# Terra Preta Nova production for sustainable agriculture within the framework of Regional Material Flow Management

Mak Đukan
51210615
IMAT 2012

Supervised by Masanori Kato and Peter Heck

13.07.2012

Dissertation Presented to the Higher Degree Committee Of Ritsumeikan Asia Pacific University In Partial Fulfillment of the Requirements for the Degree of Master of Science in International Cooperation Policy

# DECLARATION

My name is ĐUKAN, Mak, male, born on 04.12.1985. I hereby solemnly declare that I have written myself this APU Research Report IV. All the references or contents from other sources have been properly acknowledged. I will take full responsibility for any plagiarism that occurs in the original content of this paper.

Date:

Signature:

To my bellowed family that has always been there with me . . .

Mojoj dragoj obitelji, koja je uvijek bila uz mene . . .

## Acknowledgements

This is the part where the writer can let off steam and write in an un-academic way. After 23000 words I find that as a huge relief.

Two years, a lot of sweat, consultations, research and hours of writing and sitting down. . . it has been long since the IMAT program started. I remember sitting in Japan and listening to professor Peter Heck lecture on Terra Preta. We watched a video that presented Terra Preta and its Amazon origin. This was a turning point in my IMAT schooling. My interest for this highly fertile soil grew and I wanted to know more. The potential of streamlining waste flows to reproduce terra-preta-like soils grew on me as an idea. Finally, after a series of consultations I decided to write this thesis. That being said, I would foremost like to thank professor Peter Heck for introducing Terra Preta to me. I would also like to thank professor Masanori Kato, who has devoted a lot of his attention towards correcting my thesis and giving guidance.

There are many people I could acknowledge that helped me during this program. But two people stand out by a long margin and if it weren't for them I would hardly make it through the program.

I would like to give special recognition to Shifani Sood, who listened to me while I was down and made me see the positive side of everything. Your patience and craziness will never be forgotten.

There are hardly any appropriate words to acknowledge Ranahansa Dasanayake for all of this guidance in matters relating to academics and life in general. You have been a great source of inspiration and I would like to thank you for this. May you live long!

Finally I would like to give special thanks to my mom who always found time to consult and listen to me. Many merits to my father and brother who have inspired me with their global travels to see the world myself.

## Table of Contents

## List of Figures

## List of Tables

## Abbreviations

| | |
|---|---|
| TP | Terra Preta |
| ADE | Amazonian Dark Earths |
| MFM | Material Flow Management |
| TPN | Terra Preta Nova |
| HTT | Highest Treatment Temperature |
| MBT | Mechanical Biological Treatment |
| AD | Anaerobic Digestion |
| CO2 | Carbon dioxide |
| GHG | Greenhouse gas |
| FAO | Food and Agriculture Organization of the United Nations |
| GIZ | Die Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH |
| N | Nitrogen |
| P | Phosphorus |
| K | Potassium |
| Ca | Calcium |
| Mg | Magnesium |
| NUE | Nitrogen use efficiency |
| N2 | Elemental nitrogen |
| N2O | Nitrous oxide |
| SOM | Soil organic matter |
| CEC | Cation Exchange Capacity |
| US | United States |
| BC | Before Christ |
| MFA | Material Flow Analysis |
| LCA | Life Cycle Assessment |
| CFP | Carbon Footprint |
| LCI | Life cycle inventory |
| GDP | Gross Domestic Product |
| SA | Stakeholder analysis |
| DCFA | Discounted Cash Flow Analysis |
| CIA | Central Intelligence Agency |
| OMSW | Organic Municipal Solid Waste |
| MSW | Municipal Solid Waste |

## Abstract

Terra Preta is a fertile soil originating from the Amazon basin, which is characterized by its black color due to high charcoal content, known in the modern literature as biochar. Research indicates that adding this highly porous material to soil increases its nutrient and water retention and stimulates microbial activity, which typically results in higher than normal crop yields. Besides this it increases the carbon sink capacity of soil and therefore, potentially reduces atmospheric $CO_2$ levels.

Mixing charred biomass with animal and vegetal waste, rich in nutrients, created the fertile amazonian dark soils. Findings that Terra Preta (TP) might have been produced by indigenous Amazonian indians, implies that it could be reproduced today. Terra Preta and biochar are seen as alternatives to increasing crop yieds, reducing synthetic fertilizer demand and shifting the paradigms of conventional agriculture.

Reproducing Terra Preta per se would, however, be an impractical task due to the great variety of input materials. Organizing production systems that streamline such various material flows could be complex and uneconomical. Recreating the exact Terra Preta properties is also high unlikely, due to scientific uncertainties in the production process.

Terra Preta Nova was therefore defined as a term that describes a soil conditioner with terra-preta-like properties, which is produced by mixing biochar with organic residues. Examples from Germany indicate that inputs into Terra Preta Nova production could range from composted garden waste, slurry from biogas production, bacteria and biochar from sewage sludge. Many other variations exist (Figure 14). However, most material and energy systems lack such organization and are dominated by chaos. Material and energy flows are unorganized and there is no cooperation among regional stakeholders.

This thesis investigates developing Terra Preta Nova systems, using the Material Flow Management (MFM) methodology. MFM is an integrated resource management approach that holistically optimizes material and energy flows. This refers to using

technologies that interlink material and energy flows across the economy. Outputs from one segment (households, industry etc.) are seen as inputs for others.[1]

Reasons for shifting from conventional to alternative agricultural systems are given in the first part. Resource scarcity and environmental degradation of conventional agriculture are presented as the main arguments. This is followed by a review of the science on Terra Preta and biochar. Most of the discussion centers on biochar, because it is believed to be the backbone of TPs fertility.

Terra Preta Nova (TPN) systems are described in the final part, where most of the discussion focuses on feedstock requirements. Finally, the thesis describes the MFM methodology for developing Terra Preta Nova systems. Risks of applying this methodology for TPN development are given at the very end.

Results of this thesis could be used for practical field investigations into producing alternative agricultural systems that are based on Terra Preta Nova.

---

1 For instance, when industrial waste heat is used for residential heating

## Problem statement

Modern agriculture is not sustainable because it relies on linear resource consumption. Material and energy flows in agriculture are consumed and processed into low quality waste. This remains unused and in many instances poses disposal and environmental problems.

