polygon” feature of GE 7.1 on the oldest image as a baseline boundary of the lake. Afterwards, the digitized lake boundary was exported as a kml file and converted into a shapefile in QGIS 3.30.1. Buffer zones (multi-ring donuts’ structure) of 300m were defined for field sampling based on the shapefile of the lake boundary.

Step 2: Definition of classes

The internal area of each lake was assigned to four classes: algae, macrophytes, surface water, and dried land. The latter represented the bare soil areas inside the lake boundary that resulted from lake dry-ups, lake banks, or were island areas (Bareuther et al., 2020). Buffer zones were assigned to the two binary categories “built-up” and “non built-up” (Chan et al., 2008; Nguyen et al., 2022).

Step 3: Classification of GE images

A minimum of seven training polygon inputs were generated in each class with the Semi-Automatic Classification Plugin (SCP) of QGIS. Region of Interest (ROI) polygons and spectral signatures were stored for further classification of GE images. The training inputs of the built-up class were re-used from earlier images if there were no spectral differences between them. In total, approximately 6000 training polygons were created for supervised classification with the Maximum Likelihood algorithm in QGIS following the method applied by Bareuther et al. (2020). Training inputs were evaluated by Jeffries-Matusita distance and the training set was re-created if the values were < 1.8 as recommended by Richard & Jia (2006). The number of polygons in a training set was increased if the Jeffries-Matusita distance value was < 1.8. In-field cluster-wise GTPs were also collected in June 2021 in which similar spectral reflectances between algae and young macrophytes in GE images were deciphered.

Step 4: Post-classification

Post-classification was used to calculate the area of each class by masking it with respective lake boundaries and buffer boundary shapefiles. The masked raster images were then converted into shape files and the area of each class was determined using a geometry calculator rather than post-classification in QGIS.

Step 5: Accuracy assessment

To calculate the accuracy of each image classification an accuracy assessment process using the post-processing feature of the SCP plugin was performed by selecting a raster file of the classified image and a vector file of validation inputs. In total, approximately 4 000 polygons were used. Through this process, the overall accuracy, the user’s and producer’s accuracies, and the Kappa statistics from the error matrices were determined to evaluate the accuracy of the maps produced. Whenever overall accuracy was < 60 %, the number of polygons of the validation inputs was increased to improve overall accuracy.

3.3.4 Data analysis

The data was analyzed using R (4.1.0; R Core Team, 2022). For each lake, analyses were conducted separately to account for lake characteristics. Classified lake maps were used to calculate the area of built-up, non-built-up, water, macrophytes, algae, and dried land in square meters (m^2) using QGIS (Step 4). The proportion of built-up area relative to the total buffer zone was plotted to visualize trends. Using proportions instead of total areas allows to accommodate different lake sizes, making comparisons between lakes more meaningful at the same scale. The sum of the built-up and non built-up area was the same (<0.001%) across all photos per lake.

To understand the vegetation dynamics of individual lakes, the percentages of algae, macrophytes, water, and dried land were calculated whereby the sum of these values was similar for each lake (<0.005%). As before, percentages instead of total areas were used to accommodate for varying lake sizes associated with year and month, accounting for the time differences between different images and different lake size. To investigate effects of urbanization-related encroachment on lakes, the variable "wet surface area" was defined. This comprises water, macrophytes, and algae, as they are interconnected whereby water areas might be hidden by macrophytes. The correlations between built-up, non-built-up, dried surface area, and wet surface area were calculated for each lake to explore their relationships.

Correlations between daily rainfall and minimum/maximum air temperature and wet surface area of the studied lakes were determined to assess the impact of climate on ecosystem services. These climate data were obtained from an automatic weather station set up inside the GKVK campus of the University of Agricultural Sciences, Bengaluru. Correlations were calculated by taking the average minimum and maximum temperatures for the month corresponding to each photo. Subsequently, correlations were computed between the monthly average temperatures and the month of the photo. For correlations with rainfall, total rainfall during the wet season (June to September inclusive) was aggregated and associated with the following dry season. For example, images from March 2008 were linked to rainfall data from June to September 2007.

3.4 Results and Discussion

3.4.1 Seasonal and temporal dynamics of vegetation

At lake classification, there was a distinction between macrophytes and algae (or protists) as non-vegetative categories comprised dried land and water. Some similarities between the lakes were observed: within a dry season, the vegetation was highly dynamic over relatively short periods confirming results of Bareuther et al. (2020). Within a month, the coverage of macrophytes and algae may significantly increase due to the fast growth rate of macrophytes (Figure 3.2). However, it can also be reduced due to frequent fodder harvests by farmers and dredging by the lake governing authority. This harvesting and dredging activity may explain the limited correlation between macrophyte growth and climate at the smaller scale. Here the quick growth spurt may be substantially offset by a swift harvesting of vegetation as animal fodder (Alam et al., 2023) or dredging before satellite imaging.

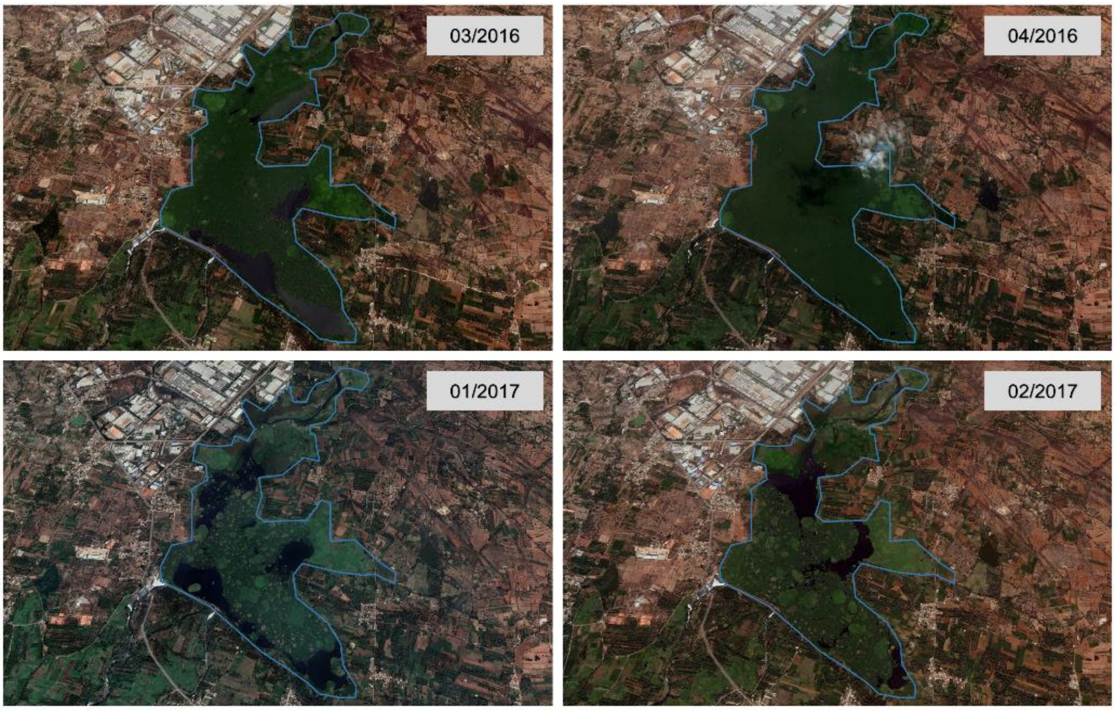


Figure 3.2 Visualization of vegetation changes within a month for Vrishabhavathi Lake (Bengaluru) in 2016 and 2017 at the same scale (Sources: Google Earth Pro 7.1, retrieved on 20.01.2021)

3.4.1.1 Urban lakes - Dodda Bommasandra and Bellandur

Both urban lakes experienced an increase in water levels over the two studied decades, accompanied by a decrease in algae and an increase in macrophytes (Figure 3.3). In Dodda Bommasandra, the increase in macrophytes was likely due to the rise in runoff flow in recent years, resulting in higher water and nutrient contents. The increased macrophyte growth, along with the rise in water runoff, has likely resulted in a decrease in dried-up land inside the lake. On the other hand, in Bellandur, the increase in macrophytes can be attributed to changes in the lake's immediate surroundings. The western lake side has become partly silted over time, creating a more favorable environment for perennial grasses to thrive (Ramachandra et al., 2017).

In the lakes of Bengaluru, over 32 genera of algae were documented, totaling more than 40 species. The predominant members in the algal community were Chlorophyceae with 13 genera, followed by Bacillariophyceae with 7, Cynaophyceae with 6, and Euglenophyceae with 4 (Mahapatra et al., 2018). Changes in the composition of the algal community over space and time are influenced by nutrient levels, the physico-chemical environment, and microclimatic factors. The distribution of nutrients within the lakes, both horizontally and vertically, is significantly impacted by factors such as solar insolation, precipitation, and wind velocity (Mahapatra et al., 2011a, Mahapatra et al., 2011b). However, the area covered by algae has significantly decreased despite the expansion of the water area. The reason for this decline might be that the water only remains in the heavily silted lake for a short period after which it overflows to nearby areas, preventing algae from thriving. Unlike in Dodda Bommasandra, Bellandur Lake has experienced an increase in dried land over the last two decades. This reflects the rapid urbanization surrounding this lake. After the year 2000, large-scale conversion of Bellandur's watershed area into residential and commercial layouts occurred, likely altering the hydrological regime and increasing silt movement into the catchment area inside the lake or low-lying areas. Furthermore, ongoing unplanned construction activities throughout the year often resulted in debris being dumped in the easiest accessible lake area (Ramachandra et al., 2017).

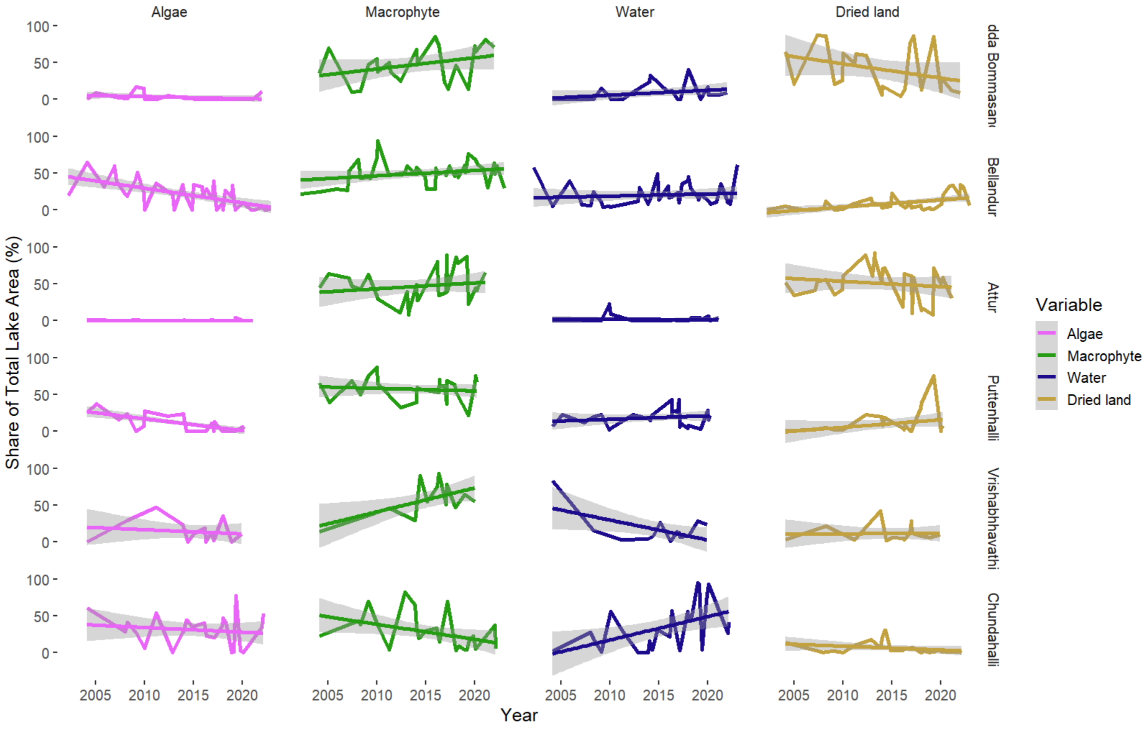


Figure 3.3 Changes in algae, macrophytes, water surface, and dried land over two decades for six lakes in Bengaluru, S-India. Percentage change out of these four variables, grey areas represent variance of the data.

