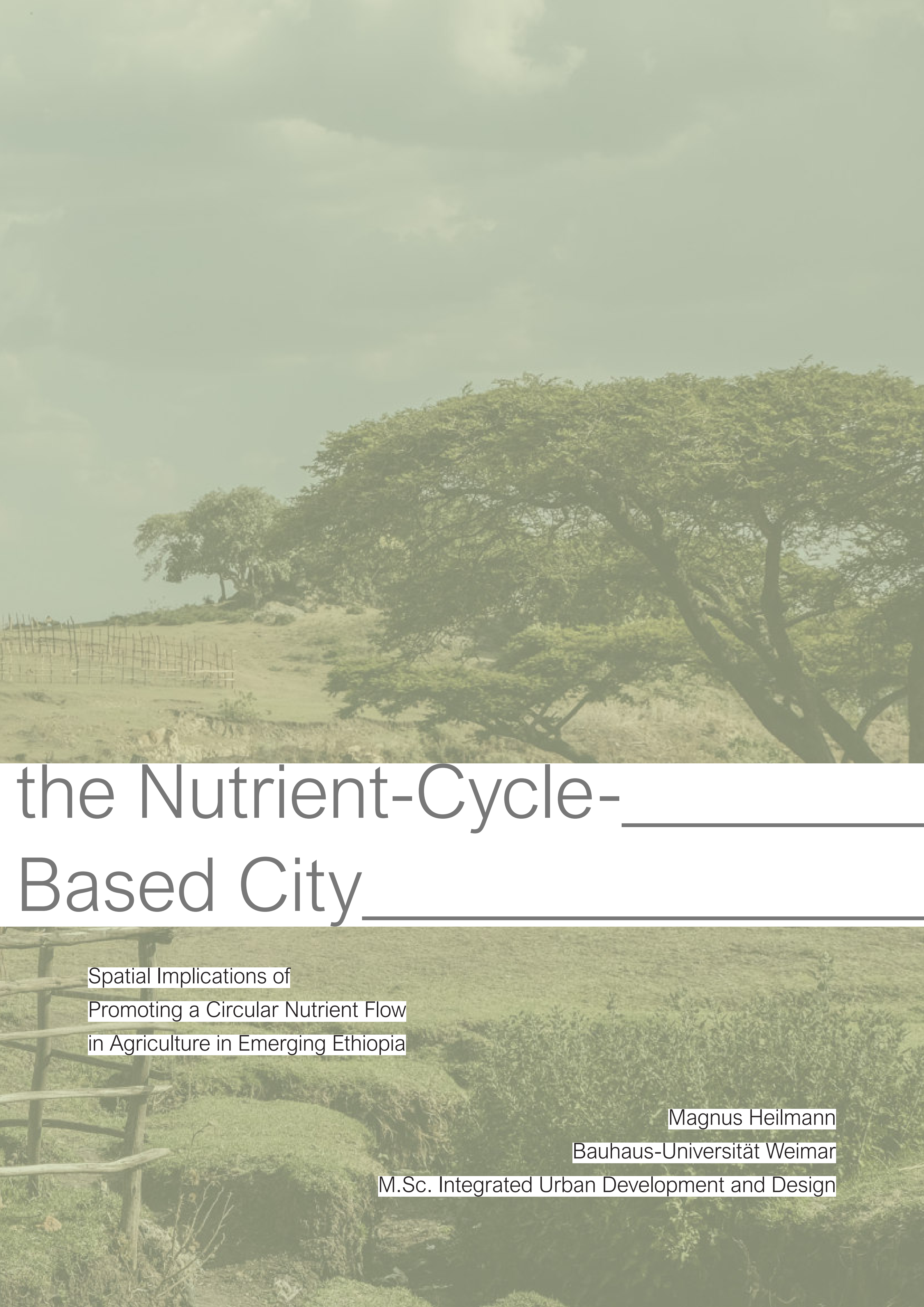

the Nutrient-Cycle-Based City

Spatial Implications of
Promoting a Circular Nutrient Flow
in Agriculture in Emerging Ethiopia

Magnus Heilmann
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M.Sc. Integrated Urban Development and Design

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Keywords: circular urbanism, food security, compost, sustainable intensification, rural development, ecological sanitation, parametric urban design

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Statutory Declaration

I hereby affirm that the Master Thesis at hand is my own written work, and that I have used no other sources and aids other than those indicated. All passages, which are quoted from publications or paraphrased from these sources, are indicated as such, i.e. cited, attributed.

This thesis was not submitted in the same or in a substantially similar version, not even partially, to another examination board and was not published elsewhere.

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Acknowledgements

As I am writing these lines, I realize they mark the end of me being a student. In anticipation of what is to come next, I want to express my gratitude to the wonderful people we lovingly call the “IUDD Bubble“, my classmate friends from 13 countries. The two-and-a-half-year journey through so many cultures, views of the world, unbelievably fulfilling yet sometimes challenging experiences, creative and exciting times on campus and in Weimar, ideas for creating a better planet through our work, has led to my final report.

The work on this study is the logical end point to my education, and it would not have been what it is now if it weren‘t for my supervisors Sven Schneider and Philippe Schmidt, who not only supported this thesis but tended the entire study program of IUDD. Thank you, for valuable insights, for helpful guidance, for steering my search for new approaches and proposals, for supporting me conduct this work.

Finally I want to say how grateful I am for the people that have been by my side during my study times and in particular the past few months. Thanks to my family at home and thanks to my flatmates in Weimar, fellow IUDD classmates in the same boat of working on their theses, for being at these two places for me, wherever I was. Thanks for making being stuck in social distancing, during a dark winter, during writing a thesis, an always bearable, most of the time even nice experience.

Foreword

This research was conducted under the framework of the network project “VIN³: Building climate-resilient cities – ecological sanitation and waste management, and organic urban agriculture for emerging cities in Sub-Saharan Africa”. It is an ongoing cooperation between the lead organisations Forschungszentrum Jülich with the Institute of Bio-and Geosciences, and the Bauhaus-University Weimar with the Chair for Informatics in Architecture.

The projects “IN³ - Integrated Infrastructure” with the research pillars technology, simulation and participation and “ClimEtSan - Capacity building in climate-smart agriculture and ecological sanitation in Ethiopia” emphasize close cooperation with the local partners of Wondo Genet College of Forestry and Natural Resources and the Addis Ababa University (EiABC). Jointly, the interdisciplinary and interinstitutional cooperation aims to combine ecological sanitation, urban agriculture, urban metabolism and city planning for practical solutions for climate-resilient spatial development in Ethiopia. The research is funded by the German Federal Ministry of Education and Research (BMBF) and the German Academic Research Service (DAAD).

Prior to the master thesis research, a study project on Circular Metabolism including site visits in Ethiopia was conducted in summer of 2019, as part of the study course of Integrated Urban Development and the larger VIN³-framework.

Special thanks go to Dr. Katharina Prost from FZ Jülich for the expert interview and to all research partners of the ClimEtSan and IN³ projects for valuable insights and inclusion in the ongoing research.

Abstract

Agriculture in low-income economies of Sub-Saharan Africa is facing multi-layered challenges: climate change threats, land degradation and unfertile soils, lack of knowledge and financial resources, all leading to low crop production and food insecurity. Urban and rural settlements at the same time often lack access to safe sanitation due to the rapidly growing population. Traditional treatment schemes of wastewater, where in place, are expensive, polluting, and fail to recognize human excreta as the valuable resource that it is by simply disposing it.

The use of dry toilets that collect human excreta for composting addresses all these issues at once: providing people with safe and affordable access to ecological sanitation, fertilizing fields, stabilizing soils, sustainable intensification of agriculture, food security, preventing pollution and ecological damage through pathogens and chemicals.

These dry toilets are the key which can close the nutrient cycle in agriculture. This research therefore proposes the “Nutrient-Cycle-Based City“, an integrated urban development model applying circular urbanism principles. Theoretical and spatial models provide guidance for the implementation of dry toilets and composting facilities in rural and urban spaces in Ethiopia.

Using parametric design methods, the proposed design strategy of the “Circular Unit“ is tested on the site of Olonkomi, Ethiopia. The flexibility and applicability of the bottom-up urban development scheme is shown through different spatial implementation scenarios.

Contents

Introduction

1. Introduction

1.1 Research background

Ethiopia's population is growing rapidly, livelihoods in rural areas are increasingly threatened by climate change challenges, progressing environmental damage, land depletion and the resulting low output of agricultural production. The living standards are lower than in more urbanised regions, access to sanitation is scarce, which further increases pollution and harms natural ecosystems. At the same time, the amount of waste is rising, a valuable resource that is currently remaining unused: In Ethiopia, most waste to date is organic and could relatively easily be repurposed.

One key to addressing these multi-layered challenges all at once can be: Providing dry toilets as a form of sustainable sanitation in order to make the nutrient flow in agriculture a circular one.

> "Ecological sanitation is not merely about a new latrine design. It is a new way of thinking:
> a closed-loop-approach to sanitation, in which excreta are returned to the soil instead of water.
> Thus, the closed-loop approach is non-polluting, keeping fresh and marine water bodies free of pathogens and nutrients.
> It is a zero-discharge approach."
>
> (Branstrator 2017; p. 35)

There is a need to come up with a more sustainable urban model that centers around the nutrient flow, an urban model that considers human waste and organic waste as a driver in urban development. That way, human excrements can be salvaged as a resource by faeces being processed to compost, a sustainable material for fertilizing land, increasing agricultural productivity and therefore improving food security – all that, while natural resilience is improved, greenhouse gas emissions and the need for irrigation are reduced tremendously, cost-efficient sanitation can be provided, and overall liveability in low-income communities and rural areas is boosted.

Integrated urban system models can help understand complex interrelations and show starting points for promoting circular resource flows in urbanism. A modular planning approach combined with parametric methods, can help apply the transformation strategy on many locations in short time spans, achieving highest impact when action is needed most promptly.

1.2 Goals and research questions

This work seeks to explore viable strategies for creating a circular nutrient flow in the agriculture in emerging low-income communities in Ethiopia. With appropriate collection from dry toilets and the respective composting schemes, human excreta become a valuable resource as compost for agricultural fields.

Two main aims are identified for local residents: Firstly, livelihood improvements are expected, namely through the provision of sanitation facilities to urban or rural communities, and an increase in agriculture production by improved nutrient availability for the farms. Secondly, environmental damage through chemical fertilizers and over-fertilization shall be avoided, as chemical fertilizers will not be needed for increasing the agricultural productivity anymore. Keeping ecosystems intact helps increase resilience against natural hazards and climate change impacts, therefore further increasing especially rural people's livelihoods.

The work is therefore framed around the central research question:

What are the spatial implications of promoting a circular nutrient cycle in agriculture in emerging communities in Ethiopia?

Guiding questions to answering the main research problem of this thesis are:

How can the model of the nutrient-cycle-based city look? How can it be implemented in a sustainable spatial transformation process in low-income economies? What actions are needed spatially and regarding maintenance and management?

An urban transformation strategy with according planning tools and defined urban modules shall be developed, that supports achieving a city or settlement that is oriented towards a circular nutrient flow. Transferrable principles shall be defined, a set of actions so to say, which can be adjusted and adapted to different localities and requirements, and implemented through good urban planning.

1.3 Methodology and research design

The work follows a design-by-research approach: The problem statement is assessed scientifically, and the solution is given through proposed design interventions. The exploration of the design solutions here seeks to design a strategy with planning tools. With them, the theoretical ideas and goals can be achieved in different surroundings and the tools themselves can be reproduced flexibly and quickly to different project requirements.

Closing the nutrient cycle is the overarching aim of this work; making the concept broadly applicable in urban planning is a main objective. With that goal, four main study phases are conducted: theoretical framework – integrated system modelling – implementation guidelines – testing and evaluation. A brief overview of the research design of this work shall be given here.

Theoretical Framework:

The research is based on the theoretical framework, conducted through literature study regarding functional aspects of the broader topic. The focus is put on a systemic understanding of processes rather than specialist technical knowledge. The status quo of topics such as nutrient use in agriculture, the composting process of human excreta, or how spaces are made up, will be explored one by one. Parallelly, new developments and trends, e.g. towards better sustainability, are explored. In a synopsis, first conclusions of interrelations and points of contact between the different themes are drawn, showing the need for a shift to a city model that takes into account how the resource of human excreta can sensibly be dealt with.

Integrated System Modelling:

Subsequently, the theoretical framework with the stated problems is processed in spatial theory.

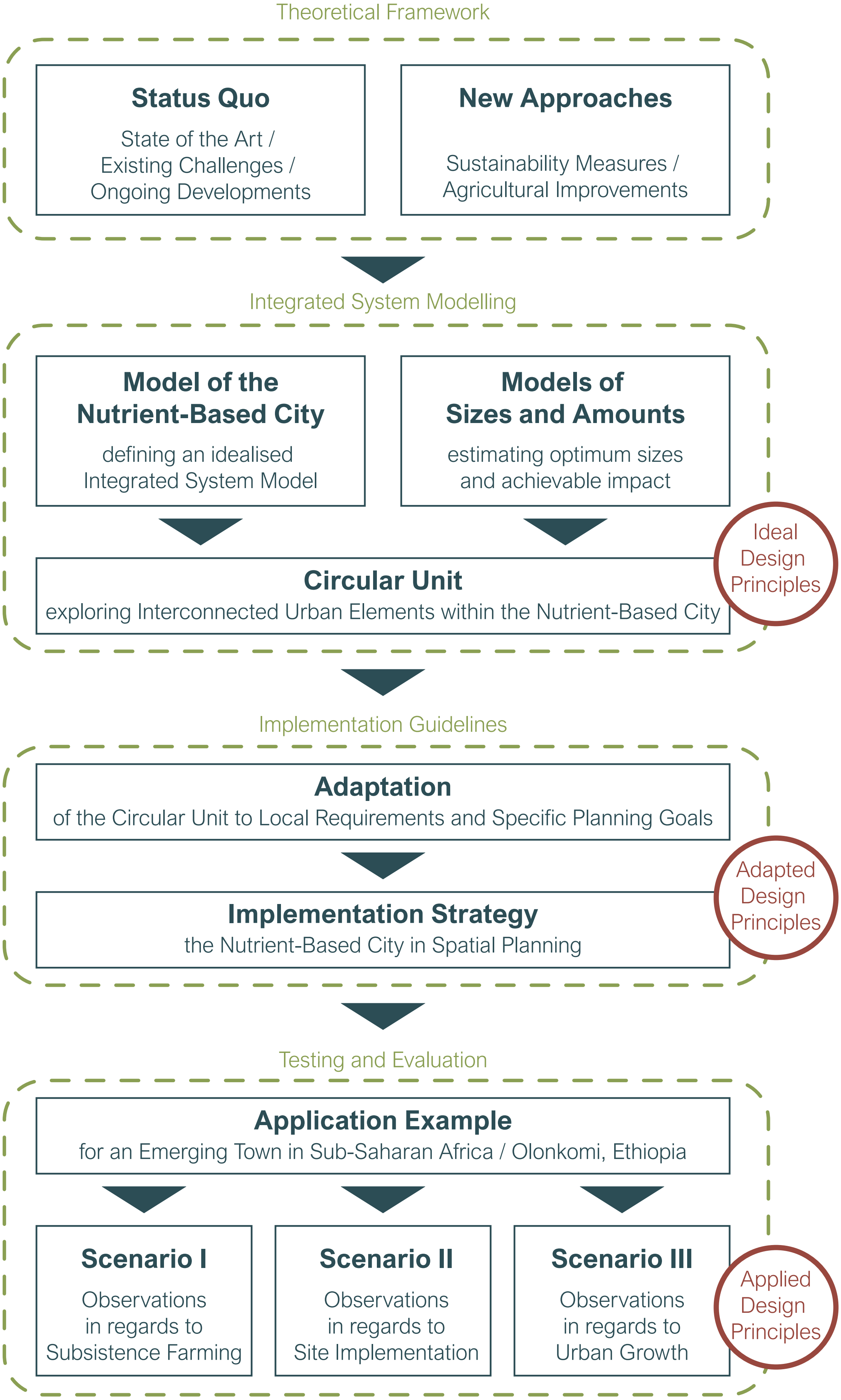


fig. 1.1: research design of this thesis

An integrated system model is proposed, the model of the "Nutrient-Cycle-Based City". It encompasses all spatial elements which are relevant to the flow of nutrients within a settlement. This theoretical model describes dependencies and interrelations between spatial elements, and introduces parameters that show the influence of the elements on one another. Here, the city is shown holistically, based on how the nutrient flow in the urban environment actually works, with urban elements that already exist (e.g. residential quarters, street network, market) and with urban elements that are to be introduced newly. The framework for closing the nutrient cycle is set by the application of dry toilets as a mode of sanitation provision (cf. dry toilets on the projects SOIL or ClimEtSan) for collection of material for composting. New urban elements for this approach include e.g. the shared toilet facilities and composting spaces.

Different calculation schemes explore the achievable capabilities and the requirements of the proposed closing of the nutrient cycle. A close look on the nutrient flow and specifically all related materials, in comparable proportions for one person, investigates questions such as:

How much compost can be produced per capita, how much agricultural fields can be intensified sustainably with this amount of compost? What are the savings compared to similar fertilization from chemical fertilizer, can conclusions be drawn in regard to pollution and CO2 emissions? How many people ideally share a toilet station, how many composting units are needed, how are they connected, how is the transport of the materials organised, what bulk amounts make sense in the local infrastructure network? How do people reach and use the new infrastructure, what distances are appropriate?

This idealised integrated system model is then used for the so-called "Circular Unit", which is the concrete spatial representation of the integrated system model. It is a set of urban elements that are directly connected through the circular nutrient flow, and contains the spatial elements exactly with the ideal size for treating the accrued resources, sustaining the respective amount of inhabitants and ultimately keeping the available nutrients within the closed system.

These steps of integrated system modelling use Ideal Design Principles that lay the base for the planning tools that this thesis proposes.

Implementation Guidelines:

The Ideal Design Principles are here being adapted to local and other requirements, different direct surroundings and specific planning goals, such as a new urban development or the transformation of existing settlements. So, the concrete strategy aimed at applying the nutrient cycle is formed by Adapted Design Principles. They are a set of modules with the same base elements, which are flexibly applicable in different surroundings and can be further adjusted to different planning requirements or local surroundings.

Next, implementation guidelines give orientation as a strategy to implement the Nutrient-Cycle-Based City by using the Circular Unit. A step-by-step approach shall describe considerations while planning structural measures, analytical steps, management and maintenance aspects etc, as well as a sensible sequence for each action considering the respective interdependencies.

Testing and Evaluation

Finally, the Circular Unit concept is tested on the town of Olonkomi in central Ethiopia, using partially automated parametric design and analysis tools. The applicability of the Adapted Design

Principles is explored not only within a Sub-Saharan context, but more specifically that of the test site. In testing the strategy on an emerging town, several different Design Principles are used as premises in urban planning. Their exemplary application on Olonkomi will test capabilities and limits of the proposed concept, and show the potential consequences for an existing settlement. Three different scenarios with different testing aims are developed for that purpose, and they will help draw conclusions and evaluations on the Circular Unit hypothesis, both with implications for rural and urban settlements.

Theoretical Framework

2. Theoretical Framework

2.1 Ongoing trends and developments

Cities, Urbanisation and Population

Our world is becoming increasingly urban. The phenomenon of urbanisation is long known, people tend to move to places with concentrated service provision, better life circumstances, societal opportunities and employment etc. In 2007, for the first time, global population living in cities outnumbered the rural population, and the trend will continue – with population growth rates on the rise and the incentives to move to urban areas getting stronger, too, in many places (Ritchie 2018).

In the Global North, where urbanisation processes have been strong for centuries, the share of urban population has reached very high numbers of 60-80% in most countries, even reaching above 95% in some states. The demographic change will have the total number of urban dwellers remain stable, or rise at low rates, with rural populations declining in most cases. In countries of the Global South, in contrast, total urbanisation rates are still much lower, with most inhabitants living in rural zones. This can be observed especially pronounced in Sub-Saharan Africa, where many countries have an urbanisation rate below 30% (e.g. Ethiopia 20.3% in 2017) (Ritchie 2018). Yet, these are countries with the highest population growth rates globally – Africa will quadruple its population between 2010 and 2100 to approx. 4.1 billion inhabitants (World Population Review 2020). Staying with the example from Ethiopia, a country with approx. 116 mio inhabitants in 2020, it will have surpassed 200 mio inhabitants by 2050 and is expected to reach almost 300 mio inhabitants by the end of the century (World Population Review 2020). Paired with rising urbanisation rates, this enormous population growth results in unprecedented urban growth and development of megacities.

The rapid increase of urban population brings many challenges for the population as well as planning authorities: the lack of access to basic services persists to be very high in many countries of the Global South. UN HABITAT defines a slum as a place, where residents "lack one or more of the following conditions: access to improved water, access to improved sanitation, sufficient living area, and durability of housing" (World Population Review 2020). Even though in most parts of Sub-Saharan Africa, the percentage of slum dwellers as part of the urban population has declined – for Ethiopia 72% in 2014 compared to 95% in 1995 – still, there is plenty of work ahead. The decentral urban structure in Ethiopia with the relatively small capital of Addis Ababa (and therefore lack of mega-slums) gives opportunity for small-scale, bottom-up and multi-central approaches to improving urban living conditions.

fig. 2.1: processes of urbanisation. (Dalzell 1987) edited by author.

The dynamic process of urbanisation can be broken down in different stages. Initial urbanisation is marked through stark population influx and densification; this is the state that most African cities are currently in. As defined by Stephen Darwell (2006), following stages of urbanisation, which result from evolving preferences and conditions in the cities, are sub-urbanisation (especially in large cities) and counter-urbanisation (a trend mostly witnessed in European countries, where wealthy people start leaving dense urban areas in search of the "ideal", "paradise-like" life in the natural countryside). Re-urbanisation is the result of low rents (keyword gentrification), people valuing urban life anew, and oftentimes government incentives as a reaction to deteriorating city cores (Darwell 2006). This is also where current strives for more sustainability come into play and try to achieve the idealised "sustainable city" – whatever concrete urban this may mean.

The idea now is to look for "shortcuts", from high urban growth rates, like currently seen in Africa, directly to a sustainable city. This would save tremendous amounts of land from urban sprawl, usually leaving almost useless snippets of land – useless for many productive land uses as well as natural development (Darwell 2006). As land is becoming scarcer, concepts for living in different urban densities, interwoven with other land uses, must be found at utmost urgence.

Sub-Saharan Africa is mostly just at the starting point of these complex development stages, which raises the question of what these shortcuts from initial urbanisation processes directly to a sustainable, inclusive and socially-just city could look like, without taking all the development steps that most cities in the Global North have passed through. With good management, urban planning and incentivisation, the high growth rates in urban population become an opportunity for increasing sustainability, resilience and future-preparedness in the emerging economies of the Global South.

Cities and food production

Regardless of the stage of urban development that a city is going through, cities are always places where people's residence and foodstuff production get disconnected. With job opportunities in handicrafts, services, manufacturing and many more, people reached monetary wealth and higher living conditions, food is being bought and produced elsewhere, and the traditional nutrient link between the production and consumption of food, that initially caused humanity to settle, is broken (Ellen MacArthur Foundation 2017; Svirejeva-Hopkins and Reis 2011). This influx of large amounts of food into a space with high usage density (and over periods of time, also other materials, like coal for factories during the industrial era, just to mention one example) results in output materials being equally concentrated in cities. Wastewater is being disposed in rivers, peri-urban ecosystems get damaged and nutrients get lost (Lin et al. 2014). Cities, however big they are, are inherently dependent on peri-urban spaces with the capability of balancing out the city's demands for material in- and output.

At the same time, trends like urban farming are becoming increasingly popular. Foodstuff production is promoted on a local, small-scale level, and over-usage of peri-urban areas reduced. Furthermore, and more importantly, material input into urban spaces becomes tangible again for the urban population, which is a factor that can help build a broad societal understanding for cities' negative impact on surrounding ecosystems (The World Bank 2008; Magid et al. 2006).

Agriculture practices, environmental damage through fertilizers, land depletion in low-income economies

Agriculture is a practice that increasingly causes environmental damage. Processes are becoming industrialised, outputs are to be increased as much as possible, and fields are expanded in areas that are not suitable for agriculture to begin with. For these reasons, more fertiliser is used, mostly artificial chemical fertilizers with high nitrogen contents (FAO 2020a; Garnett and

Godfray 2012). These fertilisers are not bound to the soil, and get washed out very easily, so that much more fertiliser must be brought out than the plants can and will use. The soils become less and less naturally resilient, so pesticides and herbicides also have to be used in increasing amounts.

As the fertiliser is washed out into rivers and oceans, it causes detrimental damage to the natural ecosystems – the high nitrogen values cause a lack of oxygen in waterbodies, an increase in algae population, the death of fish, coral and water plants (Garnett and Godfray 2012).

In Ethiopia (and large parts of Sub-Saharan Africa in general), the potential for agricultural expansion is relatively high, meaning that a large part of the growing biomass is not used for human consumption. But, especially in these regions, many mammals and bird species are endemic in very sensitive ecosystems. These natural biospheres are therefore directly threatened by expanding agriculture land (Delzeit et al. 2017; Brüggemann 6/18/2020).

Land depletion takes place the strongest in tropical climates where the topsoil layers of organic material are relatively thin and nutrient contents are low. Over time, the organic material is lost, which can be accredited to a number of factors that all decrease the soil quality:

- modern agriculture practices such as tillage with heavy industrial machinery,
- monoculture and the increased use of chemical fertilisers and pesticides,
- deforestation and removal of trees in traditional landscape structures with the intention to improve efficiency and accessibility with heavy machinery.

fig. 2.2: erosion of depleted soils in Tanzania. (The Guardian 2018)

These human interventions worsen effects of erosion and land degradation (Dalzell 1987) – and the process caused by agriculture itself is amplified by the soil composition of the tropics which, lacking the dense natural vegetation, is easily eroded away by the typical heavy rainstorms (Prost 11/13/2020; Brüggemann 6/18/2020). Nutrients and organic material are washed away into water system where they cause environmental damage (Ellen MacArthur Foundation 2017).

Sub-Saharan Africa still has a relatively low use of fertiliser and pesticides, mostly due to economic constraints of farmers. This can be an opportunity for improving land productivity in different ways than it has been done in the rest of the world, where the dramatic consequences of over-fertilisation are a real threat to natural resilience (The World Bank 2020; United Nations Organisation 2020).

Climate change threats on agriculture in tropical regions

On a global scale, changes in precipitation and average temperature are the most apparent impacts of global warming. For Sub-Saharan Africa, depending on the model, an increase in average annual temperature until 2100 between 2-5°C is expected (IPCC 2015). Specifically for Ethiopia, annual precipitation is projected to rise by 10-30%. These changes are fairly slow and can to a reasonable part be adjusted for by using different crops or breeds.

For the local level, however, climate change will mean more insecurity. Heavy rains and extended dry periods will become even more prevalent. On depleted soils, and in damaged natural eco-systems, these weather and climate threats are most harmful, especially in tropical regions of the world (IPCC 2015). We see yields get destroyed by natural disasters regularly as natural resilience is lost more and more. Natural environments are lost in the hope for sufficient food production, at the same time failing to really provide for the local population due to low agriculture efficiency (IPCC 2015).

The need for an agricultural shift in Sub-Saharan Africa

All these developments will require timely adaption measures in agriculture in Sub-Saharan Africa.

The existing agriculture production area cannot keep up with the rapid population growth - simply because all land is being used in some purpose already. The per capita cropland in Africa has declined from 0.29ha in 2000 to 0.21ha in 2018 (FAO 2020b). This value has declined in the world overall, as well, which can be assigned to better productivity. But Africa is the only continent where simultaneously, the prevalence of undernourishment has increased over the last decade, and the per capita available amount of calories has decreased (FAO 2020b).

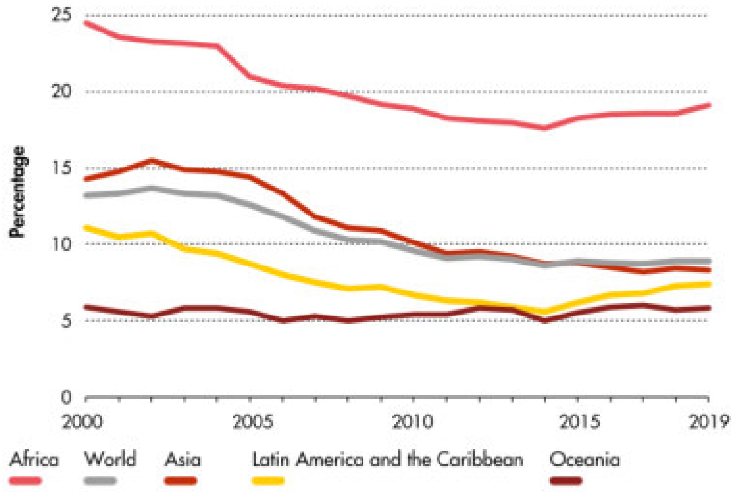


fig. 2.3: prevalence of undernourishment by region. (FAO 2020b)

Amplified by climate change effects, there will be more and more stress on the fields, and production is bound to decline even more due to more fields becoming fallow land or eroding away. Sustainable intensification of agriculture can be the way to go for Sub-Saharan Africa, as it promotes compost fertilisation in order to increase productivity while stabilising soils, not putting extra pressure on already polluted natural ecosystems, and including the population in foodstuff production processes actively for increasing social sustainability, too (Brüggemann 6/18/2020). It is a practice especially apt for Sub-Saharan Africa, as current fertilizer use there is very low, and there are no secondary industries dependent on fertiliser production and sales like elsewhere. In the nutrient-poor soils, big impact using sustainable practices can be achieved in a short amount of time (FAO 2020b).

Sustainable Development Goals of the United Nations

The United Nations have introduced ambitious Sustainable Development Goals (SDGs) to make the world a more sustainable place for the time period 2016-2030. On the way to achieving these 17 main goals, which encompass aspects of social, economic and environmental sustainability, a general paradigm shift towards more sustainable practices in all aspects of human life is strived for (United Nations Organisation 2015). Economic improvements, equal access to societal life, the reduction of inequal living conditions and improvement of environmental conditions and overall resilience are some of the main aims that the program has.

Many efforts have already been made and improvements have been achieved in many fields, yet a lot of obstacles are still to be overcome, the ongoing COVID-19 pandemic being one of the major drawbacks for reaching the 2030 SDGs. Ideally, however, all ongoing and future development projects would address as many SDGs as possible in their program. Therefore, this work as an attempt to promoting more sustainable agriculture practices as well as sanitation provision in an emerging (and thereby highly dynamic) economy, shall be framed within the UN's SDGs.

More explicitly, SDGs that this work is directly addressing are:

#2 – zero hunger

#6 – clean water and sanitation

#11 – sustainable cities and communities

#15 – life on land

As many of the SDGs are interlinked and impact each other, the following aspects are also expected to be improved through leveraging effects:

#1 – no poverty

#3 – good health and well-being

#8 – decent work and economic growth

#9 – industry, innovation and infrastructure

#12 – responsible consumption and production

#13 – climate action

fig. 2.4: Sustainable Development Goals of the United Nations addressed in this study. (United Nations Organisation 2015) edited by author.

Sustainable intensification in agriculture in Sub-Saharan Africa

One means for addressing many of the SDGs of the United Nations is sustainable intensification in agriculture in tropical regions, starting to be implemented in parts of Sub-Saharan Africa.

The agricultural productivity is generally low in many of the mentioned regions, with land being more and more depleted, and poverty limiting farmers' access to fertilizers. This is a vicious cycle: harvests are lost, overall yields are too little to sell enough for making a decent income, so investments in better technical equipment and soil improvement are impossible, further decreasing the quality of the fields.

"Sustainable intensification" practices address soil stability, resilience against climatic threats while raising agricultural productivity and foodstuff output (Brüggemann 6/18/2020). It is a multi-dimensional approach of natural and social sciences, that seeks to address food security and environmental issues in a holistic way. Key aspects include pollution prevention through use of natural fertilisers; wildlife and ecosystem-friendly practices; good land use planning for ideal use of natural resources; breeding, productivity and foodstuff distribution; as well as societal programs for acceptability, labourer education etc. Composting of animal and human manure and food waste is a key element in sustainably elevating food productivity long-term (Garnett and Godfray 2012).