Several drivers of change are stimulating the shift towards sustainable agriculture and these are a) resource scarcity b) environmental degradation and c) food security. As population continues to increase in the 21st century, and developing economies increase their living standards and demand for food, these drivers of change will become more alarming.

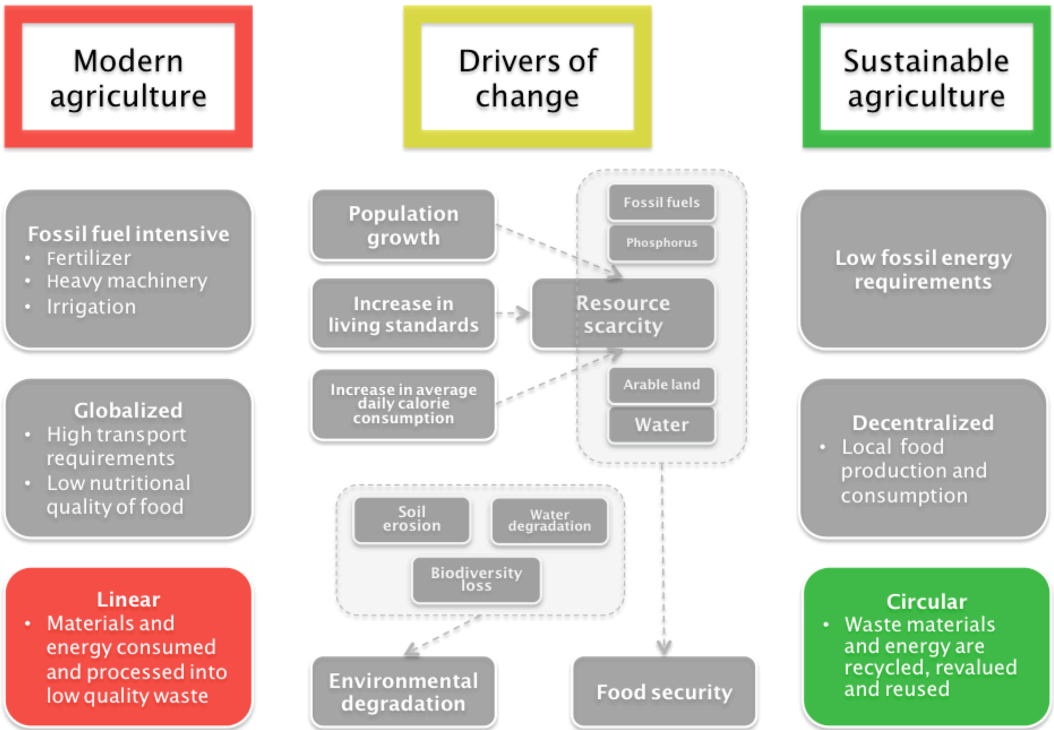


**Figure 1: Problem statement. Source: Author**

Sustainable agriculture consumes less fossil energy and recycles waste material and energy. These circular systems are decentralized and enjoy greater food security. Production of food takes place near the point of consumption making these systems less dependent on global food-trade patterns.

Terra Preta Nova technologies create circular agricultural systems. The discovery of Amazonian dark earths has sparked imagination among many scientists, business people and enthusiasts who together envisage the dark earths and biochar as solutions to modern agricultural problems.

Biochar and terra preta created a wave of interest because of their ability to increase crop growth in unfertile amazon soils. Their anthropogenic origin suggested they could be reproduced on mass scale. Is there ground for such assertions?

## Key questions

This thesis intends to answer these questions:

1) Is Terra Preta Nova a viable solution for sustainable agricultural systems?
2) Could Terra Preta Nova be used on a global level or is it just suitable for particular regional conditions?
3) What are the obstacles of creating Terra Preta Nova systems, using the Material Flow Management methodological approach?

The thesis will employ desktop research in answering the above stated questions. A research summary will be given in the concluding segment.

## Sustainability of agriculture

Agriculture is creating environmental stress on ecosystems and in some cases leading to their collapse. Modern examples that testify this are numerous. Some of the most recent cases include the Dust Bowl of central United States and the destruction of the Aral Sea ecosystem. Ancient history, however, testifies that this is not only a modern problem.

During history humans have mismanaged the land leading to collapses of entire civilizations. Soil salinization, due to excessive irrigation, is thought to be one of the main reasons for the decline of ancient Mesopotamia. In ancient Greece monoculture farming of crops like wheat, created soil erosion problems that depleted land of valuable nutrients and decreased steadily food production.

This chapter stresses that mismanaging the land, in the sense of employing intensive farming techniques, as used today, leads to collapses of ecosystems and civilizations alike.

## Environmental collapses and agriculture

Agriculture is both responsible for the rise and decline of numerous societies. Through history it has also helped induce collapses of entire ecosystems. This segment highlights some well-studied examples.

### Soil salinity in the Fertile Crescent

Humans have through most of history lived as hunter-gatherers or foragers (Salonius, 2008). Domestication of plants and animals 13000 years ago, gave early farmers the means to begin sedimentary life (Diamond, 2002). Settlements that mastered their land had the technological, demographic and economic means to displace hunter-gatherers. Food surpluses, amassed due to advanced agriculture, enabled the creation of large settlements and complex societies.

Hunter-gatherers of the Fertile Crescent in southwest Asia first developed agriculture. This is because the area was native to many useful plant and animal species that are still in domestication today (Diamond, 2002). The Fertile Crescent, known as the cradle of civilization, was home to ancient Mesopotamia, the oldest civilization in human history. The area owes its fertility to the rivers Euphrates and Tigris that flow from the mountains of East Turkey to the Persian Gulf and carry valuable nutrients and water. The rivers also contain large concentrations of salt, originating from the sedimentary rocks of the northern mountains.

River water, floods as well as excessive irrigation have increased the amount of salts in the areas ground water leading to soil salinity problems. High salt concentrations obstruct microbial soil activity and decrease the plants ability to absorb water and nutrients. Excessive irrigation exacerbates the problem by increasing the ground water table (Jacobsen & Adams, 1958). When the salty ground water increases in level, it can reach the root zone of plants. It then raises the osmotic pressure of soil water making it harder for roots to absorb water (Diamond 2006). Increased salt concentrations also make the soil less permeable, resulting in decreased yields due to less efficient plant uptake of water.