3.4.1.2 Peri urban lakes - Attur and Puttenhalli

During the observation period, Attur Lake has been repeatedly drained or blocked making it difficult to discern trends within a season. Out of 29 data points, 17 observations show no water surface and thus no algae growth. Nevertheless, the macrophyte area increased and the dried land declined during the latter part of the study period. This likely reflected rejuvenation activities such as dredging allowing accumulation of water at the eastern lake side.

Puttenhalli Lake was declared a Bird Conservation Reserve on 5 June 2014. The treatment plant at its eastern corner was insufficient to treat the heavy inflow of sewage water resulting in an increase in the water surface area, a stable macrophyte level, a decrease in the algae area, and a slight increase in the dried land due to continuous siltation process near the run-off inlet at the western side. We detected an antagonistic relationship between macrophytes and algae similar to the vegetation dynamics of other lakes.

3.4.1.3 Rural lakes - Vrishabhavathi and Chudahalli

Both rural lakes displayed a strong negative correlation between water surface area and macrophytes (see appendix Table A 3.1). This correlation may be due to the interconnectedness of these lakes along a stream. While Chudahalli is located in the center of the stream, Vrishabhavathi is situated at its base where the water flow has substantially slowed down (Figure 3.1). However, despite both lakes being in rural areas, there are notable differences in the trends observed for Vrishabhavathi and Chudahalli. Chudahalli Lake lies downstream of the south-west watershed catchment area. Consequently, any surface sealing of the upstream area by buildings leads to increased runoff and silting downstream. As a result, downstream reservoirs such as Chudahalli Lake, experience flooding. The increased flow of water in the mainstream area means that vegetation, including macrophytes, do not remain in the water for extended periods. The increase in water surface area may thus be attributed to the large volume of water runoff and relatively lower cover by macrophytes and algae. As the water surface increases, the extent of dried land decreases (Figure 3.3).

On the other hand, Vrishabhavathi Lake functions more as a water reservoir than as a traditional lake. As such, it receives municipal and industrial wastes from Bengaluru, resulting in the reservoir carrying high loads of nutrients and contaminants. The surface water area is relatively stable even if the reservoir lacks tight bunds or walls on the eastern side, allowing water to flow freely in that direction. This reservoir contains perennial grasses and water hyacinths as part of the macrophyte class. The primary macrophytes that were noted as the most prevalent were the floating water hyacinth (*Eichhornia crassipes*) and the anchored alligator weed (*Alternanthera philoxeroides*). Water hyacinth was observed to flourish during the pre-monsoon season, primarily at the onset of winter, typically in January. Subsequently, their growth rate surged significantly over the following three months, spanning from January to April. In the shallower areas at the outset, emergent *Typha sp.* largely dominates the space. In contrast, in deeper regions, free-floating macrophytes are predominantly observed.

(Mahapatra et al., 2018). Due to the inflow of additional nutrients, the macrophyte population has increased and covered most of the water surface. The presence of macrophytes likely suppressed to some extent the growth of algae (Mohamed, 2017). Over the two decades, water surface and algae covered areas have decreased (Fig. 1.). However, even taking into account the limited data points available before 2014, the water surface area and algae levels appear to be relatively stable and the fluctuation in water surface area may be due to the growth of macrophytes. The area of dried land seemed to remain stable in this reservoir because it receives municipal and industrial wastewater throughout the year.

3.4.2 Expansion of built-up areas surrounding the lakes

Urbanization around Bengaluru’s lakes depends upon the intensity of the urban-rural transformation processes (Figure 3.4). The expansion of the built-up areas around the lakes varies according to the location of the lakes. Urban lakes are obviously more exposed to the effects of growing built-up areas than peri-urban or rural ones (Figure 3.5; Chakraborty, 2022). Each lake’s surroundings have different trajectories of evolution (see appendix Figure A 3.1).

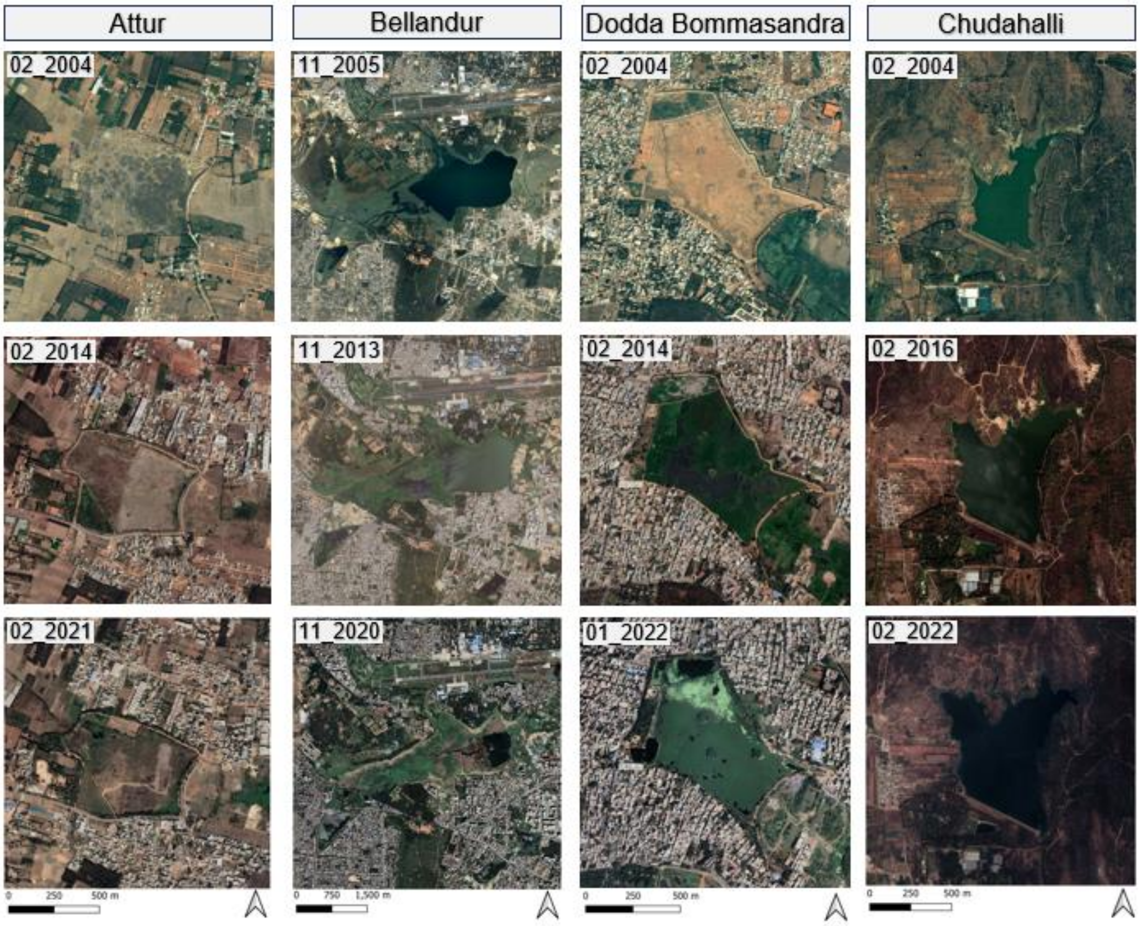


Figure 3.4 Increase in built-up areas in the four lakes in Bengaluru, S-India, (Image source: Google Earth Pro 7.1, retrieved on 23.03.2023)

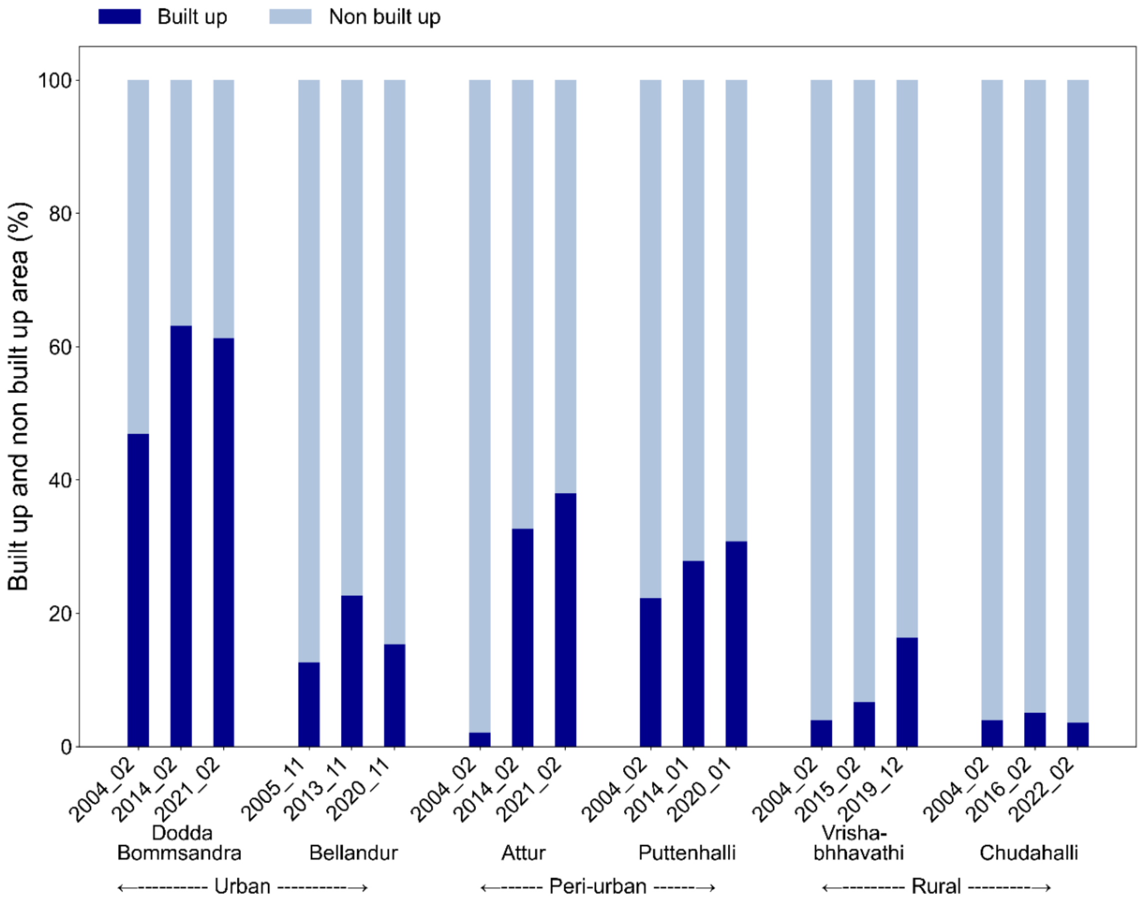


Figure 3.5 Trend of built-up areas along the urban-rural gradient in Bengaluru, S-India.