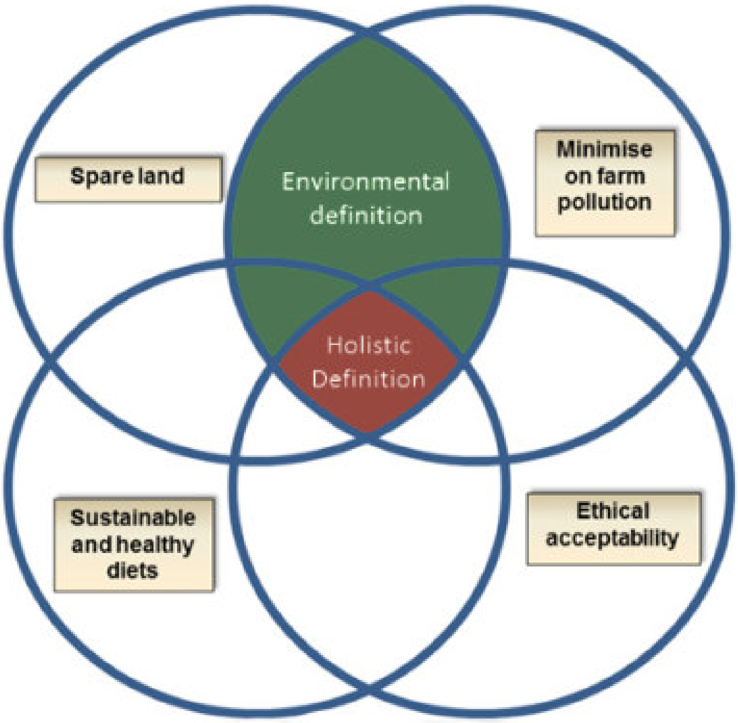


fig. 2.5: definition of sustainable intensification. (Garnett and Godfray 2012)

The concept has the highest impact on agricultural areas with a medium to low agricultural potential; most of Sub-Saharan Africa falls into that category with respective soil compositions and the typical smallholder farms there. In these areas, both from the foodstuff production point of view as well as regarding potential environmental benefits in the agricultural landscape, the improvement that can be made through sustainable intensification is the highest (Brüggemann 6/18/2020).

The implementation of sustainable intensification requires special focus on developing site-specific concepts for:

- Landscape approach and regional solution,
- Rural-urban gradient with adjusted concepts to urban scape,
- Soft factors, such as ecology and social sustainability.

Through sustainable intensification and the corresponding increase in nutrient input, more foodstuff can be produced in the same area. The only alternative for achieving similar product outputs would be expanding the cropland, which also means destruction of ecological habitats and a loss of space for urbanisation and other land uses that come with industrial and economic progress. Though very apt for Sub-Saharan Africa, big-scale implementation of sustainable intensification is only spreading slowly (Brüggemann 6/18/2020).

Attempts for sustainable sanitation provision for low-income countries

> "Ecological sanitation is not merely about a new latrine design. It is a new way of thinking: a closed-loop-approach to sanitation, in which excreta are returned to the soil instead of water. Thus, the closed-loop approach is non-polluting, keeping fresh and marine water bodies free of pathogens and nutrients. It is a zero-discharge approach."

(Esrey 2001, 43(4), p. 177)

While traditional sewage systems require immense investment costs and use huge amounts of water, and pit latrines of rural communities often pollute the direct surroundings with pathogens, dry toilets do neither use up resources, nor release pollutants into the environment. Instead they provide a resource of their own, making excreted nutrients usable instead of disposing them into rivers. However, there are also challenges when implementing such new systems. Different management methods are required and efforts have to be made for acceptance by the users and proper use of the new system (Cordova and Knuth 2005).

With the low-key technical and financial requirements and the positive environmental impact in mind, ecological/sustainable sanitation systems are becoming the method of choice for providing sanitation in low-income countries.

Circular economy in urban planning

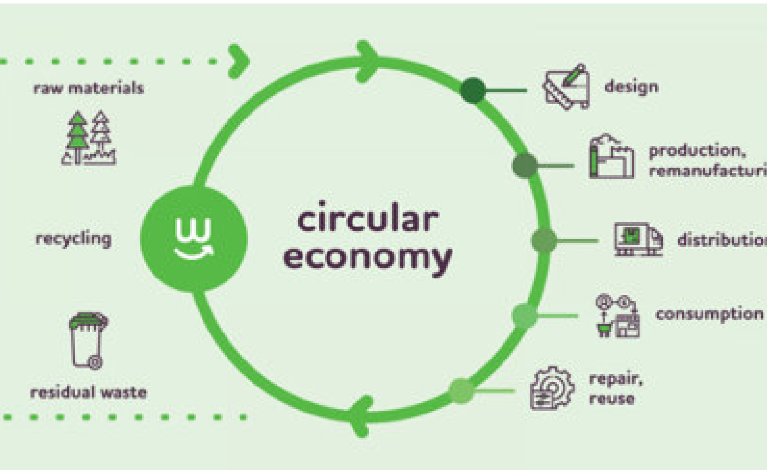


fig. 2.6: process of circular economy. (Banks 2019)

Circular economy is an alternative approach to traditional linear resource flows in economies and industries, where the elimination of waste is the main point of action. By re-using, re-purposing and recycling materials at the end of their initially intended purpose, the waste is instead considered a resource once again. The materials get salvaged, the needed resource input from outside the system is minimised, and the environmental impact, too, is reduced drastically (Banks 2019).

Initial attempts to implementing a circular economy have been made e.g. in the food and water cycle, the construction industry as well as clothing industry.

Circular urbanism is the practice of solving these circularity strives in a spatial way:

The locations of the respective resource treatments shall be placed so that an ideal resource flow is ensured – with short and practical transportation ways and a good reach for the consumers.

Urbanism as the profession standing at the interlinkage of different themes, uniting different expertises and interests is well-apt to perform supporting measures for implementing circular economy approaches. Urbanism acts on different scales, from small towns and rural communities to urban centers and megacities, and therefore has the ability to adapt an abstract idea to a new surrounding and to different environments, accommodating the idea to local needs through finding the best solution for the local community. That is the true strength of urban/spatial planning as a tool for supporting circular economy goals (Banks 2019; Chicago Metropolitan Agency for Planning 2012).

Relevance of the nutrient cycle as a model of circular economy

"Cities are concentrators of organic materials, with imbalances between inflows and outflows leading to aggregation. While this makes cities the source of large amounts of waste and negative externalities in the current economic model, these resource streams would be captured and valorised in the circular economy model. [...] Cities present a major opportunity to implement circular principles in the biocycle economy due to their characteristics, which include large scale of supply [and a] high proximity between stakeholders."

(Ellen MacArthur Foundation 2017, p. 17)

The nutrient cycle in agriculture is a quite simple resource flow, much simpler than other resource flows – it shall be explored in more detail later in this work – and is therefore chosen as an example for the circularity approach in urbanism in this work. Less stakeholders and in-between steps of the resource flow are included in the nutrient cycle, compared to e.g. the flow of a manufacturing sector. Only few elements have to be adjusted to make the nutrient flow a closed cycle – more explicitly, food production and distribution are processes that inherently function already, so the focal point only has to be on bringing the nutrients back from the consumer into foodstuff production. That way, the flow of nutrients in the light of spatial planning can be thought through very consequently, with the necessary adjustments being clarified in simple terms (Billen et al. 2009; FAO 2000; Biel 2016).

With this simplicity, it is possible to retrieve guiding principles for how circularity for different resource flows can be approached in urbanism.

2.2 Nutrient flows in the agriculture

Vegetation growth and nutrient use

For vegetation to grow, the plants need a variety of nutrients, which they retrieve from the soil. They are divided into the main nutrients or macro-nutrients, and micro-nutrients, which are only consumed in very small amounts. The plant then uses nutrients, water, atmospheric CO^2, carbon deposits from the soil and further materials for the production of organic material – uses them to grow (Stahr 2018).

The macro-nutrients are:

- Nitrogen (N)
- Phosphorous (P)
- Potassium (K)
- Magnesium (Mg)
- Calcium (Ca)
- Sulphur (S)

Among the essential micro-nutrients are:

- Iron (Fe)
- Copper (Cu)
- Manganese (Mn)
- Zinc (Zn)
- Boron (B)

In soils typically used for agriculture, the micro-nutrients are available sufficiently. The macro-nutrients nitrogen, phosphorous and potassium are the ones that are of critical importance for plant growth, and therefore need special attention.

Nitrogen is in the soil as nitrate (NH3-), dissolved in water, and therefore directly available to the plants, but can also be lost quite easily through flushing out (called leaching, which causes eutrophication and environmental damage). Furthermore, nitrogen is found in ammonium (NH4+), bound in clay soils and humus. The ammonium is over time being transformed into nitrate through microorganisms in the soil, so then it is also available to the plants (Stahr 2018). This natural process called nitrification can only function in healthy soils with humus, microorganisms and small animals.

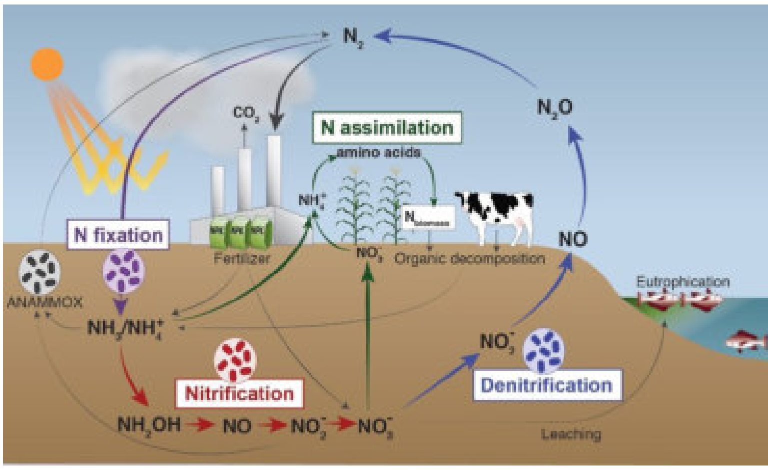


fig. 2.7: nitrogen cycle in the environment. (Lehnert 2016)

Phosphorous (as the phosphate P2O5) can be found in the soil as a mineral, and just like potassium, is directly available to the plants.

A lack of these three macro-nutrients causes problems with plant growth, a surplus is the biggest issue with nitrogen and phosphorus (as nitrate and phosphate). Excessive growth of cultivation plants can cause malformations. Additionally, plants become more susceptible to diseases and pests, both of these factors ultimately cause failure of the cultivation (Stahr 2018).

The plant binds the nutrients in organic material as it grows, and the more intense the cultivation practiced is, the more nutrients are bound. They are taken away from the field when the crops are harvested, and as the plant is consumed by livestock or humans, the nutrients also get consumed. But they are not lost forever, instead they get discarded from the body in different chemical structures, and can be potentially returned to the field for the plants anew. (FAO 2020b).

Broken nutrient flow with use of chemical fertilizer – currently most practiced

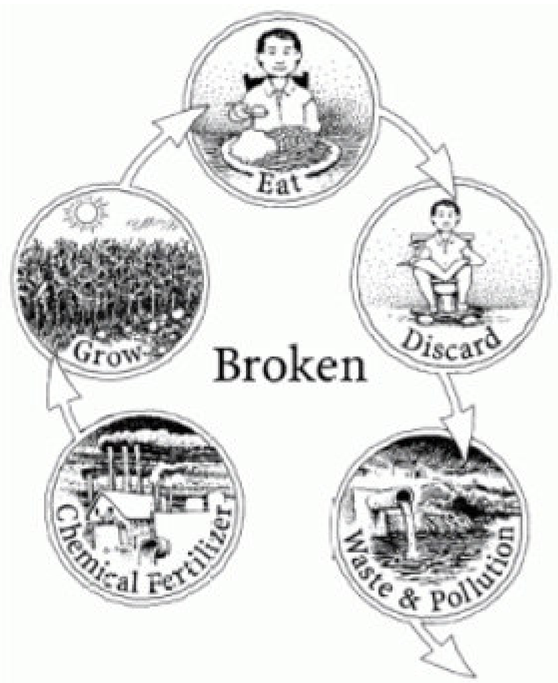


fig. 2.8: the broken nutrient cycle. (Jenkins 2005)

Many times, animal manure is reused in some form for agriculture, so the nutrients remain within the agriculture cycle. But currently, human excreta are mostly wasted through the central blackwater sewages and the corresponding water treatment plants. The nutrients contained in these highly nutrient-rich substances are wasted and get lost to the nutrient cycle in the agriculture (Jenkins 2005). In order to keep plant production as high as desired, it is necessary to replace these nutrients with chemical fertilizer instead. This broken nutrient cycle uses much more nutrients than would be needed for the same amount of plant production if the nutrients were not wasted and drawn from the cycle.

The chemical fertilizer – the most popular mixture is a combination with nitrogen, phosphorus and potassium, sometimes enriched with additional micro-nutrients – is produced in artificial ways. Nitrate is produced in the so-called Haber-Bosch-Process, a chemical process where atmospheric nitrogen is transformed to ammonia, further processed to ammonia nitrates which are then directly used in fertilizer (Smil 2016; Roth 2017). The process requires high pressure and high temperatures, which makes it energy-intensive and causes huge CO^2-emissions: In 2017, CO^2-emissions from ammonia production alone accounted for 0,4% of all worldwide CO^2-emissions (150 mio. tons) (US Geological Survey 2017).

Potassium can be mined in many regions of the world in a salt compound.

Phosphorous is also a resource that can be mined. But phosphorous (to be exact: the phosphate deposits) is finite – some sources estimate that, at current consumption speed, the resource would be completely used up within the next 50-100 years (Cordell 2010; Roth 2017). As up to 80% of the world's reserve of phosphate is found in Morocco, high international dependence on few production states is an increasing issue. For these reasons, phosphate will become a scarce resource quite soon, and investigations for the re-use of phosphorous dissolved in waste-water are ongoing.

Phosphate and nitrate both are not naturally available in surface water - but through the chemical fertilizer, which is artificially added to the topsoil, they get into waterbodies in large amounts. The chemical substances in artificial fertilizers are not bound to the soil, but dissolvable in water very easily and therefore flushed from the fields into waterbodies, where they can cause excessive growth of plants, a phenomenon that can be witnessed e.g. in the so-called algae blooms more and more frequently (Stahr 2018).

This causes severe damage to natural ecosystems, when the nutrients enrich there, and an ecological imbalance emerges. If brought onto fields over a longer period of time, nitrate also penetrates into deeper soil layers where it can pollute ground water, often used for drinking water supplies. This can be seen in many parts of Europe and North America, where intensive industrialised agriculture has been going for decades, and increasingly also in Asian countries (Ellen MacArthur Foundation 2017; Roth 2017).

A factor that further increases nitrate accumulation in waterbodies is urbanisation, i.e. the concentration of humans in a small space. Food is not being consumed (and human waste discarded) at the place of foodstuff production, but concentrated in a very small space. So the large amounts of nutrients that are carried in stay in the concentrated area, are often flushed away through a singular waterbody, and stay concentrated in the direct vicinity, where the environmental damage gets bigger and bigger (Forster 2010; Biel 2016)

The circular nutrient flow – intact cycle

fig. 2.9: the intact nutrient cycle. (Jenkins 2005)

The ideal, circular nutrient flow does not require chemical fertilizer in such high amounts. In the ideal scenario, all nutrients that are excreted after consumption are kept in the circle, animal manure as well as human excreta as well as organic waste as well as organic by-products from vegetable and cereal production. Composting these materials closes the nutrient cycle. A closed system results, where the nutrient elements are re-purposed over and over, with necessary fertilizer input and waste output at a minimum (Jenkins 2005).

“The Human Nutrient Cycle is an endless natural cycle. In order to keep the cycle intact, food for humans must be grown on soil that is enriched by the continuous addition of organic materials recycled by humans, such as humanure, food scraps and agricultural residues. By respecting this cycle of nature, humans can maintain the fertility of their agricultural soils indefinitely, instead of depleting them of nutrients, as is common today.”

(Jenkins 2005, p. 10)

This absolutely limits environmental damage through agriculture and improper waste management, and it has a great impact on the agriculture itself, too. It is one of the main tools used for sustainable intensification, the practice that tries to mitigate negative side effects that come with traditional intensification through increased fertilizer input, while still achieving higher agricultural output with a high nutrient use efficiency (Brüggemann 6/18/2020).

Nitrogen-use-efficiency and how to increase agricultural productivity

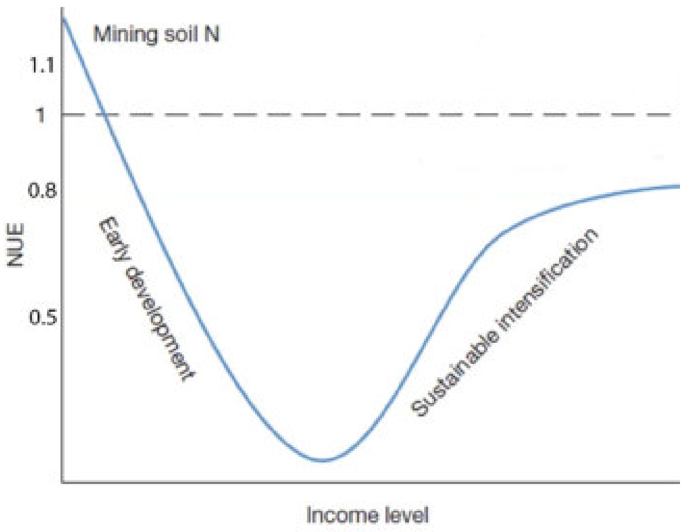


fig. 2.10: the development of nutrient-use-efficiency with rising income levels of a developing economy. (Brüggemann 6/18/2020)

The nitrogen-use-efficiency (NUE) describes the ratio of nitrogen bound in outputs (crops) to those bound in inputs (soil-bound nitrogen, fertilizer). It is an indicator that shows the productivity of agriculture and the amount of unnecessary/ wasted fertilization. A high value describes nutrient-efficient agriculture, which can mean either:

- a negative ratio of fertilizer input and crop output at early stages of non-industrialised agriculture in low-income economies. No nitrogen is added to the soil through fertilization, instead nitrogen is extracted through the output (NUE above 100%, i.e. mining soil nitrogen). This is the case in large parts of Sub-Saharan Africa, or
- a close-to-perfect ratio of fertilizer input and crop output at later stages of industrial agricultural development in high-income economies. This can be achieved through sustainable intensification and good monitoring. Values of up to 80% NUE can be achieved, currently to be observed e.g. in parts of Europe.

In most cases, however, the NUE is currently far lower than this, between 35-60%, meaning that not even half of the nutrients put into the agriculture system are actually processed by the crops. These values are especially low for many parts of East and Southeast Asia and the Americas, but can be expected to rise through a change of agricultural practices (Brüggemann 6/18/2020). Western countries where the NUE is currently increasing all went through this “dip” of low NUE. Sustainable intensification for low-income economies tries to find shortcuts for countries like in Sub-Saharan Africa, of how the NUE can be kept high while agriculture output and income level increase.

Composting – how to, benefits, limitations

> “Compost is the mixture of organic matter digested aerobically that is used to improve soil structure and provide nutrients”
>
> (FAO 2000)

Composting is a controlled process that safely disintegrates organic matter and makes it usable once again for other living organisms. It most commonly takes place in large bins/containers or on a pile. The phases of composting are (Román et al. 2015; Dunst 2015; Misra et al. 2003):

1. Mesophilic phase. Several days. Microorganisms start decomposing soluble substances like sugars.
2. Thermophilic and hygienization phase. Several days to few months. Bacteria decompose complex materials like cellulose. Temperatures between 45-70°C kill harmful bacteria and viruses, the compost is hygienic and free of pathogens.
3. Cooling and mesophilic phase II. Several

weeks. Decomposition of complex structures continues, fungi become active. pH normalises at a slightly alkaline level.

4. Maturation phase. Several weeks. Secondary reactions occur, important humic acids are produced.

To ensure complete decomposition and safe hygienization, it is recommended to decidedly start the composting process by compiling all material within a few days, so that the chemical reactions start in the pile at the same time and high temperatures can develop in all parts of the material (Misra et al. 2003).

Most essential aspects that should be ensured for a successful composting process are (Dunst 2015; Gottschall 1985):

- Proper humidity: The starting material should not be too dry, nor saturated with water.
- Constant oxygen flow: This can be achieved with adding porous materials, such as straw.
- Mixture of starting material: Should have balanced contents of nutrients, carbon, etc.
- Additive materials: Added mineral soils or biochar/ash add micro-nutrients and increase the surface.

Benefits of using compost as a fertilizing method (Hansen 2015; Dunst 2015; Fechner 2018):

- The slow release of nutrients. As over 75% of the nutrients are organically fixed in the humus, they cannot be lost through flushing anymore and become available to the plant over time – perfect for how crops grow and the fruit ripens: over many months or years, not during a few weeks directly after fertilizing with a chemical fertilizer.
- Humus creates vital and stable soil, rich with microorganisms and fungi, and able to retain and store large amounts of water. Resilience against natural disasters, land degradation and soil erosion are improved. Overall productivity of the soil is improved.
- Pathogens and germs in the waste are killed, pollution and nature damage are prevented.
- Nitrate and other pollutants can not get into the environment, because they are decomposed during the composting process. Environmental damage is mitigated.
- Natural antibiotics and resistances are built within the soil, meaning better living conditions for crops.

Disadvantages of using compost include a high demand for space and labour, the possible loss of nutrients (this can be the case with improper handling and storage of the compost, where parts of the nitrogen can get released into the atmosphere, if the thermophilic phase does not start quickly enough), and possible health risks through infections (this can be mitigated through proper handling of contaminated starting materials, such as manure). The disadvantages, however, do not compare to the major advantages of compost use in agriculture (Dunst 2015).

2.3 Recovering human excreta

Conventional treatment schemes for human excreta

Typically, human excreta are collected together with other household and municipal waste waters in large (underground) sewer systems. Later, the waters need complicated and expensive cleaning in dedicated treatment plants.

The investment costs for these systems as well as maintenance cost are extremely high, too high for many low-income economies, which is why the systems are faulty in many cases, or waters are disposed into the environment unfiltered, where detrimental damage is caused (The World Bank 2008). Further problems are caused through the climate crisis, where extreme weather events can cause mixed sewage systems to reach maximum capacity, overflow, and take permanent damage (United Nations Organisation 2015).

This way of dealing with human excreta tends to misjudge human excreta: it should not be considered a waste, it should instead be seen as a valuable resource, extremely rich in nutrients and energy.

A valuable resource that can be salvaged

Human excreta are a highly nutrient-dense substance. The dry mass of combined human urine and faeces contains 5.5-7.5% nitrogen, 3.7-4.6% phosphorous and 2.2-3.5% potassium, the most vital macro nutrients commonly used for fertilising soil (N, P, K). This is more than 3 times the amounts that are found in livestock manures typically used in agriculture, such as pig, cattle, horse. Equally important, there is no excess of one nutrient, like it can be the case with pure organic kitchen waste (the micro-nutrient natrium) (Dunst 2015).

Furthermore, the C:N ratio lies between 6-10:1, meaning there is about 6-10 times more carbon in the substance than nitrogen. This means that human excreta are an excellent substance to be processed into high quality compost – the human excreta would therefore be mixed with other organic substances, such as kitchen wastes. They have a much higher C:N ratio between 15-60:1; agricultural wastes such as straw or woodchops have a C/N ratio well over 120:1. Mixed with the highly nutritious human excreta, the ideal C:N ratio in compost of around 25-35:1 can easily be reached (Dalzell 1987).

This valuable resource should not go unused – new ways of salvaging the value have to be come up with and implemented.

Ongoing projects in Europe use a central system with vacuum pipes to collect human excreta, and further use them for energy generation. With technical steps, the nutrients can be recovered isolatedly, and in different combinations, solutions or precipitates can be used for fertilisation (Harder 2019). This is a successful yet highly technical solution that comes with relatively high investment and maintenance costs, and it does not include the additional benefits for soil stability that compost does.

Composting toilets for a singular household transform human excreta to compost within the toilet itself. They are a technical device, where constant air ventilation and energy supply has to be secured, and the purchasing cost is also quite high (Morgan 2007). Due to the sole use of human faeces, the compost often does not have ideal properties, regarding nutrient and carbon concentration, for being used in agriculture.

So-called dry toilets are for only collecting human excreta; further treatment (i.e. composting) takes place at a different location. These toilets are mere collection devices – a cheap, effective and simple-to-maintain solution that can be flexibly used in different surroundings and settings (Morgan 2007).

As of yet, such a more low-tech solution with dry toilets seems to be better apt to the local conditions in Ethiopia and shall therefore be the focal point for this study.

Dry toilets - sanitary treatment of human excreta and conversion to compost

A central advantage of dry toilets for composting compared to conventional treatment schemes like sewers or, in low-income economies, open defecation, is the fact that the composting process makes human excreta a safe and sanitary material. Issues like leakages in the collection system can cause pathogens to be released into the environment where people can get into contact with them, e.g. via polluted water. Severe diseases and even increased fatality rates are the result (Ellen MacArthur Foundation 2017; World Health Organisation 1992).

Different collection principles are in practice: dry toilets with or without diversion of urine and faeces.

Collection of urine in separate containers can be sensible, because it is, in contrast to faeces, not polluted by bacteria, viruses or parasite eggs, neither by residues of pharmaceuticals, and can therefore be used for fertilisation directly. This saves time and space for the composting process. But it requires more knowledge and maintenance for proper use of the toilet, and in shared facilities this always runs the risk of improper application, and resource being lost because it cannot be used in the desired way (Harder 2019).

fig. 2.11: example of a dry toilet. ClimEtSan. (Prost 11/13/2020)

Dry toilets without urine diversion can use tools like a simple plastic bucket as the collection container. It is essential after each use of the toilet, that all excreta be covered with a dense organic material (sawdust or woodchops can be used, fluffy wood shavings are to be avoided, because air can penetrate, which causes bad odours). Properly used, this way of excreta collection is odour-free, meaning that the dry toilet can be placed pretty much anywhere, even inside people's homes (Jenkins 2016). After a few days, the buckets should be closed with a lid; then, they can remain for several weeks. Decomposition does not start unless oxygen gets mixed into the mass.

For human faeces being able to be composted, hygienic collection and treatment is necessary. This eliminates bacteria, viruses and parasite eggs as well as residues of pharmaceuticals, synthetic hormones, and ultimately prevents diseases and bad odours during and after the composting process (Dalzell 1987). The composting process, as with any organic material that is supposed to decompose, can be aided by addition of other materials, such as mineral soils/ ash, and air-bearing materials, such as straw.

When sufficient mass has been collected (the necessary amount mostly depends on climate and the size of the composting pile/bin), it should be collected in the composting bin with all additive materials, thoroughly mixed. Layers of straw in between ensure oxygen access to inner parts of the compost pile, so that anaerobic bacteria initiate the thermophilic decomposition process (Jenkins 2005).

Preparing the compost pile should to be done by trained personnel, as these people have to avoid getting into contact with the germ-containing excreta, and because only thorough execution can guarantee a successful and safe composting process (Jenkins 2005). The duration depends on outside factors, such as temperature and air humidity; field studies of the ClimEtSan project in Ethiopia have shown that the hygienization phase that makes the material sanitary through high temperatures in the compost pile takes about 4-6 weeks, and the finished product can be used after 10-12 weeks (Prost 11/13/2020).

fig. 2.12: composting bins used in the field study of the ClimEtSan project in Wondo Genet, Ethiopia. (Prost 11/13/2020).

Composting human excreta in implementation - good practice examples

There are ongoing projects trialling toilets for composting human excreta. This section takes a look at requirements for implementation in countries of the Global South and lessons learned, which can be considered principles to go by for the conduction of this study.

Especially in urban settings with a large amount of users to be expected, user-friendliness and maximum ease of use should be strived for. Proper maintenance and staff supporting with questions regarding use help with people’s acceptance of alternative sanitation provision (Cordova and Knuth 2005; World Health Organisation 1992; Cardone et al. 2018). These are aspects going far beyond mere accessibility of the toilet facilities, yet are at least equally as important in order for the interventions to function well.

ClimEtSan, an ongoing integrated study in Ethiopia (“Capacity building in climate-smart agriculture and ecological sanitation in Ethiopia”), investigates an integrated method for “ecological sanitation provision, composting and bio-charcoal in Ethiopia, in cooperation with IN³, which focuses on corresponding spatial planning aspects. [The approach explores,] how circular economy with the respective technologies can connect food security and climate protection.” (Prost and Brüggemann 2020) Central in the ongoing field study are centrally provided dry toilets on a college campus in Wondo Genet, Ethiopia. The adjacent composting facility combines the collected excreta with local organic waste, field waste (different types of straw) and bio-charcoal that is a by-product of the new technology “Noah stove”, a micro-gasifier stove for private households that saves tremendous amounts of wood and emissions during cooking, and makes the cooking process more safe (Prost and Brüggemann 2020).

fig. 2.13: project scheme for nutrient recovery of ClimEtSan. (Prost 11/13/2020)

Previous projects of similar goals include studies of the Ecological Sanitation Research Program (EcoSanRes) by Stockholm Environmental Institute, which investigated different methods for ecological sanitation amongst others in Malawi, Kenya and Zimbabwe (Morgan 2007; Andersson and Minoia 2017), and Sustainable Organic Integrated Livelihoods (SOIL), a project by a US-American non-profit organisation focussing on sanitation improvements in Haiti. In this latter case, dry toilets are provided to private households and collected by the project team, for the excreta to be composted centrally. Parts of the compost are being redistributed to the participating families who can use it in private gardens (Kramer 2011, 2019).

ClimEtSan as well as SOIL chose not to divert urine and faeces for reasons of easier management and user-friendliness. Space limitations, in the collection container and at the composting location, are not a big restraint here, and since they are in tropical regions, decomposition happens rather quickly, so it is not a problem not to have the urine directly available to be put onto the fields (Prost and Brüggemann 2020; Kramer 2011).

A challenge that dry toilet projects are facing in many countries of the Global South, also in Ethiopia, is local preferences. Many people, especially women, prefer washing themselves with water instead of toilet paper after using the toilet. But water should not be added into dry toilets, even if they collect urine and faeces together. Possible solutions include for example providing a second dry toilet bucket in each bathroom stall dedicated only to washing, not for collection of excreta (Prost 11/13/2020).

For these reasons, it seems that centrally provided, shared dry toilets with a combined collection of urine and faeces are the most appropriate sanitation method for the uses of this study, and shall be considered a given in the further investigations.

2.4 Spatial elements in the urban / rural environment

Spatial organisation of urban landscapes

An inhabited space is made up of different spatial elements defined by their use. Some spaces are used for living, others for recreation, for transport, for working, for production, for administration, for social events, for food production. This is true for any density – no matter if it is a dense urban center, a rural area or mixed industrial zone. Then, there are functional linear elements connecting these elements. Streets, train tracks, informal pedestrian paths are some of the most obvious, water and electricity network, sewage system are hidden but exist in material, other connections are immaterial, such as waste collection or product delivery using mobile vehicles (Alexander 1977).

The more closely the spatial organisation of (urban) landscapes is explored, the more intertwined and dependent does everything appear to be. Christopher Alexander in his "A Pattern Language" further includes community aspects into the urban set of modules that he calls "patterns", such as family structures, neighbours' relations etc. He describes each of the patterns in relation to other, bigger and smaller patterns, and all related functionalities of these patterns, thus creating a language that defines and describes what cities/towns are.

„In short, no pattern is an isolated entity. Each pattern can exist in the world only to the extent that is supported by other patterns: the larger patterns in which it is embedded, the patterns of the same size that surround it, and the smaller patterns which are embedded in it."

(Alexander 1977)

This inseparable interdependency between the elements makes working with what a city is extremely complex. For that reason, this work will focus on those urban elements that are spatially determinable, and attempt to define them by the interrelations and dependencies between these elements, rather than also considering the interrelations themselves an urban element on their own, the way Alexander does. With this approach, time and resource constraints for this work can be taken account of, while a systemic understanding of the proposed model is still ensured.

Productive landscapes

Productive landscapes are pieces of land that produce foodstuff for human or animal consumption and productive forests. As established before, these areas are currently mostly disconnected from urban centers, with rural towns and villages often being surrounded by productive landscapes (Bohn and Viljoen 2009; Viljoen 2005).

fig. 2.14: shared cultivated field in Addis Ababa, fertilised with sustainably sourced community compost. Part of the IN³ field studies. Image by author, 2019.

Most productive landscapes today depend on the many consumers who are concentrated in cities and the use of their produce in high-density inhabited areas. The resulting need for transportation and management are a stressor for the natural environment, the human population and infrastructure alike. For that reason, contemporary urban planning has started attempts to re-link these detached functions, for instance with promoting urban agriculture programs, and striving for a "continuous urban productive landscape" which supports an integrated approach to food production and urban design (Bohn and Viljoen 2009; Viljoen 2005).

There are different models for classifying productive landscapes. The following definitions are derived from a project in Cuba as well as relevant professional research (Altieri 1999; Bohn and Viljoen 2009; Correa De Oliveira 2020; Viljoen 2005). The definition identifies agriculture areas according to size, cultivator and targeted consumer:

1. Peri-urban enterprise farms, cultivated by workers. Size: >2ha.
2. Farms for producers' consumption (i.e. subsistence farming), cultivated by a family or workers. >1ha.
3. Family gardens, cultivated by one family. Size: <1000m²; yield: 8-12kg/m²/yr.
4. Intensive cultivation gardens, cultivated by several families. Size: Between 1000m² and 3000m²; yield: 8-12kg/m²/yr.
5. High yield gardens, cultivated by co-operative enterprises. Size: 5000-10000m²; yield: 25kg/m²/yr.