Soil salinity played a major role in the breakup of the Mesopotamian civilization. Increases in agricultural production in the Fertile Crescent, lead to more intensive irrigation. Water from the great rivers was diverted via constructed water canals. Ultimately this practice increased the salinity of soil and salty ground water levels, leading to a decrease in crop yields. The water canals themselves did not prove efficient, since silt accumulations often disrupted water distribution.

Records show that barley production decreased continuously from 2537 liters per ha in 2400 B.C to 897 per ha in 1700 B.C. Surpluses of primary agricultural production that once fed the cities of Mesopotamian civilization, decreased gradually over time leading to a decline of Mesopotamian complex society. Along with this, Mesopotamia lost to Babylon the political and cultural leadership of the region. Many of the great Mesopotamian cities demised to villages or mere ruins (Jacobsen & Adams, 1958).

### Water erosion in Ancient Greece

Ancient Greece faced a different kind of soil problem – erosion due to intensive grain cultivation and grazing. Erosion leads to the loss of the most fertile soil layer, know as topsoil. Forces of wind and water remove this soil layer, when agricultural fields are left exposed or barren. This occurs as a consequence of intensive farming, where growing of one single crop, leaves the soil without crop cover for a significant time period during the year. The effect is amplified when a field is sloped, because it is more prone to water erosion. Plato vividly described soil erosion in ancient Greece:

> *What now remains of the formerly rich land is like the skeleton of a sick man. . . . Formerly, many of the mountains were arable. The plains that were full of rich soil are now marshes. Hills that were once covered with forests and produced abundant pasture now produce only food for bees. Once the land was enriched by yearly rains, which were not lost, as they are now, by flowing from the bare land into the sea. The soil was deep, it*

> *absorbed and kept the water in loamy soil, and the water that soaked into the hills fed springs and running streams everywhere.*
>
> *Taken from* Manning (2004)

Losses of topsoil lead the Greeks to adopt commercial crops, like grapes and olives that can be growth on thinner soils. Although soil erosion is not directly linked to the their demise, it made the Greeks more vulnerable by forcing them to rely on trade for food (Hillel, 1991) - an analogy that could directly be linked to today's globalized production and distribution of food.

### Wind erosion in the United States

North American cultivation of cash crops during colonial times set the stage for widespread soil erosion in the United States. During that time Virginia became the center for tobacco cultivation. Growing tobacco was profitable because it fetched more than six times the price of any other crop and could survive the travel across Atlantic.

Tobacco cultivation, on the other hand, strips more then ten times the nitrogen and thirty times the phosphorus from soil than do typical food crops. Nitrogen and phosphorus are nutrients that are essential for crop growth.

Growing tobacco on its own depleted the land of nutrients after just five years of cultivation. Since land was in abundance, the farmers just migrated westwards in search of fertile soil (Montgomery, 2007).

Intensive agriculture spread across the United States. Years of this practice lead to intensive water and wind erosion, which caused severe dust storms during the 1930's. This period is commonly known as the Dust Bowl, as the dust storms were so powerful that they buried entire human settlements.

## Decline of the Aral Sea

Expansion of irrigated agriculture in the Aral Sea Basin lead to the conversion of virgin land into productive agricultural fields. Despite the economic development that followed, this devastated the Aral Sea ecosystem and society.

During the Former Soviet Union the economies of the Central Asian states were dependent upon the central governments rule. In 1960s officials in Moscow decided to make the region the union's agricultural hub. The main aim was to increase the union's self-sufficiency in cotton and rice production. Towards achieving this aim, water was diverted from two main regional rivers, the Amu Darya and Syr Darya, through a system of irrigation canals.

Central Asia developed economically and agriculture still has an important role in the economies of contemporary Central Asian states. Agriculture accounts for 19% of GDP in Kazakhstan and 38% in the Kyrgyz Republic and employs between 20 to 50% of national labour force in central Asian states (Qadir et al., 2009).

However, intensified agriculture and economic development came at an expense of a full-scale environmental crisis that involved a severe drop in water levels, reclining shorelines of the Aral Sea, declining soil quality and increasing human diseases and economic disarray.

Until 1998, the Aral Sea has lost more than 60% of its area and approximately 80% of its volume (Shah et al., 2005). Fisheries that once served as main sources of revenue, declined dramatically. Intensive irrigation, on the other hand, caused wide spread soil salinization and decreased the fertility of soil. The reclining crop yields incentivized farmers to increase the use of fertilizer, herbicides and pesticides in order to maintain and expand production. These chemicals found their way back into the rivers, the Aral Sea and groundwater. A dramatic increase in human diseases followed and Table 1 documents this.

**Table 1: Agriculture induced human diseases in the Aral sea basin: Source: (Shah et al., 2005)**

| Disease | Impact |
|---|---|
| Typhoid | 29-fodl increase |
| Viral hepatitis | 7-fold increase |
| Paratyphoid | 4-fold increase |
| Hypertonia, heart disease, gastric and duodenal ulcers | Up to 100% |
| Increase in premature births | Up to 31% |
| Liver cancers | Up to 200% |
| Gullet cancers | Up to 25% |
| Oesophageal cancers | Up to 100% |
| Cancer in young persons | Up to 100% |
| Infant mortality (1980-89) | Up to 20% |

These negative impacts demonstrate how agricultural expansion aimed at increasing food production, can lead to devastating feedbacks (Shah et al., 2005). They also testify to the devastating power of conventional agriculture to change natural systems.

## Agriculture in time of resource scarcity

Intensification of agriculture has been the main driver of crop yield growth since the middle of the 20th century (Wood et al., 2005). This mainly included increasing yields per hectare of land. Technological breakthroughs of the Green Revolution, a period of major agricultural advances, enabled achieving this.  These advances include: a) introducing new "miracle varieties" of wheat and rice that yielded more grain per unit of total biomass b) artificial fertilizers that allowed greater net primary productivity c) massive investment in irrigation infrastructure (Cassman, 1999) d) agrochemicals (pesticides, herbicides and insecticides) and e) heavy farm machinery.