3.4.2.1 Urban lakes - Dodda Bommasandra and Bellandur

Dodda Bommasandra has the highest share of built-up area within the buffer zone. In 2004 it occupied 47% of the total buffer area, and exceeded 60% in 2014 with little change until 2021 (Figure 3.5). For Bellandur Lake, which historically was used for the cultivation of paddy rice (*Oryza sativa* L.) and vegetables as well as for fishing (D’Souza, 2007), the built-up area within the 300m buffer zone has increased from 13% in 2005 to 23% in 2013, before decreasing to 15% in 2020. This trend may be caused by misclassification of dumping areas around the lake as built-up areas. This is indicated by two big spots classified as built-up areas in 2013 on the eastern side and the south-western side in 2020 which have turned into green areas by 2020 (Figure 3.6).

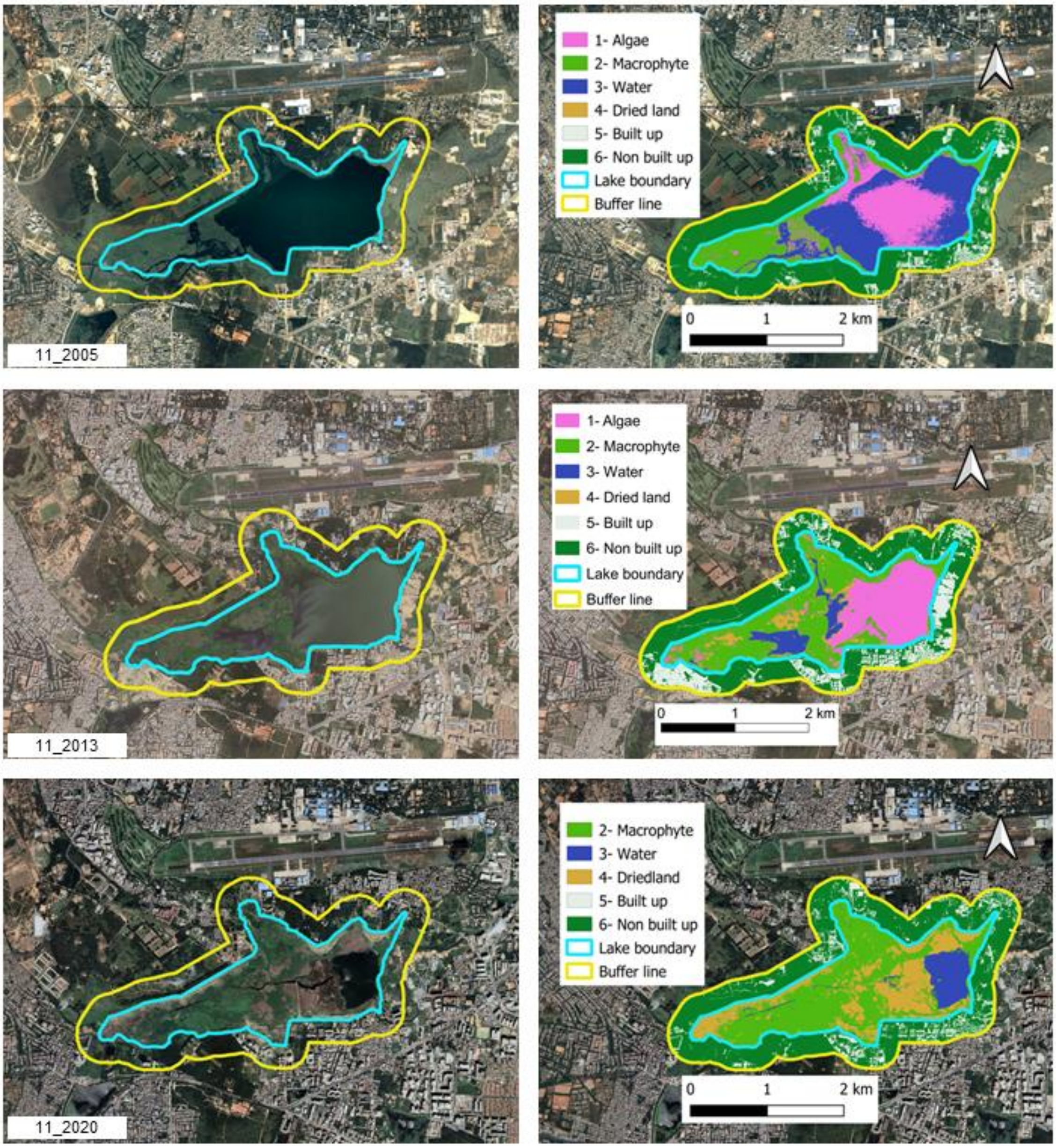


Figure 3.6 Land use classification in Bellandur Lake, Bengaluru, S-India using a supervised classification QGIS 3.22 (Image source: Google Earth Pro 7.1, retrieved on 23.03.2023)

3.4.2.2 Peri-urban lakes - Attur and Puttenhalli

The 300m buffer around Attur has experienced a steep rise (2% to 33%) in the built-up area from 2004 to 2014, and a further increase to 38% from 2014 to 2021. This location is well-connected with easily accessible rail and metro lines and nearby (within 5km) to the major road network of Doddaballapur and Bellary road (NH-44) that connects to the Kempegowda International Airport of Bengaluru. This confirms earlier reports that Bengaluru's growth pattern is polycentric in nature and the fastest growth has occurred in multiple peripheral areas (Taubenböck et al., 2009; Nagendra et al., 2012).

In 2004, Puttenahalli Lake was primarily surrounded by some commercial buildings and residential layouts. In 2008, Bengaluru Metropolitan Transport Corporation (BMTC) started building a bus depot in the south-eastern part of the buffer zone and after three years, Karnataka Power Transmission Corporation Limited (KPTCL) started establishing a power station in the north-eastern part of the buffer area. Therefore, the built-up area around this lake has experienced a consistent increase of about 5% in each time interval (Figure 3.5).

3.4.2.3 Rural lakes - Vrishabhavathi and Chudahalli

A rapid increase in built-up area from 6.5% to 16.0% from 2015 to 2019 was detected in Vrishabhavathi. Since 2007-08, Toyota and other steel and auto part companies have started establishing their plants along the western side of this reservoir. Consequently, engineering colleges and residences started developing around this area causing a high increase in built-up areas. In contrast, the built-up area around this lake remained constant throughout the study period in Chudahalli Lake which is known for its picnic spots in the countryside. The built-up area around this lake mainly consists of a resort and some mud roads along the lake in the buffer zone. Therefore, the slight deviation in the built-up area may reflect misclassification errors due to seasonal changes in vegetation.

3.4.3 Lake ecosystems along urban-rural gradient

The dried surface area in each lake which represents the loss of water surface exhibits varying correlations with the surrounding built-up (Table 3.2). These correlations can be attributed to the unique characteristics of each lake, such as embankments around the lakes, depth of the lakes, and connectivity with other bodies of water. These variations underscore the nuanced nature of lake ecosystems, where diverse factors play crucial roles in shaping the relationships between urbanization and the extent of dry lake surface. Interestingly, no clear pattern of the dry surface area within lakes emerged along the urban-rural gradient. This suggests that the effects of urbanization on lakes are not uniform but rather site-specific. Satellite image-based identification of lake areas filled with silt was challenging, whereby in our case, only true color images were used to identify water and dried land without high additional spectral information. However, even with this limitation our approach yielded insights into the increasing dry surface area of urban lakes such as Bellandur, which is susceptible to disposal of sewage water and construction debris (Bharath and Umesh, 2017; Prasad, 2019). The depth of the lakes should also be regularly measured to assess the rate of siltation in each lake. Such monitoring will provide a better understanding of these ecosystems.

Table 3.2 Correlations between built-up and dried surface for each lake along urban-rural gradient in Bangaluru, S-India.

	Urban		Peri-urban		Rural	
	Dodda Bomsandra	Bellandur	Attur	Puttenhalli	Chudahalli	Vrishabhavathi
Correlation with built-up areas	0.461	0.148	-0.076	0.362	0.438	-0.167

The wet surface area of urban and peri-urban lakes, increased with rainfall (Table 3). However, the correlation coefficient between rainfall and wet surface area varied across different lake types. For the smaller lakes, such as Attur and Dodda Bomsandra, we observed a stronger positive correlation while larger lakes like Puttenhalli and Bellandur exhibited only a moderate positive correlation. The perennial lakes, Vrishabhavathi and Chudahalli, showed the lowest correlation. Interestingly, rural lakes showed a negative correlation with rainfall while urban and peri-urban lakes showed a positive correlation.

3.5 Conclusions

Our study shows that the density of built-up areas around the lakes decreases along the urban-rural gradients. The increase of built-up areas in the buffer zone does not always positively correlate with the wet surface area of the lakes. This disparity may point to factors such as the inflow of sewage water from other areas, or blockage and siltation of lakes. Our analysis underlines the importance of understanding lake vegetation dynamics due to urbanization at the periphery of the lakes. The data show that each lake has its own distinct characteristics, whereby the quality and quantity of sewage inflow interacts with the effects of peripheral built-up in the lake buffer zone and beyond. While our study contributes to a better understanding of the role of urbanization encroachment on lakes in Bengaluru, more profound analyses of its effects on ecosystem services would be interesting. This requires longer-term interdisciplinary studies with social-ecological surveys and field inventories.

Chapter 4

General discussion and conclusions

4.1 Introduction

This thesis aimed at exploring the carbon and nutrient flows under rapid urbanization in the S-Indian megacity of BengaluruChapter 2 shows determined CO_2-C emissions at different N levels under a complex crop rotation in the peri urban area of Bengaluru. Chapter 3 shows the effects of increases in built-up areas surrounding selected lakes. In this final chapter, I will return to the original research objectives and hypotheses and reflect on scientific methods used to address the objectives and hypotheses. Also addressed will be some implications of the results at the local level.

4.2 Study 1 and its research findings

The main hypothesis of Study 1 (Chapter 2) was that N fertilization enhances CO_2 emissions in crop cultivation under different management intensities in a complex crop rotation. This study was to contribute to a better understanding of the effects of management intensity (increasing levels of N fertilizer treatment and irrigation), typically found in rural-urban transition areas of S-India, on soil respiration. Our results of a multi-year experiment add to the growing body of knowledge on soil mineralization under intensification but also provide valuable data for global predictions of C emissions such as much needed by the Intergovernmental Panel on Climate Change (IPCC).

This study did not allow a direct comparison of CO_2 emission between rainfed and irrigated conditions as both fields had different use histores. Both experimental fields showed similar patterns of CO_2 emission at different soil and crop characteristics as well as N fertilization levels except for soil moisture. Reasons for the above effects are thoroughly discussed in Chapter 2.

4.3 Study 2 and its research findings

This study was triggered by the fact that water bodies in urban areas underwent severe transformation due to urbanization resulting into a discharge of urban wastewater and other pollutants (Martínez-Arroyo & Jáuregui, 2000; Naselli-Flores, 2008; He et al., 2011). The results showed that lake ecosystem dynamics are positively correlated with rainfall in the case of drier lakes, whereas an increase in the built-up area in the surrounding lakes was not strongly linked to changes in the wet surface area of the lakes.

4.4 The implications of these findings at the local level

The described studies are important because due to urbanization, peri urban areas are facing tremendous pressure on soil and water resources, and policy makers or farmers have an interest in adopting more sustainable ways of using soil and water. Study 1 confirms that CO_2 emission increases at higher levels of N fertilization. Study 2 demonstrates that urbanization affects lake's ecosystem dynamics by increasing runoff, sewage flow and siltation process which leads to accumulation of nutrients and pollutants in the lakes. These findings shall make farmers and policy makers aware of the consequences of haphazard and uncontrolled urbanization on peri-urban agricultural and lake ecosystems along the urban-rural gradient in Bengaluru and in other similar rural-urban ecosystems of Asia.