It is proposed to interweave appropriate types of productive landscapes with the urban/suburban/peri-urban/rural surroundings of the respective location and its demands (Viljoen 2005). Simultaneously, all previously described measures considering composting schemes, promotion of sustainable intensification etc. have to equally be interlinked with and adjusted to the type of urban surrounding, residential density and targeted consumer (subsistence farming/production for sales) (Brüggemann 6/18/2020).

2.5 Introduction to the study site: Ethiopia

Urbanisation/demographics

Ethiopia is one of the world's most populated countries with high population growth rates over 2.5% p.a., currently at 114,000,000 inhabitants total (World Population Review 2020). Less than 4% of the population live in a city bigger than 1 million inhabitants – the country is characterized by a small urban population share at 20.3%, and by 2050 is expected to be one of the few remaining countries with a rural majority at 61% of the population. However, as the population is growing, urban areas are growing over-proportionally, and this bears a big developmental chance: With good urban planning, sustainable food production can become an integrated driver of urbanisation processes, shaping urban – and by that means, also rural – settlements in a resilient, sustainable way.

Current agriculture practices and use of nutrients

The current use of land for cultivation in Ethiopia is neither productive enough nor environmentally or economically sustainable. A large portion of the land is farmed by smallholders for subsistence food production (68% of the population is occupied in agriculture (World Population Review 2020)) with different crops and some livestock, with little to no coordination and a low knowledge base (FAO 2020b). Fertilisation happens through cattle manure (if the dung is not used for construction instead), not at all, or at increasing (yet overall very low) amounts, chemical fertilizer.

Major challenges and potentials for agriculture in Ethiopia can be summarised as follows:

- Ethiopia faces several major risks directly threatening agriculture: extreme weather events, land scarcity, erosion, loss of soil fertility and land degradation (Román et al. 2015).
- Ethiopia's agriculture production is limited by the small amount of nutrients available, caused by natural conditions and environmental challenges as well as population poverty (Brüggemann 6/18/2020).
- Smallholder farms have the largest gap between actual production and ecological potential; closing that gap has a high potential to in turn improve natural stability and crop yields (Brüggemann 6/18/2020).

Deforestation and removal of hedges and solitaire trees is becoming more and more prevalent, with the goal of improving access to the field with heavy tools, and ultimately, higher productivity. The opposite is the result: the soils become less stable, organic material and humus are missing, the soil becomes less fertile and erodes more quickly.

Regularly applying compost would address all these challenges and potentials:

> "Large quantities of organic matter need to be supplied to soils in the tropics and subtropics in order to provide plant nutrients, to help moisture retention and to keep the soil structure in good condition. Because the rate of organic matter oxidation is fast, due to high soil temperatures, frequent additions of compost are required."

(Dalzell 1987, p. 43)

Rural patterns / rural urbanism

The multi-ethnic state that Ethiopia is can also be observed in traditional rural settlement patterns. In different regions, villages tend to take different forms of clustering the buildings. What they have in common is often a strong sense of community and a rather low-density structure, where residential plots are mixed with productive plots, natural areas etc. Bigger villages, small towns and cities often form stretched alongside a main street or around a market place at an intersection of pathways, and they can multiply in size in a matter of a few years, both in informal ways as well as with centrally funded housing programs (OECD/PSI 2020; The World Bank 2015; Brüggemann 6/18/2020).

Development policy review

With a strong primacy in Ethiopia (the capital city as the only major urban centre), efforts are being made to counterbalance this, by promoting development of rural areas and so-called intermediary cities, which will see the highest population growth in the coming years. This will transform the country to a polycentric urban structure with more dynamic city development, fostered through investments in industry and trade in these smaller hubs (OECD/PSI 2020; The World Bank 2016).

There are several national policies that support this overarching goal, directly targeting e.g. poverty reduction, the commercialisation of smallholder agriculture for improved livelihoods, manufacturing industry, or strengthening the linkages between urban and rural areas. Due to that, all urban development policies inherently also target the development of rural zones – the connection between the two already being much stronger and more direct than in many neighbouring countries (OECD/PSI 2020; The World Bank 2015).

“The new Rural Development and Strategy Policy (RDSP) was the first comprehensive development plan specifically aimed at rural areas [in 2003]. The plan was designed to address persistently low agricultural growth, food shortages, and disproportionately higher levels of poverty in rural areas.” (OECD/PSI 2020). While poverty did decline a lot in the following years, environmental and land distribution problems, caused in part by flaws of the plan, detract from its success.

The existing plans do fail to find solutions for the problems caused by the Ethiopian land ownership laws, which have not changed since the 1990s. The way ownership and land use rights are regulated cause land to remain far below the agricultural potential, with plots becoming smaller and smaller, and less productive due to improper cultivation of the unmanaged fields. People have to work longer hours for lower profits, resulting in lower production, produce shortages even in wealthier urban areas, malnutrition, and lower income. The fact that people have to be occupied in agriculture in order to own land further limits the options for diversifying one’s occupation (OECD/PSI 2020).

Ongoing projects, good practice references

Self-sufficiency is the goal for Ethiopia. As a country with limited resources facing so many multi-layered challenges, only integrated approaches with circular systems that can support themselves are able to achieve sustainable improvements – economically, environmentally, and socially (The World Bank 2020).

NESTown (New Ethiopian Sustainable Town) is a model town in Buranest, Ethiopia, that reacts to the need for self-sustaining, closed-loop urban planning approaches in practice. It applies a bottom-up approach to urban development, flexible enough to react to changing requirements and unprecedented developments.

Four pillars were formulated for the project: “(I) the loop of urban practices, (II) the security in filling basic needs, (III) the increase of living standards for individuals and the group and (IV) the rules of urban cohabitation.” (Oswald and Schenker 2010). The underlying idea for the urban structure is a system that includes education, energy generation, material provision, resource collection (e.g. rain water that can be used for drinking water as well as irrigation of cultivated lands), waste management – an urban system that becomes stable in itself through the active contribution and participation of its community.

Different urban elements make the incentive for urban development, these can be a central square, a public institution or the church. A structure of ring roads and so-called nuclei, which represent the different functions needed in urban life, make up the structure of the city. Adapted to the requirements of the specific locality, the bottom-up development of the sustainable town through the future inhabitants themselves begins in a decentralised way. As the town grows and informal activities or houses emerge, the initial plan can be adjusted and NESTown can flexibly keep growing (Oswald and Schenker 2010).

fig. 2.15: community construction work in Buranest, part of NESTown project. (Hefti 2012)

While NESTown gives an urban development scheme, showing how closed-loop urbanism can become a planning paradigm for Ethiopia's emerging towns, the aforementioned ClimEtSan and IN³ projects explore one resource loop that would then be integrated as one of the development drivers of such planning.

Test location (Olonkomi)

The test location of the town Olonkomi is located in the Dendi woreda (district) in the Oromia region, approx. 70km west of the national capital Addis Ababa, in the central Ethiopian highlands at an elevation of ~2,200m. The population is approximately 13,000-15,000 inhabitants, it is a typical Ethiopian small town surrounded by agricultural lands. The town is a market town and has a number of shops and services as well as municipal, health and education facilities and is therefore also the destination for people living in the rural surroundings.

It was chosen for its context-specific typical characteristics and for the fact that in-depth on-site analyses of the town had been conducted previously. This can in part make up for currently ongoing limitations to international travel, so that appropriate conduction of this study can nevertheless take place.

At a later stage in this work, a more detailed analysis of the test location will be eaborated, which lays the base for further parametric studies of the proposed circularity concept.

2.6 Synopsis and points of contact

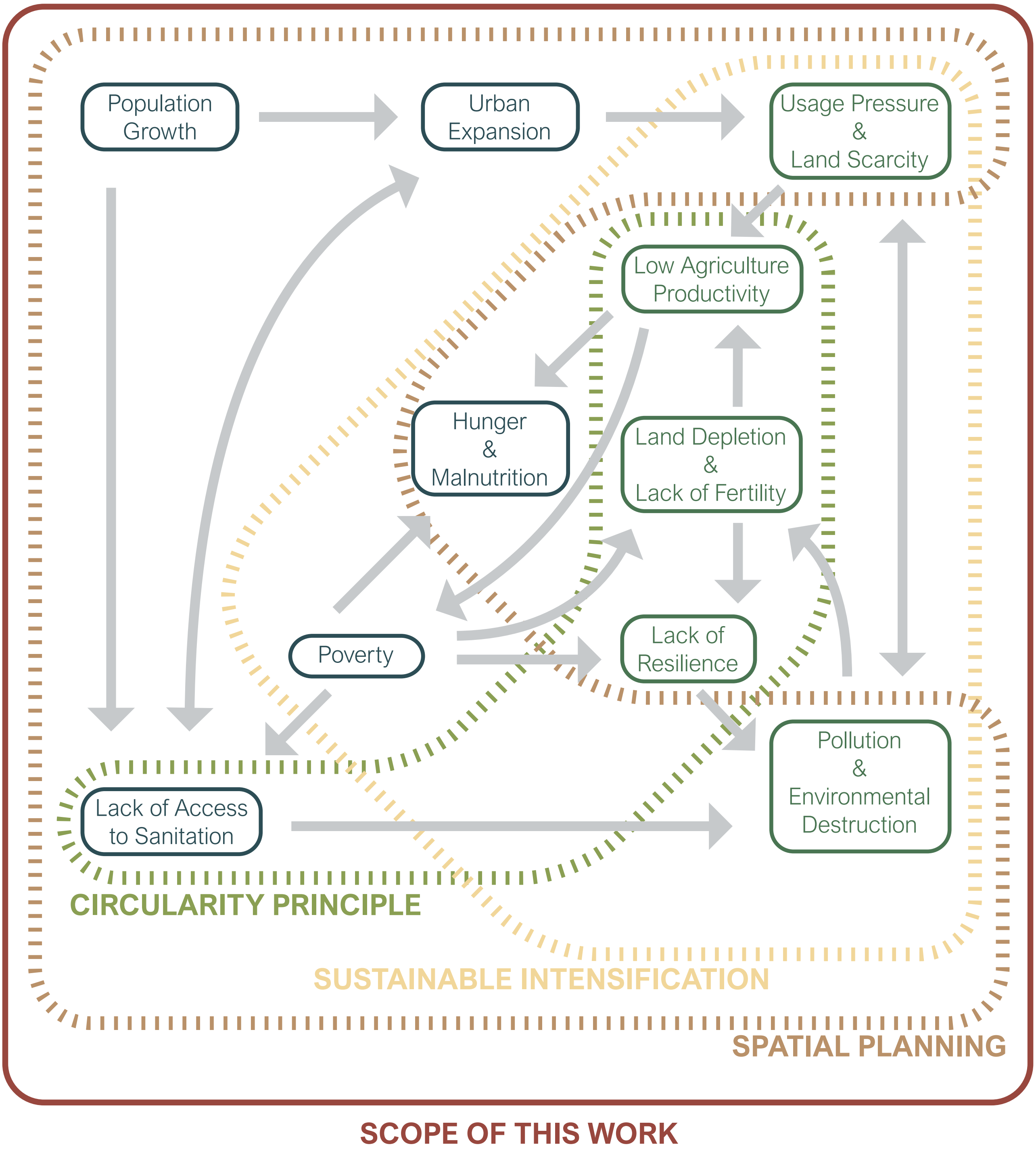


fig. 2.16: matrix of challenges to be addressed in this thesis.

This thesis seeks to address multi-layered and interconnected issues concerning different areas of life, in an integrated manner. To tackle these challenges, multiple precepts are being brought together, namely spatial planning, sustainable intensification in agriculture and the principle of circular resource flows.

Closing the Nutrient Cycle

3. Closing the nutrient cycle

3.1 Overview of approach

There are a number of sequences building on one another in the formulation of this work. Closing the nutrient cycle is the overarching aim, making the concept broadly applicable in urban planning is a main objective.

Initially, the integrated urban system model will be elaborated. It is centred around the flow of nutrients and shows the urban elements that are inherently connected through spatial relations and the relation of material (i.e. nutrient) flows. This model of the Nutrient-Based City is theoretical, quite abstract, but it shows very well the many connections between the nutrient cycle and urban management, and gives first ideas for possible steering points in urban planning.

The second theoretical model that is developed deals with the nutrient flow and the different materials more specifically. Broken down to one person's yearly consumption and production, the sizes-and-amounts-model shows what impact can be achieved with closing the nutrient cycle, for example regarding the reduction of green-house gas emissions, or improved fertilisation capabilities.

Both these theoretical models culminate in the formulation of the Circular Unit (CU), a proposal for the ideal spatial configuration of a partially self-sustaining urban unit with a circular nutrient flow.

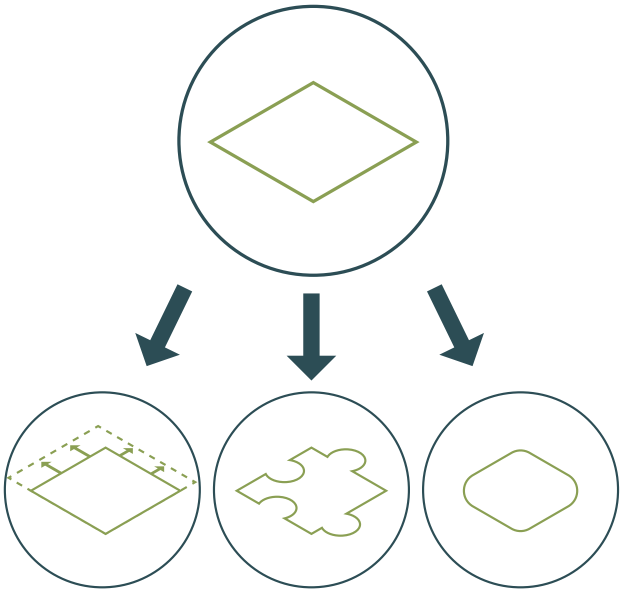


fig. 3.1: scheme: adapting the ideal prototype CU to different spatial and contextual requirements

This ideal design principle is then adapted to different pre-set circumstances, formulating Adapted Design Principles of the "Circular Unit".

Finally, an overview of possible approaches to implementing the system is given in the imple-mentation strategy. The guidelines include vital aspects for the success of the CU concept in practice.

the Nutrient-Cycle-Based City

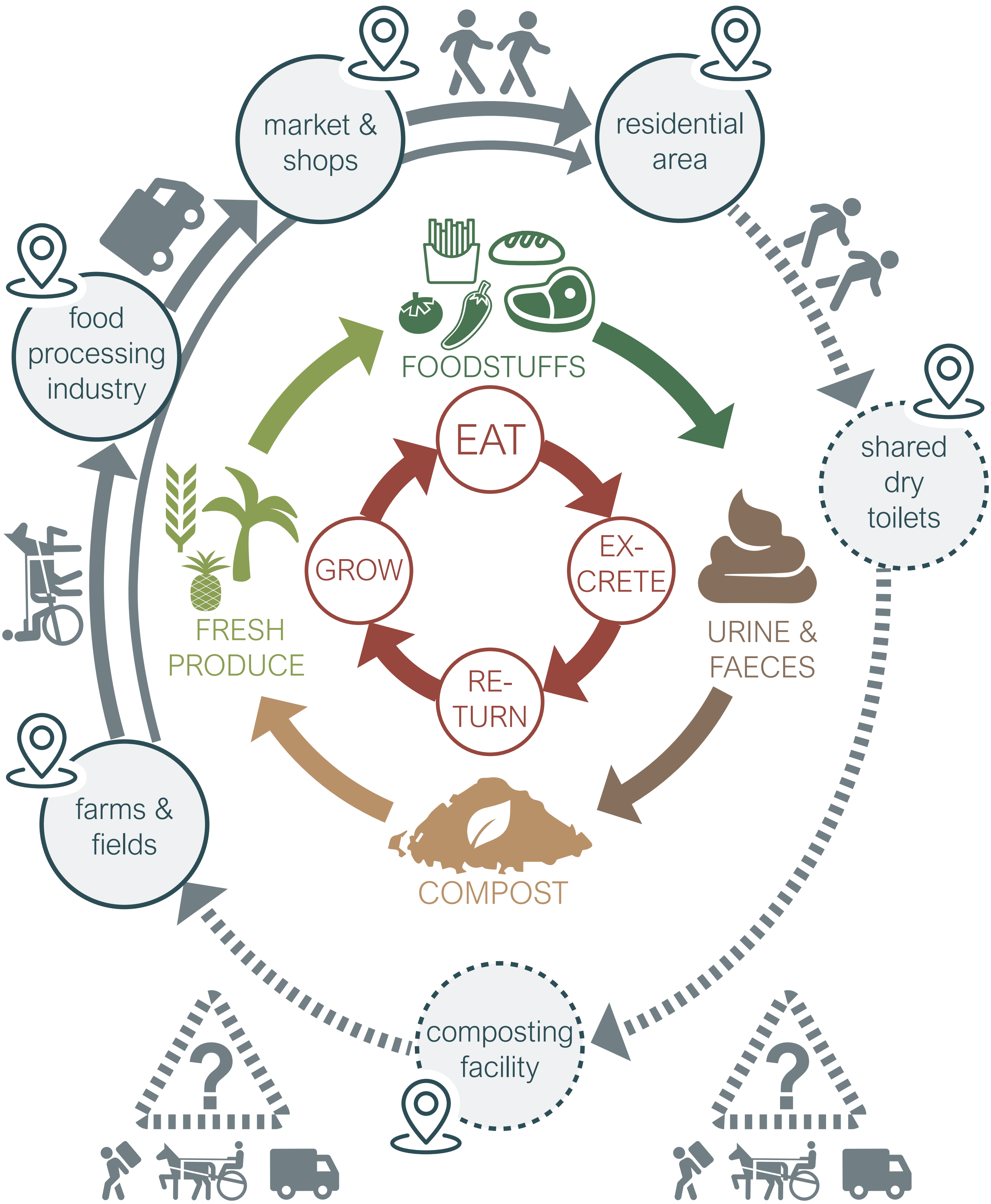


fig. 3.2: the Nutrient-Cycle-Based City integrated system model

3.2 The Nutrient-Cycle-Based City

Integrated system model

The model of the Nutrient-Cycle-Based City, as it is proposed here, uses different circular flows to illustrate nutrient action (inner ring), nutrient-bearing materials (second ring), and nutrient-related urban elements with their respective connectors (outermost ring). Of course the focus here will be on human consumption of nutrients; parallel patterns of livestock consumption shall not be further elaborated in this study.

Nutrient action (inner ring):

The driving force of the nutrient flow, of course, is the consumption of nutrients: humans (and livestock) eating food, which was grown on cultivated lands. After the consumer used up as much energy as needed, they excrete the remaining nutrients. Next, the nutrients get decomposed and returned to the soil, where they ultimately foster new life and grow as plants.

Nutrient-bearing materials (second ring):

The related materials in which the nutrients are contained are: Foodstuff – urine and faeces – compost – vegetal biomass.

Complex chemical processes transform the material into one another, with a big part of the nutrient elements (mainly these are nitrogen, potassium, phosphorous) remaining within the material, and only small parts being lost to the atmosphere.

Now the key difference in this Nutrient-Cycle-Based City model is that the human wastes are being collected and kept within the cycle, the figurative leak in the system where faeces and urine are flushed down the drain, gets closed.

Nutrient-related urban elements (outermost ring):

Starting with the production of foodstuff, the first spatial element that can be identified are farmlands and cultivation fields. Often, yet not always, they are located in rural areas with a low population density, and ideally on fertile, healthy lands. After harvest, the produce is transported to the next station in the cycle of nutrients, most often to a location of the food processing industry.

From here, parts of the produce are used for livestock feed, the part for human consumption, however, gets transported to a marketplace, distributor, merchant, or shop.

To date, these transportation steps mostly rely on the street network of the location, ideally a combination of paths through the fields accessible for farming vehicles, and a reliable street network for further transportation with trucks or animal-drawn carts. Relatively large distances between these urban elements can be balanced by a good transportation network.

The next step, where food is bought (or collected) by the consumer and brought back to the location of consumption (i.e. the residence), requires short distances. Ideally, shops and marketplaces are in walking distance of few hundred meters from people's houses. The residential areas anyway require good connection to other spatial elements. In case of subsistence farming or with private gardens being cultivated for food support, these agricultural areas should equally be located close to people's homes to ensure that the time spent on the way to and from the field is as short as possible. This in turn poses high stakes on the municipal street network that should be quite close-knit in such cases.

These spatial elements and their connectors are all existing already – even if in different shapes and qualities – they are the basic structure that all human-inhabited space has in common.

The following urban/spatial elements incl. connectors are new proposals that are necessary for closing the nutrient cycle:

Toilet stations with dry toilets for the collection of human faeces and urine. On an urban level in the Ethiopian context, facilities shared between a number of households are the most viable concept. It is, however, of urgent concern, that the toilet facilities be reachable by all desired users through pathways that are sufficiently short and comfortable to take multiple times per day. What this means concretely may differ in different contexts, e.g. related to residential density, and is to be established prior to project implementation. In certain circumstances, upgrades will have to be made to the footpath network, as well, to ensure quick access and avoid obstacles. (In other contexts, alternative collection schemes for faeces and urine may be more fitting: urine diverting toilets or collection of excrements via dedicated vacuum toilets in each residential unit. These options, however, exceed both the scope and the site-context of this work and are therefore not further investigated and proposed.)

Subsequently, the collected excreta have to be decomposed to form compost that is sanitary and safe to use in food production. This obviously requires a dedicated space with appropriate equipment. And it requires respective transportation possibilities for the raw material. Whether that be via the road network with collection vehicles, or through individuals with suitable collection devices, the options are manifold.

The last and final step in returning the nutrients to the food production cycle is to get the compost to the agriculture area; again, proper transportation possibilities are required. And this includes all different types of productive landscapes – large enterprise farms, subsistence fields, private gardens, greenhouses, or urban farming spaces. Therefore very important, a distribution scheme is to be established, for example sales points for the compost or a model where people regularly using the toilet facilities are assigned a specific amount of compost each year.

In the open field, the compost works all its benefits – fertilisation for the plants, improving soil health and stability, ecological value and overall natural resilience. The need for filling currently existing nutrient gaps in agriculture with chemical fertilizer is reduced tremendously.

3.3 Impact of closing the nutrient cycle

Leverage effects of other sustainability improvements

When applying a closed nutrient cycle concept through composting human excreta, there are additional aspects that have big leverage effects on the impact that can be achieved through the measures.

In low-income economies, where people cook mostly with open wood fires, the use of so-called micro-gasifier stoves, such as the "Noah Stove" model made from clay, or similar models from metal, is promoted. They are intended to save large amounts of wood compared to an open flame, and improve kitchen safety. Their by-product, bio-charcoal, is a valuable additive to compost – with its porous structure and high carbon content, it helps quickly hygienise the compost, bind the nutrients to the compost, create a porous soil where plants can grow very well and a lot of water can be retained.

Educating the users of the system is key. Only people who understand the benefits of composting and people who experienced that it is a safe and odourless process will use the system in the long-run, and it can take several vegetation periods for the effects on the field to be sustainably visible. And only with good information and system management will people spread the word and the system might be established in other communities.

A good starting point to this can be sensitising people for waste collection. Organic wastes are abundant in Ethiopia, and can be an essential additive to compost made with human excreta, as they are an easy way for balancing nutrient and humidity contents. Functioning collection schemes for organic wastes serve as a leverage for the composting system and boost overall sustainability of the local communities.

Sizes-and-Amounts-Model – what can be achieved by closing the nutrient cycle

The flow of nutrients becomes a circular flow when the different materials that are linked to nutrient transport are connected and monitored accordingly. The proposed concept for closing the nutrient can achieve the following impact, exemplarily reduced to one individual person within one year:

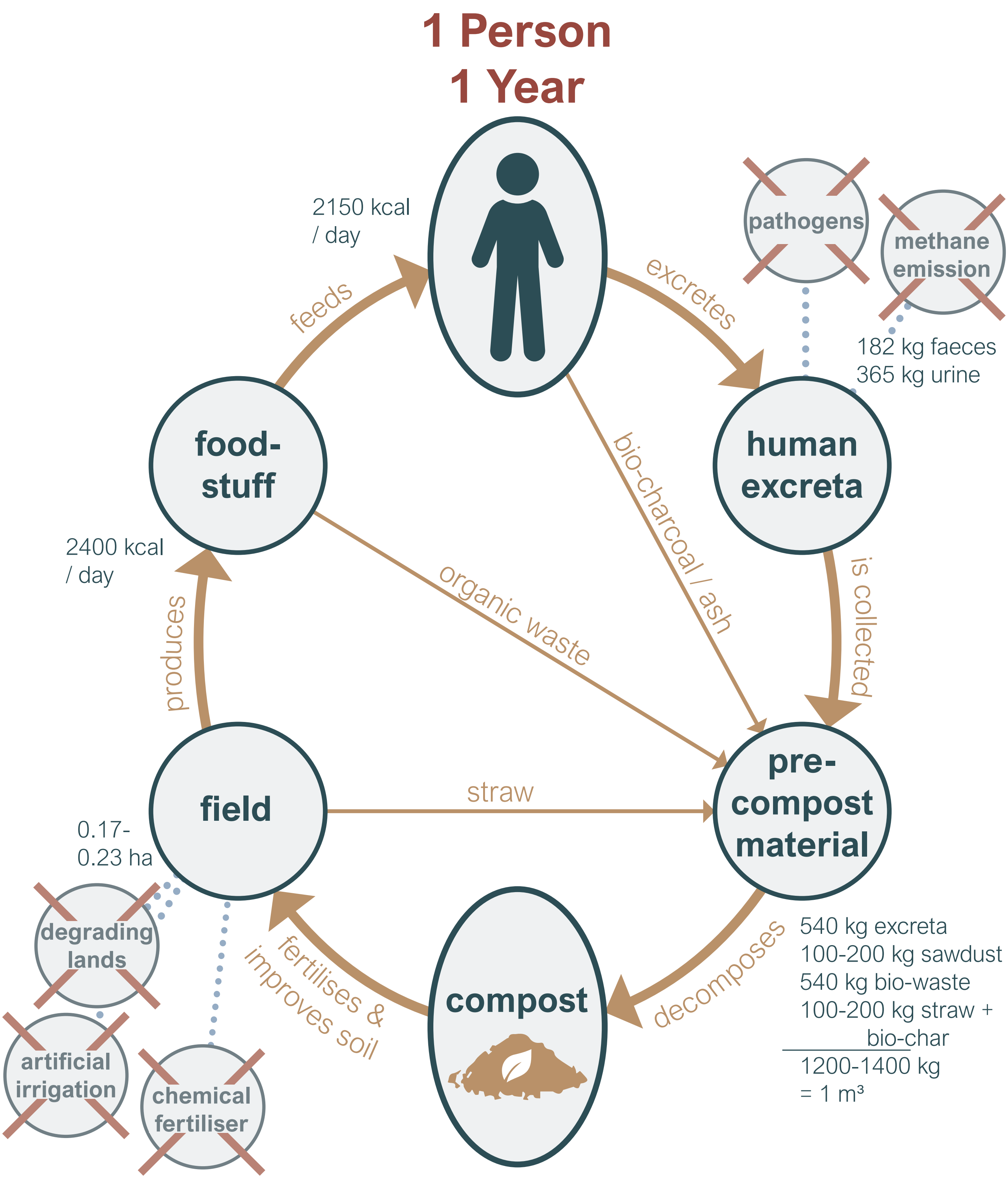
One person excretes about 400-500g faeces per day, 180kg per year, and around 1l of urine, equalling 365l per year. The amounts can differ quite substantially – these numbers are averages that can be expected in a tropical-subtropical climate with diets based on cereals, pulses and vegetables, with large amounts of fibre and little animal protein (World Health Organisation 1992; Prost and Brüggemann 2020).

The excreta get collected together with a cover material inside the dry toilets, i.e. sawdust.

Concerning the composting process, field studies in Ethiopia showed that equal amounts of excreta and organic waste produce the highest quality compost (Prost 11/13/2020). This amount is less than the per capita produced bio-waste (from households and agriculture). Straw which can be from different cereals, such as wheat or teff, and bio-charcoal from wood stoves, is further needed for successful composting. These additives are by-products of the material cycle and can be kept within the system by utilizing them for the compost. This adds up to roughly 1200-1400kg or 1m³ of pre-compost material.

This material decomposes to roughly 720-800kg of finished compost within 10-12 weeks – once again also depending on climate and humidity levels. The absolute nitrogen content results from the mixture of resources and additives, and reaches 1.3% or 13g/kg of compost. This is close to ideal, like the carbon-nitrogen ration of roughly 25:1 (Prost 11/13/2020; Dunst 2015).

the Sizes-and-Amounts-Model



110 kg CO_2 saved

sufficient for: 0.07 ha

~ 800 kg

N-content: 13 g/kg
C:N-ratio ~ 25:1

fig. 3.3: impact estimation (Sizes-and-Amounts Model)

The field size needed to feed one person in low-income economies such as Ethiopia is 0.17ha per capita, slightly lower than the world average at 0.23ha (FAO 2020a). In Ethiopia, the fields produce roughly 2400 kcal worth of foodstuff per capita per day, 2150 kcal of which is actually being consumed – one of the highest ratios in the world (FAO 2020b).

The proportion of field that can be fertilised with 800kg of compost can only be estimated, as it highly depends on local soil conditions, climate and most importantly the grown crops. Also, only about 20% of the nutrient contents in compost become plant-available in the first year, so each year with compost fertilisation, the crop output will increase more and more. For field crops, which are less nutrient-intensive, an average need of 5-20 tons (or 1.8-15.4m³) per hectare per year is a reasonable assumption. Intensive vegetable cultures may require up to ten times this amount (Fechner 2018; Prost 11/13/2020; Román et al. 2015; Biel 2016; Hansen 2015).

Calculation example:

> 20% plant-available nitrogen of 13g/kg = 2.6g/kg compost per year.
>
> Maize ideally requires 75 kg pure nitrogen per hectare per year.
>
> So in the first year of compost application maize requires: 75kg/ha * 1/2.6 = 28.8 t compost per hectare per year.
>
> As the nutrients accumulate in a healthy soil and more of it becomes plant-available each year, after the second year, only about a third of the initial requirement is still needed per year; alternatively, a cycle where in some years, no compost is put onto the field can be applied (Hansen 2015; Fechner 2018). Additionally, in depleted soils like in Ethiopia, any addition of nutrients and humus helps improve crop output and soil stability, even if it is less than the ideally desired amount.
>
> For the following calculations, an average between different crops and a long-term requirement is assumed at 12t per hectare per year.
>
> One person produces 0.8t of compost per year, which at requirements of 12t is sufficient for ~0.065-0.07ha, or 38-40% of the field area needed to feed one person in Ethiopia (0.17ha).

To summarize, the compost produced by the excreta and organic waste of one person is enough to fertilize 40% (or 0.07 ha) of the cultivation area needed for this person.

This closed cycle of materials strongly improves dependencies from outside the system:

A healthy, stable soil with high water-bearing capabilities requires much less irrigation. Depending on the crop, a reduction of up to 100% is possible in subtropical regions, which is a great release on communities suffering from water-related stress (FAO 2000).

On a large scale, CO² emissions can be reduced if use of chemical fertilizer was assumed instead of compost. The production of chemical fertilizer in equal nutrient amounts conventionally requires 110kg for the same field area, and causes additional environmental damage in the countries of mineral mining (Heinzlmaier 2013).

With the sanitary treatment of human excreta and less pathogens disposed in the environment, human health improves, as does the environmental status.