These innovations led to an increase in grain production by 250% during the period from 1950 to 1984 (Pfeiffer, 2006). New varieties were characterized by shorter time between seeding and maturity. While this allowed more harvest per season, artificial fertilizers and irrigation enabled farmers to maintain soil productivity.

Agriculture of the Green Revolution is not sustainable because it relies on constant inputs of nonrenewable materials and energy. This relates to mineral reserves for fertilizer production, fossil fuels and arable land expansion. Extraction and exploitation of these resources is beyond sustainable means. Water is also included in this, but is not in the scope of this thesis.

### Arable Land

Crop production occupies 11% of the globe's land surface or one third of estimated arable land. Greater share of the remaining arable land (90%) is located in Latin America and Sub Saharan Africa (FAO, 2003).

However, most of the global increase in food production (80%) was achieved by land intensification (greater production per ha) and not arable land expansion (Shah et al., 2005). Arable land per person actually declined 40%, while average grain yields more than doubled (1961/63 – 1997/99). This has come at an expense of decreasing soil quality. Estimates indicate that about 80% of the world's agricultural land suffers moderate to severe erosion, while 10% experiences slight erosion (Pimentel, 2006).

In areas with a limited availability of arable land, increases in food production will have to be achieved through further agricultural intensification. Unless greater efficiency in fertilizer, agrochemicals and water application is achieved, this will lead to even greater ecosystems damage.

### Nutrients

Nutrients are essential for plant growth and the most important ones are phosphorus, nitrogen and potassium. Plants absorb these from soil and when they are limited, plant growth declines. Modern agriculture supplements the soil nutrients through synthetic fertilizer use. However, production of these fertilizers is very resource intensive. Phosphorus and potassium are mined and are limited in supply. Nitrogen is on the other hand abundant, but obtaining it from air requires using the energy intensive Haber Bosch process.

### *Phosphorus*

Estimates of phosphorus production indicate that by 2033 demand for phosphorus will outpace supply, raising concerns about peak phosphorus – an analogy to the theory of peak oil (Elser & White, 2010). Demand for phosphorus is predicted to increase by 50% - 100% by 2050 (Cordell et al., 2009) and this will mainly be driven by a gradual change towards diets richer in meat and dairy products (Schröder et al. 2011). An additional need for fertilizer P may be triggered by an increase in biofuel production (Schröder et al., 2011).

Concerns about phosphorus are also triggered by the uneven distribution of the remaining reserves (Vaccari, 2009). Most of the reserves are located in Morocco, China and the United States (Cordell et al., 2009), in order of magnitude. Together these countries hold 83% of the world's reserves and account for two thirds of annual production (Vaccari, 2009).

As phosphorus reserves continue to decline and food demand continues to increase, these countries will yield more geopolitical power. In order to ensure food security, other countries will have to resort to technologies that increase the efficiency of phosphorus use.

### *Nitrogen*

Nitrogen is the most widely limiting nutrient in terrestrial ecosystems. Nutrient leaching and gaseous emissions limit nitrogen uptake by plants (Lavelle et al., 2005). Without synthetic nitrogenous compounds we would not be able to produce roughly half of today's world food (Smil, 2011).

Pre-industrial agriculture relied on three ways in which to provide N for crops: a) recycling of organic waste (mainly crop residues and animal and human waste) b) crop rotations including N-fixing legumes and c) planting of leguminous cover crops that were then plowed under ground as green manure (Smil, 2002).

The Haber Bosch process of ammonia synthesis created the means to substantially increase plant-available nitrogen production. Greater food production on a global level followed. However, the Haber Bosch process is not sustainable because it fixes nitrogen from air by using large amounts of natural gas - a non-renewable resource.

The increased usage of readily available nitrogen in agriculture also created a misbalance in the natural nutrient flows. Conventional agriculture is highly inefficient in nitrogen application. Nitrogen use efficiencies (NUE) – defined as the percentage of fertilizer-N recovered in aboveground plan biomass during the growing season – ranges in EU agriculture from just 38% in France and the Netherlands to 42% in Germany and 44% in Italy (Smil, 2011). The remaining nitrogen is lost into water bodies leading to water degradation, or returns to the atmosphere, either as $N_2$ or $N_2O$ (Lavelle et al., 2005), the latter being a powerful greenhouse gas. Inefficient use of nitrogen fertilizer is also an economic loss and a waste of natural gas, the prime feedstock in nitrogen production (Smil, 2011).

### Fossil energy

Conventional food production has become increasingly dependent on fossil fuel use. Innovations of the Green Revolution increased the energy flow to agriculture by an average of 50 times its traditional energy input (Pfeiffer, 2006). Consequently, the food sector currently accounts for around 30% of world energy consumption and 20% of total GHG emissions (FAO, 2011).

Agricultural energy usage is projected to rise due to an a) increase in human population by 40% and b) increase in living standards that will stimulate more intensive meat and dairy product consumption (Bruinsma, 2009). Most of the increase in food production is expected from more intensive cultivation. A breakdown of energy usage in intensive farming is given in Figure 1.

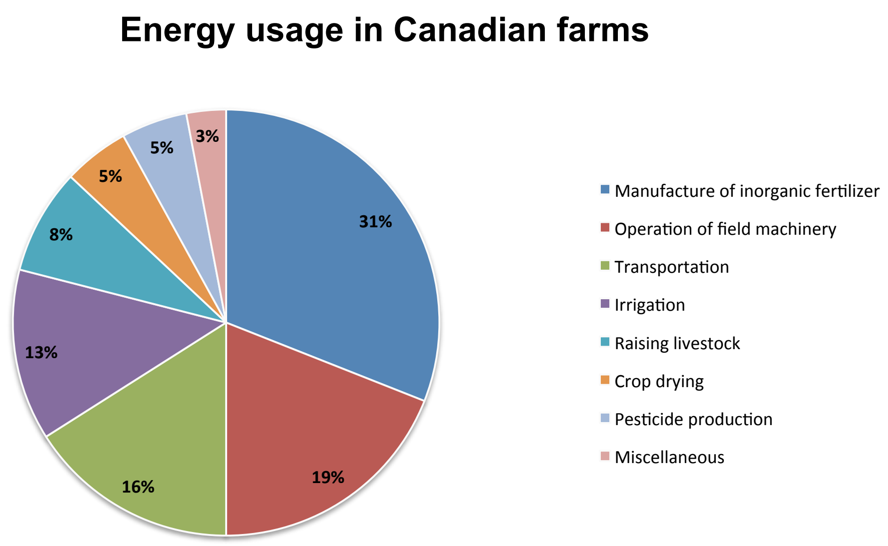


**Figure 2: Energy use in intensive agriculture. Source: Pfeiffer (2006)**

## Review of non-conventional agricultural solutions

Non-conventional agricultural solutions can be defined as technological approaches to agriculture that aim to maximize resource use efficiency. This segment will present solutions other than Terra Preta Nova technologies.