4.5 Recommendations

Sustainable urban development is a key challenge for the rapidly urbanizing cities of the Global South. To ensure sustainability in soil and water flows along rural-urban gradients, farmers, policy makers, and private sector actors should be made aware of the consequences of higher management intensities on the crop lands as a consequence of rapid urbanization around the wetlands and other water bodies. For future studies, this study recommends:

- To assess the effect of irrigation on CO_2 emissions, experiments should also be conducted under more controlled conditions with similar soil properties.
- To measure total carbon emissions for the entire crop duration, the frequency of measurements should be increased.
- Soil microbial properties should also be analyzed when assessing the effects of nitrogen fertilizer application on GHGs emissions from soils. This will help to understand the soil biology of the study area.
- Microclimatic conditions of the lake should be considered when analyzing the effect of weather on lake ecosystems.

- Detailed information on lake rejuvenation and fodder collection activities should be collected for each lake to better understand sudden changes in lake macrophytes. This will support the analysis of the relationship between macrophytes and other water parameters of the lakes.
- Lake soil, water, and macrophyte samples should also be collected and analyzed to study the effects of nutrient flows or contaminants on the lake.

4.6 References

Abalos D, Sanchez-Martin L, Garcia-Torres L, van Groenigen JW, Vallejo A (2014) Management of irrigation frequency and nitrogen fertilization to mitigate GHG and NO emissions from drip-fertigated crops. Sci Total Environ 490:880–888. https://doi.org/10.1016/J.SCITOTENV.2014.05.065

Adviento-Borbe MAA, Haddix ML, Binder DL, Walters DT, Dobermann A (2007) Soil greenhouse gas fluxes and global warming potential in four high-yielding maize systems. Glob. Change Biol 13(9):1972–1988. https://doi.org/10.1111/J.1365-2486.2007.01421.X

Alam MS, Velayudhan SM, Dey DK, Adilieme C, Malik PK, Bhatta R, König S, Schlecht E (2023) Urbanisation threats to dairy cattle health: Insights from Greater Bengaluru, India. Trop Anim Health Prod 55, 350. https://doi.org/10.1007/s11250-023-03737-7

Allison SD, Wallenstein MD, Bradford MA (2010) Soil-carbon response to warming dependent on microbial physiology. Nat. Geosci 3(5):336–340. https://doi.org/10.1038/ngeo846

Anwar M, Patra DD, Chand S, Kumar A, Naqvi AA, Khanuja SPS (2005) Effect of organic manures and inorganic fertilizer on growth, herb and oil yield, nutrient accumulation, and oil quality of French basil. Commmun. Soil Sci. Plant Anal., 36, 1737–1746. https://doi.org/10.1081/CSS-200062434

Araya A, Gowda PH, Rad MR, Ariyaratne CB, Ciampitti IA, Rice CW, Prasad PVV, (2021) Evaluating optimal irrigation for potential yield and economic performance of major crops in southwestern Kansas. Agric Water Manag. 244:106536. https://doi.org/10.1016/J.AGWAT.2020.106536

Bareuther M, Klinge M, Buerkert A (2020) Spatio-temporal dynamics of algae and macrophyte cover in urban lakes: A remote sensing analysis of Bellandur and Varthur wetlands in Bengaluru, India. Remote Sensing, 12(22), 3843. https://doi.org/10.3390/rs12223843

Bartley R, Henderson A, Prosser IP, Hughes AO, McKergow LA, Lu H, Brodie J, Bainbridge Z, Roth CH (2003) Patterns of erosion and sediment and nutrient transport in the Herbert River catchment, Queensland. Consultancy Report. August 2003, CSIRO Land and Water, p 59

Bhagat RB (2018) “Urbanisation in India: Trend, Pattern and Policy Issues”, Working Paper No. 17, International Institute for Population Sciences, Mumbai.

Bharath J, Umesh Y (2017) Why Bellandur Lake Clean-Up Exercise Could Snap Many Human Linkages, The Economic Times. Retrieved on July 31, 2023, from https://economictimes.indiatimes.com/news/politics-and-nation/why-bellandur-lake-clean-up-exercise-could-snap-many-human-linkages/articleshow/58411010.cms

Bhat S, Ramachandra TV, Mahesh M (2017) Macrophytes of Bangalore Wetlands, ENVIS Technical Report 126, Energy and Wetlands Research Group, CES, Indian Institute of Science: Bangalore, India.

Bogue DJ (1959) Internal migration. In: Hauser D, ed. The Study of Population: An Inventory Appraisal. Chicago: University of Chicago Press

Brinkley C (2012) Evaluating the benefits of peri-urban agriculture. J Plan Lit, 27(3), 259-269. https://doi.org/10.1177/0885412211435172

Brockerhoff MP (2000) An urbanizing world. Population Bulletin, 55(3), 1–43.

Brucet S, Poikane S, Birk S, Lyche Solheim A (2013) Biological assessment of European lakes: ecological rationale and human impacts. Freshw Biol, 58, 1106-1115. https://doi.org/10.1111/fwb.12111

Buchanan F (1870) A journey from Madras through the countries of Mysore, Canara, and Malabar (2nd ed., Vols. I–3 Madras: Higginbotham and Co.

Buerkert A, Hoffmann E, Suddapuli Hewage R, Goenster-Jordan S, Sourav SK, Mock A, Vazhacharickal PJ, Subbarayappa CT, Mudalagiriyappa, Hanumanthappa DC, Peth S., Wachendorf M (2021) Crop production under urbanisation: An experimental approach to understand and model agricultural intensification. Urban Book Series 71–83. https://doi.org/10.1007/978-3-030-79972-4_7/COVER

Buerkert A, Piepho H-P, Sourav SK, Hoffmann E, Vazhacharickal PS, Subbarayappa CT. Wachendorf M (2023) Agricultural intensification effects on spatial growth variability of staple crops in South India. Field Crops Res 301:109032. DOI: 10.1016/j.fcr.2023.109032

Carpenter SR, Lodge DM (1986) Effects of submersed macrophytes on ecosystem processes. Aquat Bot, 26, 341–370. https://doi.org/10.1016/0304-3770(86)90031-8

Chakraborty S, Maity I, Dadashpoor H, Novotný J, Banerji S (2022) Building in or out? Examining urban expansion patterns and land use efficiency across the global sample of 466 cities with million inhabitants. Habitat Int., 120, 102503. https://doi.org/10.1016/j.habitatint.2021.102503

Chan JCW, Demarchi L, Van de Voorde T, Canters F (2008) Binary classification strategies for mapping urban land cover with ensemble classifiers, IGARSS 2008 – 2008 IEEE Int Geosci Remote Sens Symp Proc, Boston, MA, USA, III - 1004-III – 1007. https://doi.org/10.1109/IGARSS.2008.4779522

Chen GC, Tam NFY, Ye Y (2010) Summer fluxes of atmospheric greenhouse gases N2O, CH4 and CO2 from mangrove soil in South China. Sci Total Environ 408(13):2761–2767. https://doi.org/10.1016/J.SCITOTENV.2010.03.007

Chen S, Li G, Zhuo Y, Xu Z, Ye Y, Thorn JP, Marchant R (2022) Trade-offs and synergies of ecosystem services in the Yangtze River Delta, China:

response to urbanizing variation. Urban Ecosyst, 25(1), 313-328. https://doi.org/10.1007/s11252-021-01150-2

Chen M, Zhang H, Liu W, Zhang W (2014). The global pattern of urbanization and economic growth: evidence from the last three decades. PloS one, *9*(8), e103799. https://doi.org/10.1371/journal.pone.0103799

Chenery HB, Taylor L (1968) Development patterns: among countries and over time. The Review of Economics and Statistics, 391-416.

Chu H, Lin X, Fujii T, Morimoto S, Yagi K, Hu J, Zhang J (2007) Soil microbial biomass, dehydrogenase activity, bacterial community structure in response to long-term fertilizer management. Soil Biol Biochem, 39(11), 2971-2976. https://doi.org/10.1016/j.soilbio.2007.05.031

Comaroff J (2011) Theory from the south: Or, how Euro-America is evolving toward Africa. Paradigm.

Curtin D, Wang H, Selles F, McConkey BG, Campbell CA (2000) Tillage effects on carbon fluxes in continuous wheat and fallow–wheat rotations. Soil Sci Soc Amer J 64(6):2080–2086. https://doi.org/10.2136/SSSAJ2000.6462080X

Cyril S, Oldroyd J, Renzaho A (2013) Urbanisation, urbanicity, and health: A systematic review of the reliability and validity of urbanicity scales. BMC Public Health, 13(1), 513. https://doi.org/10.1186/1471-2458-13-513

D’Souza R (2007) A study on Bellandur tank and changes due to urbanisation; A CASUMM Publication: Bangalore, India.

D’Souza R, Nagendra H (2011) Changes in public commons as a consequence of urbanization: The Agara lake in Bangalore, India. Environ Manage, 47 , 840–850. https://doi.org/10.1007/s00267-011-9658-8

Darwish TM, Atallah TW, Hajhasan S, Haidar A (2006) Nitrogen and water use efficiency of fertigated processing potato. Agric Water Manag 85(1–2):95–104. https://doi.org/10.1016/J.AGWAT.2006.03.012

Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440:165–173. https://doi.org/10.1038/nature04514

Di Clemente R, Strano E, Batty M (2021) Urbanization and economic complexity. Sci Rep, 11(1), 1–10. https://doi.org/10.1038/s41598-021-83238-5

Dittrich C (2007) Bangalore: Globalization and Fragmentation in India’s Hightech-Capital. ASIEN, 103, 45–58. https://doi.org/10.11588/asien.2007.103.15054

Elmqvist T, Goodness J, Marcotullio PJ, Parnell S, Sendstad M, Wilkinson C, Fragkias M, Güneralp B, McDonald RI, Schewenius M, Seto KC (2013) Urbanization, biodiversity and ecosystem services: Challenges and opportunities: A global assessment. Urbanization, Biodiversity and

Ecosystem Services: Challenges and Opportunities: A Global Assessment, 1–755. https://doi.org/10.1007/978-94-007-7088-1/COVER

Enwall K, Nyberg K, Bertilsson S, Cederlund H, Stenström J, Hallin S (2007) Long-term impact of fertilization on activity and composition of bacterial communities and metabolic guilds in agricultural soil. Soil Biol Biochem, 39(1), 106-115. https://doi.org/10.1016/j.soilbio.2006.06.015

ESG (2009) Report of workshop on “Urban lakes as ecological, cultural and public spaces.” Bangalore: Environment Support Group (ESG) and Karnataka State Council for Science and Technology. http://static.esgindia.org/campaigns/lakes/action/ESG_UrbanLakesWorkshop_Report_260909.html

Evans DL, Falagán N, Hardman CA, Kourmpetli S, Liu L, Mead BR, Davies JAC (2022) Ecosystem service delivery by urban agriculture and green infrastructure–a systematic review. Ecosyst Serv, 54, 101405. https://doi.org/10.1016/j.ecoser.2022.101405

Fox S (2012) Urbanization as a global historical process: Theory and evidence from sub-Saharan Africa. Popul Dev Rev, 38(2), 285–310. https://doi.org/10.1111/j.1728-4457.2012.00493.x

Friedmann J (2006) Four theses in the study of China’s urbanization. Int J Urban Reg Res, 30: 440–451. https://doi.org/10.1111/j.1468-2427.2006.00671.x

Fuss R (2020) Greenhouse Gas Flux Calculation from Chamber Measurements (R package version 0.4-4 R Foundation, Vienna, Austria. https://cran.r-project.org/web/packages/gasfluxes/index.html