In the long-run, agricultural productivity will increase significantly on the more productive, healthy soils. This is a contribution to feeding the growing population and to react to shrinking agricultural areas due to population growth and land consumption.

the Circular Unit

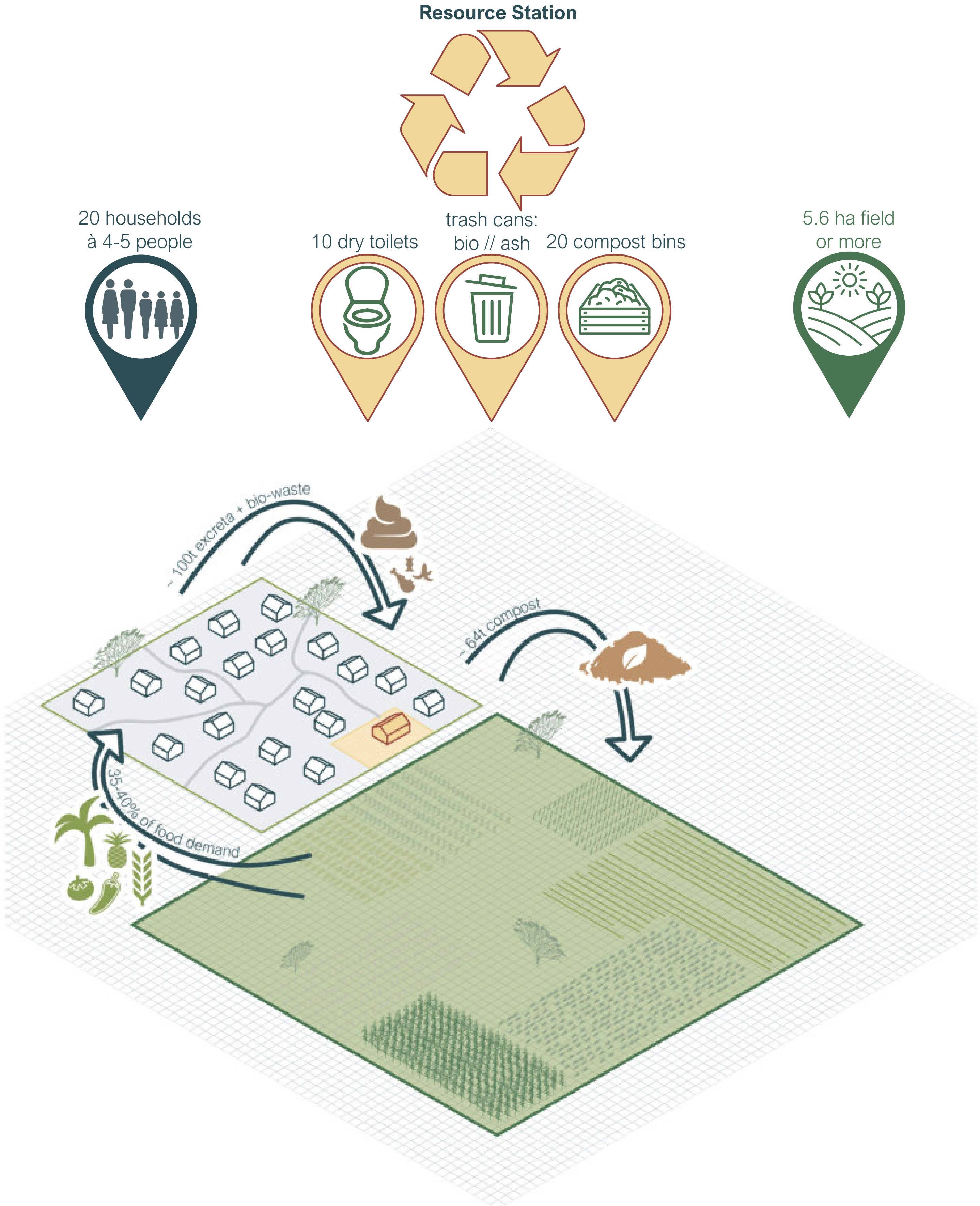


fig. 3.4: the spatial configuration of the Circular Unit

3.4 The “Circular Unit”

The ideal principle of the Circular Unit

The Circular Unit is the scaled-down spatial representation of the Nutrient-Cycle-Based City. It is a closed circular system with all spatial elements and participating actors related to the circular nutrient scheme. In its standard form, the ideal principle represents an ideal (and unadjusted) configuration of how the design should look.

The Circular Unit (CU) encompasses:

- 20 households of average Ethiopian size (total: 80-90 inhabitants);
- The so-called “Resource Station” (RS), which includes:
    - 10 dry toilets shared between the inhabitants;
    - two central waste collection bins: for organic waste, and for charcoal/ash originating from cooking with open fire or a woodburning stove that may be provided to inhabitants;
    - a central composting station with 20 composting bins at 1m^3 each; and
- 5.6ha cultivation area (fields, urban gardens, etc) which are completely fertilised by the compost produced in the Circular Unit.

These dimensions are based on the aforementioned assumptions for human excreta, organic waste and necessary additives to the compost. Per year, a total of 80m^3/96t starter mass, equalling 48m^3/64t of finished compost can be expected per Circular Unit. After each ~18 days, 1m^3 of mass will be accumulated through all household users, which is a good amount for successful composting, e.g. in a dedicated wooden bin. With a decomposition time of 10-12 weeks, 4 composting cycles per year can be run in each bin, meaning 20 bins are needed in total for the 80m^3 starter mass.

With this amount of produced compost, the Circular Unit is able to:

- fertilize fields that provide 38-40% of people’s food demand, depending on dietary preferences, type of farming etc;
- reduce the irrigation need by up to 100%;
- reduce CO^2 emissions by up to 8.8t/year compared to chemical fertilizer use;
- reduce emission of further greenhouse gases, such as methane, usually emitted from improper organic waste treatment;
- stop environmental degradation through pathogens and chemicals;
- stabilize soils and create a more resilient environment for cultivation plants, human inhabitants and natural ecosystems.

Limitations of the Circular Unit are:

- For provision of sufficient foodstuff for 20 households/90 people, around 13.6ha of fields are necessary. The “missing” 8ha of land have to be fertilized in a different way; the foodstuff has to be “imported” into the Circular Unit. Therefore, this land is not considered part of the Circular Unit.
- A cover material for the dry toilets is not part of the discussion due to the complex supply conditions. The ideal material is sawdust, but few places produce sawdust as a by-product, however, if pruduced, it is produced usually in high supply, for instance by enterprises producing construction material. Therefore, it is recommended that sawdust be brought in from outside the Circular Unit.
- The provision of other resources – namely public services, provision of water and energy, as well as greywater treatment are not considered in this scheme. They are not directly interlinked with the nutrient cycle and are to be provided externally.

The Circular Unit in its shape and form is quite flexible – many of the elements can be located apart and connected by other means than mere spatial closeness. However, there is a variety of generally applicable recommendations for the spatial configuration within the Circular Unit:

- The dry toilets have to be set up in a user-centered and inclusive way to ensure consistent community use. This includes adaptation to local preferences (e.g. use of toilet paper vs. cleaning oneself with water) and tendering to all genders (dedicated space for women with appropriate access to women's hygiene products and discrete disposal options).
- Toilets should be located close to the composting area to save transport cost and time, as the material is heavier before than after the composting process. A combined building with a footprint of around 170m² is sufficient. Further, there should be some covered space for collecting straw from the fields (needed for successful composting) and a covered space for a person responsible for maintenance, supervision, explanation of the toilet station use, during day hours.
- Users should be able to reach the toilet station within a 150m/2min walking distance. Spatial separation from residential buildings is not necessary, as there are no odours from the toilets nor the composting facilities with proper use. Not separating the spaces, and the possibility for users to see the odourless composting process can actually help normalise composting human excreta and therefore boost user acceptance.
- The collection bins for organic waste and charcoal should be located in direct proximity to the toilets so that depositing household waste is a convenient task that can be combined with the walk to the toilet.
- The field(s) should be located as close as possible to the composting facilities. Depending on the type of agriculture, it is important that the fields are easily reachable for the inhabitants. For enterprise farming, more distant fields are also suitable, with appropriate road connections and transportation schemes for transporting compost and produced goods. Non-motorised transportation is to be preferred in the light of aiming at a climate-friendly strategy with the Circular Unit. For the Ethiopian context, animal-drawn carts are the vehicle of choice.
- The configuration scheme for the fields should take into consideration local landscape elements and potential additional value for ecologiy, such as the inclusion of continuous hedges, tree lanes or water drenches that exceed the limit of one Circular Unit.

The Circular Unit as proposed here is a system that is closed in itself; it can function quite stable and independently as a means of ensuring that basic needs of the inhabitants are fulfilled. But, of course connections to other Circular Units, to the direct surroundings and the urban fabric are needed, and the ideal Circular Unit is merely the basic spatial representation of an idea, which has to become applicable in different spatial configurations.

The independent configuration of the Circular Unit allows for a bottom-up implementation in different settings, where small clusters can start being covered by it, with adjacent neighbourhoods following a different sanitation method.

Adapted principles of the Circular Unit

The following examples are adaptions of the ideal design principle to various preconditions, grouped in various themes. These adapted design principles show more detailed spatial adjustments of the ideal Circular Unit principle, which are considered useful for the Ethiopian context.

The list, however, is not necessarily complete – the Circular Unit is a prototype that can be moulded in many more ways according to specific project needs, or different spatial and user surroundings.

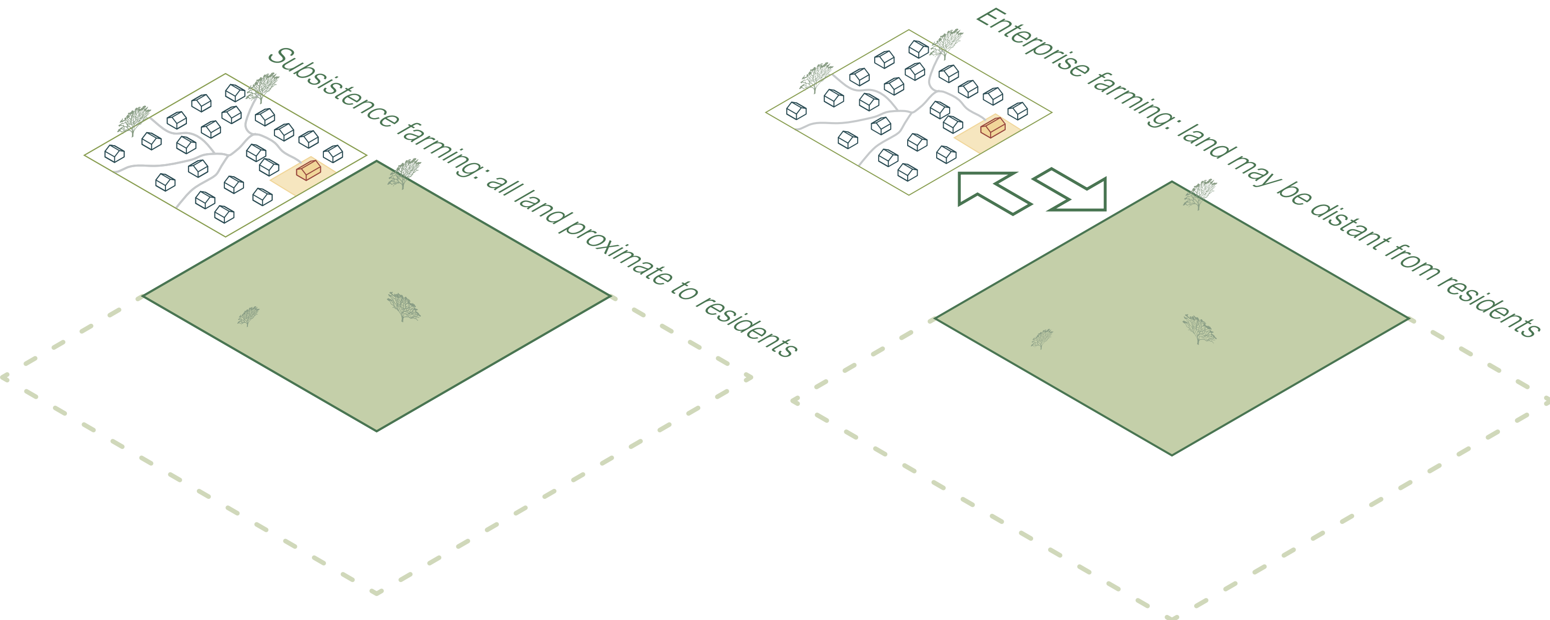


fig. 3.5: Circular Unit adaptations in regard to cultivation patterns

Adaptations in regard to cultivation patterns:

If the field is cultivated for self-subsistence purposes by farmers living in the Circular Unit, it is desirable that the field be located in direct vicinity of the houses and the composting station. This saves long travel and transportation times. If sufficient space is available, The total amount of 13ha that are needed to feed the population should be considered part of the Circular Unit. This can be achieved through adding chemical fertilizers into the agriculture practices, or through the reduction of compost amounts brought into the cultivation area yearly.

For Circular Units, where the respective field to be fertilized is cultivated by a farm enterprise or a farmers' union, the direct local proximity is less important. The compost can be transported with different vehicles, also depending on the dispersion scheme. In case the inhabitants are mostly employed in non-agriculture businesses, it might be a good solution to sell the compost to farms and establish good connection and transport schemes.

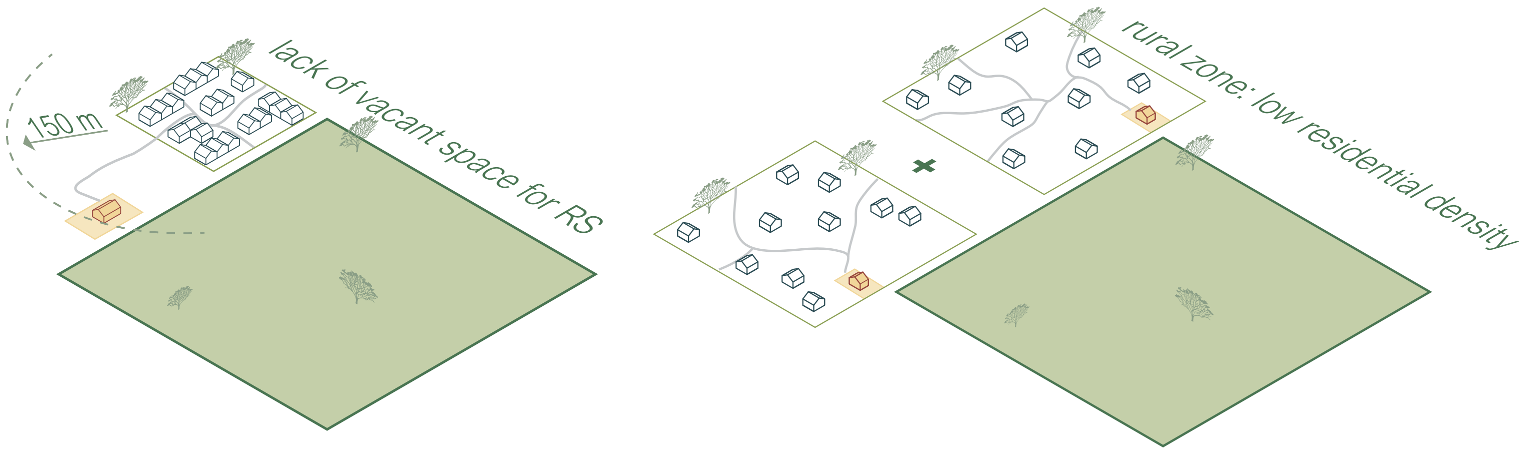


fig. 3.6: Circular Unit adaptations in regard to existing settlement structures

Adaptations in regard to existing settlement structures in Ethiopia:

Concerning existing Ethiopian settlements, it is especially their respective constructed density that changes preconditions for the Circular Unit, therefore requiring changes in its spatial configuration. In informal urban settlements – often found on the fringe of larger cities and sometimes in the centre of small cities, there is hardly any vacant space or unbuilt surface, which can make it challenging to construct the toilet/composting facility. However, the high-density settlements' advantage is that the optimal/possible walking radius of 150m makes the search for vacant space relatively more easy, because it does not have to be located directly within the household cluster to guarantee short distances for all users.

For medium-density settlements of urban, suburban or rural areas, the Circular Unit can be implemented in a way close to its "purest" form. It can flexibly be adapted to the respective urban form of an unplanned path network or a formal street grid, for instance.

For very rural zones where distances between households are larger, splitting a unit into smaller units of 5 or 10 households may be an option, or even giving toilets to households to use individually. In such cases however, a good knowledge transfer is essential to balance out the lack of a maintenance person readily available at the toilets for maintenance, supervision and personal guidance. Furthermore, a good scheme for regular collection of people's collected excreta would have to be established. For composting, it is best to acquire large amounts of material at the same time. If the material is not sufficient, decomposition can go incompletely, and dangerous pathogens may survive, contaminate fields and be a health threat to humans.

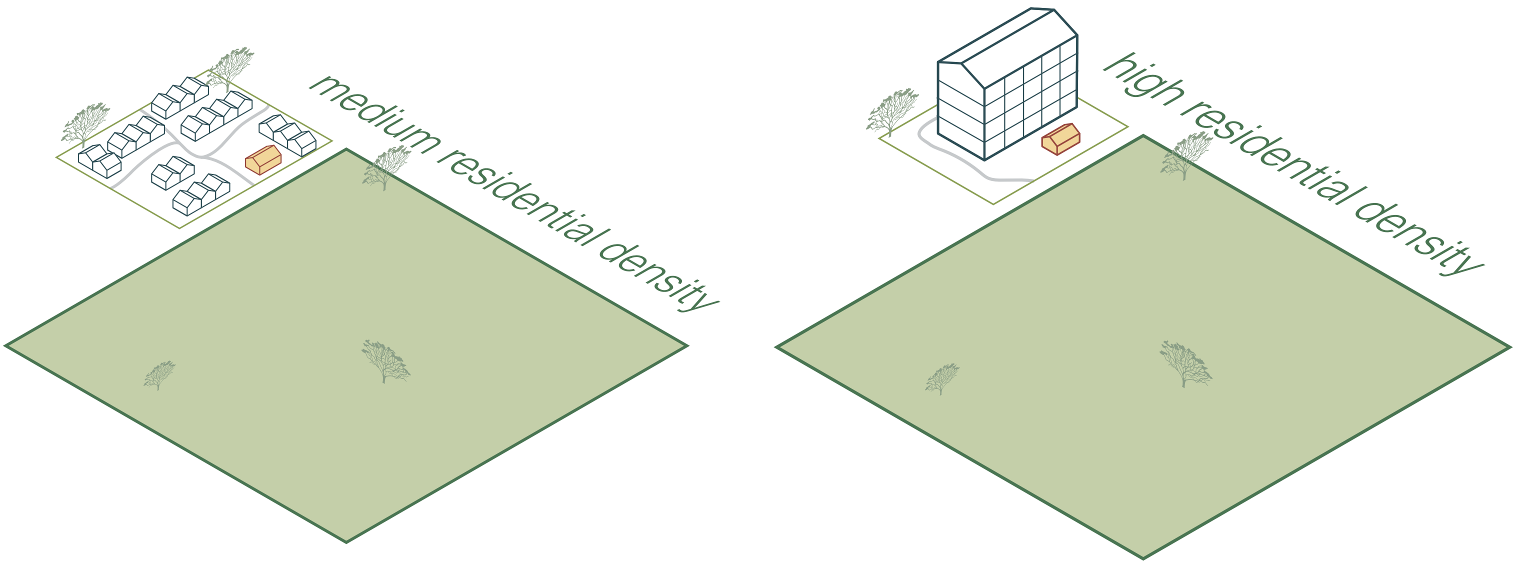


fig. 3.7: Circular Unit adaptations in regard to new urban developments

Adaptations in regard to new urban developments:

For new settlement developments, rural or urban settings, different desired residential densities have an impact on the Circular Unit configuration. For less dense settlements or rural settings, it is important that all residents stay within a 2min/150m walking radius to the toilets. Quite logically, the denser the settlement, the less space is occupied by the households, however the combined toilet and composting facility requires the same amount of space, as it should not be on different storeys due to transportation difficulties of the materials.

In dense condominium development schemes, the Circular Unit can be considered a temporary outhouse shared between families, which at a later stage of development, when water-based sanitation gets provided to the neighbourhood, can be easily re-purposed, e.g. for storage or similar things.

When buildings get even higher, the Circular Unit is not as appropriate anymore, as people have to climb many stairs and because there will be too many toilet houses needed within the urban scape at relatively small spaces. Now the Circular Unit could be scaled up to 40-50 households that are in reach, but quite quickly with many users, the toilets are not shared private toilets anymore, but rather almost public toilets, and that my come with improper use and unhygienic conditions.

Adaptations in regard to different types of users:

In urban centres with regular visitors of public institutions, such as municipality, court of law, schools, and other irregular users, an inclusion of sanitation facilities for these people in a Circular Unit can be considered. Options include splitting the 10 shared toilets proportionally for public and residential users, or even detaching the toilets spatially, and having service staff collect the collection containers from different toilets to be composted together at one location.

It is recommended for irregular and residential users to have separate toilets to use, to guarantee proper use with an available person giving instructions and maintaining the facility, and in case of improper use by an irregular user, not to cause disorder in residents' sanitation facilities.

3.5 Implementation strategy

Implementation of Circular Units

Some guidance shall be given on how the implementation of Circular Units in the local community can take place. This strategy supports decision-making by giving questions that lead through the process. However, the low-scale bottom-up nature of the CU concept inherently requires a sensitive planning approach, geared to the local conditions and community customs. The considerations stated here are intended to be well generic for being useful in different societal contexts of the world, yet they are slightly more tailored to the Ethiopian environment.

1. Demand inquiry

It is proposed for the system to be implemented on a demand-driven basis. Communities will be most invested in adopting the new system if they want it. Pilot projects can be a good way to start implementation somewhere in the community, and expanding it, as other inhabitants start to see the advantages in practice. A "modular city" of CUs with RSs with the integration of other modes of sanitation provision might be the result, where parts are serviced by CUs and others by traditional sewage systems. Further cycles of demand inquiry mean constant transformation of the system, and possible replacements e.g. with changing availability of financial resources. The need for fertilization can also be a factor initiating strives for implementing the CU.

2. Situation assessment

How do people currently defecate? What are typical daily paths they take? If people tend to walk relatively short distances, the distance to the new Resource Station should adopt to this. Where could the RS be installed? Are there vacant spaces, buildings that could be refurbished? Is a combination of the RS with other services an option, like schools, churches etc?

3. Implementation Planning

Who are potential local partners for the construction? Who can be put in place for maintenance, are there existing community organizations/ unions? Who will make sure that there is sufficient cover material provided at all times? Solving these questions is essential for the success of the CUs: It is to be aimed at highest user-convenience (or high user-involvement) to ensure continuous hygienic conditions. That includes regular maintenance and cleaning, central provision of cover materials, ideally access to water and soap. Who can take care of the composting process and dispersing it to the respective fields?

4. Planning the connections of the Circular Unit

Which households and Resource Station shall be connected to which fields? Are the users of the toilets the same as the people that will use the compost on their fields? If not, the constant connection has to be ensured by different ways of management. In dense urban locations with users in non-farming occupation, forming a set of services can be a good option, with maintenance, cleaning, organisation of distributing the finished compost being given as a package to an external service provider.

5. Education

Before use of the toilets starts, training has to take place. Ideally, the maintenance staff will also have a contact person during community use, after the initial training. Training must include information of proper use of the toilet, and proper use of the composting bins. Lack of knowledge can cause improper use, bad smells, unhygienic, even health-threatening conditions, and ultimately failure of the CU system. Ideally, the trained and responsible personnel manning the Resource Station is paid for their work.

6. Inauguration

As the system is to be opened to its users, some form of inauguration shall be made. A celebratory manor of the event will help strengthen community ties between the different users, and serves as a good frame for user introduction to the workings of the new system. As important as it is that the maintenance staff be well-educated about the system, as important is it for the users. A thorough introduction and building knowledge about the idea of dry toilets and human excreta composting, which is fairly strange to many people, is the only way to ensure that the users are comfortable with using the facilities, and confident about the advantages of the system.

The implementation strategy further used in this study

For the application examples which show different scenarios of implementation in Olonkomi, the first steps of this strategy are assumed to have been conducted. The focus is put more on the spatial implications of a possible system implementation, less on a wholistic understanding of the societal implications, as well.

Because the implementation strategy does investigate a spectrum of questions that makes broad implementation in different basic frameworks possible, assumptions for the testing case here had to be made. They lay the base for all scenarios, but will be further specified for each respective exploration per scenario:

1. There is high demand for Circular Units in all scopes of exploration. All inhabitants shall be reached by the concept.
2. The situation is assessed in a way that is possible from a distance through spatial studies, without a dedicated site visit. Paired with generic knowledge of Ethiopian and local customs, a rough idea of the local situation will be established.
3. Investigating the questions of local implementation planning exceeds both the scope of this work and the distance restraints with currently limited travel possibilities. It is assumed that all necessary requirements can be met concerning sufficient staff and materials.
4. Spatial explorations are being conducted on the connections of Circular Units, using parametric design methods. The premises laying the base for these explorations will be elaborated for each scenario in the following.
5. / 6. These steps are not further investigated in the testing strategy, because they have a lesser spatial component, depend on local conditions and require knowledge of both society in general and the local community.

Application Evaluation

4. Application Example Site Implementation and Concept Evaluation

4.1 Parametric testing approach and application strategy

The approach to applying the Circular Unit design principle to a specific example site in Ethiopia within the frame of this work is an approach of parametric testing. Firstly, the site of Olonkomi is thoroughly analysed with different methods to lay the base for further investigation. After that, a series of parametric explorations on three central themes of Adapted Design Principles of the Circular Unit is conducted, each with a slightly different approach and investigation aims, followed by an evaluation for each of the thematics.

1. Olonkomi site analysis

As an initial step, the current spatial situation of the town of Olonkomi and its surrounding area is analysed. The analysis is based on results of a site visit in May 2019 through a study group including the author (within a study project as part of the IN³ framework), satellite imagery from the years 2002, 2012, 2019 and 2020 (Landsat / Copernicus 2020; Maxar Technologies 2020; CNES / Airbus 2020), as well as further computational analyses using parametric tools.

Parameters that were analysed include:

- Topography and Environment: large landscape elements, such as rivers, steep hills etc. They can be considered obstacles in urban or agriculture development.
- Street network: Main roads, secondary roads, footpaths. Main lines of access and transportation of goods.
- Cultivation areas: location and type of agriculture, size of fields. Source of goods, destination for compost and workers.
- Urban form: type of settlement, structural organisation, vacant plots. How access is organised, where interventions are possible in a simple way.
- Inhabitants: location of households, residential density. System users and producers of raw material, consumers of foodstuff.
- Public services: location of markets, public institutions. Potential system users and producers of raw material.

2. Parametric Testing using Application Scenarios based on a specific premise

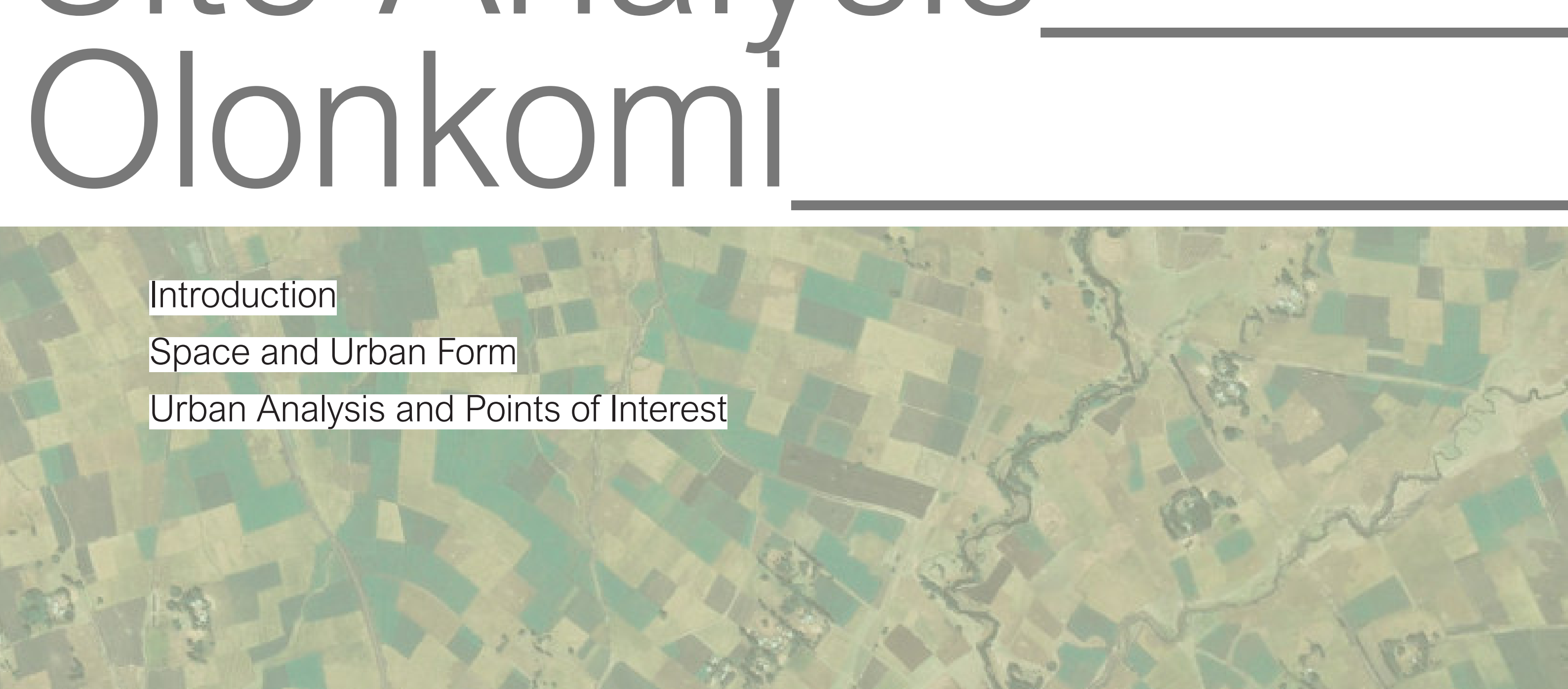
These analysed parameters inform partially automated design implementation codes using Rhino/ Grasshopper programs. This assessment gives orientation for where transformation through interventions for the Circular Units should take place;furthermore, explorations on possible limitations of implementing the Circular Unit concept can be made.

Three scenarios were selected to be applied on the site of Olonkomi, making use of the respective themes of the Adapted Design Principles.

For ensuring that the cases are somewhat comparable, the Circular Units for the testing are all set up with peri-urban agriculture areas. Possible supplements of urban gardening and community or personal gardens on plot are not considered in this simplified application scheme.

The parametric explorations are used as a tool to draw conclusions, evaluate the impact of the proposed Circular Unit concept, and estimate the spatial consequences of its implementation. Different assessment criteria and evaluation aspects give indication for the suitability of the concept and how it can best be applied in regards of a specific precondition.

Site Analysis
Olonkomi



4.2 Site analysis: Olonkomi

The test location of the town Olonkomi is located in the Dendi woreda (district) in the Oromia region, approx. 70km west of the national capital Addis Ababa, in the central Ethiopian highlands at an elevation of ~2,200m. At the latest national census in 2007, it had 5,500 inhabitants (Population Census Commission of Ethiopia, 2007). As the total number of urban dwellers in Ethiopia has increased by +140% between 2007 and 2020 (12 million to 28.7 million, acc. to World Population Review 2020), Olonkomi is estimated to house approx. 13,000 inhabitants in 2020.

On-site observations were conducted by the author in May 2019 for a university study project within the VIN³ cooperation project. They are a valuable base for understanding the urban context of Olonkomi. The town is an important marketplace with people from surrounding villages selling their produce and manufactured goods, with direct connections to the capital via the main road, which is in good condition. Local shops are predominantly in the food-processing industry as well as construction workshops and services. People often have private gardens adjacent to their homes, or bigger pieces of cultivated land outside of town as a contribution to their living. There are public institutions, such as a municipal town hall, court of law, secondary schools and hospitals.

The urban form is generally organically grown over time, mostly in an informal manner. Most of Olonkomi is characterised by newer urban developments from the past two decades with cart-accessible roads at the city edges mixed with traditional settlement structures, where houses cluster around a yard, separated from the outside by hedges and not directly accessible with donkey carts. The old town centre that is grouped around a traditional market is relatively denser.

The following pages give an introduction to the town: First with satellite images and site photographs (CNES / Airbus 2020; Landsat / Copernicus 2020; Maxar Technologies 2020), then with base maps, and finally through analysis of the urban and residential structure, a crucial step to be conducted before the further parametric strategy testing.

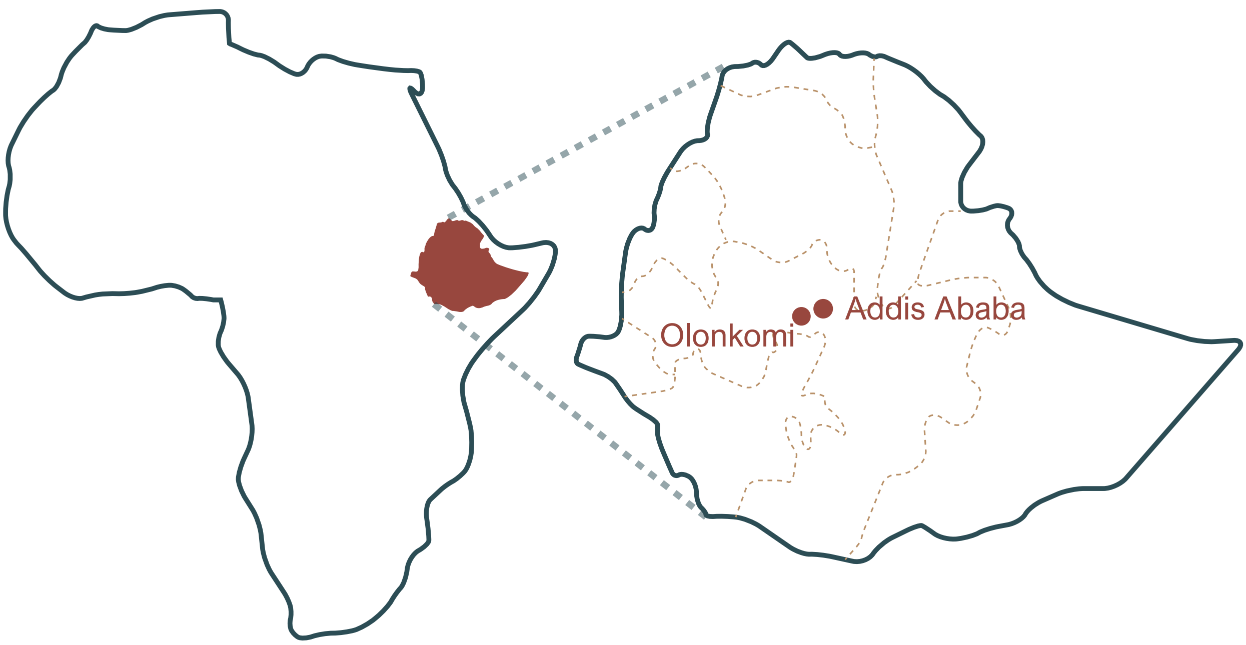


fig. 4.1: location of Olonkomi within Africa and the regions of Ethiopia

fig. 4.2: satellite image of Olonkomi (CNES / Airbus 2020; Landsat / Copernicus 2020; Maxar Technologies 2020); photographs of the urban scape (May 2019, taken by author)

Space and urban form

Olonkomi is situated on the edge of a hillside, where the landscape becomes more flat and even. The rolling landscape is predominantly used for self-sustaining agriculture, bare for the steeper hill Northeast of the town, the direct surroundings of town and the direct vicinity of one of the numerous small streams which all generally flow from North to South.