Wood et al (2005) mention in the Millennium Ecosystems Assessment that these are the most efficient methods to reduce the impact of conventional agriculture:

1) Increasing nitrogen fertilizers use efficiency
2) Improving soil quality through carbon sequestration
3) Irrigation efficiency

Irrigated rice based cropping systems as well as wheat and maize-soybean rotations provide food for about half of the human population and account for more than 80% of all grains that enter international markets. Meeting future food demand will include implementing the above methods in the most productive cultivated systems globally.

Increasing the productivity of these systems is seen as the primary measure to meet the growing demand for food. An increase in productivity of global cereal production by just 1%, through one of the above named measures, could lead to savings of 6.7 million hectares of additional land that would otherwise be required (Wood et al., 2005).

## Increasing nitrogen use efficiency

Nitrogen fertilizer use efficiency can be increased by management methods aiming at achieving synchrony between N supply and crop nitrogen demand. Successful management methods include:

1) Significant reductions in fall applied N-fertilizer with a shift to applications in spring or in time of planting
2) Fragmentation of N-fertilizer application during the entire growing season rather than a large single application
3) Increases in manure application and legume rotations.

However, implementing these management measures is mostly limited by the extent of farmer's education and willingness to modify existing agricultural practices. Examples from the US demonstrate that farmer education is one of the primary obstacles to increasing nitrogen use efficiency (Cassman et al., 2002).

## Carbon sequestration

Carbon sequestration, on the other hand, includes adopting methods that increase soil organic carbon - carbon associated with soil organic matter. Soil organic matter is plant and animal material in various stages of decomposition. The decomposition of biomass increases soil carbon, storing it in soil for a given period of time. The end product of decomposition is humus – dark or black organic matter that is highly resistant to further decomposition.

Soil organic matter affects soil quality by storing and supplying nutrients (nitrogen, phosphorus and potassium) and micronutrients. It increases the soil water holding capacity, improves soil structure and eliminates diseases and pollution. Crop cultivation, harvesting, erosion and natural decomposition decrease over time organic matter in soil (Cooperband, 2002). Soil organic matter is then oxidized and returns to the atmosphere as carbon dioxide, completing the short-term carbon cycle.

Soil is in effect a store of carbon and as such can be used to decrease atmospheric carbon levels. Methods that aim in doing so reduce the decomposition of soil organic carbon or increase the amount of highly stable carbon in soil.

Methods that reduce the decomposition of soil organic carbon include reducing tillage intensity, decreasing or ceasing the winter fallow period, using winter crop cover and changing from monoculture to rotational cropping (West & Post, 1997).

On the other hand, recent years have seen a plethora of research on biochar – charcoal produced specifically for soil amendment. Findings of biochar in ancient Terra Preta soil indicate to its stability and potential for long term carbon storage. Research has also shown that biochar can significantly increase crop yields, due to mechanisms that are yet to be scientifically determined and classified. This method will be discussed in detail in this thesis.

### Increasing water use efficiency

Water use efficiency is defined as the ratio of water used by crops and the gross quantity extracted for irrigation use. The global average for water efficiency is 43% although more arid regions have higher efficiency rates, compared to least water-constrained countries (Wood et al., 2005). Many technologies have been developed to increase water use efficiency. Besides saving water, these also increase yields adding to their significance.

Microirrigation systems, such as drip and micro-sprinklers, are among the most commonly discussed technologies. These achieve efficiencies in excess of 95%. Currently only 0.7% of irrigated farmland worldwide has been subject to microirrigation (Wood et al., 2005).

There are many other methods that are discussed but in general these pertain to water conservation methods, increasing effective rainfall use, careful landscape design using shelterbelts and reusing urban wastewater for agriculture.

## Terra Preta Nova technologies

Amazonian Dark Earths (ADE) or Terra Preta (TP) are soils that contain large stocks of stable organic matter and high nutrient levels. Their fertility is much higher than the surrounding soils, which is demonstrated through substantially greater crop yields. Terra Preta has been a source of intensive scientific interest in the last 10 years. Main reason for this is the presumably anthropogenic origin of Terra Preta. Archeological findings of pottery on Terra Preta locations suggest that indigenous Indians have produced it to amend local unfertile soils. This implied that Terra Preta could be generated today and its powerful properties used to tackle present agricultural problems.

Reproducing Terra Preta per se would, however, be a very challenging task. This would require significant research effort and logistical expertise. Amazonian Dark Earths are composed of a multitude of different input materials, which includes various residues of animal and vegetal origin. Reasons for the highly positive effects of Terra Preta soil on crop yields still haven't been scientifically determined. High black carbon contents or biochar are, however, believed to be the key (Lehmann, 2009).

Managing a steady stream of these input materials would be impractical (Lehmann, 2009) and possibly much too expensive. The differing properties of Terra Preta are also a reflection of the local hydrological, geological and biological regimes (Lehmann, 2009). Using Terra Preta in temperate zones could then yield very different results, than using it in tropical areas where it was discovered.

Terra Preta is then rather a theoretical concept than a practical solution. Modern discussions should focus on developing Terra Preta Nova technologies (Lehmann, 2009); the most well known being biochar. Terra Preta Nova per se is a less known concept, but its production would include mixing biochar with composted organic waste materials.