Gaumont-Guay D, Black TA, Griffis TJ, Barr AG, Jassal RS, Nesic Z (2006) Interpreting the dependence of soil respiration on soil temperature and water content in a boreal aspen stand. Agric Forest Meteorol 140(1–4):220–235. https://doi.org/10.1016/J.AGRFORMET.2006.08.003

Gautam VK, Gaurav PK, Murugan P, Annadurai M (2015) Assessment of surface water Dynamics in Bangalore using WRI, NDWI, MNDWI, supervised classification and KT transformation. Aquat Procedia, 4, 739–746. https://doi.org/10.1016/j.aqpro.2015.02.095

Glaeser EL (2014) A world of cities: The causes and consequences of urbanization in poorer countries. J Eur Econ Assoc, 12(5), 1154-1199. https://doi.org/10.3386/w19745

Glibert PM, Harrison J, Heil C, Seitzinger S (2006) Escalating worldwide use of urea—a global change contributing to coastal eutrophication. Biogeochem 77:441–463. https://doi.org/10.1007/s10533-005-3070-5

Goldman M (2011) Speculating on the next world city. In Worlding Cities: Asian Experiments and the Art of being Global, 31, 229–258. https://doi.org/10.1002/9781444346800.ch9

Gollin D, Jedwab R, Vollrath D (2016) Urbanization with and without industrialization. J Econ Growth, 21, 35-70. https://doi.org/10.1007/s10887-015-9121-4

Gowda K, Sridhara MV (2007) Conservation of tanks/lakes in the Bangalore metropolitan area. Manag Environ Qual, 18, 137–151. https://doi.org/10.1108/14777830710725812

Gu C (2019) Urbanization: Processes and driving forces. Sci China Earth Sci, 62(9), 1351–1360. https://doi.org/10.1007/S11430-018-9359-Y/METRICS

Guo Y, Zheng H, Wu T, Wu J, Robinson BE (2020) A review of spatial targeting methods of payment for ecosystem services. Geogr Sustain, 1(2), 132-140. https://doi.org/10.1016/j.geosus.2020.04.001

Hanson PJ, Edwards NT, Garten CT, Andrews JA (2000) Separating root and soil microbial contributions to soil respiration: A review of methods and observations. Biogeochem 2000 48(1):115–146. https://doi.org/10.1023/A:1006244819642

Häring V, Manka'Abusi D, Akoto-Danso EK, Werner S, Atiah K, Steiner C, Lompo DJP, Adiku S, Buerkert A, Marschner B (2017) Effects of biochar, waste water irrigation and fertilization on soil properties in West African urban agriculture. Sci Reports 7(1):1–13. https://doi.org/10.1038/s41598-017-10718-y

Hashimoto S, Komatsu H (2006) Relationships between soil CO2 concentration and CO2 production, temperature, water content, and gas diffusivity: implications for field studies through sensitivity analyses. J For Res 11:41–50. https://doi.org/10.1007/s10310-005-0185-4

He C, Tian J, Shi P, Hu D (2011) Simulation of the spatial stress due to urban expansion on the wetlands in Beijing, China using a GIS-based assessment model. Landsc Urban Plan, 101(3), 269–277. https://doi.org/10.1016/j.landurbplan.2011.02.032

He Y, Wang W, Chen Y, Yan H (2021) Assessing spatio-temporal patterns and driving force of ecosystem service value in the main urban area of Guangzhou. Sci Rep, 11(1), 3027. https://doi.org/10.1038/s41598-021-82497-6

Heimsch L, Lohila A, Tuovinen JP, Vekuri H, Heinonsalo J, Nevalainen O, Korkiakoski M, Liski J, Laurila T, Kulmala L (2021) Carbon dioxide fluxes and carbon balance of an agricultural grassland in southern Finland. Biogeosci 18(11):3467–3483. https://doi.org/10.5194/BG-18-3467-2021

Henderson V (2003) The urbanization process and economic growth: The so-what question. J Econ Growth, 8, 47-71. https://doi.org/10.1023/A:1022860800744

Hettiarachchi M, Morrison TH, Wickramsinghe D, Mapa R, De Alwis A, McAlpine CA (2014) The eco-social transformation of urban wetlands: A case study of

Colombo, Sri Lanka. Landsc Urban Plan, 132, 55–68. https://doi.org/10.1016/j.landurbplan.2014.08.006

Hoffmann EM, Jose M, Nölke N, Möckel T (2017) Construction and use of a simple index of urbanization in the rural–urban interface of Bangalore, India. Sustainability, 9(11), 2146. https://doi.org/10.3390/su9112146

Hope KR (1998) Urbanization and urban growth in Africa. J Asian Afr Stud, 33(4), 345-358. https://doi.org/10.1163/156852198X00104

Howarth RW (2008) Coastal nitrogen pollution: a review of sources and trends globally and regionally. Harmful Algae, 8:14–20. https://doi.org/10.1016/j.hal.2008.08.015

Iaquinta DL, Drescher AW (2000) Defining the peri-urban: Rural-urban linkages and institutional connections. Land Reform, Land Settlement and Cooperatives. 8-27.

Iqbal J, Ronggui H, Lijun D, Lan L, Shan L, Tao C, Leilei R (2008) Differences in soil CO2 flux between different land use types in mid-subtropical China. Soil Biol Biochem 40(9):2324–2333. https://doi.org/10.1016/J.SOILBIO.2008.05.010

Jain R, Kishore P, Singh DK (2019) Irrigation in India: Status, challenges and options. J Soil Water Conserv 18(4):354-363. https://doi.org/10.5958/2455-7145.2019.00050.x

Jain R, Kishore P, Singh DK (2019) Irrigation in India: Status, challenges and options. J Soil Water Conserv, 18(4 https://doi.org/10.5958/2455-7145.2019.00050.x

Jones-Smith JC, Popkin BM (2010) Understanding community context and adult health changes in China: Development of an urbanicity scale. Soc sci med, 71(8), 1436–1446. https://doi.org/10.1016/j.socscimed.2010.07.027

Krishna MB, Chakrapani BK, Srinivasa TK (1996) Water birds and wetlands of Bangalore: A report on the status, water quality, plankton and birds of the lakes in and around Bangalore and Maddur, Karnataka, India. Bangalore: Birdwatchers’ Field Club of Bangalore and Bangalore Urban Division, Karnataka State Forest Department.

Kulkarni T, Gassmann M, Kulkarni CM, Khed V, Buerkert A (2021) Deep drilling for groundwater in Bengaluru, India: A case study on the city’s over-exploited hard-rock aquifer system. Sustainability 13(21):12149. https://doi.org/10.3390/SU132112149/S1

Kumar U, Nayak AK, Shahid M, Gupta VVSR, Panneerselvam P, Mohanty S, Kaviraj M, Kumar A, Chatterjee D, Lal B, Gautam P, Tripathi R, Panda B.B. (2018) Continuous application of inorganic and organic fertilizers over 47 years in paddy soil alters the bacterial community structure and its influence on rice production. Agric. Ecosyst. Environ., 262, 65–75. https://doi.org/10.1016/j.agee.2018.04.016

Kumar U, Shahid M, Tripathi R, Mohanty S, Kumar A, Bhattacharyya P, Lal B, Gautam P, Raja R, Panda BB, Jambhulkar NN, Shukla AK, Nayak AK (2017) Variation of functional diversity of soil microbial community in sub-humid tropical rice-rice cropping system under long-term organic and inorganic fertilization. Ecol. Indic, 73, 536–543. https://doi.org/10.1016/j.ecolind.2016.10.014

Lewis WA (1954) Economic development with unlimited supplies of labour. Manchester School, 22: 139–191 https://doi.org/10.1111/j.1467-9957.1954.tb00021.x

Li P, Zhang R, Xu L (2021) Three-dimensional ecological footprint based on ecosystem service value and their drivers: A case study of Urumqi. Ecol Indic, 131, 108117. https://doi.org/10.1016/j.ecolind.2021.108117

Likitswat F, Sahavacharin A (2023) Landscape change analysis: Ecosystem services in the peri-urban agriculture of Bangkok. J Archit Plann Res (JARS), 20(2), 25-38. https://doi.org/10.56261/jars.v20i2.249694

Liu L, Greaver TL (2010) A global perspective on belowground carbon dynamics under nitrogen enrichment. Ecol Lett, 13(7), 819-828. https://doi.org/10.1111/j.1461-0248.2010.01482.x

Lloyd J, Taylor JA (1994) On the Temperature Dependence of Soil Respiration. Funct Ecol 8(3):315. https://doi.org/10.2307/2389824

Lugato E, Berti A, Giardini L (2006) Soil organic carbon (SOC) dynamics with and without residue incorporation in relation to different nitrogen fertilisation rates. Geoderma, 135, 315-321. https://doi.org/10.1016/j.geoderma.2006.01.012

Lynch J, Cain M, Frame D, Pierrehumbert R (2021) Agriculture’s contribution to climate change and role in mitigation is distinct from predominantly fossil CO2-emitting sectors. Front Sustain Food Sys 4:300. https://doi.org/10.3389/FSUFS.2020.518039/BIBTEX

Mabin A (2014) Grounding southern city theory in time and place. In S. Parnell & S. Oldfield (Eds.), The Routledge handbook on cities of the global South, (pp. 21–36. Routledge.

Magill AH, Aber JD, Hendricks JJ, Bowden RD, Melillo JM, Steudler PA (1997) Biogeochemical response of forest ecosystems to simulated chronic nitrogen deposition. Ecol Appl 7(2):402. https://doi.org/10.2307/2269508

Mahapatra DM, Chanakya HN, Ramachandra TV (2011a) C: N ratio of Sediments in a sewage fed Urban Lake. Int J Geol, *5*(3), 86-92.

Mahapatra DM, Chanakya HN, Ramachandra TV (2011b) Role of macrophytes in sewage fed urban lake. Institute of Integrated Omics and Applied Biotechnology, *2*(8), 1-9.

Mahapatra DM, Joshi N, Ramachandra TV (2018) Insights to bioprocess and treatment competence of urban wetlands. J Environ Manage, 206, 1179–1191. https://doi.org/10.1016/j.jenvman.2017.10.054

Manka'abusi D, Lompo DJP, Steiner C, Ingold M, Akoto-Danso EK, Werner S, Häring V, Nyarko G, Marschner B, Buerkert A (2020) Carbon dioxide and gaseous nitrogen emissions from biochar-amended soils under wastewater irrigated urban vegetable production of Burkina Faso and Ghana. J Plant Nutr Soil Sci 183(4):500–516. https://doi.org/10.1002/jpln.201900183

Martínez-Arroyo A, Jáuregui E (2000) On the environmental role of urban lakes in Mexico City. Urban Ecosyst, 4, 145–166. https://doi.org/10.1023/A:1011355110475

McDonald RI (2009) Ecosystem service demand and supply along the urban-to-rural gradient. Journal of Conservation Planning, 5, 1–14

McDonald RI, Green P, Balk D, Fekete BM, Revenga C, Todd M, Montgomery M (2011) Urban growth, climate change, & freshwater availability. Proceedings of the National Academy of Sciences of the United States of America, 108(15), 6312–6317. https://doi.org/10.1073/pnas.1011615108

Miraftab F, Kudva N (2015) Cities of the global South reader. Routledge.