The town centre is a relatively dense informally grown settlement that groups around the market square, the residential quarters South of the main street and the settlements along the street are fairly formalised, with a rectangular street layout. The edges of the town are less dense and a combination of new informal settlements erected in the past five years, and traditional settlements with typical round hut typologies and trees and hedges in a communal structure: former small villages that became immersed in the growing town of Olonkomi.

The streets are unpaved, except for the main street, and they are very busy on a market day in the centre where shops line the streets, and quite calm towards the city edges, where most paths are not accessible for cars, or even animal-drawn carts.

A: formalised residential area

B: informal old town centre

C: traditional church hill

D: informal low-density fringe

E: linear settlement at main road

F: traditional low-density area

G: housing typologies

H: street profiles

J: landscape impressions

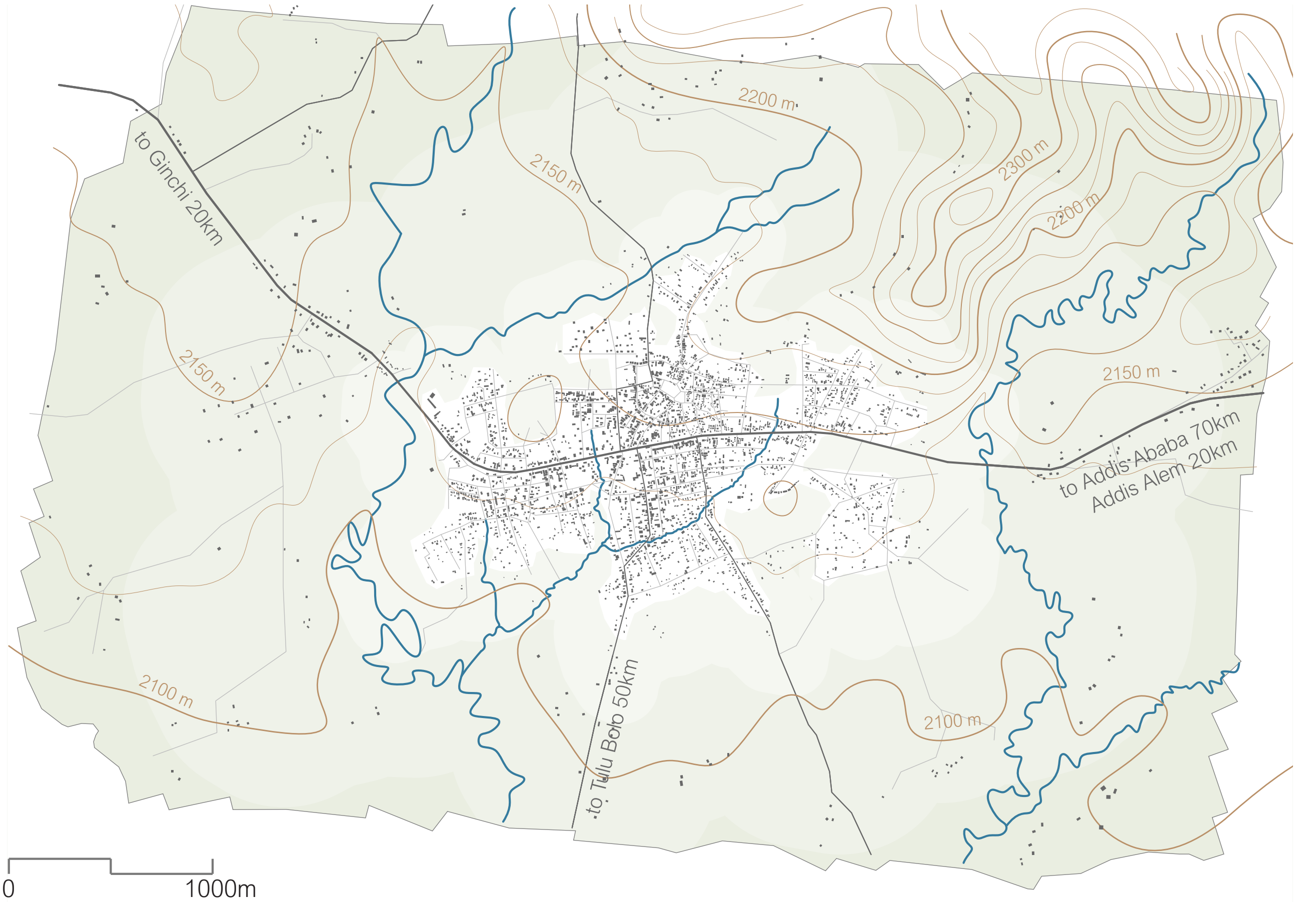


fig. 4.3: topographical map of Olonkomi

Urban analysis and points of interest

Olonkomi is situated 70km West of the national capital Addis Ababa, the regional centres of Ginchi and Addis Alem with extended services are located approx. 20km East/West of the town at around 2200m above sea level. Olonkomi formed at the crossroads of the national highway A4 with the connecting road to Tulu Bolo in the South, limited in its extension to the North by a more rugged countryside.

The city covers basic societal services, also for inhabitants of the rural hinterland: municipality offices, court of law, several schools and sports courts, two Orthodox churches on little hills within the city boundaries, and all shops and services needed for daily life.

Additionally to statistical estimations regarding the number of inhabitants, the study site was analysed based on current satellite imagery and a site visit conducted in May 2019. It is estimated, that a total of 3,440 households reside within the shown boundary, roughly 3,000 of which are part of the built-up area of the town. This would mean 13,800 to 15,800 inhabitants in the study site, considering that almost all houses in Olonkomi are single family homes. The map shows the residential density in the town centre in a radius-based calculation scheme: The darker the map, the more households live in direct proximity to the investigated house (the measure here is the ideal walking distance of 150m/2min).

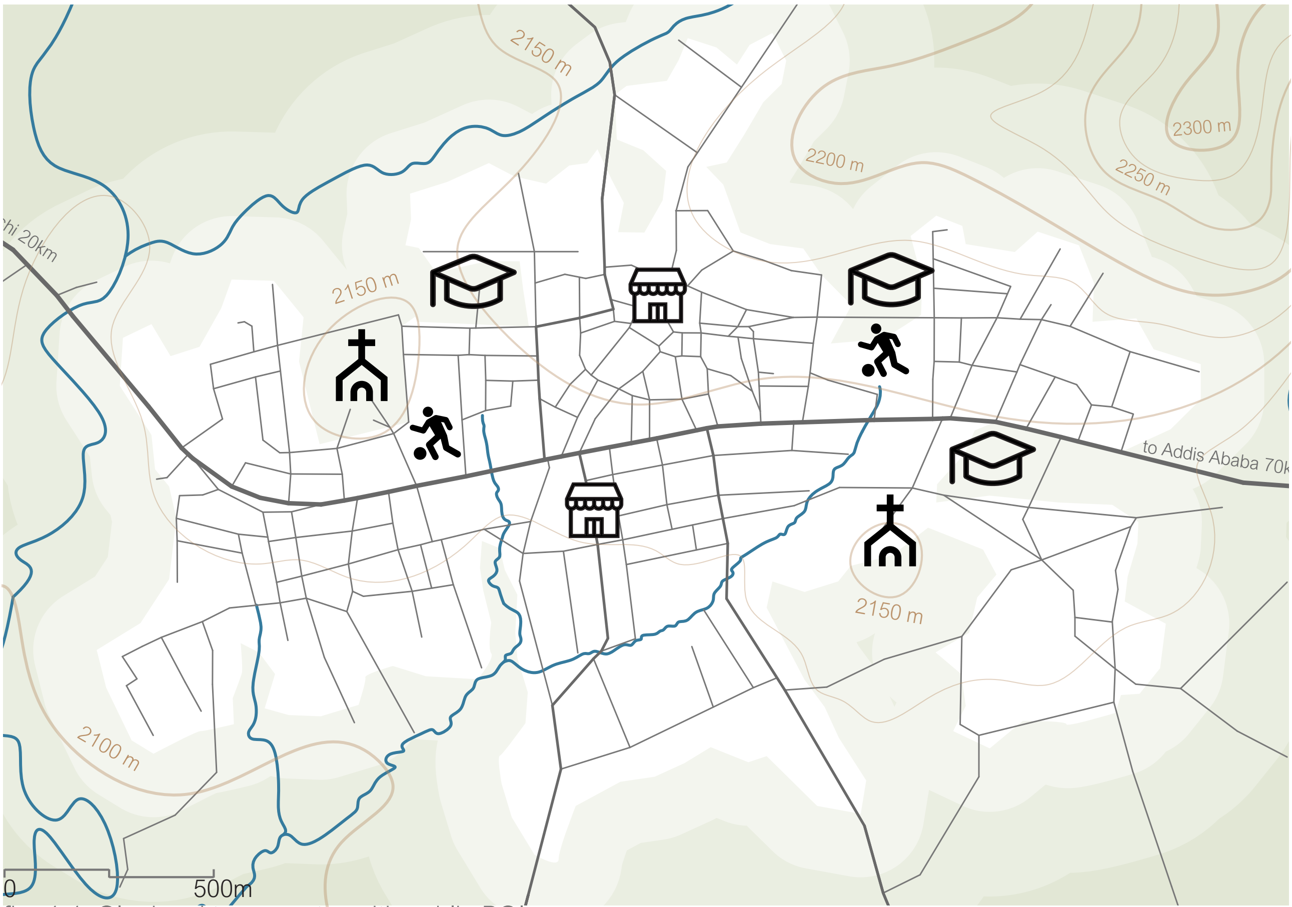


fig. 4.4: Olonkomi town center with public POIs

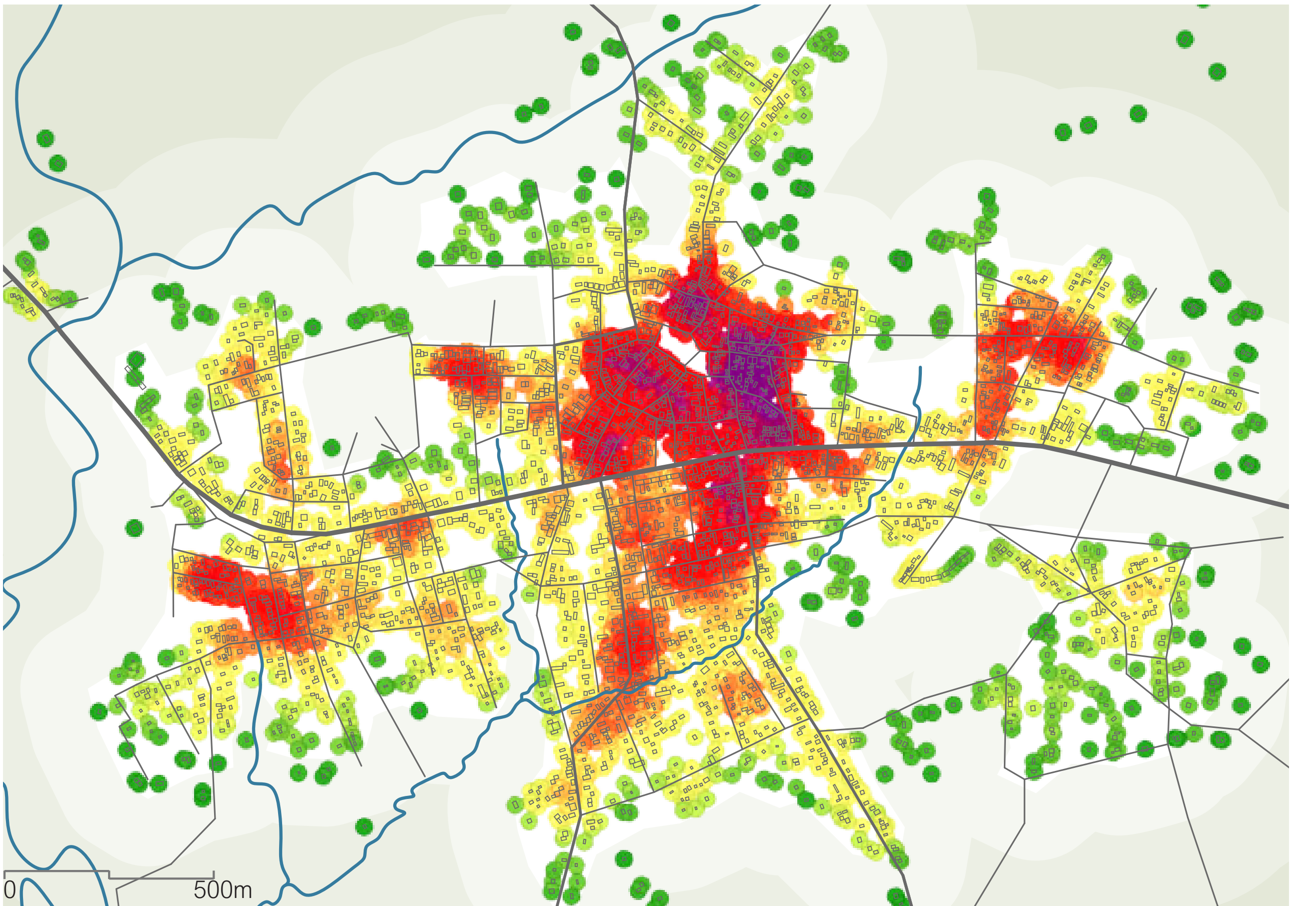


fig. 4.5: Olonkomi town center: residential density (radius-based calculation of distances between households)

Parametric Tests Scenario I

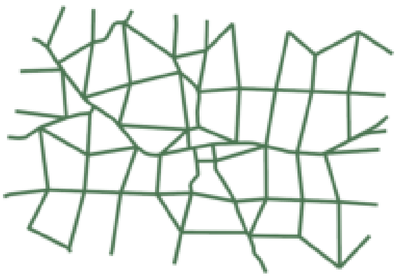
4.3 Parametric testing of the Adapted Design Principles

Scenario I: rural settlement patterns

Applying adaptations in regard to ways of cultivation and rural settlement patterns.

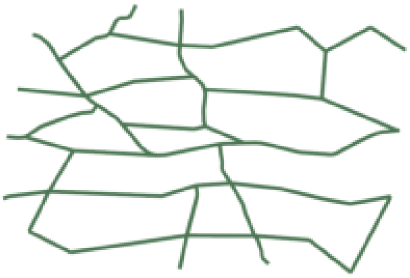
In the first scenario, the spatial configuration of areas dominated by self-subsistence farming is explored using three different variants. Observations shall be made on how the different urban forms perform in different evaluation criteria. They imitate regionally typical settlements in order to explore if these traditional structures of living are suitable for the Circular Unit concept, and how urban planning should respond to implementing the Circular Unit (e.g. for providing infrastructure and services).

The three hypothetical design variants of Olonkomi with different assumed typical rural settlement structures are:



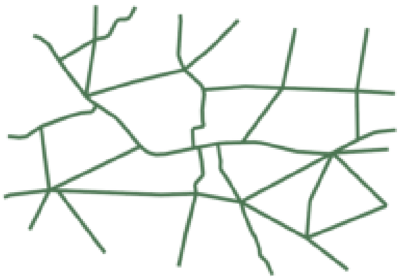
- VAR 1: sprawled settlement structure

This structure is a quite prevalent one in the Oromia Region, where the test site Olonkomi is located. A close-knit street/path network interconnects the rural area, and houses are organised on individual plots in clusters, forming communities with the neighbouring inhabitants. For the purpose of this study, the pattern has been adjusted slightly in a way that houses are grouped more densely and the field area is to be used communally. This ensures that all the walking distance between the houses can be limited, and that the coherent cultivation zone be used more efficiently.



- VAR 2: linear settlement structure

The linear settlement structure typically develops along a main road, when informal shops or stalls are opened in search of new employment opportunities. Other instances where linear settlements occur include places where the landscape restricts construction in some form, e.g. swampy areas, or traditional patterns, as quite common in ribbon settlements of Central and Southern Ethiopia. For the purpose of this study, it is assumed that these factors exist, to make for a comparable variant where the settlement configuration can be compared to other urban forms.



- VAR 3: circular settlement structure

Another typical rural settlement structure is the circular form. Households start to cluster around a node, this can be of many different kinds: a central landscape element, such as a large tree, a place where water can be found, or a street intersection with a small market; and a small village forms. In regions where this structure exists, mostly the villages have a similar distance to one another, forming a mesh-like structure.

The variants were generated with semi-automated parametric design methods. The computational approach, results and a comparing discussion are elaborated in the following.

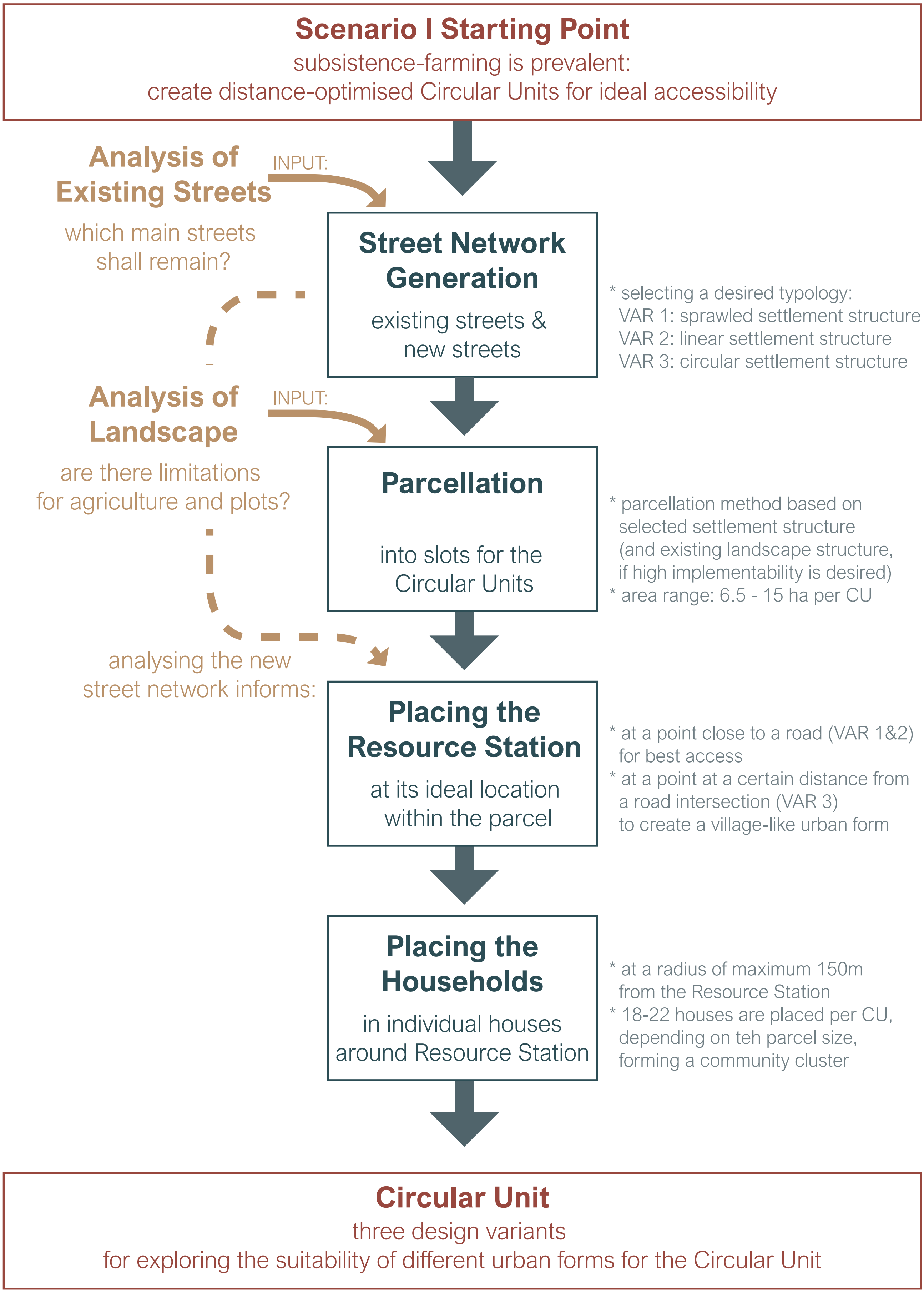


fig. 4.6: parametric approach to Test Scenario I

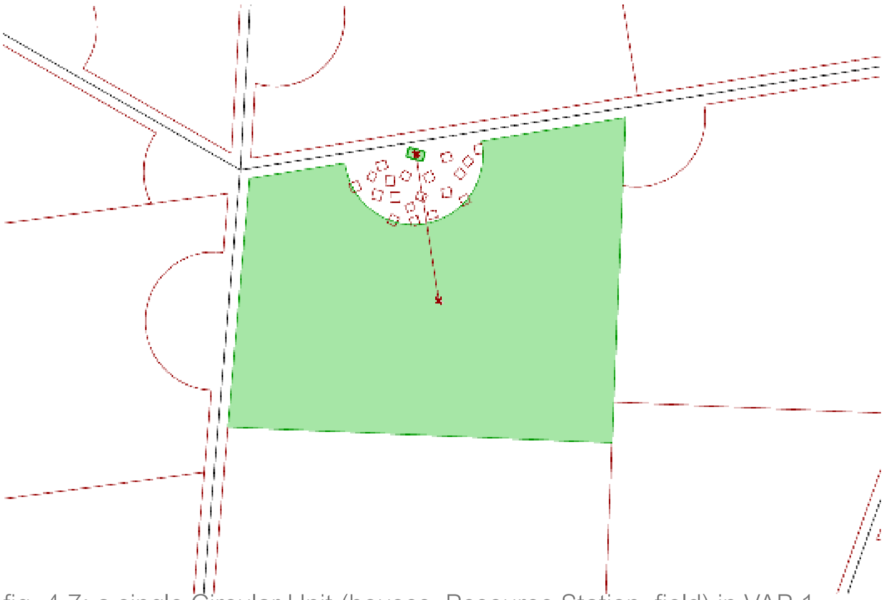


fig. 4.7: a single Circular Unit (houses, Resource Station, field) in VAR 1

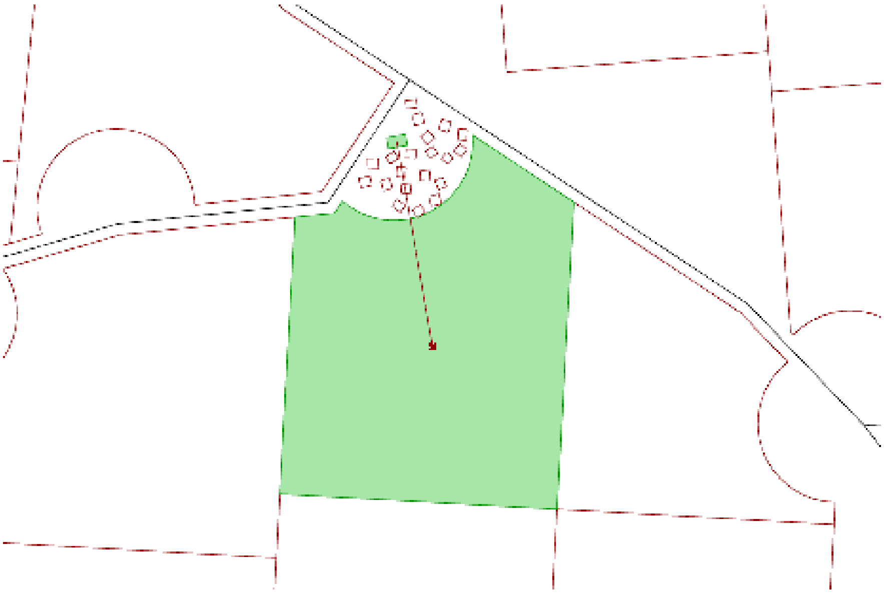


fig. 4.8: a single Circular Unit (houses, Resource Station, field) in VAR 2

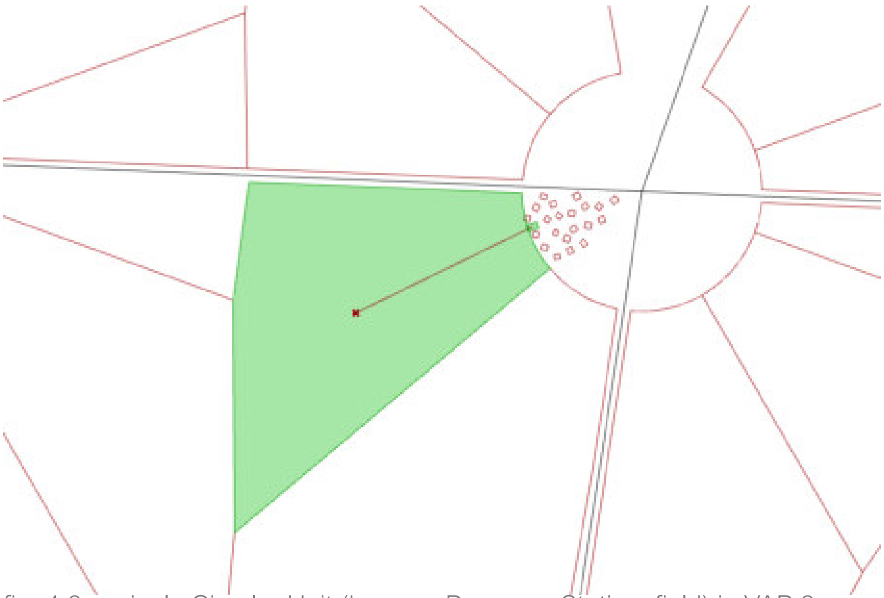
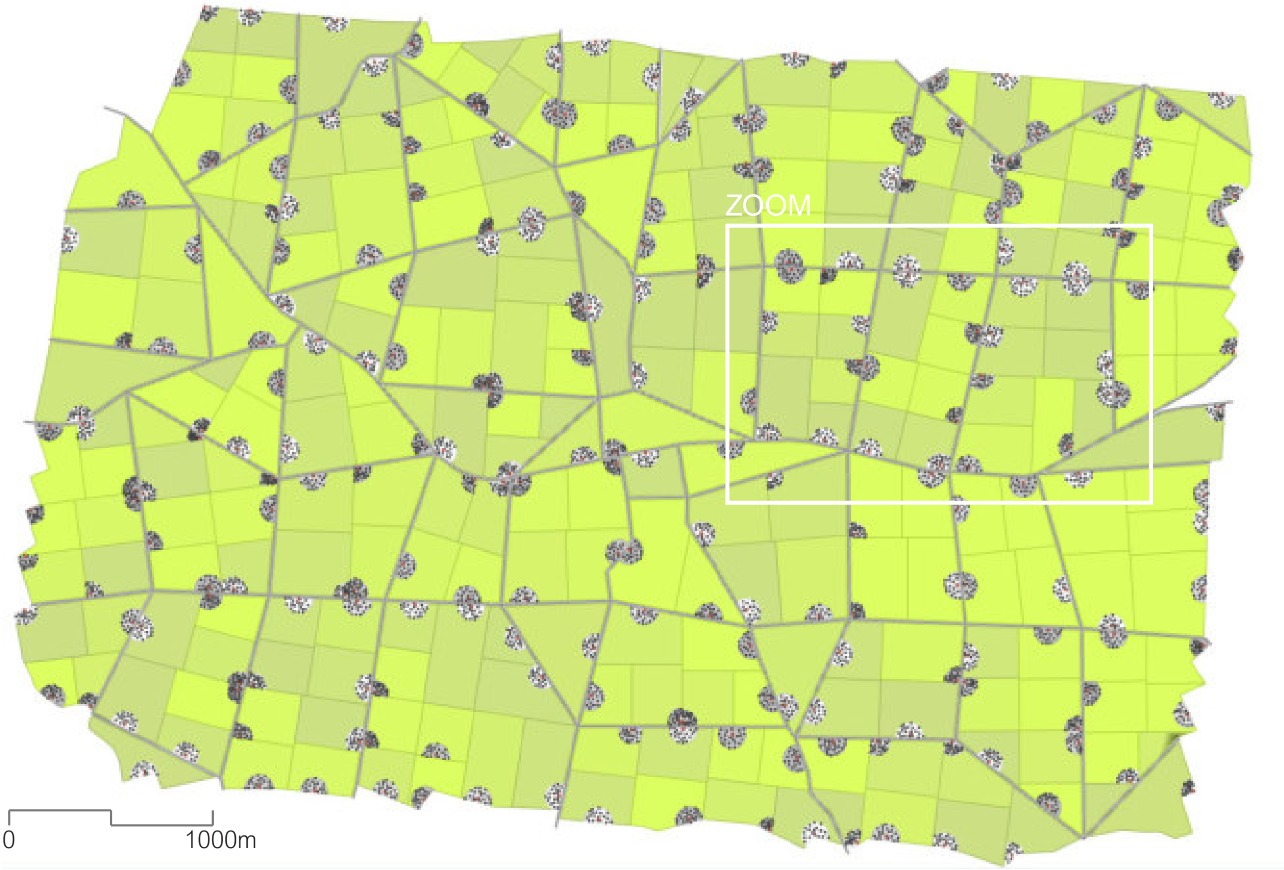


fig. 4.9: a single Circular Unit (houses, Resource Station, field) in VAR 3



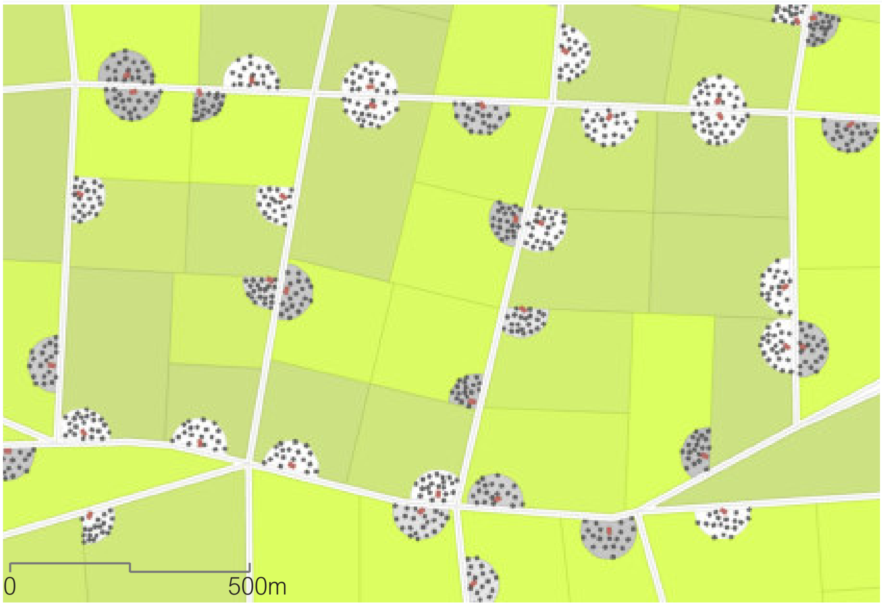


fig. 4.10: results VAR 1 - sprawled settlement structure

The resulting spatial configuration for VAR1 shows the population equally spread out over the zone, loosely clustered in Circular Units along the partly existing roads. The respective fields are directly behind the community cluster of households, which is grouped around the Resource Station. In a configuration like this, it could be extended to further house shared kitchen facilities or an access point to water. The rectangular shape of the fields of course is quite flexible when it comes to being adjusted to site-specific natural/topographical conditions.