## Discovery of Terra Preta

Terra Preta has been discovered throughout Amazonia and estimations predict it occupies 10% of the land area. Patches of Terra Preta are described ranging from less than a hectare up to several square kilometers. Most of the findings are along water bodies, mainly major rivers (Glaser & Birk, 2012).

Research suspects that Terra Preta was purposefully developed by a complex pre-Colombian civilization. Accounts of this civilization were made available by the explorations of a pre-Colombian Spanish explorer named Francisco de Orellana. His reports testify of a civilization that developed along the banks of the Amazon basin and that could have numbered in millions. Orellana testifies about armed conflicts with the indigenous Indians and describes cities rich in culture and food (Bates, 2010).

Accounts of this civilization were lost and it is presumed that European diseases wiped it out. Archeological findings in the past two centuries have, however, made discoveries of large amounts of pottery on grounds where Terra Preta was found. Carbon dating of shells found in the pots, demonstrated that they are of very ancient origin (Bates, 2010).

Whether Terra Preta was made purposefully or not is still unsure. Although implications exist, there is no scientific evidence indicating that forgotten agricultural techniques for large scale soil fertility improvement are responsible for Terra Preta genesis (Glaser & Birk, 2012). Research rather suggests that its creation and discovery was unintentional.

Larger food production, stimulated by the discovery of Terra Preta could have triggered population growth in the Amazon region. Population increase then created greater organic waste quantities. Managing these wastes could have included mixing them into compost-like piles in the ground and adding charcoal from fires. Such management of these materials might have lead to a self-enhancing and self-organizing process where Terra Preta was produced on a larger scale (Glaser & Birk, 2012).

## Terra Preta properties and genesis

Terra Preta soils are mostly distinguished by a distinctive black coloration caused by elevated concentrations (70 times higher than surrounding soil) of charred biomass (Glaser et. al., 2001). This is today known as biochar and is thought to be one of the main sources of Terra Preta's high fertility. These soils also contain various residues of vegetal (ash, leaves and diverse palm fronds, manioc residue, seeds etc.) and animal (bones, blood, fat, feces, chelonian carapaces, shells etc.) origin (Kern et al., 2009). Mixing these organic materials resulted in highly fertile soils rich in stable carbon (biochar) and nutrients, especially phosphorus and calcium (Lehmann, 2009). These soils also demonstrate a significantly higher cation exchange capacity, base saturation and PH values than in the surrounding soils (Steiner et al., 2009). Due to differences in input materials, there are many varieties of Terra Preta soil that share similar but not equal properties (Lehmann, 2009).

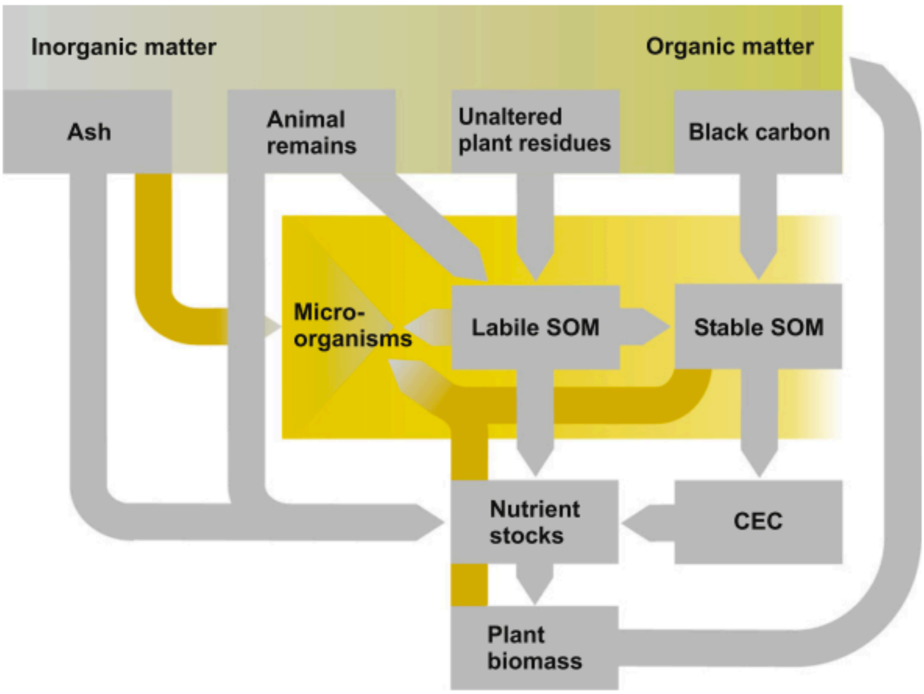


**Figure 3: Model of Terra Preta genesis. Source:** Glaser & Birk (2012)

Creating Amazonian Dark Earths enabled the transformation of infertile Amazon soils into productive soils rich in organic carbon. Stability of soil organic matter (SOM) in ADE is six times greater than in surrounding soils. This is despite the high weathering rates that are 100 times greater than in mid-latitudes (Woods & Denevan, 2009).

Biochar is the primary reason for the high SOM stability and high cation exchange capacity (CEC) present in Terra Preta soils (Glaser & Birk, 2012). Biochar in ADE is also connected to the soils high nutrient retention and water holding capacity, and is associated with high and persistent microbial activity (Woods & Denevan, 2009). High stability of biochar in Terra Preta ensures the soils maintain their high fertility over a longer time period.

## Biochar as the backbone of Terra Preta Nova production

Biochar is the only element of the Terra Preta production chain that can be replicated on mass scale using modern technologies. Discussions on Terra Preta Nova production, therefore, in large extent involve producing biochar and mixing it with locally available organic waste material.

Research on biochar, however, is not in agreement regarding its effects on soil properties. Biochar can be produced from a multitude of feedstock materials, leading to differing effects on soil. Even the positive results are subject to ambiguity and this disables drawing general conclusions. The future of Terra Preta Nova, therefore, lies in learning, which biochar production pathways (varying in feedstock used, biochar production conditions etc.) lead to soil quality improvements and increases in crop yields.

Biochar is in most cases discussed in the literature, independently from Terra Preta Nova. Research is evolving mainly around its effects on soil properties, plant growth and production technologies. This chapter will outline the main conclusions of the biochar debate by reviewing the current literature. Gaining a perspective on its importance will require first looking at the overall biochar-for-environmental-management strategy.