Mohamed ZA (2017) Macrophytes-cyanobacteria allelopathic interactions and their implications for water resources management—A review. Limnologica, 63, 122–132. https://doi.org/10.1016/j.limno.2017.02.006

Montgomery MR (2008) The urban transformation of the developing world. science, 319(5864), 761-764. https://doi.org/10.1126/science.1153012

Moran-Rodas VE, Chavannavar SV, Joergensen RG, Wachendorf C (2022) Microbial response of distinct soil types to land-use intensification at a South-Indian rural-urban interface. Plant Soil 473(1–2):389–405. https://doi.org/10.1007/S11104-021-05292-2

Mundoli S, Unnikrishnan H, Nagendra H (2017) The “Sustainable” in smart cities: ignoring the importance of urban ecosystems. Decision, 44, 103-120. http://dx.doi.org/10.1007/s40622-017-0152-x

Nagendra H, Gopal D (2010) Street trees in Bangalore: Density, diversity, composition and distribution. Urban For Urban Green, 9, 129–137. https://doi.org/10.1016/j.ufug.2009.12.005

Nagendra H, Gopal D. (2011) Tree diversity, distribution, history and change in urban parks. Urban Ecosyst, 14, 211–223. https://doi.org/10.1007/s11252-010-0148-1

Nagendra H, Sudhira HS, Katti M, Schewenius M (2013) Sub-regional assessment of India: Effects of urbanization on land use, biodiversity and ecosystem services. In: Elmqvist, T., et al. Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7088-1_6

Nair J (2005) The promise of the metropolis: Bangalore’s twentieth century. New Delhi: Oxford University Press.

Naselli-Flores L (2008) Urban Lakes: Ecosystems at Risk, Worthy of the Best Care. Materials of the 12th World Lake Conference, Taal 2007. 1333-1337.

Navya PK (2021) Bengaluru’s changing rainfall patterns: expert points to climate change - Citizen Matters, Bengaluru. https://bengaluru.citizenmatters.in/bengaluru-rainfall-climate-change-ksndmc-study-65200

Negassa W, Price RF, Basir A, Snapp SS, Kravchenko A (2015) Cover crop and tillage systems effect on soil CO2 and N2O fluxes in contrasting topographic positions. Soil Tillage Res 154:64–74. https://doi.org/10.1016/J.STILL.2015.06.015

Oldfield EE, Bradford MA, Wood SA (2019) Global meta-analysis of the relationship between soil organic matter and crop yields. Soil 5(1):15–32. https://doi.org/10.5194/SOIL-5-15-2019

Parikh J, Sandal G, Jindal P (2015) Climate resilient cities: Vulnerability profiling of twenty Indian cities. In: Dev, S., Babu, P. (eds) Development in India. India Studies in Business and Economics. Springer, New Delhi. http://dx.doi.org/10.1007/978-81-322-2541-6_16

Patil VS, Thomas BK, Lele S, Eswar M, Srinivasan V (2019) Adapting or chasing water? Crop choice and farmers’ responses to water stress in peri-urban Bangalore, India. Irrig Drain 68(2):140–151. https://doi.org/10.1002/IRD.2291

Peng Q, Dong Y, Qi Y, Xiao S, He Y, Ma T (2011) Effects of nitrogen fertilization on soil respiration in temperate grassland in inner Mongolia, China. Environ Earth Sci 62(6):1163–1171. https://doi.org/10.1007/S12665-010-0605-4/TABLES/5

Peralta EM, Belen AE, Buenaventura GR, Cantre FGG, Espiritu KGR, De Vera JNA, Perez CP, Tan AKV, Jesus IBBD, Palomares P, Jonathan C, Briones A, Ikeya T, Magbanua FS, Papa RDS, Okuda N (2019) Stream Benthic Macroinvertebrate Assemblages Reveal the Importance of a Recently Established Freshwater Protected Area in a Tropical Watershed1. Pac Sci, 73(3), 305-320. https://doi.org/10.2984/73.3.1

Petrakos G (1989) Urbanization and international trade in developing countries. World Dev, 17(8), 1269-1277. https://doi.org/10.1016/0305-750X(89)90237-4

Pickett STA, Cadenasso ML, Grove JM, Boone CG, Groffman PM, Irwin E, Kaushal SS, Marshall V, McGrath BP, Nilon CH, Pouyat RV, Szlavecz K, Troy A, Warren P (2011) Urban ecological systems: Scientific foundations and a decade of progress. J Environ Manage, 92(3), 331-362. https://doi.org/10.1016/j.jenvman.2010.08.022

Potts D (2009) The slowing of sub-Saharan Africa's urbanization: Evidence and implications for urban livelihoods. Environ Urban, 21(1), 253–259. https://doi.org/10.1177/0956247809103026

Potts D (2012) What do we know about urbanisation in sub-Saharan Africa and does it matter? Int Dev Plan Rev, 34(1), v–xxii. http://dx.doi.org/10.3828/idpr.2012.1

Power AG (2010) Ecosystem services and agriculture: tradeoffs and synergies. Philosophical transactions of the royal society B: Biol Sci, 365(1554), 2959-2971. https://doi.org/10.1098/rstb.2010.0143

Prasad CS, Anandan S, Gowda NKS, Schlecht E, Buerkert A. (2019) Managing nutrient flows in Indian urban and peri-urban livestock systems. Nutr Cyc Agroecosys 115(2): 159–172. https://doi.org/10.1007/S10705-018-9964-0/TABLES/4

Prasad JVNS, Rao CS, Srinivas K, Jyothi CN, Venkateswarlu B, Ramachandrappa BK, Dhanpal GN, Ravichandra K, Mishra PK (2016) Effect of ten years of reduced tillage and recycling of organic matter on crop yields, soil organic carbon and its fractions in Alfisols of semi arid tropics of southern India. Soil Till Res 156:131–139. https://doi.org/10.1016/J.STILL.2015.10.013

Prasad, P. (2019) Slum sprawl, debris dumping on rise near Bellandur lake. The New Indian Express. Retrieved on September 21, 2023, from https://www.newindianexpress.com/cities/bengaluru/2019/jul/30/slum-sprawl-debris-dumping-on-rise-near-bellandur-lake-2011362.html

Pugh C (1995) Urbanization in developing countries: an overview of the economic and policy issues in the 1990s. Cities, 12(6), 381-398. https://doi.org/10.1016/0264-2751(95)00083-X

R Core Team. (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/

Ramachandra TV, Aithal BH (2016) Bengaluru's reality: Towards unlivable status with unplanned urban trajectory. Curr Sci, 110, 2207–2208.

Ramachandra TV, Aithal BH (2019) Bangalore. In The Wiley Blackwell Encyclopedia of Urban and Regional Studies, John Wiley and Sons: Hoboken, NJ, USA, 1–21. https://doi.org/10.1002/9781118568446.eurs0014

Ramachandra TV, Kumar U (2008) Wetlands of greater Bangalore, India: Automatic delineation through pattern classifiers. Electron Green J, 26(26 http://dx.doi.org/10.5070/G312610729

Ramachandra TV, Ahalya N, Payne M (2003) Status of Varthur Lake: Opportunities for Restoration and Sustainable Management, Technical Report 102, Centre for Ecological Sciences, Indian Institute of Science: Bangalore, India.

Ramachandra TV, Vinay S, Mahapatra D, Varghese S, Aithal BH (2016a) Water Situation in Bengaluru. ENVIS Technical Report 114. Environmental Information System, CES, Indian Institute of Science, Bangalore, India.

Ramachandra TV, Asulabha K, Sincy V, Bhat S, Aithal B (2016b) Wetlands: Treasure of Bangalore, ENVIS Technical Report 101, Energy and Wetlands Research Group, CES, Indian Institute of Science: Bangalore, India.

Ramachandra TV, Mahapatra DM, Bhat SP, Asulabha K, Varghese S, Aithal BH (2014) Integrated Wetlands Ecosystem: Sustainable Model to Mitigate Water Crisis in Bangalore; ENVIS Technical Report 76; Environmental Information System, CES, Indian Institute of Science: Bangalore, India.

Ramachandra TV, Mahapatra DM, Vinay S, Varghese S, Asulabha K, Bhat S, Aithal BH (2017) Bellandur and Varthur Lakes Rejuvenation Blueprint, ENVIS Technical Report 116, Environmental Information System, CES, Indian Institute of Science: Bangalore, India.

Ramachandra T V Sincy V Asulabha K Mahapatra D M Bhat S P & Aithal B H (2018) Optimal Treatment of Domestic Wastewater through Constructed Wetlands. J Biodivers, 9, 81–102.

Rao TP, Ito O (1998) Differences in root system morphology and root respiration in relation to nitrogen uptake among six crop species. Jap Agric Res Quart 32:97-103.

Ravindrababu B, Rajegowda M, Janardhanagowda N, Girish J (2010) Weekly, monthly and seasonal rainfall at Bengaluru in Karnataka. J Agric Meteorol, 12, 263–265. http://dx.doi.org/10.54386/jam.v12i2.1322

Rey A, Petsikos C, Jarvis PG, Grace J (2005) Effect of temperature and moisture on rates of carbon mineralization in a Mediterranean oak forest soil under controlled and field conditions. Europ J Soil Sci 56(5):589–599. https://doi.org/10.1111/J.1365-2389.2004.00699.X

Rice BL (1897a) Mysore: A gazetteer compiled for government, revised edition: Vol. I . Mysore in general. Westminister: Archibald Constable and Company.

Rice BL (1897b) Mysore: A gazetteer compiled for government, revised edition: Vol. II . Mysore, by districts. Westminister: Archibald Constable and Company.

Rochette P, Flanagan LB, Gregorich EG (1999) Separating soil respiration into plant and soil components using analyses of the natural abundance of carbon-13. Soil Sci Soc Am J 63(5):1207–1213. https://doi.org/10.2136/SSSAJ1999.6351207X

Ruser R, Flessa H, Russow R, Schmidt G, Buegger F, Munch JC (2006) Emission of N2O, N2 and CO2 from soil fertilized with nitrate: Effect of compaction, soil moisture and rewetting. Soil Biol Biochem 38(2):263–274. https://doi.org/10.1016/J.SOILBIO.2005.05.005

Sahasranaman A, Bettencourt LMA (2021) Life between the city and the village: Scaling analysis of service access in Indian urban slums. World Dev, 142, 105435. https://doi.org/10.1016/J.WORLDDEV.2021.105435

Sainju UM, Jabro JD, Stevens WB (2008) Soil carbon dioxide emission and carbon content as affected by irrigation, tillage, cropping system, and nitrogen fertilization. J Environ Qual 37(1): 98–106. https://doi.org/10.2134/JEQ2006.0392

Salinas-Garcia JR, Hons FM, Matocha JE, Zuberer DA (1997) Soil carbon and nitrogen dynamics as affected by long-term tillage and nitrogen fertilization. Biol Fertil Soils, 25, 182-188. https://doi.org/10.1007/s003740050301

Sauvy A (1952) Trois mondes, une planète. L'Observateur, 118, 14.