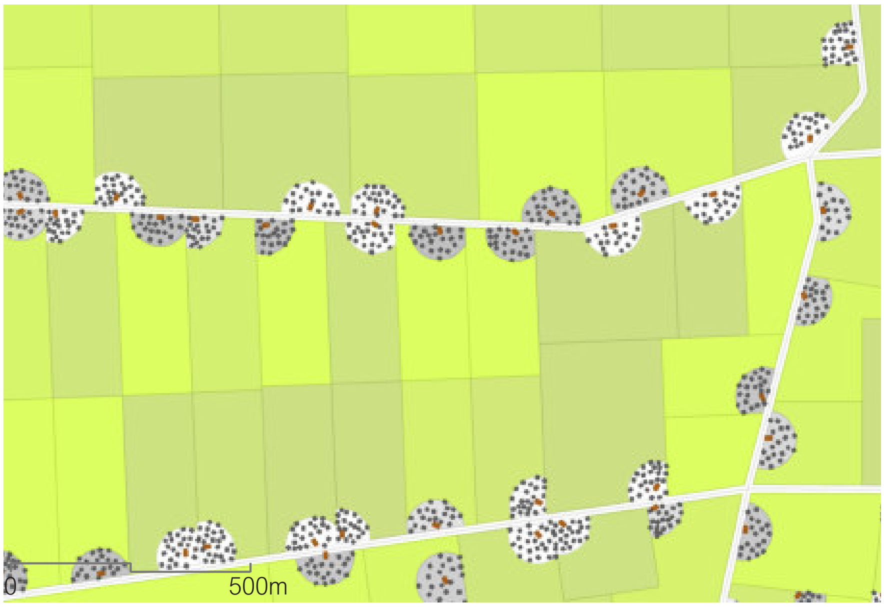


fig. 4.11: results VAR 2 - linear settlement structure

The population is in VAR2 more densely clustered along the street network, which has been reduced and complimented in some places to form long ribbons. People still are grouped in individual Circular Units, but they lie more closely to one another than in the previous variant. The respective fields are directly behind the community cluster of households, which is each grouped around the Resource Station. Here, the fields take a narrower, more elongated shape.

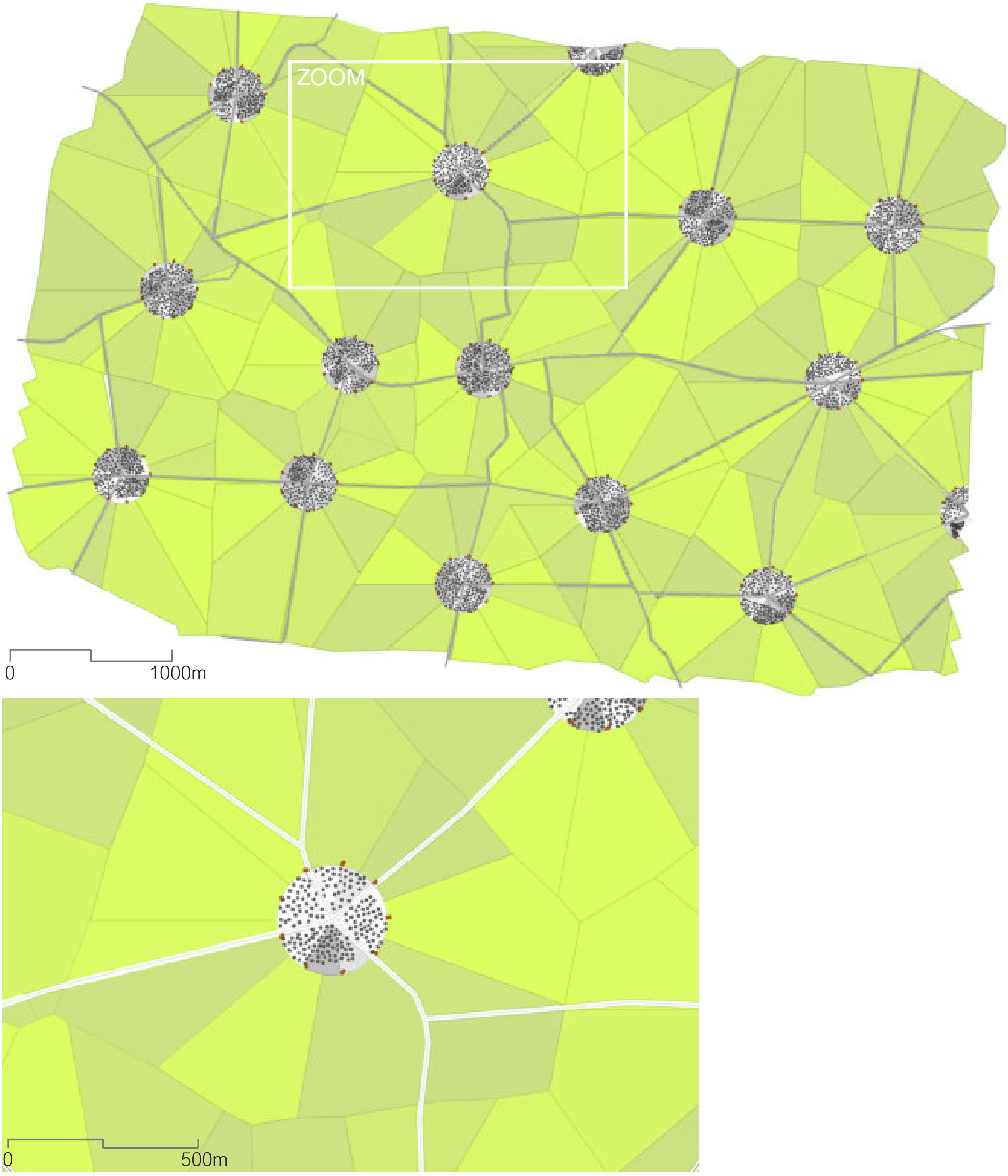


fig. 4.12: results VAR 3 - round settlement structure

In this variant VAR3, several Circular units form a small village around a street node each. The Resource Station would here be placed between the houses and the fields in this instance. This way, a village can form, and the shared (and not public) toilets remain in a space within each CU community, not at the busy center point of the village. The distance between each of the little villages is similar, and there is a web-like street network connecting them to one another. The agriculture area is organised in a similar way, where slices according to the location of the respective CU within the village extend behind the settlement.

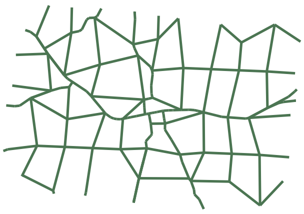
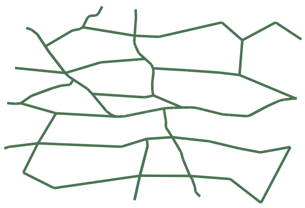
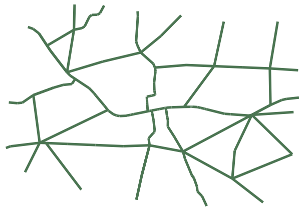
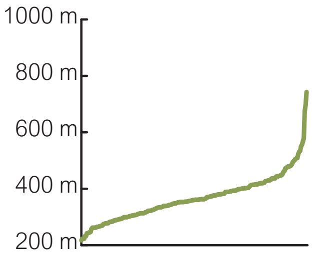
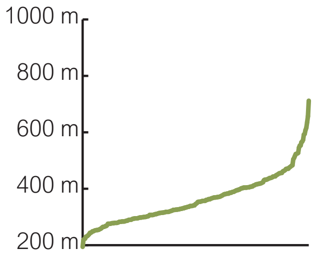
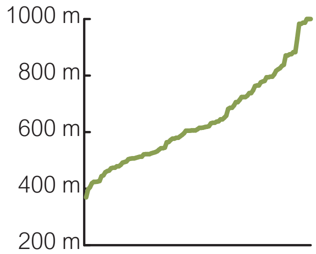
	 VAR 1: sprawled settlement structure	 VAR 2: linear settlement structure	 VAR 3: circular settlement structure
no. of households	4823	5558	2740
no. of Circular Units	246	278	137
average field area	8.0 ha	6.8 ha	13.6 ha
distribution of transport distances per Circular Unit (composting station to most distant point of field)			
transport distance (average)	369 m	361 m	638 m
ratio transport distance / field area (average)	46 m / 1 ha	53 m / 1 ha	47 m / 1 ha
street network length	74.3 km	50.6 km	52.0 km
open space cohesion / ecological value	-	+	++

fig. 4.13: performance comparison of the three design variants in scenario I

The sprawled and circular settlement structure perform slightly better regarding a possibly low transportation distance of the compost to the field, with 46 and 47 meters per hectar of field, respectively. For the linear settlement structure with its narrow, long-ish fields, the transportation distance is 15% longer.

Regarding themes of land consumption, eco-logical cohesion, landscape value and climate resilience, it can be expected that the linear and circular structures with more concentrated housing, a better result can be achieved. With similar residential densities, larger cohesive green spaces can be seen, which strengthens its buffer capacity and ecological value.

For urban planning and municipal service provision, the denser settlement structures of VAR2 and VAR3 are better. Less street network is needed to cover the area, similarly, less water pipes will be needed. With the rounded settle-ments, different levels of service can be provided in the different villages to enhance the coverage for the population.

Overall, it seems that all three investigated settlement structures are well-apt for using the Circular Unit concept. The highest positive impact, with improvements in liveability, environ-ment and agriculture can most likely be expected with the round settlement pattern, and the linear one, respectively.

Parametric Tests Scenario II

Scenario II: implementation in an existing small city (Olonkomi, Ethiopia)

Applying adaptations in regard to existing settlement structures in Ethiopia.

This scenario looks at the implementation of the Circular Unit concept in an existing city with as sensitive structural interventions as possible, while aiming to reach all inhabitants. It is explored, what consequences can be drawn for optimum walking and transportation distances in practice in Ethiopia, and what are suitable sequences for the implementation of the Circular Unit in a bottom-up approach. The parametric explorations are laid out on a basic loop mechanism, which clusters the existing households to a Circular Unit (CU) with a Resource Station (RS) on vacant spaces and an agricultural field. Within this frame, different selection methods for the sequence, in which the clustering happens, are studied:

- Different ways of clustering the households. This gives guidance to how the shortest walking distances for people to their shared toilet facilities can be generated, and furthermore shows if all population (or what percentage of the population) can be reached by the provision of sanitation with Circular Units.

- Different ways of assigning the field to the Circular Unit. This shows the consequences for necessary transportation efforts for the compost to reach the cultivation area.

These explorations aim at giving guidance for the implementation of the Circular Unit on a conceptual level, regardless of the planning method that is chosen. The lessons learned are helpful both for computational and traditional planning methods that seek to integrate aspects of the Circular Unit in an existing urban (or rural) environment.

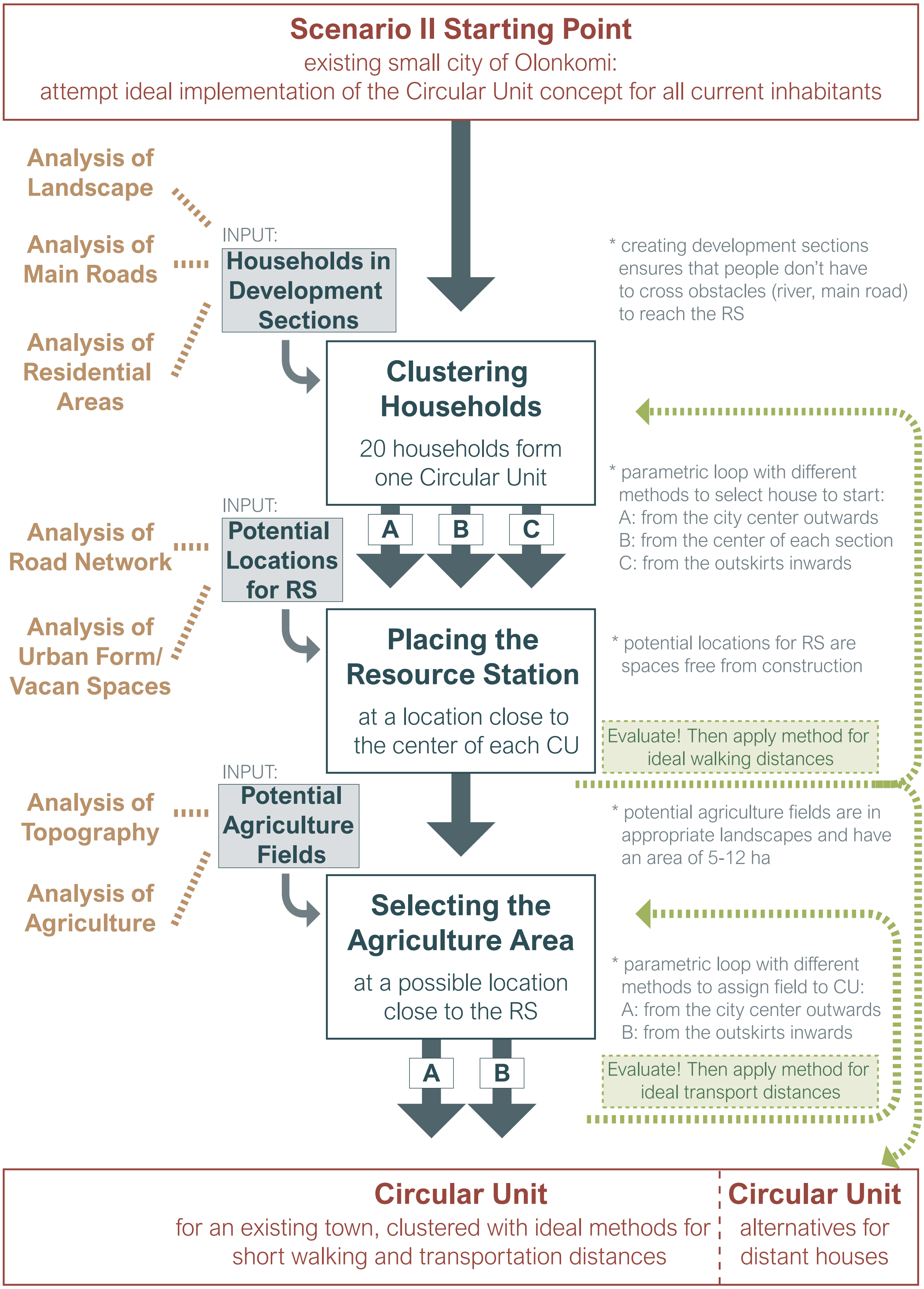


fig. 4.14: parametric approach to Test Scenario II

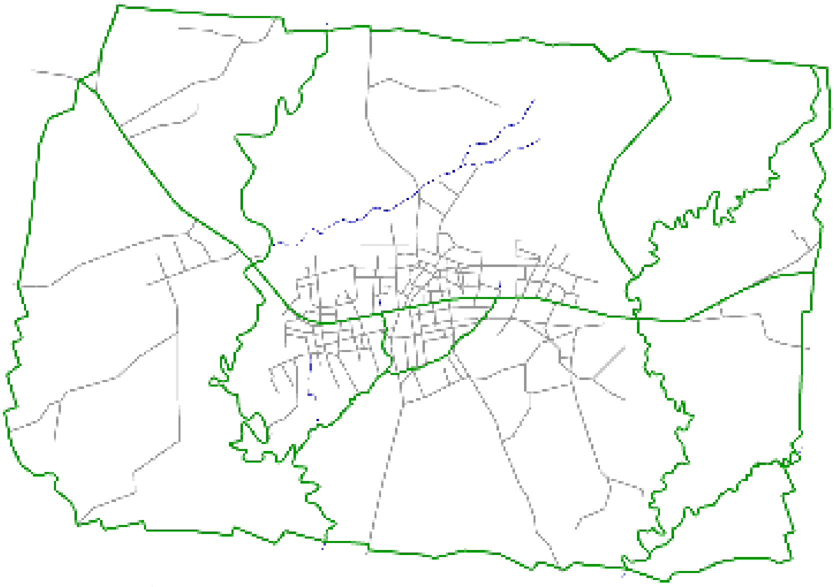


fig. 4.15: Development Sections: separated by main roads, rivers and hill ridges

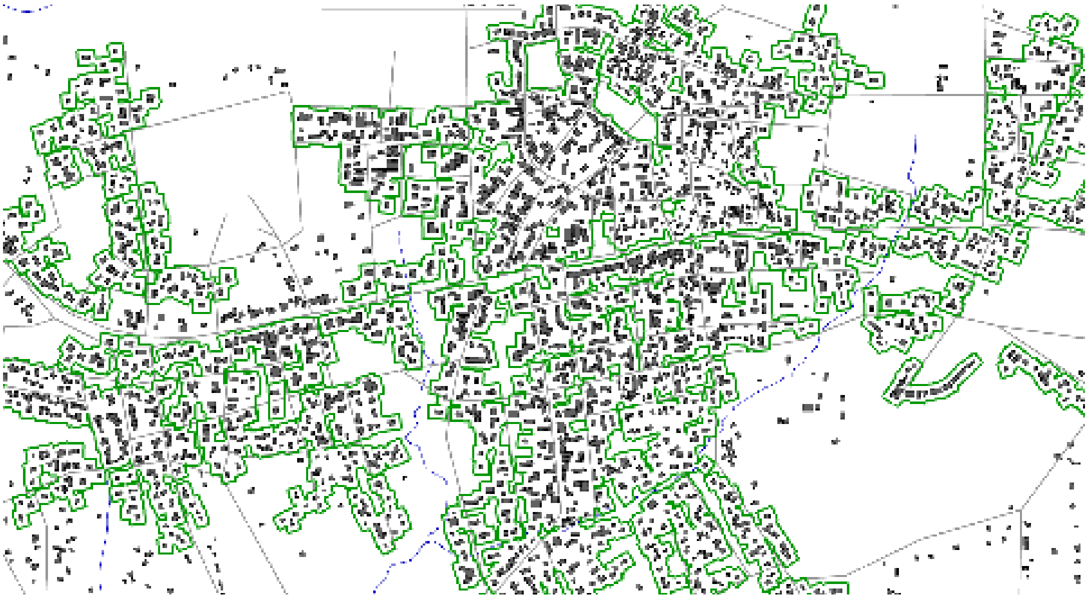


fig. 4.16: Potential Locations for Resource Stations: vacant urban spaces (>8m from a building)

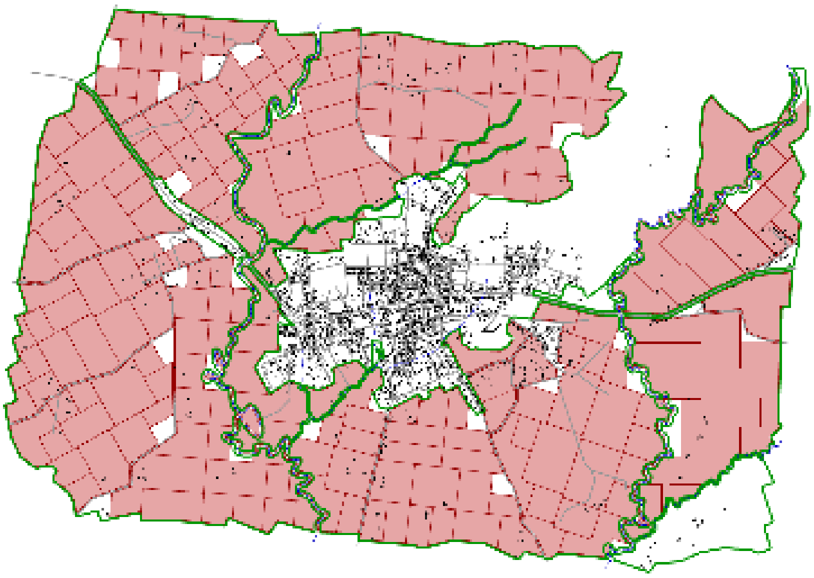


fig. 4.17: Potential Agriculture Fields: built-up areas, roads, topographic obstacles excluded

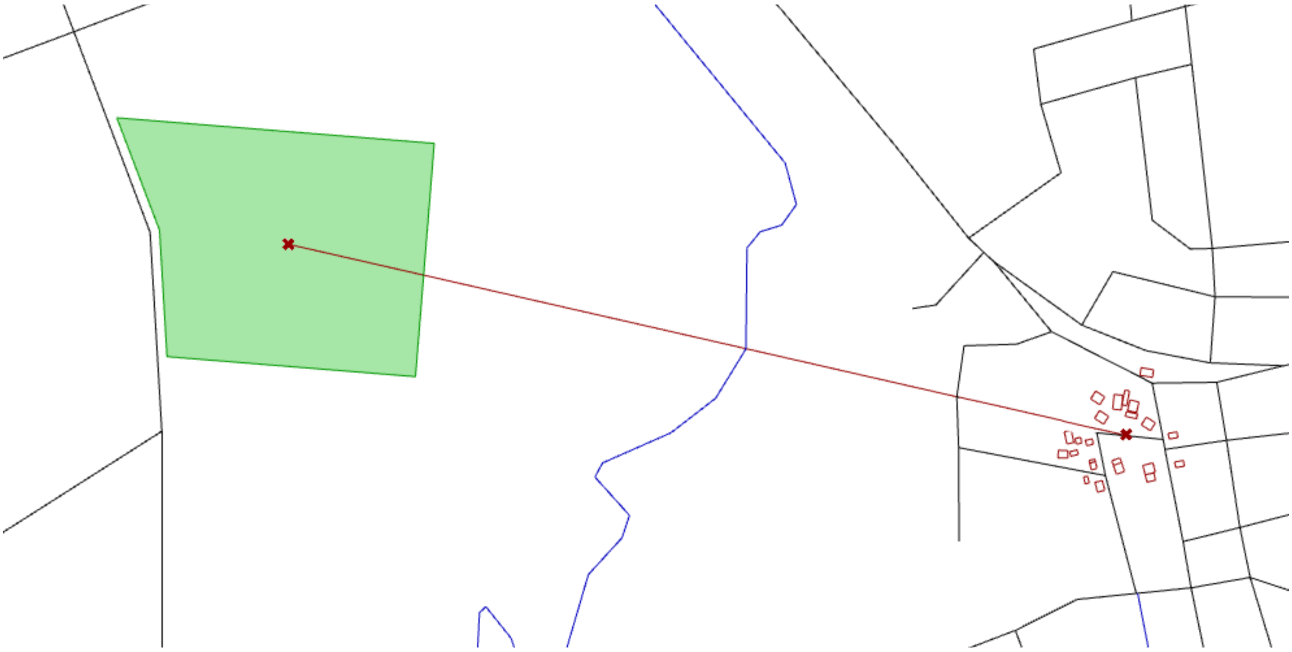


fig. 4.18: a single Circular Unit (houses, Resource Station, field) in scenario II

The Circular Unit consists of the cluster of 20 existing households (in small towns like Olonkomi, households can be assumed identical with houses, as they are single family homes). They are clustered together; next, the location for the Resource Station, which holds toilets, waste collection and composting facilities, is determined. The potential locations can be defined in different ways, here, they were defined as all points within spaces outside a radius of 8m from buildings. Other possibilities that could be applied, are e.g. public buildings, in which the RS could be included or for instance all streets. The location chosen is the one potential location closest to the center of the household cluster. Similarly, the field is assigned to the CU. More advanced selection mechanisms could include the path travelled via roads, or take into account who currently owns and cultivates the field.

Different methods for parametrically clustering the households were tested, based on different selection methods for the initial house to start the cluster with:

- Method A: selects the house closest to the city center (within each development section), finds the 19 closest houses and clusters all of them to a CU, and iterates once again for the remaining houses in each section.

- Method B: selects the house closest to the center of the respective development section, finds the 19 closest houses and clusters all of them to a CU, and iterates once again for the remaining houses in each section.

- Method C: selects the house furthest from the city center (within each development section), finds the 19 closest houses and clusters all of them to a CU, and iterates once again for the remaining houses in each section.

As can be seen in the comparison maps on the right, the clusters in all methods differ in area size according to the residential density and selection method. Method C seems to deliver the neatest solution of clustering houses, with the least amount of overlapping areas. For the rural zones, clusters are not really walkable anymore; this is where the CU concept might reach limits. The walking distances in the result of each method will be investigated in the following:

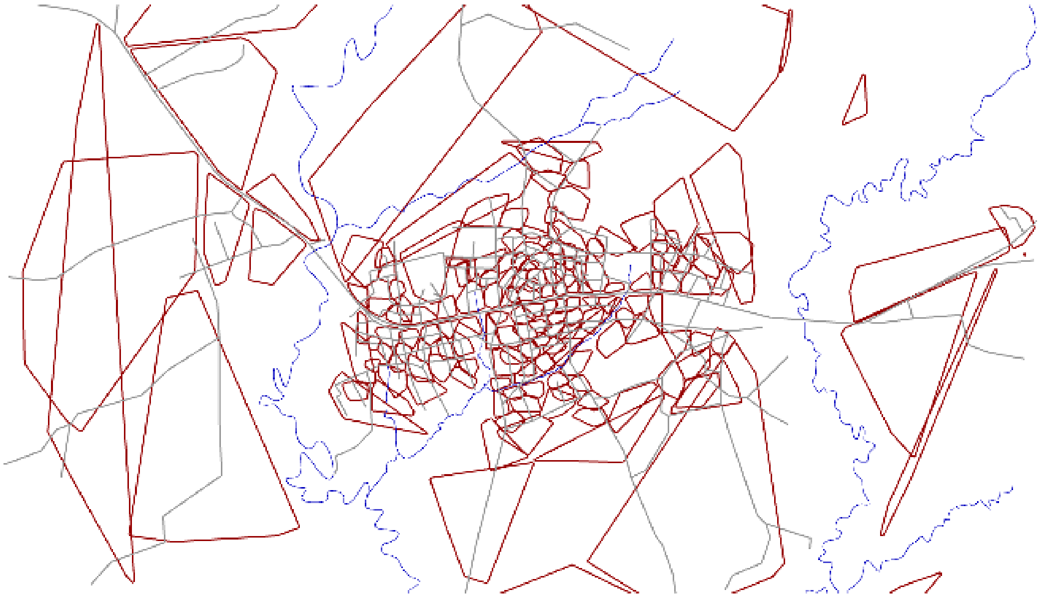


fig. 4.19: Method A household clusters: start clustering from city center outwards

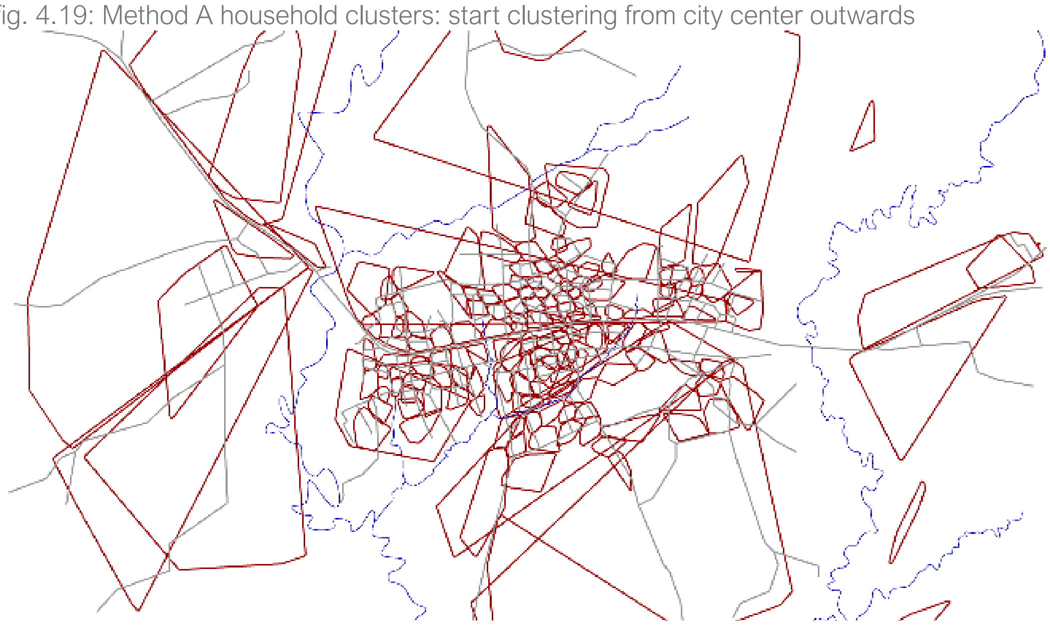


fig. 4.20: Method B household clusters: start clustering from center of each Development Section

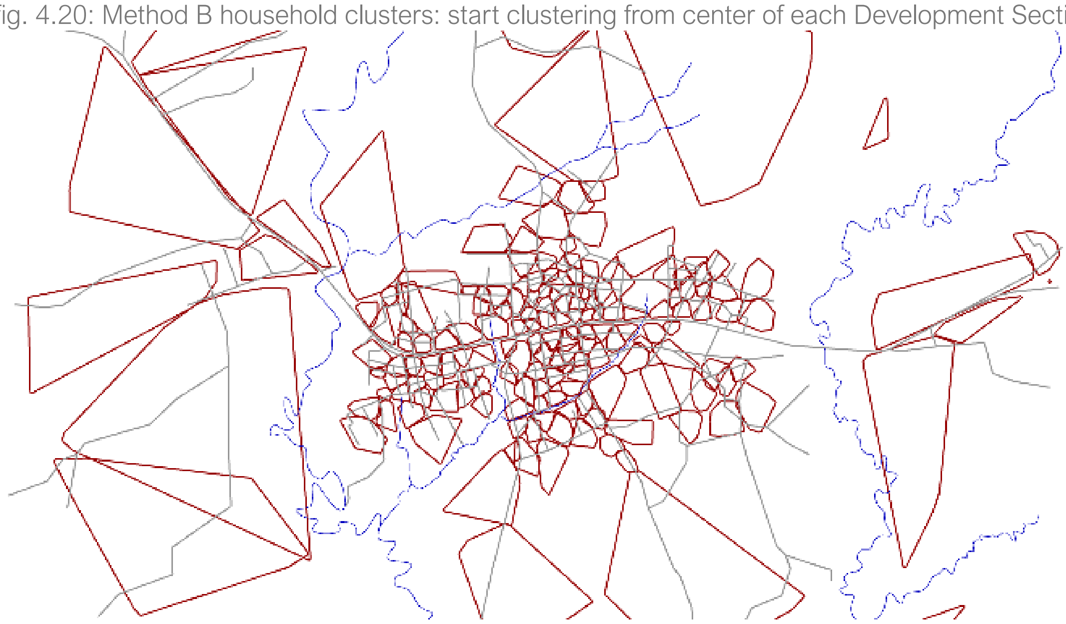
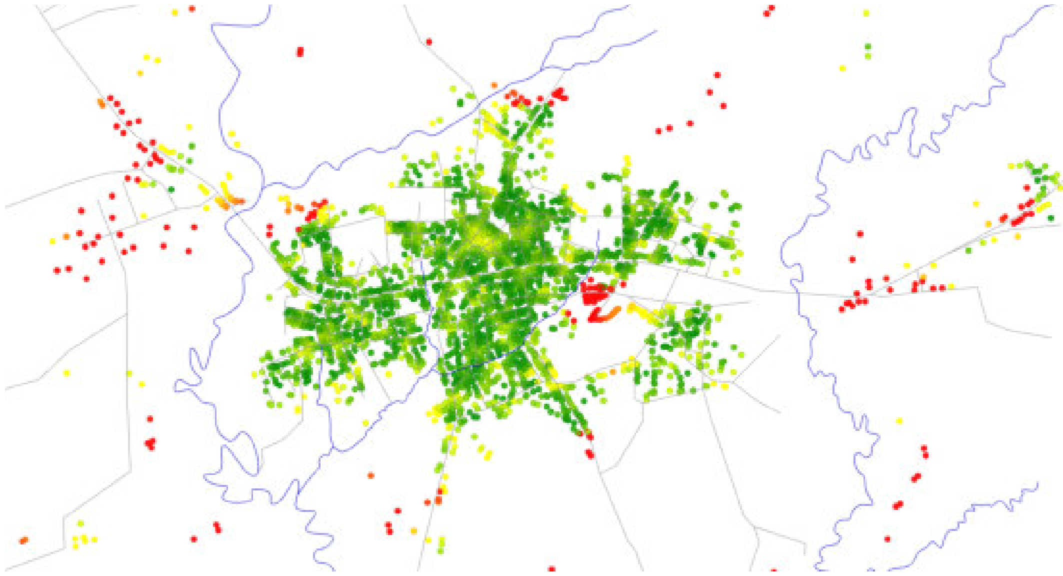


fig. 4.21: Method C household clusters: start clustering from the outskirts of the city inwards



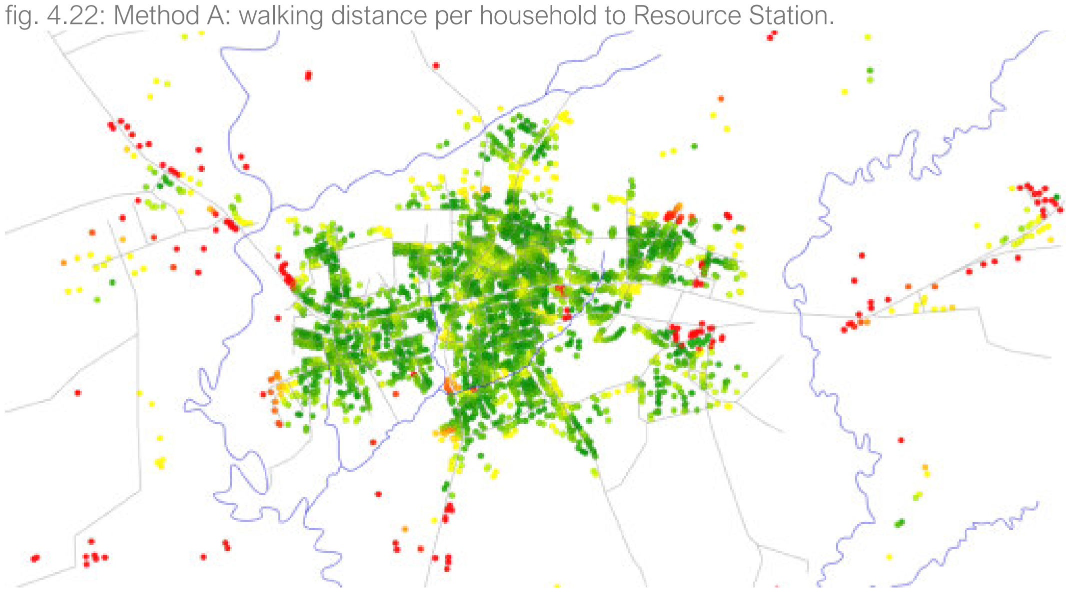
walking distance:

Method A:

Ø all houses:
134.7 m

Ø inside city:
79.5 m

fig. 4.22: Method A: walking distance per household to Resource Station.