## Biochar for environmental management

Biochar has received increasing attention since Lehmann (2007) revealed that its production and application to soil can sequester the $CO_{2eq}$ of about a third of annual US fossil-fuel emissions (1.6 billion tons of carbon in 2005). Using biochar to amend degraded soils could sequester carbon while increasing crop yields. Biochar production can also be coupled with renewable energy generation.

The attractiveness of biochar stems from the facts that it provides solutions for some of the most pressing environmental issues:

1) Greenhouse gas emission reduction through displacing fossil fuel energy generation with renewable energy and long term storage through stabilizing carbon in ground
2) Amelioration of degraded soils and subsequent increase in crop yields per hectare

This segment will define biochar and its physical and chemical properties, describe the biochar strategy and compare it with other geoengineering proposals. This will be followed by an assessment of the most important effects of biochar on altering soil properties.

### Biochar defined

Brownsort et al. (2010) define biochar as a porous carbonaceous solid, which has physiochemical properties suitable for the safe and long-term storage of carbon in the environment and, potentially, soil improvement.

In simple terms, biochar is the carbon-rich product obtained when biomass, such as waste wood, fruit shells etc. is heated in an oxygen-deprived environment. Biochar is distinguished from charcoal in that it is mainly produced with the intention of applying it to soil.

### Production process

Biochar is produced through thermochemical conversion of organic material in an oxygen-depleted environment (Brownsort et al., 2010) - a process called pyrolysis. Pyrolyzing biomass yields two main products and these are char and bioenergy in the form of bio-oil and syngas. Pyrolysis processes can be modified to increase the amount of each product (Table 2). Main variables that are altered are: the heating rate, peak temperature and residence time of biomass at peak temperature.

Higher heating rates and temperature and shorter residence time will be applied when the primary goal is to produce bioenergy (fast pyrolysis). Heating of biomass releases a multitude of gaseous compounds and heat. These products can be captured to produce energy carriers such as electricity, bio-oil or hydrogen. When the primary goal is to maximize the amount of char produced, lower residence time and slow heating rate will be utilized (slow pyrolysis).

**Table 2: Fate of initial feedstock mass between products of pyrolysis processes. Source: Developed from** Sohi et al. (2009)

| Process | Liquid (bio-oil) | Solid (biochar) | Gas (syngas) |
|---|---|---|---|
| FAST PYROLYSIS<br>Moderate temperature (~500 °C)<br>Short hot vapor residence time (<2s) | 75%<br>(25% water) | 12% | 13% |
| INTERMEDIATE PYROLYSIS<br>Low-moderate temperature<br>Moderate hot vapor residence time | 50%<br>(50% water) | 25% | 25% |
| SLOW PYROLYSIS<br>Low-moderate temperature<br>Long residence time | 30%<br>(70% water) | 35% | 35% |

Higher char yields, however, do not imply higher yield of stabilized carbon. The char resulting from slow pyrolysis consists of fractions of contrasting recalcitrance - fractions of char that are unstable and would be lost quickly when applied to soil. Nevertheless, these lost fractions could provide short-term agronomic benefits. Fast pyrolysis, on the other hand, produces more stable carbon but in lower quantities (Brownsort et al., 2010).

Biochar properties will largely depend on the processing conditions and feedstock. Depending on the production temperatures, biochar will have differing cation exchange capacity, pH level and surface area. Figure 4 shows that the optimum properties depend on the temperature of the pyrolysis process. In this particular example, shown in Figure 4, the optimum processing temperatures were between 500 and 550 °C (Lehmann, 2007).. The highest surface area, believed to be the most important biochar characteristic, was achieved at these temperatures,

High biochar surface area is the product of numerous pores that develop in the pyrolysis process. The pores act as a "sponge" for nutrients and water as they retain these essential materials in soil. This makes them available to plant roots and leads to higher crop yields.

Nutritional value of biochar in soil will largely depend on the biomass feedstock. Biochar can be produced from a multitude of biomass sources and these include various energy crops, agricultural wastes, compost, manure/animal waste, and kitchen waste and sewage sludge. These various materials will result in differing quantities of nutrients retained in biochar itself. For more information on biochar production technologies, please refer to Appendix 2.

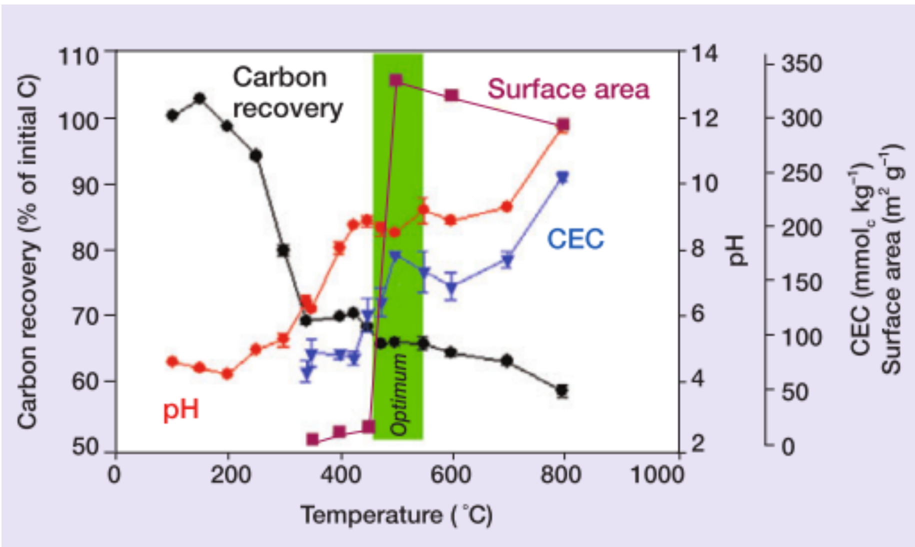


**Figure 4: Optimum biochar properties as a function of processing temperature. Source:** Lehmann, (2007)

## Multiple benefits of biochar use

Biochar application for environmental management yields four complementary goals and these are:

1) Soil improvements
2) Mitigation of climate change
3) Waste management
4) Bioenergy production

### *Soil improvements*

Soil improvements are derived mainly from changing existing soil properties and this includes increasing soil surface area, nutrient and water retention capacity and increasing microbial activity. Besides this, biochar is believed to be the most stable form of soil organic carbon. In other words, biochar does not mineralize rapidly like other soil organic matter but stays in soil for hundreds to thousands of years. Biochar soil application, therefore, could lead to atmospheric carbon sequestration.