Schirpke U, Tasser E, Leitinger G, Tappeiner U (2021) Using the ecosystem services concept to assess transformation of agricultural landscapes in the European Alps. Land, 11(1), 49. https://doi.org/10.3390/land11010049

Schneider A, Woodcock C (2008) Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census information. Urban Stud, 45, 659–692. http://dx.doi.org/10.1177/0042098007087340

Scott A, Storper M (2003) Regions, globalization, development. Regional Studies, 37: 579–593. https://doi.org/10.1080/0034340032000108697a

Sen A, Nagendra H (2021) The differentiated impacts of urbanization on lake communities in Bengaluru, India. Int J Urban Sustain Dev, 13:1, 17-31. https://doi.org/10.1080/19463138.2020.1770260

Shaw A, Satish MK (2006) Metropolitan restructuring in post-liberalized India: Separating the global and the local. Cities, 24, 148–163. https://doi.org/10.1016/j.cities.2006.02.001

Sierra J (1997) Temperature and soil moisture dependence of N mineralization in intact soil cores. Soil Biol Biochem 29(9–10):1557–1563. https://doi.org/10.1016/S0038-0717(96)00288-X

Singh RP, Mundra MC, Gupta SC, Agrawal SK (1999) Effect of integrated nutrient management on productivity of pearl millet-wheat cropping system. Indian J Agron, 44, 250–253. https://doi.org/10.18520/cs/v119/i8/1343-1348

Smit W (2021) Urbanization in the Global South. Oxford Research Encyclopedia of Global Public Health. https://doi.org/10.1093/ACREFORE/9780190632366.013.251

Snyder CS, Bruulsema TW, Jensen TL, Fixen PE (2009) Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric Ecosyst Environm 133(3–4): 247–266. https://doi.org/10.1016/J.AGEE.2009.04.021

Søndergaard M, Johansson LS, Lauridsen TL, Jørgensen TB, Liboriussen L, Jeppesen E (2010) Submerged macrophytes as indicators of the ecological quality of lakes. Freshw Biol, 55, 893–908. https://doi.org/10.1111/j.1365-2427.2009.02331.x

Sridhar K, Reddy A., Srinath P (2012) Is it Push or Pull? Recent Evidence from Migration into Bangalore, India. Journal of International Migration and Integration / Revue de l integration et de la migration internationale. http://dx.doi.org/10.1007/s12134-012-0241-9

StataCorp (2017) Stata Statistical Software: Release 15. StataCorp LLC, College Station, TX. https://download.stata.com/download/

Steinhübel L, von Cramon-Taubadel S (2020) Somewhere in between towns, markets and jobs – agricultural intensification in the rural–urban interface. J Develop Stud 57(4):669–694. https://doi.org/10.1080/00220388.2020.1806244

Sudhira HS, Nagendra H (2013) Local Assessment of Bangalore: Graying and Greening in Bangalore – Impacts of Urbanization on Ecosystems, Ecosystem Services and Biodiversity. In: Elmqvist, T., et al. Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7088-1_7

Sudhira HS, Ramachandra, TV, Raj KS, Jagadish KS (2003) Urban growth analysis using spatial and temporal data. Journal of the Indian Society of Remote Sensing, 31, 299–311. https://doi.org/10.1007/BF03007350

Sudhira HS, Ramachandra TV, Raj KS, Jagadish KS (2003) Urban growth analysis using spatial and temporal data. Journal of the Indian Society of Remote Sensing, 31, 299–311. https://doi.org/10.1007/BF03007350

Sudhira HS, Ramachandra TV, Subrahmanya MHB (2007) City profile Bangalore. Cities, 24, 379–390. https://doi.org/10.1016/j.cities.2007.04.003

Swain BB, Teufel N (2017) The impact of urbanization on crop–livestock farming system: a comparative case study of India and Bangladesh. J Soc Econ Develop 19(1): https://doi.org/10.1007/s40847-017-0038-y

Tang J, Qi Y, Xu M, Misson L, Goldstein AH (2005) Forest thinning and soil respiration in a ponderosa pine plantation in the Sierra Nevada. Tree Physiol 25(1):57–66. https://doi.org/10.1093/TREEPHYS/25.1.57

Taubenböck H, Wegmann M, Roth A, Mehl H, Dech S (2009) Urbanization in India—Spatiotemporal analysis using remote sensing data. Comput Environ Urban Syst, 33, 179–188. https://doi.org/10.1016/j.compenvurbsys.2008.09.003

Taubenböck H, Wegmann M, Roth A, Mehl H, Dech S (2009) Urbanization in India – Spatiotemporal analysis using remote sensing data. Computers, Environment and Urban Systems, 33, 179–188. https://doi.org/10.1016/j.compenvurbsys.2008.09.003

Tomlinson BR (2003) What was the Third World? J Contemp Hist, 38(2), 307–321. https://www.jstor.org/stable/3180660

Trask BS (2022) Migration, urbanization, and the family dimension.

UN (2019) United Nations, Department of Economic and Social Affairs, Population Division. World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420) New York: United Nations.

UN, Department of Economic and Social Affairs, Population Division (2022) World Population Prospects 2022: Data Sources. (UN DESA/POP/2022/DC/NO. 9)

UNDESA (United Nations Department of Economic and Social Affairs) (2018) Population Facts No. 2018/1.

UN-Habitat (United Nations Human Settlements Programme) (2004) The challenge of slums: Global report on human settlements 2003. Management of Environmental Quality: An International Journal, 15(3), 337-338.

UN-Habitat (United Nations Human Settlements Programme) (2013) State of the world's cities 2012/2013: Prosperity of cities. Routledge.

Unnikrishnan H, Mundoli S, Nagendra H (2017) Making water flow in Bengaluru: planning for the resilience of water supply in a semi-arid city. J Sus Urban Plan Prog, 2(1), 63–72. https://doi.org/10.18063/JSU2017.01.002

Varalakshmi LR, Ganeshamurthy AN (2012) Heavy Metal Contamination of Water Bodies, Soils and Vegetables in Peri-Urban Areas: A Case Study in Bangaluru. J Hortic Sci, 7(1), 62–67. https://doi.org/10.24154/jhs.v7i1.392

VDLUFA (1997) Methodenbuch Band I. Die Untersuchung der Böden, 4th Edition. VDLUFA Verlag, Darmstadt, Germany

Verma R, Singh SP, Raj KG (2003) Assessment of changes in water-hyacinth coverage of water bodies in the northern part of Bangalore city using temporal remote sensing data. Curr Sci, 84, 795–804. http://www.jstor.org/stable/24107584

Vlahov D, Galea S (2002) Urbanization, urbanicity and health. J Urban Health, 79(4, Suppl. 1), S1–S12. https://doi.org/10.1093/jurban/79.suppl_1.s1

Weiler DA, Giacomini SJ, Recous S, Bastos LM, Pilecco GE, Dietrich G, Aita C (2018) Trade-off between C and N recycling and N2O emissions of soils with summer cover crops in subtropical agrosystems. Plant Soil 433(1–2):213–225. https://doi.org/10.1007/S11104-018-3831-2/FIGURES/5

Wilhelm JA, Smith RG (2018) Ecosystem services and land sparing potential of urban and peri-urban agriculture: A review. Renew Agric Food Syst, 33(5), 481-494. https://doi.org/10.1017/S1742170517000205

4.7 Appendix

Table A 2.1 Fertilizer dosages (in kg ha^{-1}) in the two cropping system experiments at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India. Adapted from Buerkert et al. (2021)

		Rainfed Dry season			**Irrigated Dry season**				**Wet season**		
Years	Fertilizer	Maize	F.Millet	Lablab	Cabbage	Tomato	Chili	Eggplant	Maize	F.Millet	Lablab
2016	N_{low}	50	25	10	-	-	-	-	50	50	10
	N_{medium}	75	37.5	15	-	-	-	-	100	75	15
	N_{high}	100	50	25	-	-	-	-	150	100	25
	P	21.8	17.5	4.4	-	-	-	-	32.7	21.8	4.4
	K	31.1	31.1	8.3	-	-	-	-	41.5	41.5	8.3
2017	N_{low}	50	25	10	30	23	-	25	50	50	10
	N_{medium}	75	37.5	15	60	46	-	50	100	75	15
	N_{high}	100	50	25	90	69	-	75	150	100	25
	P	21.8	17.5	4.4	17.5	17.5	-	17.5	32.7	21.8	4.4
	K	31.1	31.1	8.3	41.5	19.9	-	16.6	41.5	41.5	8.3
2018	N_{low}	0	0	0	0	0	-	0	0	0	0
	N_{medium}	50	25	12.5	30	23	-	25	50	25	12.5
	N_{high}	150	50	25	60	46	-	50	150	50	25
	P	21.8	17.5	4.4	17.5	17.5	-	17.5	32.7	21.8	4.4
	K	31.1	31.1	8.3	41.5	19.9	-	16.6	41.5	41.5	8.3
2019	N_{low}	0	0	0	0	-	0	0	0	0	0
	N_{medium}	50	25	12.5	30	-	75	25	50	25	12.5
	N_{high}	150	50	25	60	-	150	50	150	50	25
	P	21.8	17.5	4.4	17.5	-	32.7	17.5	32.7	21.8	4.4
	K	31.1	31.1	8.3	41.5	-	62.3	16.6	41.5	41.5	8.3
2020	N_{low}	0	0	0	0	-	0	0	0	0	0
	N_{medium}	50	25	12.5	30	-	75	25	50	25	12.5
	N_{high}	150	50	25	60	-	150	50	150	50	25
	P	21.8	17.5	4.4	17.5	-	32.7	17.5	32.7	21.8	4.4
	K	31.1	31.1	8.3	41.5	-	62.3	16.6	41.5	41.5	8.3
2021	N_{low}	0	0	0	0	-	0	0	0	0	0
	N_{medium}	50	25	12.5	30	-	75	25	50	25	12.5
	N_{high}	150	50	25	60	-	150	50	150	50	25
	P	21.8	17.5	4.4	17.5	-	32.7	17.5	32.7	21.8	4.4
	K	31.1	31.1	8.3	41.5	-	62.3	16.6	41.5	41.5	8.3

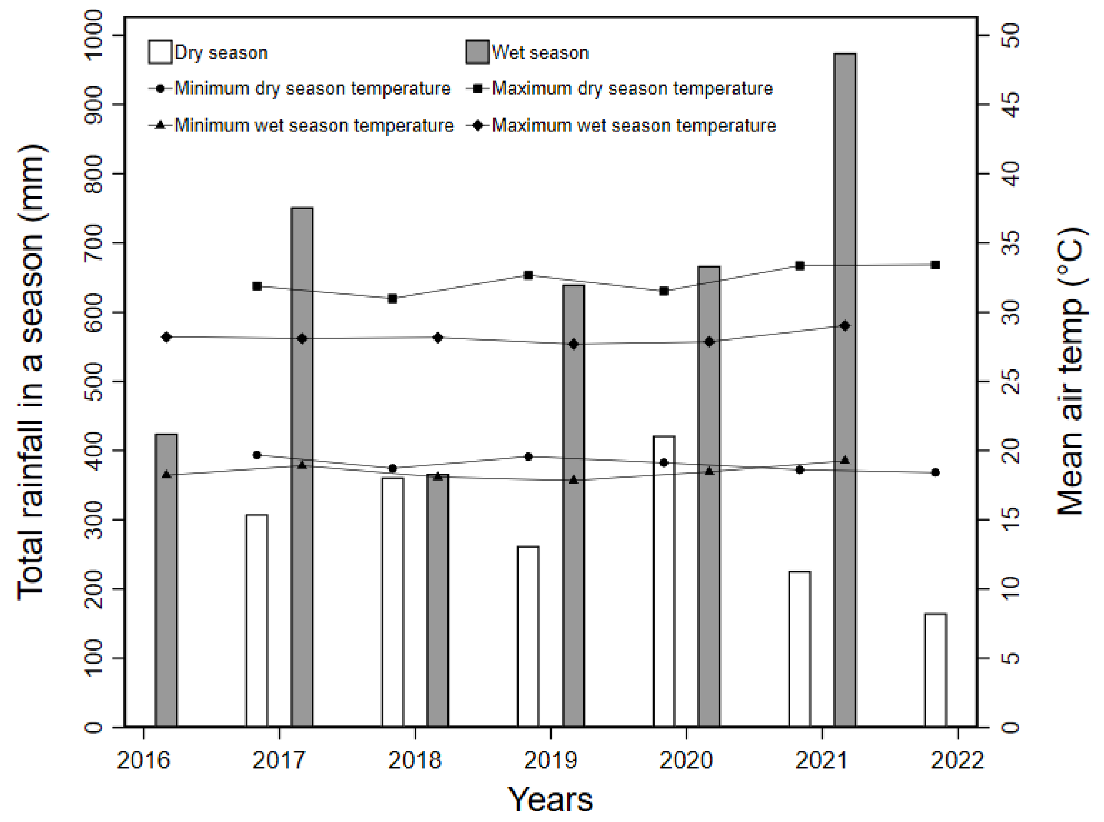


Figure A 2.1 Maximum and minimum mean air temperature and total rainfall distribution at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India from June 2016 until June 2022.