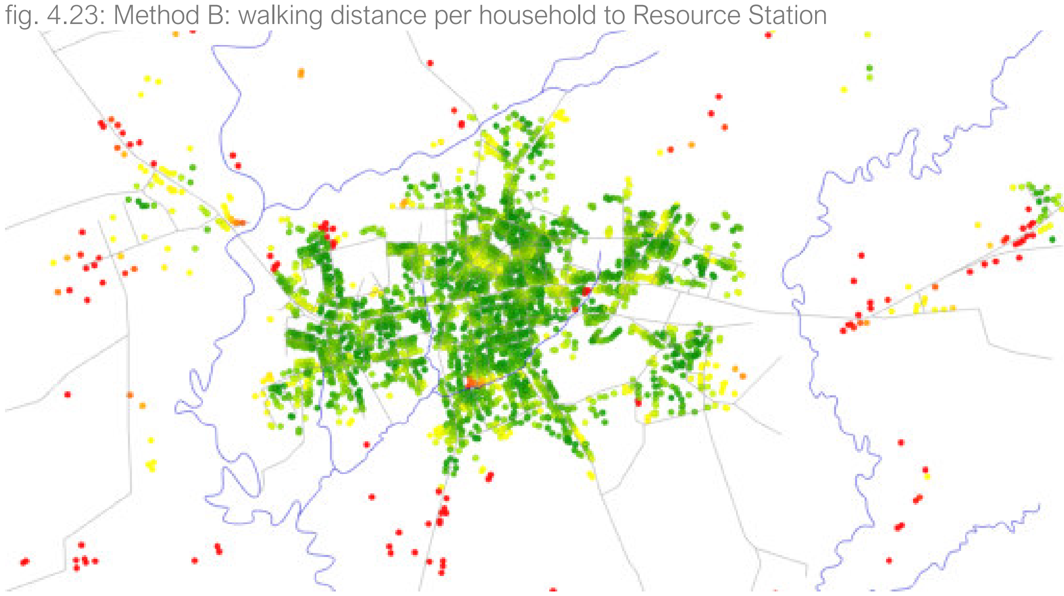


Method B:

Ø all houses:
136.0 m

Ø inside city:
82.8 m

fig. 4.23: Method B: walking distance per household to Resource Station



Method C:

Ø all houses:
112.0 m

Ø inside city:
75.6 m

fig. 4.24: Method C: walking distance per household to Resource Station

no. of households reached:

20

18

15

Method A:

no. CUs with <20 reached: 5

no. CUs with <15reached: 26

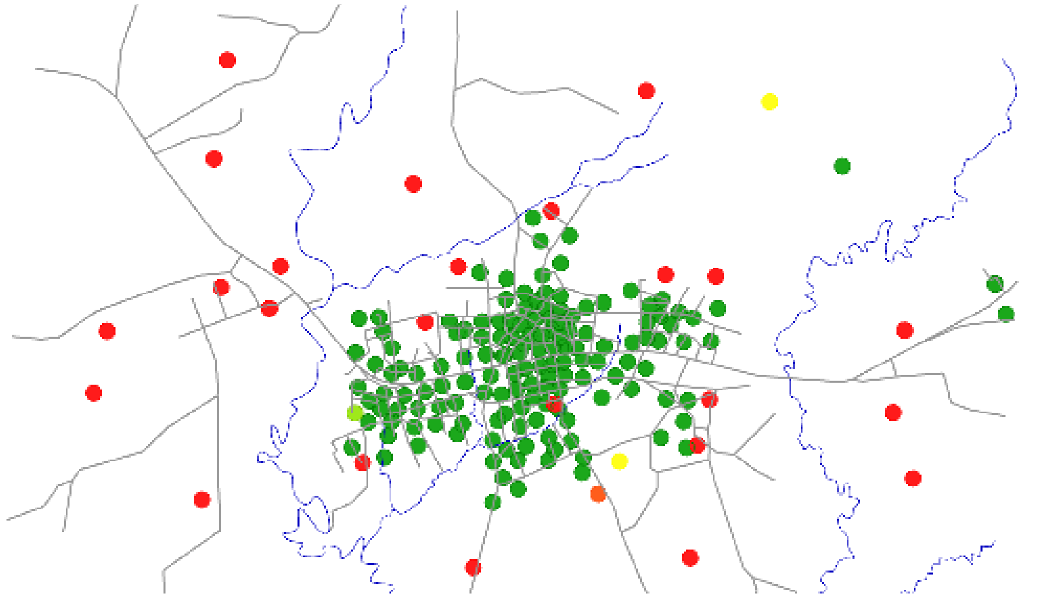


fig. 4.25: Method A: number of households per Circular Unit within 150m/2min walking distance

Method B:

no. CUs with <20 reached: 13

no. CUs with <15reached: 22

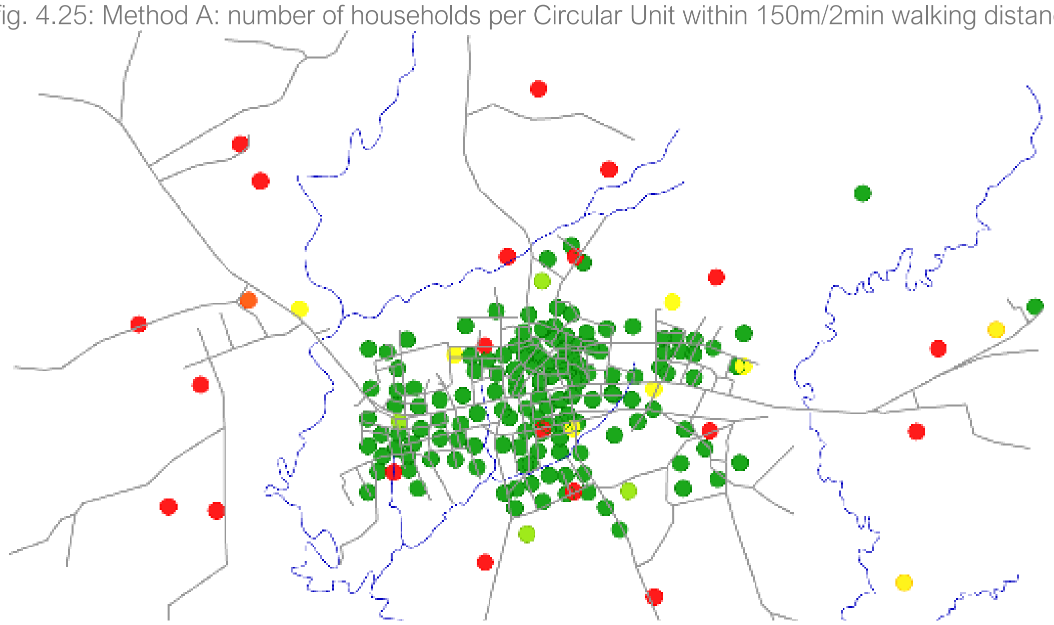


fig. 4.26: Method B: number of households per Circular Unit within 150m/2min walking distance

Method C:

no. CUs with <20 reached: 6

no. CUs with <15 reached: 18

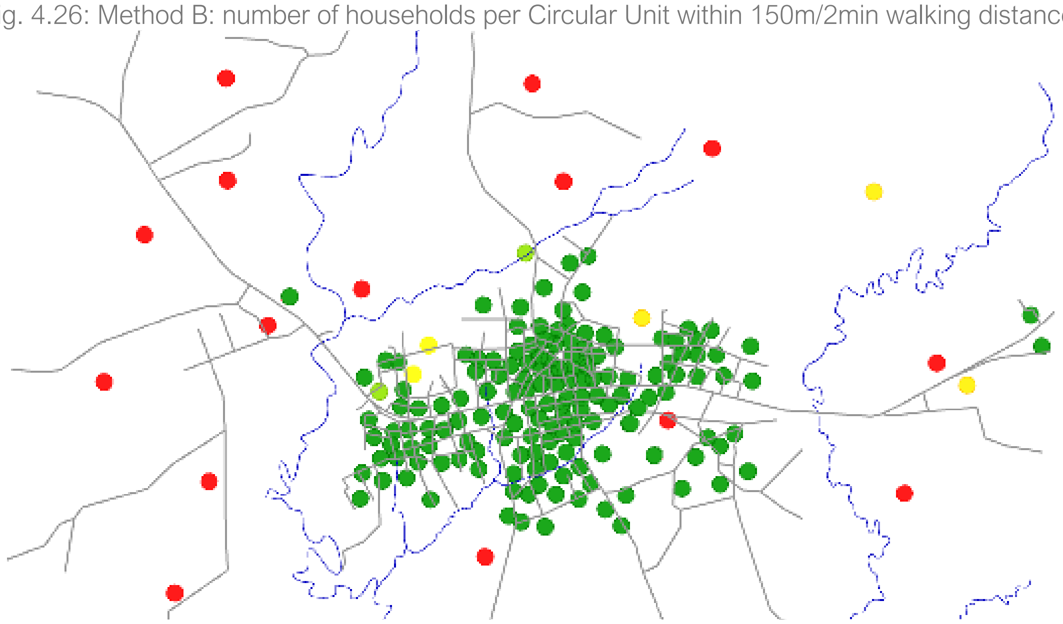


fig. 4.27: Method C: number of households per Circular Unit within 150m/2min walking distance

The different methods of clustering households can be seen in the resulting differing walking distances. The average walking distance from each household to its connected Resource Unit is comparable for methods A and B, while method C with an average of 112m created the best results. The differences are less significant, when the outer clusters with extremely long walking distances are excluded, and the average for only the inner city clusters (defined as all CU clusters with an average <150m) is counted, but still recognizable: Method C creates clusters with walking distances roughly 6% shorter than methods A and B. This can be explained when looking at the shape of the cluster in the different methods: starting from a center point and working the way outwards, somewhat half-moon-shaped clusters are formed, as the already clustered households are in a circle around the initiating center point. In contrast, when starting from the outside and working the way toward the center point, more round shaped clusters emerge, which makes for shorter walking distances from all points within.

When comparing the individual Circular Units generated from each method, differences can be seen by the number of households that are within the ideal walking distance of 150m/2min. Two measures were introduced: Circular Units, in which less than 20 households are within that walking distance. For these units, individual solutions could be found, for example re-clustering the distant households into other adjacent CUs, or leaving them as a part of the CU, if the walking distance does not exceed an extreme limit (proposed threshold: 200m). Other CUs, in which less than 15 households are within a 150m walking distance, require different solutions. The shared toilet and waste collection facilities are not appropriate in these conditions; they could be replaced by a collection system with individual dry toilets distributed to each household, for instance. Again, method C performs the best. With the clustering generated by it, for the smallest amount of existing households in Olonkomi, alternative Circular Unit solutions have to be established; most of the existing households can perfectly be served by the Circular Units.

Different ways of assigning the field to the CU

Similarly, different methods for assigning an agriculture field to each Circular Unit have been explored, based on the selection sequence of the Circular Unit to start with:

- Method A: selects the Resource Station of the Circular Unit furthest from the city centre, finds the closest agriculture field for it and connects to it, and iterates once again for the remaining CUs.

- Method B: selects the Resource Station of the Circular Unit closest to the city centre, finds the closest agriculture field for it and connects to it, and iterates once again for the remaining CUs.

The distance between the Resource Station and its assigned field is largely different between the two methods: Method A starts with the least central CU, selects the field closest to it, which is for all the first iterations with CUs quite close, as there is farmland all around the town. As the iterations progress, however, and central CUs get assigned a field, the only “available” ones are quite far away, far beyond the city limits, which creates some long transportation distances.

This does not occur when the opposite direction is applied, in method B: The first CUs to be assigned a field are the ones from the city centre, they get assigned relatively proximate fields just outside of the city limits. When the CUs at the outskirts get assigned their respective field, the fields in direct proximity are most likely already connected to a CU in the centre, so the compost

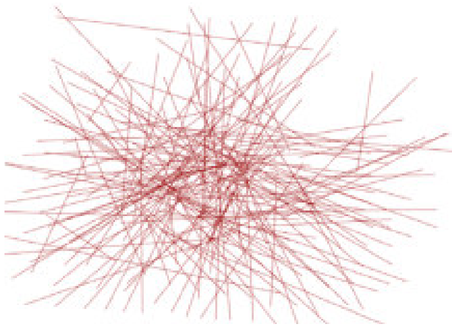
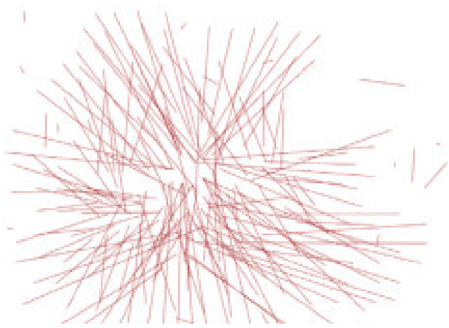
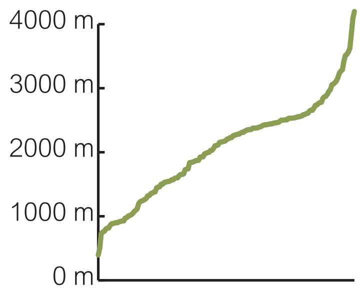
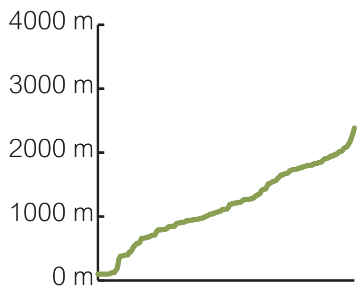
	Method A: picking a field starting with a Circular Unit from the outskirts inwards	Method B: picking a field starting with a Circular Unit from the centre outwards
direct connection from Resource Station to center point of field in each CU mapped		
distribution of transport distances per Circular Unit (composting station to center point of field)		
transport distance (aver-age)	2.060 m	1.170 m
travel time (animal-drawn cart)	15-21 min	8-12 min
cumulative transport distance per year (all 172 CUs, 80 runs for 80 m³ compost total)	28.352 km	16.136 km

fig. 4.28: comparison of transport distances between Resource Station and agriculture field within Circular Unit with different clustering methods

from the urban edge also has to be transported. All Circular Units have to organise and manage the compost transport, not only the ones in the city centre; in a way, this seems to be a fairer model. The time that has to be spent for each trip to the field is lower at 8-12 compared to 15-21 minutes by donkey cart, and the total distance travelled per year for all the compost produced by the CU is also significantly lower, which is an important factor concerning cost-efficiency and climate impact, if motorised vehicles were to be used.

Summarizing, the parametric sequence that produces the best results in regard of walking distances and transport distances is: (a) moving inward for clustering the households into CUs starting at the outskirts of the city, and (b) moving outward for assigning the field to the CUs, starting at the city centre.

This methodology was applied on Olonkomi once more, to show what a successful and sensitive implementation of the Circular Unit concept in an existing small town in rural Ethiopia could look like.

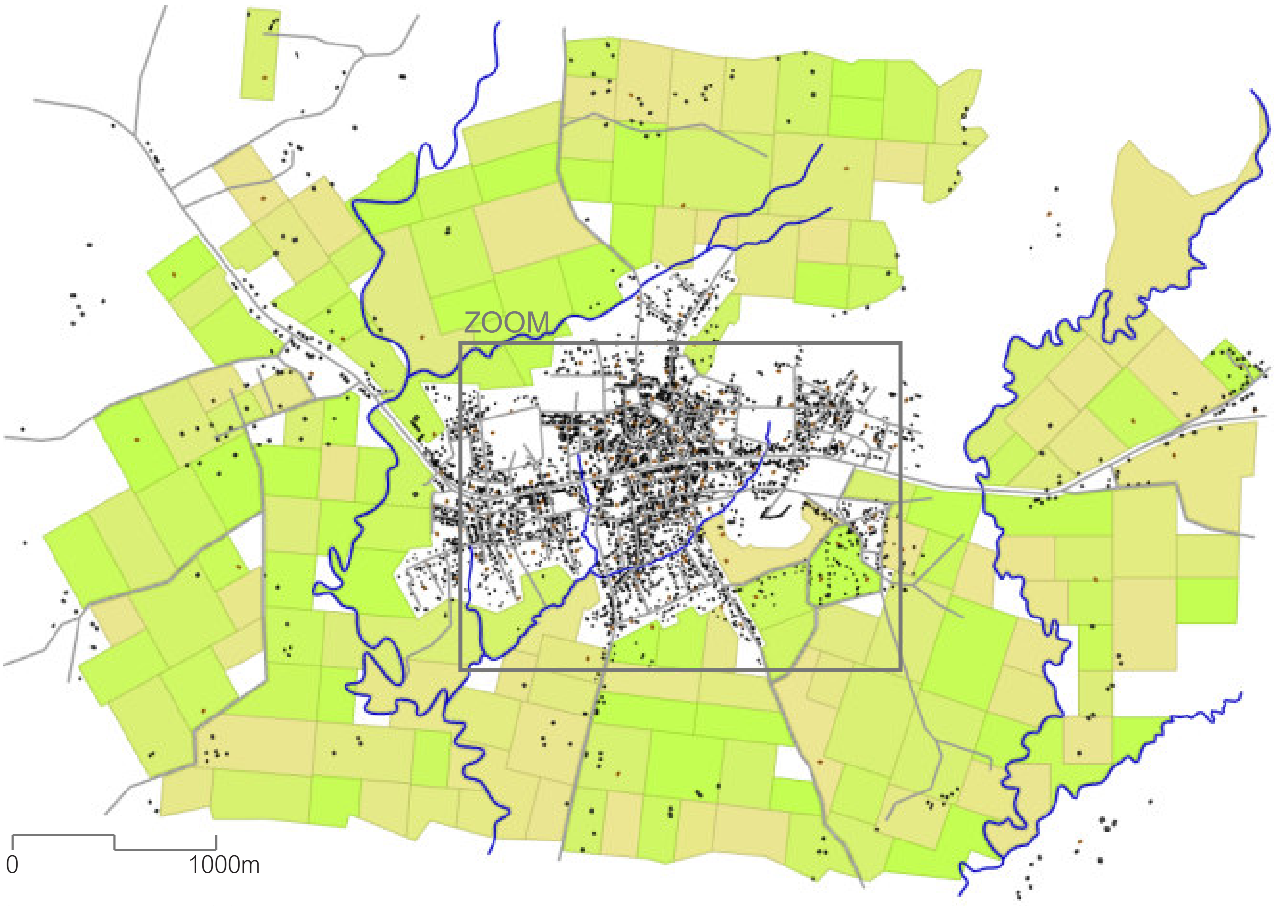


fig. 4.29: results of Circular Units in Olonkomi using optimum parametric implementation methods

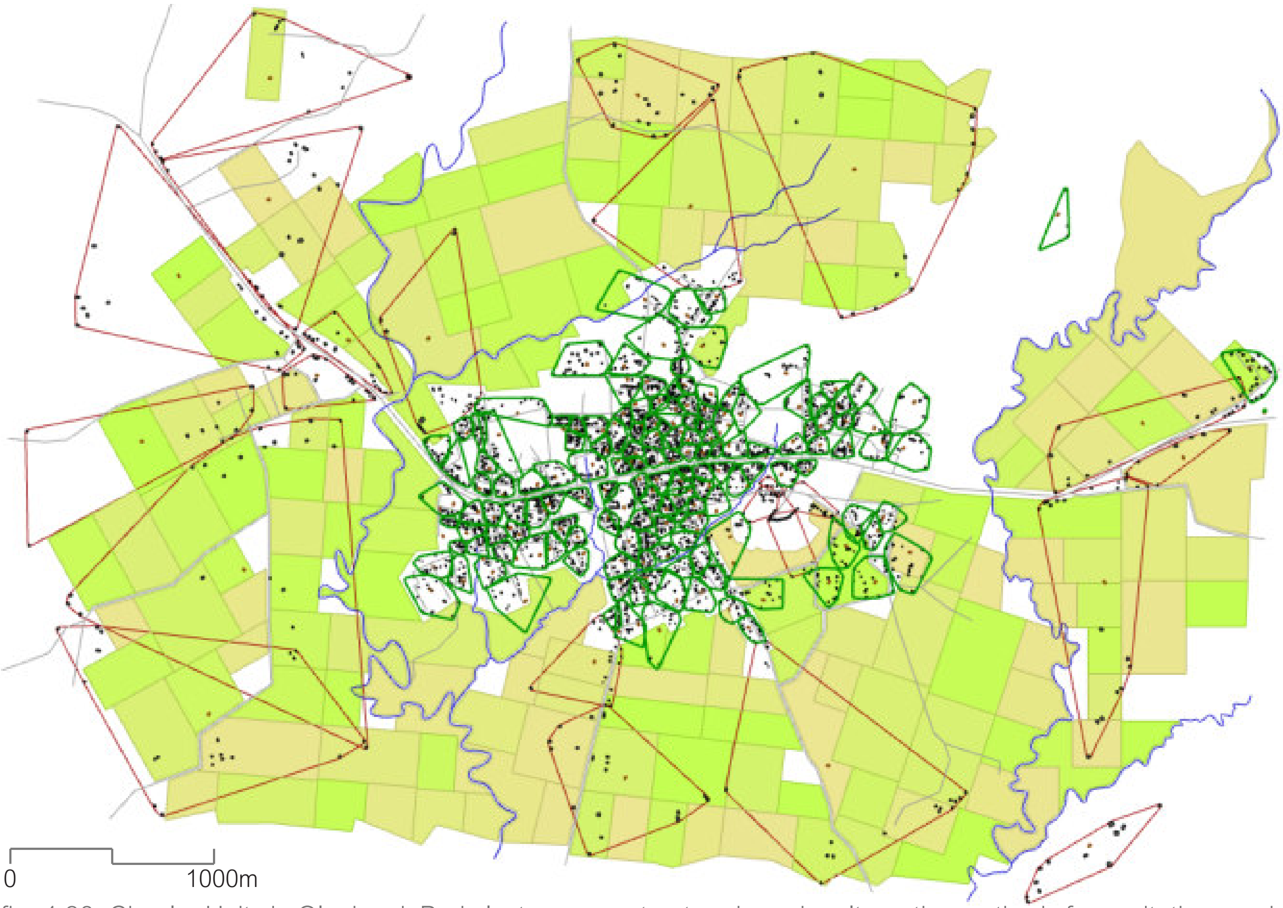


fig. 4.30: Circular Units in Olonkomi. Red clusters are not apt and require alternative methods for sanitation provision

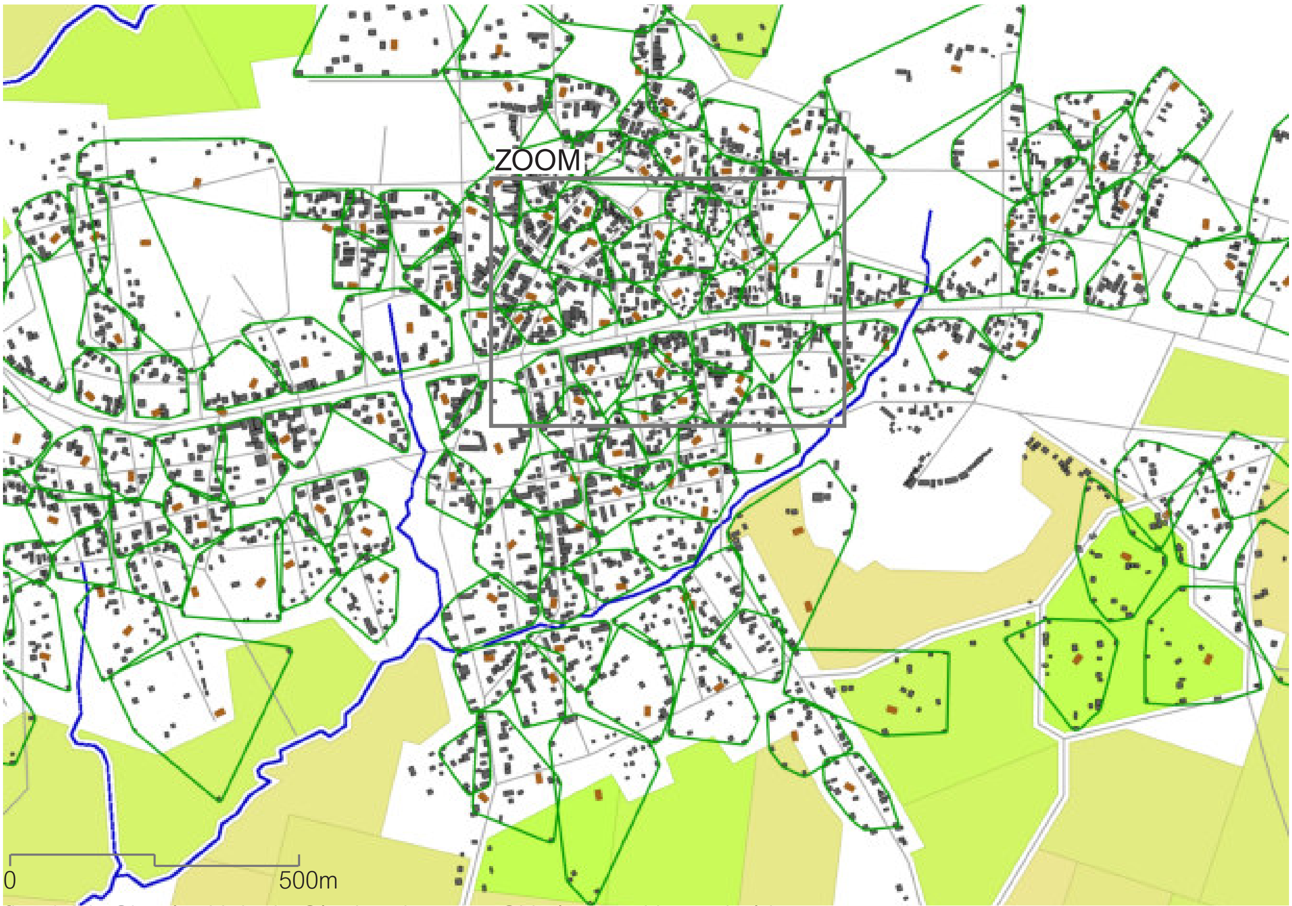


fig. 4.31: Circular Units in Olonkomi, zoom. CU clustered households

fig. 4.32: Circular Units in Olonkomi, zoom. CU clustered households and Resource Station (brown buildings)

Parametric Tests___ Scenario III________

Scenario III: urban growth

Applying adaptations in regard to new urban developments.

The third and final scenario looks into Ethiopia's close future, with an urban growth scenario based on the Circular Unit of a then medium-sized city. It is explored, at what point the system reaches limits in terms of population size, distances, available land, and transportation management.

Using computational design methods, urban growth is simulated. The small town of Olonkomi currently has ~3000 households in the built-up area and an additional ~400 households in the extended study area. The simulation generates a grown medium-sized city with a total of roughly 21,000 households or just under 100,000 inhabitants. This is an urban development that currently many Ethiopian cities are experiencing: The largest increase in urban population is expected to take place in small to medium sized cities.

The approach to the urban growth model foots on propositions of model projects for emerging towns in Ethiopia, such as the NESTown project in Buranest. The proposals for street layout and housing typology were considered a base and appropriated to this simplified urban expansion study.

To this fictional medium-sized city, the Circular Unit concept is applied, using the parametric methods that were assessed to be performing best in the previous Scenario II. With a bigger population and inherently a larger populated area, transport distances to the agricultural fields are expected to increase, as well. This opens the questions of when transportation with local methods, such as animal-drawn carts, will reach limitations. The observations help attempting to make robust estimations for the applicability of the Circular Unit to different city sizes or urban-rural configurations.

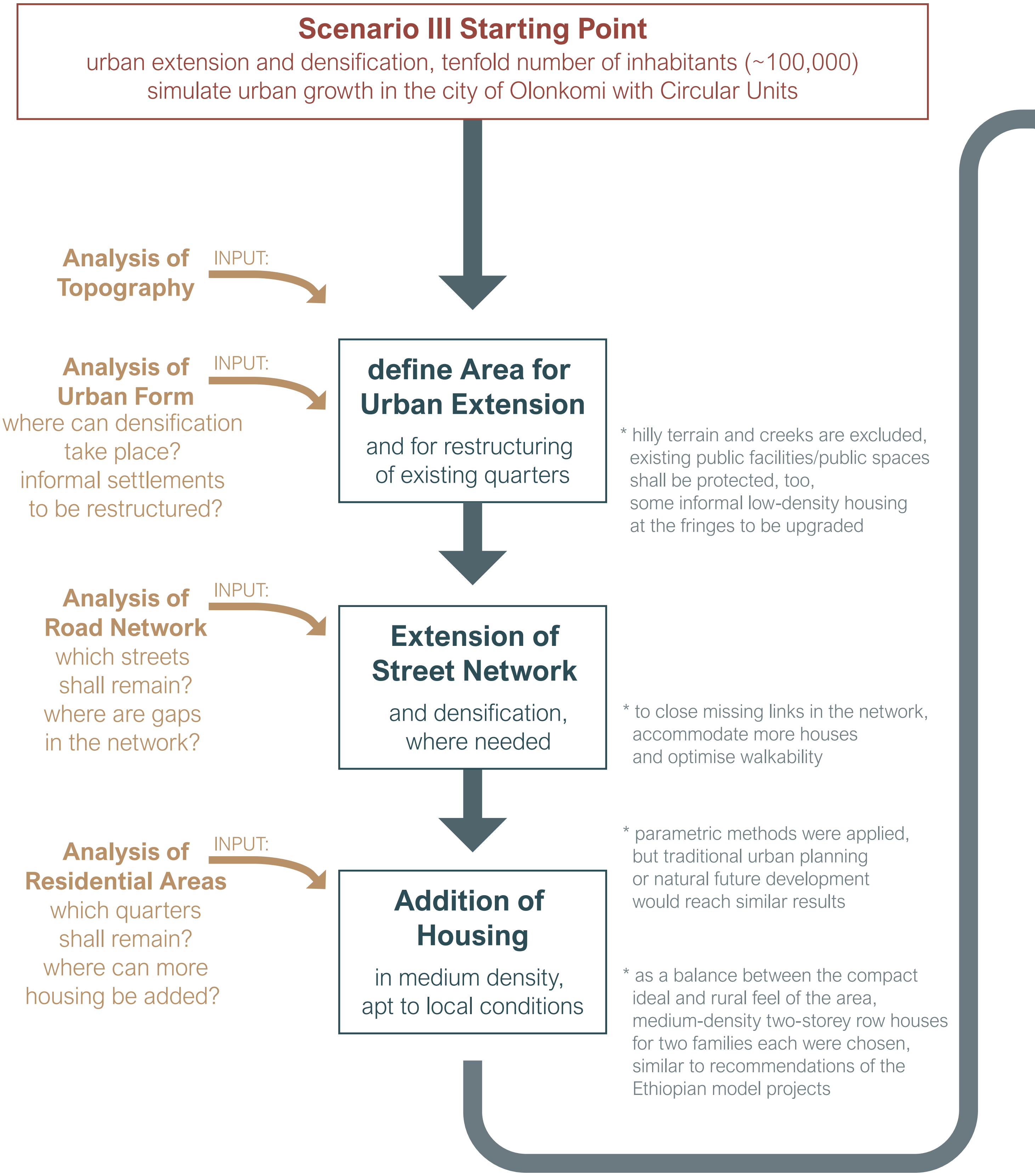
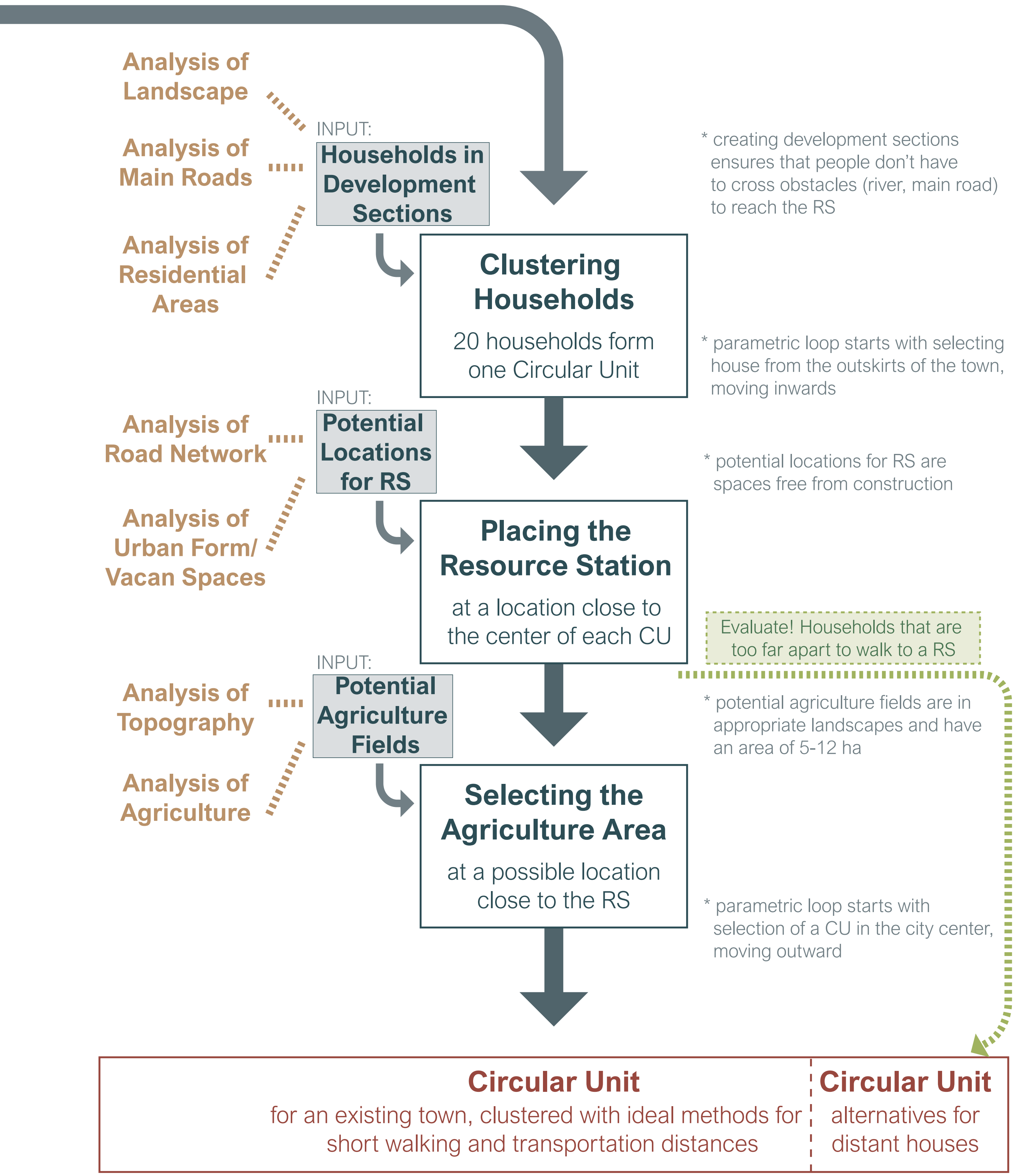


fig. 4.33: parametric approach to Test Scenario III


Analysis of Landscape
Analysis of Main Roads
Analysis of Residential Areas
INPUT:
Households in Development Sections
* creating development sections ensures that people don't have to cross obstacles (river, main road) to reach the RS
Clustering Households
20 households form one Circular Unit
* parametric loop starts with selecting house from the outskirts of the town, moving inwards
Analysis of Road Network
Analysis of Urban Form/ Vacan Spaces
INPUT:
Potential Locations for RS
* potential locations for RS are spaces free from construction
Placing the Resource Station
at a location close to the center of each CU
Evaluate! Households that are too far apart to walk to a RS
Analysis of Topography
Analysis of Agriculture
INPUT:
Potential Agriculture Fields
* potential agriculture fields are in appropriate landscapes and have an area of 5-12 ha
Selecting the Agriculture Area
at a possible location close to the RS
* parametric loop starts with selection of a CU in the city center, moving outward
Circular Unit
for an existing town, clustered with ideal methods for short walking and transportation distances
Circular Unit
alternatives for distant houses

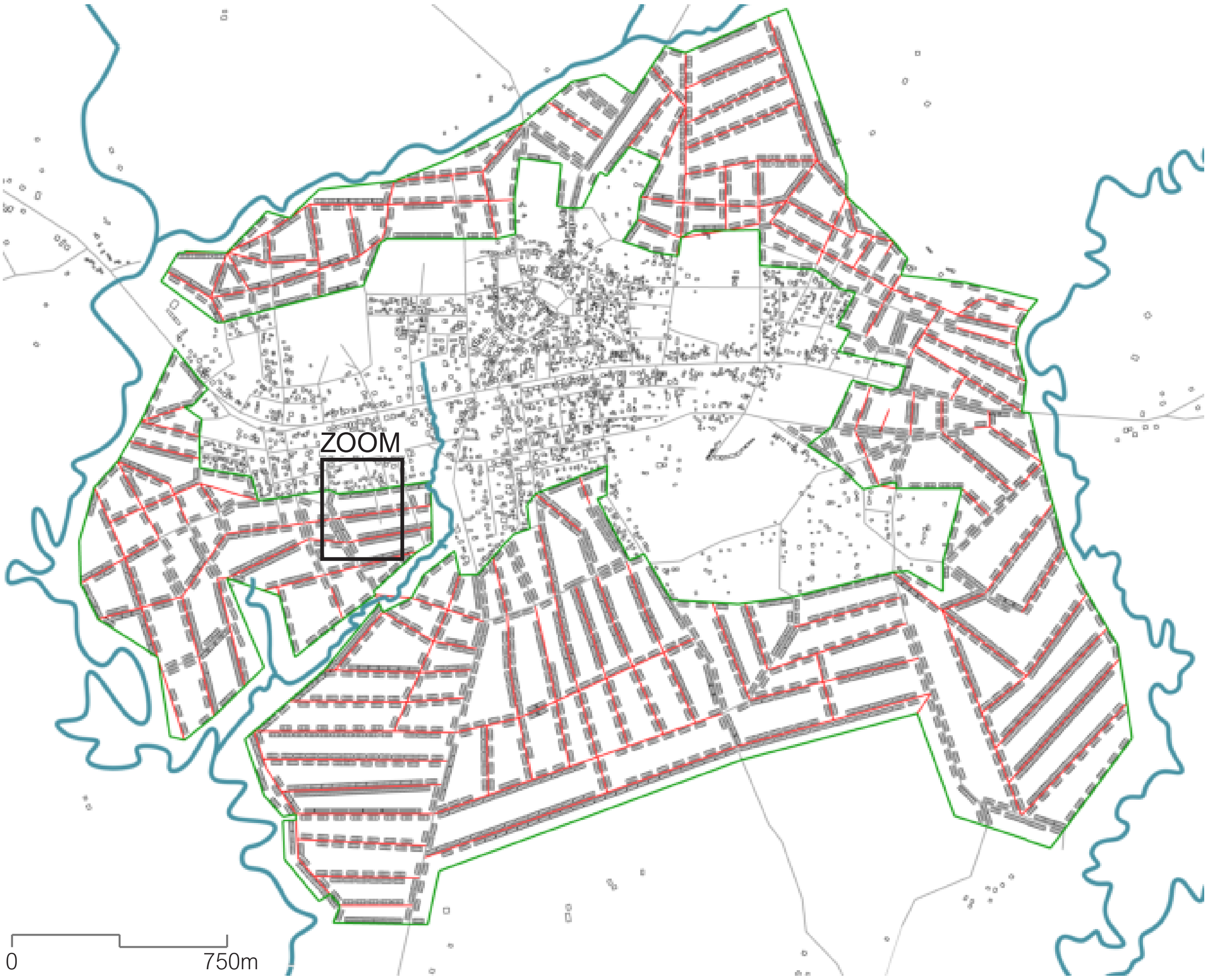
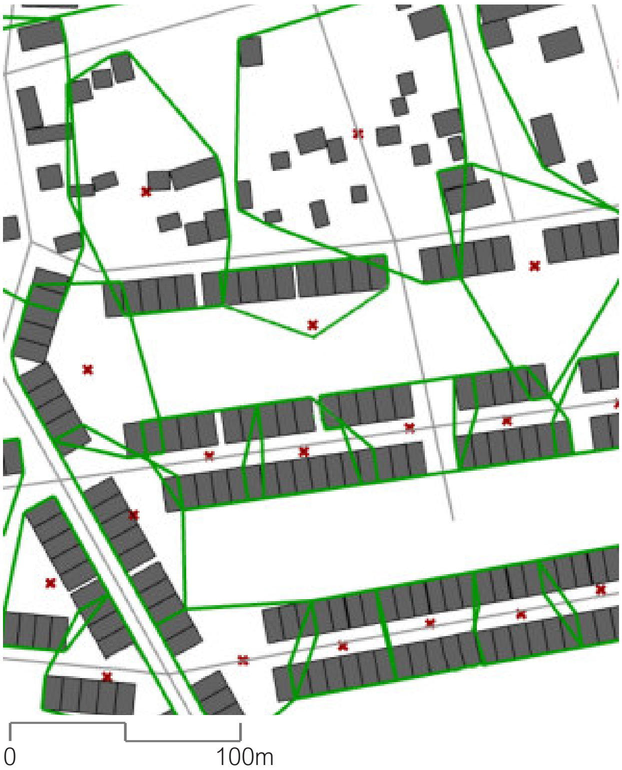


fig. 4.34: urban extension/renewal areas (green), street network extensions (red), additional housing

The urban extension areas (shown in green) lie around the existing centre of Olonkomi; in the West, North and East limited by natural barriers: streams and a hill ridge, and in the South extending into the agriculturally dominated open landscape. The extended and densified street network includes the existing path system and connects seamlessly to the roads. The housing typology that was chosen is a two-storey medium density solution of attached row houses (in this case houses are attached), which take inspiration from ongoing urban model projects in Ethiopia, such as the NESTown in Buranest.

fig. 4.35: Circular Units clusters. Note: 2 households per new row house, 1 household in existing house



Clustering the households into Circular Units follows the same principle as in Scenario II, where a household is picked, and it selects the 19 closest households within the urban development section. As there are two households per row house, they usually get clustered together. The way the parametric model is set up, it does not distinguish between new and existing households. Staying purely with the parameter of distance is a deliberate decision, which aims at preventing a clear separation between the residents of existing quarters and the adjacent new developments. So, where the walking distances imply that clustering new and existing households into a “mixed” Circular Unit is the most convenient, it is proposed that way in the map, as well.

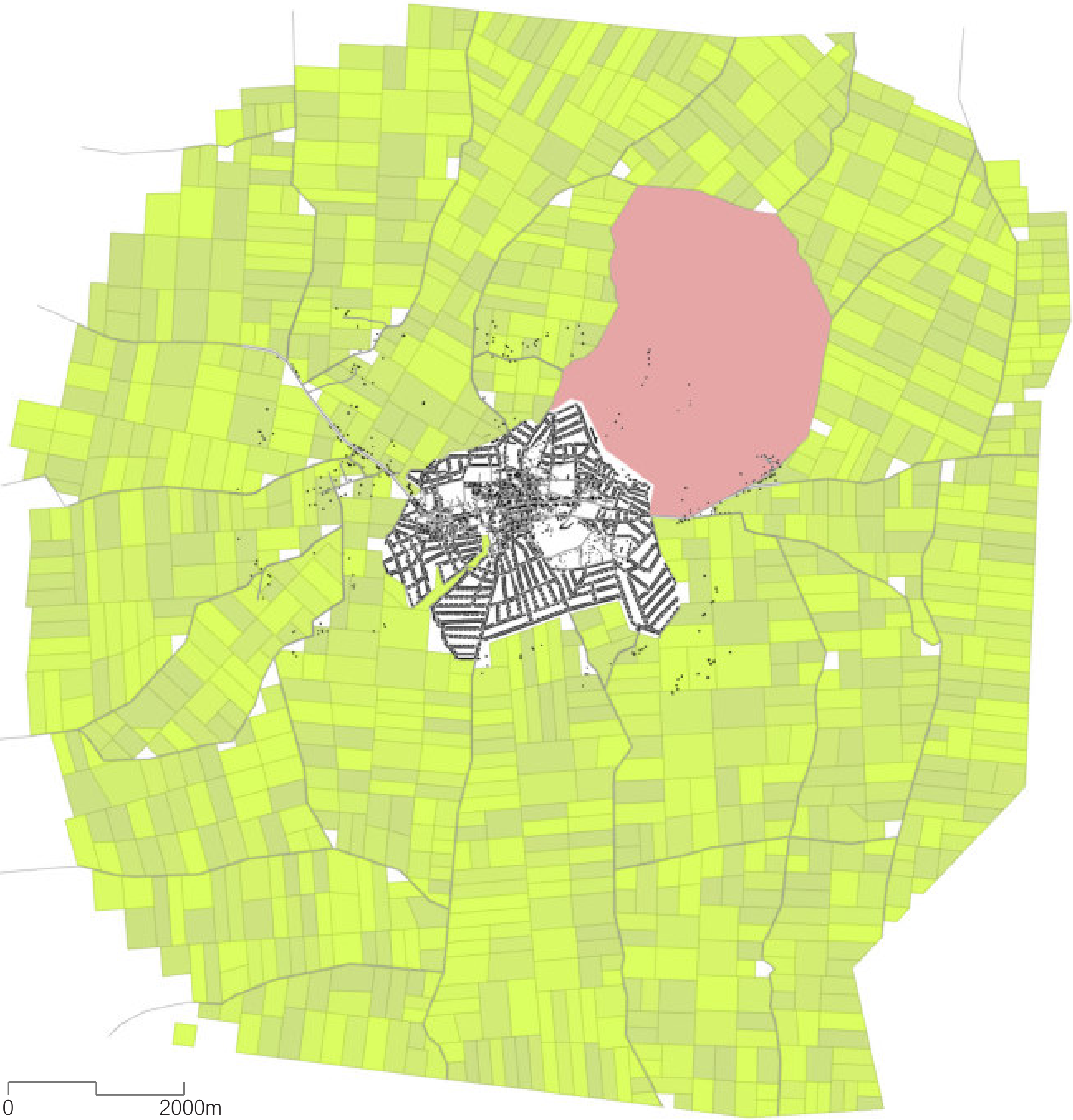


fig. 4.36: results of Circular Units in Olonkomi using optimum parametric implementation methods

The resulting map showing the implemented Circular Unit concept was generated using the parametric decisions that were deemed most successful in the comparing studies from Scenario II: clustering households starting from the outside of each development section moving inwards; and selecting the corresponding field for each CU starting from the city centre, moving outwards. The total agriculture area for the city with 100,000 inhabitants, which is estimated to be able to be fertilized through the compost produced in the Circular Units, is depicted here with a total size of 9.288 ha and an average field size of 8.6 ha. This is however, at current agriculture productivity averages, not sufficient to completely feed the population. Note that the hilly, steep and forested area is spared from agriculture development (shown in red).

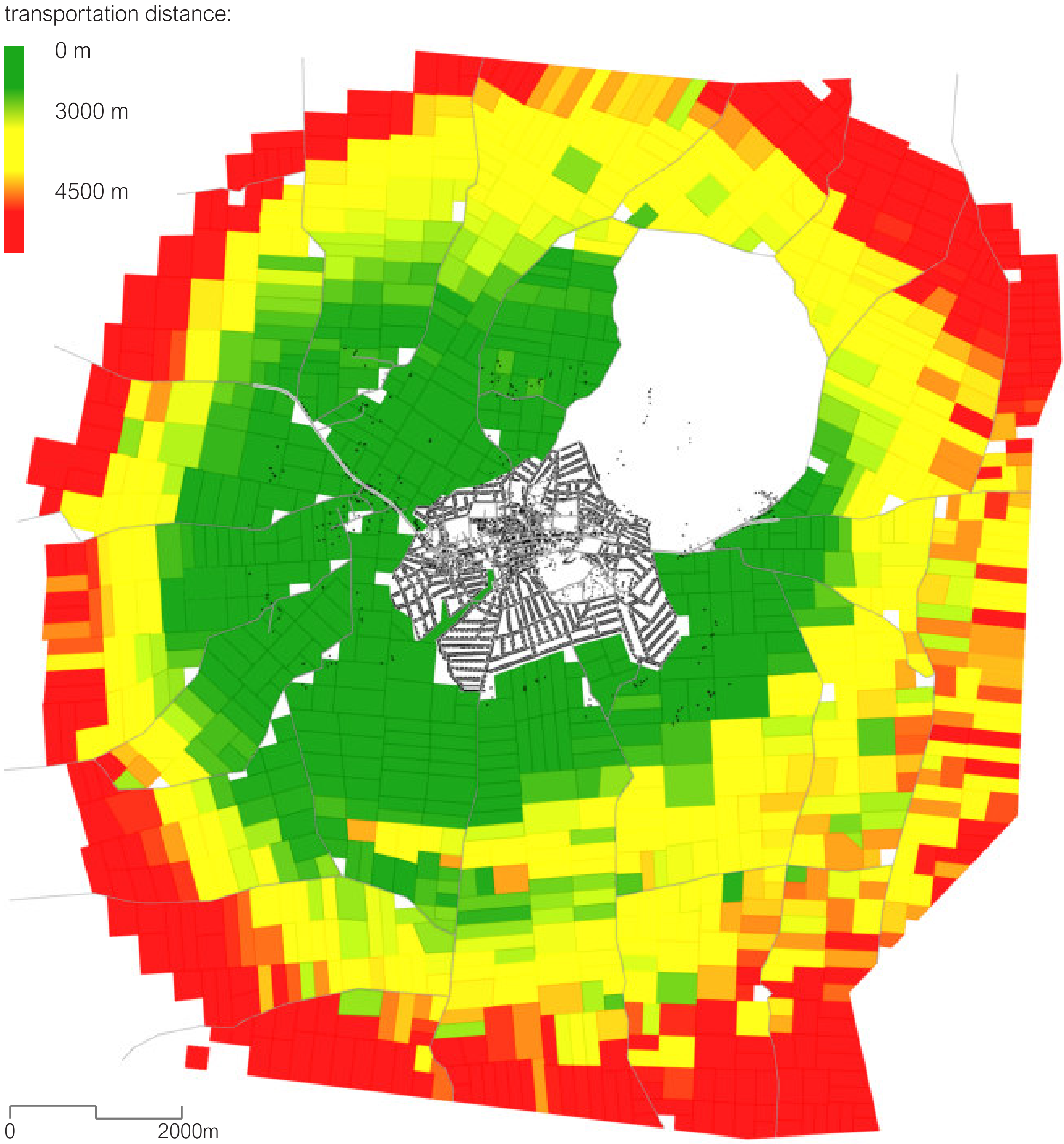


fig. 4.37: transport distance between Resource Station and assigned agriculture field (fields are shown)

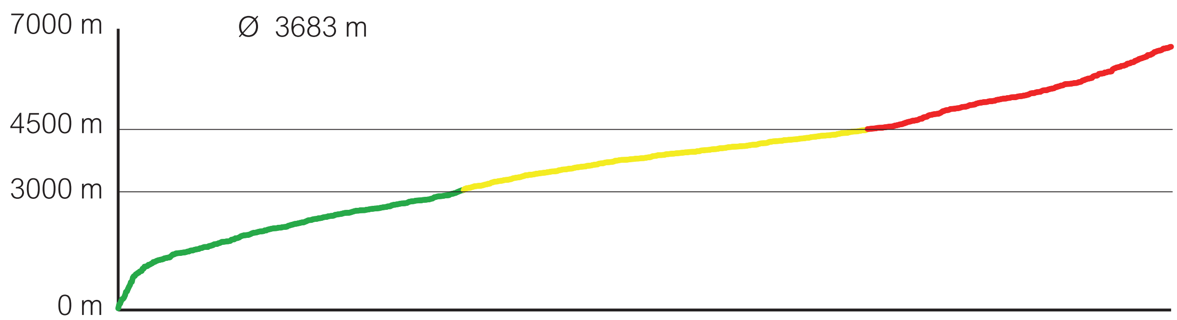


fig. 4.38: distribution of transport distances per Circular Unit (Resource Station and center of field)

Scenario III simulates the implementation of the CU in a much more densely populated city. The residential density in the urbanised area is around three to four times higher (an estimated 15.000 people per km² compared to 3.800 in the existing town), and that shows at the average walking distances for the inhabitants to the toilets in the Resource Station of their Circular Unit. The average in the 100,000 inhabitants scenario decreases to 41.3m, where inhabitants of the new developments oftentimes only would have to walk 20-30m to the shared facilities.

That being said, another value shows a significant increase compared to the small town: The transport distance for the produced compost to reach the field outside of town.

The average distance to be crossed per CU is 3683m, a way that has to be done around 80 times a year per CU, assuming that 1m³ of compost can be transported in one run. Considering local customs, the current state of low economic development in Ethiopia and the need to avoid motorised vehicles due to high GHG emissions and financial limitations, animal-drawn carts are the ideal mode of choice. When transporting goods, they typically travel at a speed of 4.5-7 kph (or roundabout 1km in 10 minutes). This puts a limitation to the distance that can or should be crossed with these vehicles, an ideal range can be assumed at up to 30 minutes for the one-way trip, and an absolute maximum at an expected travel time of 45 minutes.

These thresholds divide the 1080 total Circular Units into roughly equal amounts of 360 CUs with their field at a distance under 3km, 360 CUs with their field at a distance of 3-4.5km and 360 CUs with their field at a distance larger than 4.5km from the Resource Station. The latter Circular Units are above the indicated maximum distance and therefore will have to adapt their transportation regime, either with setting aside more time for additional staff to transport the compost and distribute it onto the field, by selling the compost to a third party that then would have to organise transportation, or by adopting a different transportation method, e.g. with a motorised vehicle that could be shared with other Circular Units.

Assuming the premise of only site-typical, non-motorised traffic for compost transportation should be kept while implementing the Circular Unit concept as a given, a limit to the implementation of the CU in regards to population size of a compact city can be calculated. In the example here, 360 CUs had distances that were too long, that means 7.200 households with 33.120 inhabitants. For the remaining 14.400 housrholds with 66.240 inhabitants, in contrast, the field would be at a reachable distance.

If a medium-density city of 66.000 inhabitants is in a location where around 85-90% of the land in the direct surroundings are suitable for agriculture (free from other large settlements, topographic obstacles or natural preservation areas), it can be assumed that the Circular Unit concept as proposed is a suitable measure to provide sanitation to the inhabitants and improve the agricultural productivity.

Reflection

5. Reflection

5.1 Summary of findings

This research investigated the spatial implications of promoting a circular nutrient flow in agriculture in Ethiopia. With the introduction of the urban integrated model of the Nutrient-Cycle-Based City, key connections and interdependencies between material flows and the related urban elements were shown. Central urban elements to be promoted for closing the nutrient cycle are elements that collect human excreta and re-integrate the contained nutrients into the circular resource flow.

For the on-site organisation of this resource flow in low-income economies, the “Circular Unit“ is proposed: An urban entity for 20 households with a closed nutrient loop, which is partially self-sustainable. Human excreta are collected in shared dry toilet facilities, and subsequently decomposed to nutrient-rich compost with great fertilizing capabilities.

Applying the compost to the field addresses environmental problems such as land degradation, erosion, stress through climate change challenges and ecological damage. Simultaneously, and very important for the local communities, the agricultural output of the cultivation areas is increasing tremendously, improving issues of food security, malnutrition, impoverishment.

In addition to these resource-related improvements, the concept also finds sustainable answers to sanitation provision in low-income economies, especially for small cities or rural areas. The dry toilets are a cost-efficient way of providing safe and hygienic sanitation to communities in a way that can be applied with small local interventions, without changes to existing sanitations systems with only partial coverage.

The compost
that can be produced from the excreta
and organic waste of one person
is enough to fertilise
40% of the cultivation area
needed to provide enough food
for themselves.

From an urban development perspective, the parametric tests on the location of Olonkomi show the Circular Unit in different exemplary implementation scenarios.

Investigating different implementation scales, different density, different urban form, different spatial configuration altogether, shows how flexibly the Nutrient-Cycle-Based City can be implemented using the Circular Unit approach: It can be applied in most traditional rural settlement patterns and small towns in Ethiopia.

It is adaptable to existing conditions in different settlements, for example by finding alternative modes of collection or transportation in places where distances would be too long for walking. Further, it can be a central driver in rural/urban development, where a group of households directly clusters around a Resource Station to form a small community village, or where the shared facilities help bond residents of new urban developments to those of existing settlements.

When implementing the concept in an entire existing small town, there is a sequence for formulating the Circular Units in order to create shortest walking distances while reaching most existing households, and shortest transport distances for the compost between composting facility and field: households should be clustered starting from the city fringes towards the center; fields are ideally assigned starting the opposite way.

The framework for possible scales of implementation, specifically in Ethiopia, but certainly in all countries of a similar societal and economic position, showed to be ranging from a small community of roughly 20 households up to a small city of 66,000 inhabitants, where compost transportation with conventional methods reaches limitations.

It should be emphasized, though, that the Circular Unit is considered a prototype that should always be adapted to local precepts. So, for instance the study's findings regarding size limitations become extendable, if appropriate methods for collectiion, dispersion and transportation of the compost in a climate-friendly way can be found; or for example compost use in urban gardens is established.

The implementation can in all cases be a bottom-up approach, initiated in the communities with individual groups forming Circular Units, or a more large-scale, city-wide intervention for sanitation provision through the responsible government authorities.

For the success of the implementation, good community involvement has shown to be key in comparable pilots and ongoing projects around the world. Including the potential users in the process and a good knowledge management concerning proper use and upkeep are essential. Only if the users do use the system at all times can it have its biggest impact, only then can the many advantages become directly apparent to the local community, and only then can the Circular Unit spread and more communities will be reached.

5.2 Limitations of the study and outlook on further research

The study is following an upcoming approach of centering urban development around a specific resource flow, focusing on the spatial implications of such measures. Especially with the nutrient flow, this has rarely been done, much less for countries of the Global South, and therefore there are obviously limitations to what the study was able to investigate, which gives room for refinements and further research to be conducted.

Connections can be made to the agriculture sciences, where instead of assuming an average prodictivity and necessary land area as was done here, different crops (e.g. Ethiopian cereals vs. wheat and maize), cultivation schemes (e.g. monocropping vs. intercropping), and the influence of rising productivity through sustainable intensification on the area needed to feed one person could be conducted. This can have direct influence on the spatial configuration of the Circular Unit, with smaller neccessary field areas for instance.

From a sociology point of view, the integration of the Circular Unit and its following role as a connector within local communities and an urban point of attraction would be important. This would help refining the broad implementation guidelines which this study proposes, to further guide the implementation process and ensure community empowerment, acceptance, long-term use of the system, and good integration of the new elements into the urban fabric.

Looking at the way the computational tests were set up, possible improvements include introducing a way of analysing existing land ownership of the respective site, so that fields would be assigned to Circular Units not solely based on distance, but also on the residents already cultivating the land. Similarly, further site-specific factors could be included, such as the topographical terrain for generating easy transport routes and a landscape/field organisation most resilient to extreme weather events and erosion.

The scale that was chosen for testing the strategy allows for a somewhat holostic understanding of the spatial implications. It can be understood how the urban fabric would react to introducing the Resource Stations on a small scale; at the same time what limitations of the concept in terms of distances and city size are on a larger scale. But the scale is still not big enough to dinstinctly show for the positive landscape and ecology effects that sustainable intensifictaion through compost use is expected to have. Green corridors, ecological connections and such can very well be combined with sustainable agriculture, but they do require a larger scale of investigating how these landscape elements should be placed in coherence with natural, site-specific conditions, and in relation to urban settlements.

5.3 Transfer of lessons learned

There are lessons that can be taken from this study, stepping away from the nutrient cycle in agriculture and dry sanitation provision.

Contemporary urban planning will more and more need planners to center their work around the flow of resources and materials. The climate crisis already severely affects most regions of the world - it is absolutely essential that ways of closing all resource cycles are found quickly. Good urban planning can do that - as this study shows, with often small interventions, small tweaks to the system that have an impact on many levels.

The takeaway of this exemplary study of circularity in urbanism should be that the urban elements that we plan, regardless of the cultural environment, have to serve the strive towards circular flows - and this research shows just how to do that with few broad basic steps. Firstly, understanding the respective resource flow, secondly looking at its relation to urban elements (or, as Christopher Alexander would call them, “patterns“) and their existing connections - in order to finally propose the new or changed urban elements that are needed to make for a more sustainable, future-prepared, circular city.

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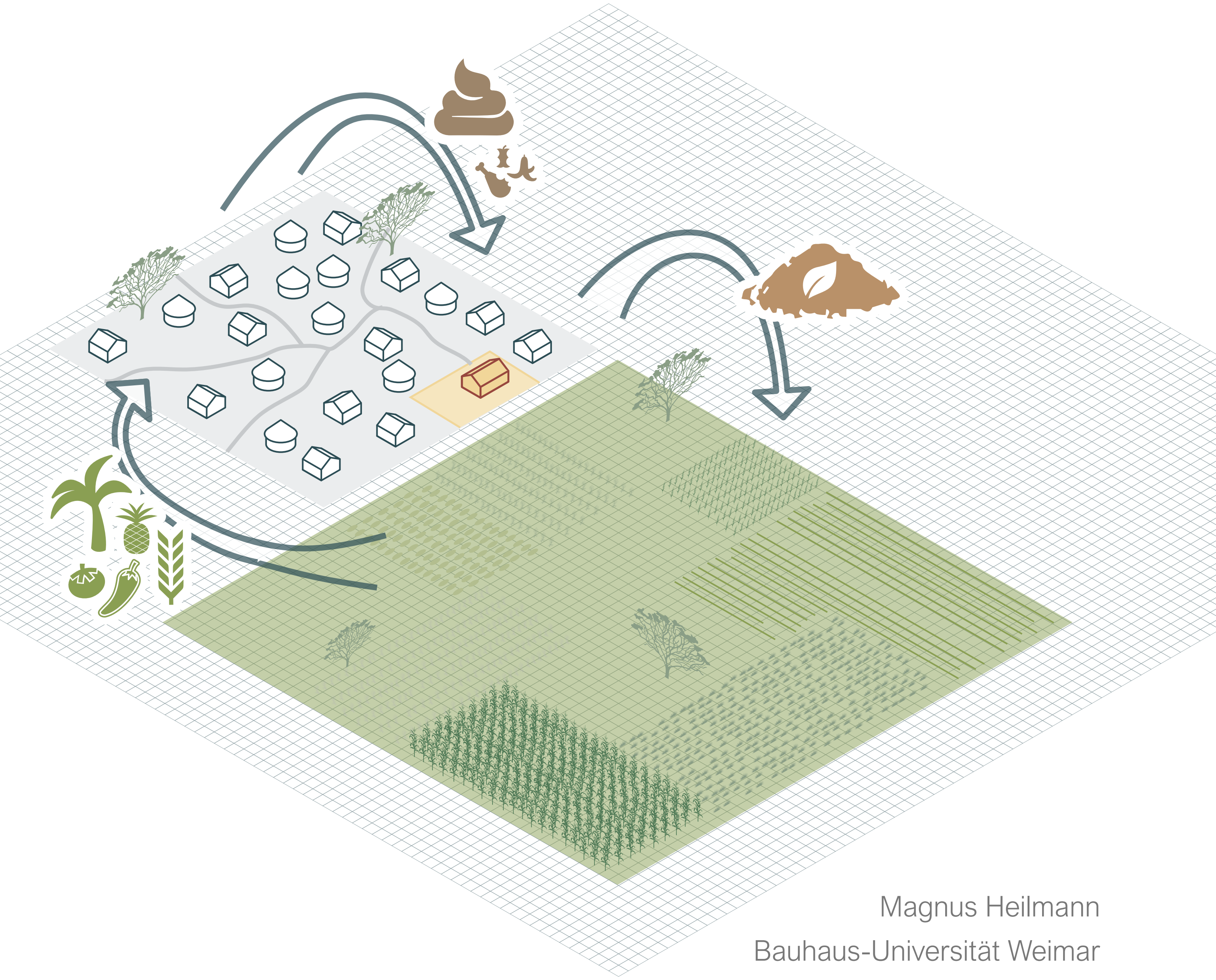

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