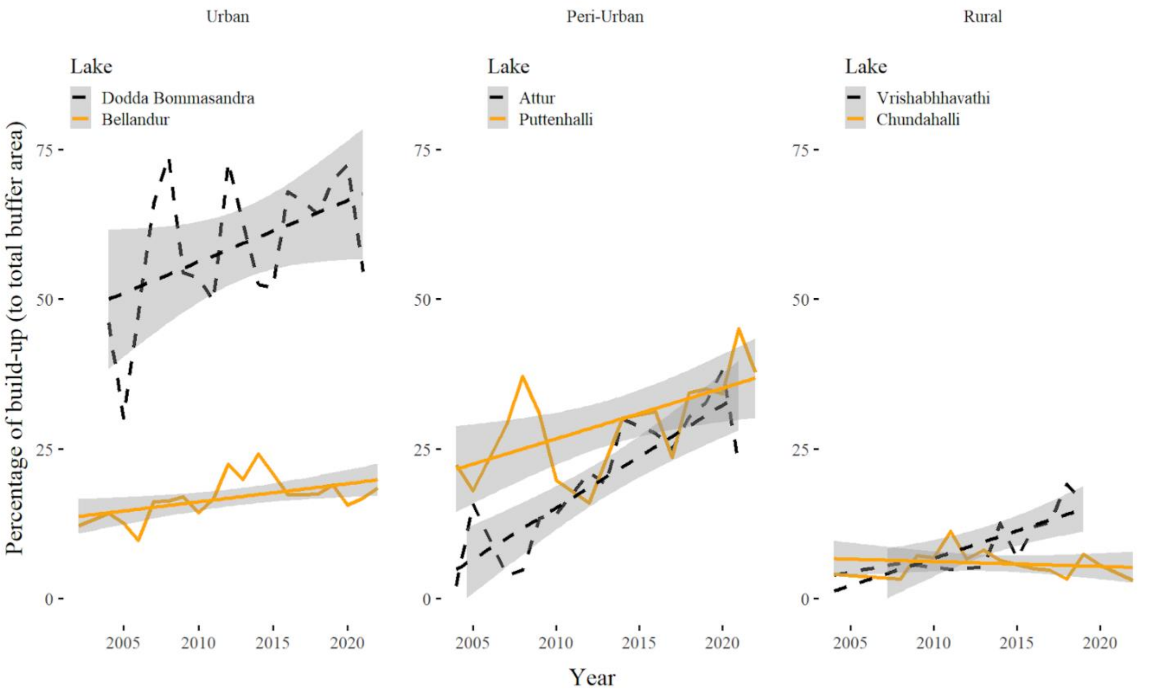


Figure A 3.1 Time series expansion graph of percentage built-up share from total buffer zone around each selected lake.

Table A 3.1 Example of pairwise correlation matrix between built-up versus algae, macrophyte, surface water, and dried land in Vrishabhavathi (n=14) and Dodda Bommasandra lakes (n=28), India.

Vrishabhavathi	Algae	Macrophyte	Surface water	Dried land
Build-up	-0.399	0.493	-0.158	-0.167
Algae		-0.405	-0.374	0.177
Macrophyte			-0.562	-0.423
Surface water				-0.221

Attur	Algae	Macrophyte	Surface water	Dried land
Build-up	-0.082	0.089	-0.063	-0.072
Algae		-0.152	-0.154	0.141
Macrophyte			-0.025	-0.979
Surface water				-0.174

Puttenhalli	Algae	Macrophyte	Surface water	Dried land
Build-up	-0.522	0.069	0.013	0.270
Algae		-0.292	-0.177	-0.262
Macrophyte			-0.193	-0.579
Surface water				-0.424

Dodda Bommasandra	Algae	Macrophyte	Surface water	Dried land
Build-up	-0.293	-0.532	-0.089	0.498
Algae		0.138	-0.007	-0.275
Macrophyte			0.338	-0.928
Surface water				-0.627

Chudahalli	Algae	Macrophyte	Surface water	Dried land
Build-up	0.104	0.164	-0.323	0.436
Algae		-0.242	-0.539	0.154
Macrophyte			-0.639	0.163
Surface water				-0.523

Bellandur	Algae	Macrophyte	Surface water	Dried land
Build-up	-0.137	0.102	-0.081	0.207
Algae		-0.475	-0.402	-0.425
Macrophyte			-0.435	-0.033
Surface water				-0.138

Contributions to further publications

Agricultural intensification effects on spatial growth variability of staple crops in south India

Citation:

Buerkert, A., Piepho, H.P., Sourav, S.K., Hoffmann, E., Vazhacharickal, P.S., Subbarayappa, C.T. and Wachendorf, M. 2023. Agricultural intensification effects on spatial growth variability of staple crops in South India. *Field Crops Research* 301, 109032. https://doi.org/10.1016/j.fcr.2023.109032

Abstract

Little is known about the effects of intensification of cropping systems on the short-distance variability of total dry matter (TDM) yield of field crops in tropical cropping systems. To fill this knowledge gap, we used a factorial on-station experiment on a heavily weathered, tropical Nitisol in S-India consisting of a rainfed and an irrigated trial with low (N1), medium (N2), and high (N3) levels of mineral nitrogen (N) application. These fertilizer treatments were combined with a rotation of maize, finger millet, and lablab to investigate the development of TDM in two cropping cycles of three years each. Across six consecutive experimental years and for all crops our data show that at a total annual rainfall varying from 366 to 998 mm TDM yields in the irrigated field were higher than under rainfed conditions. Irrespective of the water regime, crop type, and N level, yields of maize ($P < 0.0001$) and millet ($P < 0.0001$) but not lablab significantly declined over time. The decline was stronger in irrigated than in rainfed crops and followed the sequence maize = finger millet > lablab. Log-transformed sample variance in grids of 1.2 × 1.2 m was higher in irrigated than in rainfed crops and variance declined stronger over time for both rainfed cereals in N1 plots without N followed by N2 and N3 plots. No N effects were noted in the legume lablab. When variances were standardized for TDM levels, we observed strongest growth of coefficients of variation over time in N1 plots of rainfed maize. Most differences in point estimates of trends were not significant at the 5% level due to relatively large standard errors. The results provide important insights for small-scale farmers and scientists in designing more efficient field experiments whose precision depends on plot size and number of replications.

Estimating nitrogen fixation in lablab (Lablab purpureus) and finger millet (Eleusine coracana) on a Dystric Nitisol in S-India.

Citation:

Mock, A., Ingold, M., Vazhacharickal, P.S., Sourav, S.K., Dittert, K. and Buerkert, A. Estimating nitrogen fixation in lablab (Lablab purpureus) and finger millet (Eleusine coracana) on a Dystric Nitisol in S-India. *Journal of Plant Nutrition and Soil Science* (re-submitted 12.09.2023).

Abstract

Background: In a long-term field experiment (2016-2022) with different fertilizer levels in subtropical S-India, crop yields of low nitrogen (N) plots were unexpectedly high. To assess the diazotropihic N_2 fixation of lablab (*Lablab purpureus* L. Sweet) and possible associative N_2 fixation of finger millet (*Eleusine coracana* L.) Gaertn), an experiment was conducted during the 2021 Monsoon season within the above mentioned long-term field study. Two approaches were used to estimate the quantity of N derived from the atmosphere (Ndfa): the dilution method using a ^{15}N labeled fertilizer and the natural abundance method.

Method: For the ^{15}N dilution method irrigated maize (*Zea maize* L.), finger millet, and lablab were labeled with two split applications of 10% ^{15}N fertilizer amounting to 15 kg N ha^{-1}. Maize was selected as the non-fixing reference plant to estimate diazotrophic N_2-fixation. The whole aboveground biomass of the labeled plants were harvested at maturity and analyzed for total DM, N, and ^{15}N concentration.

Results: N_2 fixation efficiency for lablab was 52% to 69% depending on the calculation method, corresponding to 40-53 kg N ha^{-1}. For finger millet the natural abundance method resulted in an estimated N_2 fixation of 5 kg N ha^{-1}, which was poorly supported by the results of the dilution method as the reference plant maize was only poorly labeled.

Conclusion: Labeling of maize might have been diluted due to unexpected associative N_2 fixation or N-uptake from deeper unlabeled soil N pools. The data underline the important role of symbiotic N_2 fixation in crop rotation systems of Southern India.

Crop Production Under Urbanisation: An Experimental Approach to Understand and Model Agricultural Intensification

Citation:

Buerkert, A., Hoffmann, E., Hewage, R.S., Goenter-Jordan, S., Sourav, S.K., Mock, A., Vazhacharickal, P.S., Subbarayappa, C.T., Mudalagiriyappa, Hanumanthappa, D.C., Peth, S., Wachendorf, M. 2021. Crop Production Under Urbanisation: An Experimental Approach to Understand and Model Agricultural Intensification. In: Hoffmann, E., Buerkert, A., von Cramon-Taubadel, S., Umesh, K.B., Pethandlahalli Shivaraj, P., Vazhacharickal, P.J. (eds) The Rural-Urban Interface. The Urban Book Series. Springer, Cham. https://doi.org/10.1007/978-3-030-79972-4_7

Abstract

Rural–urban transformation has major implications on agricultural land use. This is also the case in the southern Indian city of Bengaluru, where farmers shift from low intensity subsistence agriculture under rainfed conditions to irrigated, market-oriented production of crops and vegetables. As little is known about the effects of this intensification on water use, nutrient leaching, losses of carbon and nitrogen, and soil quality, a long-term experiment was established under well-defined on-station conditions to generate a typical intensity gradient in an in situ laboratory of change. Measurements of key agronomic, soil-related, and meteorological parameters at high temporal and spatial resolution allow to assess externalities and efficiencies of resource use and to predict long-term consequences of intensification on agricultural sustainability. The two long-term rotation experiments established under rainfed and irrigated conditions also allow to collect and calibrate ground-based multi- and hyperspectral crop reflectance data needed for upscaling to high resolution satellite images that cover a North–South research transect across the rural–urban interface of Bengaluru.

Declaration in accordance with § 8 of the General Provisions for Doctoral Degrees at the University of Kassel dated 14.07.2021.

1. I herewith give assurance that the submitted dissertation "Plant growth, water quality, carbon and nutrient flows in rural-urban cropping systems in Bengaluru, India" is the product of my work alone.
2. I affirm that I have not used any sources or aids other than those explicitly cited. All passages that are drawn from published or unpublished writings, either word-for-word or in paraphrase, have been clearly identified as such.
3. Please check where applicable

   The dissertation or parts of it

   ☐ has/have not been used in another doctoral or tenure process in Germany or abroad.

   ☐ has/have been submitted in another doctoral or tenure process in Germany or abroad:

   Title:
   University and year of submission:
   Art der Prüfungs- oder Qualifikationsleistung:
   Published in:

   The submission refers to the following part(s) of the dissertation:
   [Part(s) of the dissertation]
4. Both, the submitted digital version and the submitted written copies are identical.
5. Third parties were not involved in the drafting of the content of this dissertation; most specifically I did not employ the assistance of a commercial dissertation advisor.
6. In case of a cumulative dissertation: I have documented the participation of co-authors by attaching a written statement signed by all of the co-authors outlining which parts of jointly written contributions are attributed to which co-authors.
7. I confirm the correctness of the above mentioned statements.

01.11.2023
Date

Signature