### *Mitigation of climate change*

Soils worldwide contain around twice as much carbon (1500 Gt) as the atmosphere (750 Gt), and three times more than the amount in vegetation (560 Gt). Soils therefore constitute an enormous reservoir of carbon. Conventional agricultural practices that lead to soil erosion (topsoil loss) etc. accelerate the loss of soil carbon by inducing its oxidation and release in the form of atmospheric gasses.

Stabilizing biomass in the form of biochar and placing it in soil is a form of decreasing the release of carbon from soil to the atmosphere (Bruun, 2011). Carbon is locked from the short-term carbon cycle. The result is a reduction in greenhouse gasses and associated decrease in the atmospheric warming effect.

Figure 5 compares a normal and biochar based agricultural system. Carbon stabilization in soil makes biochar soil conditioning carbon-neutral. Additional energy production during pyrolysis will offset fossil fuel use, making the entire process carbon-negative (Lehmann, 2007).

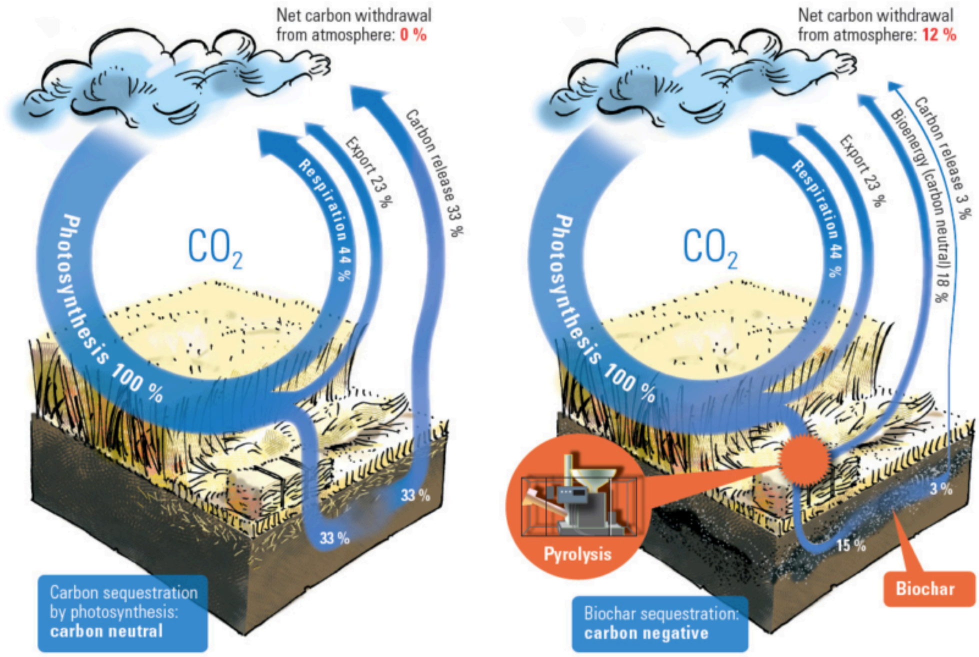


**Figure 5: Comparison of carbon cycling in a biochar-based and normal agricultural system. Source:** Bruun (2011)

### *Waste management and bioenergy production*

Biochar can be generated from waste materials, meaning that its production will incentivize the formation of waste management schemes. Waste flows that can be used in the process often include organic waste from agricultural or industrial production. This includes animal manure, garden waste and materials like paper mill wastes. Pyrolyzing these wastes not only leads to biochar and bio-energy production, but it also decreases costs associated with conventional waste management schemes.

### *Other benefits*

Biochar production from local organic waste would decrease landfill methane emissions and energy used in long-distance transport of waste. Pyrolyzing biomass like animal manures would also eliminate pathogen problems associated with direct manure application to soil (Lehmann & Joseph, 2009). Using animal manure for biochar production would also eliminate bad odors from the manure (International Biochar Initiative, 2012).

### Greenhouse gas emission reductions

Biochar production is a carbon-negative process, meaning that it leads to an overall removal of carbon from the atmosphere (under conditions that bioenergy is produced). Figure 6 describes the entire process in more detail, indicating to indirect savings in carbon dioxide emissions and other GHG emission avoidance. The discussion that follows is based on the study made by Woolf et al. (2010). This is the most comprehensive study on biochar GHG emission reductions. According to the authors, these are the potential reductions:

1) Higher crop growth derived from global biochar applications would lead to an increase in the plant-biomass carbon dioxide uptake
2) Biochar applications to soils would reduce other soil GHG emissions. This mainly relates to decreasing nitrous oxide emissions from nutrient runoff caused by soil erosion and over fertilization of land
3) When biochar is produced from waste feedstock, like animal manure or organic waste, methane emissions are reduced as well. These stem from better manure management and an overall decrease in landfill emissions

Other indirect benefits of producing biochar also include the avoided emissions of transporting waste to landfills etc. ( Lehmann & Joseph, 2009a).

Globally biochar use could offset a maximum of 12% of current anthropogenic emissions, but only if certain sustainability criteria are met. These include the following:

a) There is no land clearance to provide biomass feedstock
b) Agricultural land is not used due to negative consequences for food security and because it may induce negative land use elsewhere
c) Extraction rates of agricultural and forestry residues are sufficiently low to prevent soil erosion

d) Industrially treated waste biomass that poses a risk of contamination is not used

e) Biochar production systems rely on technologies that have low GHG emissions compared to low-tech solutions predominant in developing countries. These are mainly open kilns for charcoal production that emit large amounts of soot and other greenhouse gasses

f) There is a net primary productivity increase due to positive effects of biochar on soil fertility and crop growth

Generating GHG emission reductions through biochar application would necessitate meeting all of the above-mentioned criteria. This could prove to be rather challenging, which is why the 12% GHG reduction estimate needs to be taken conservatively.

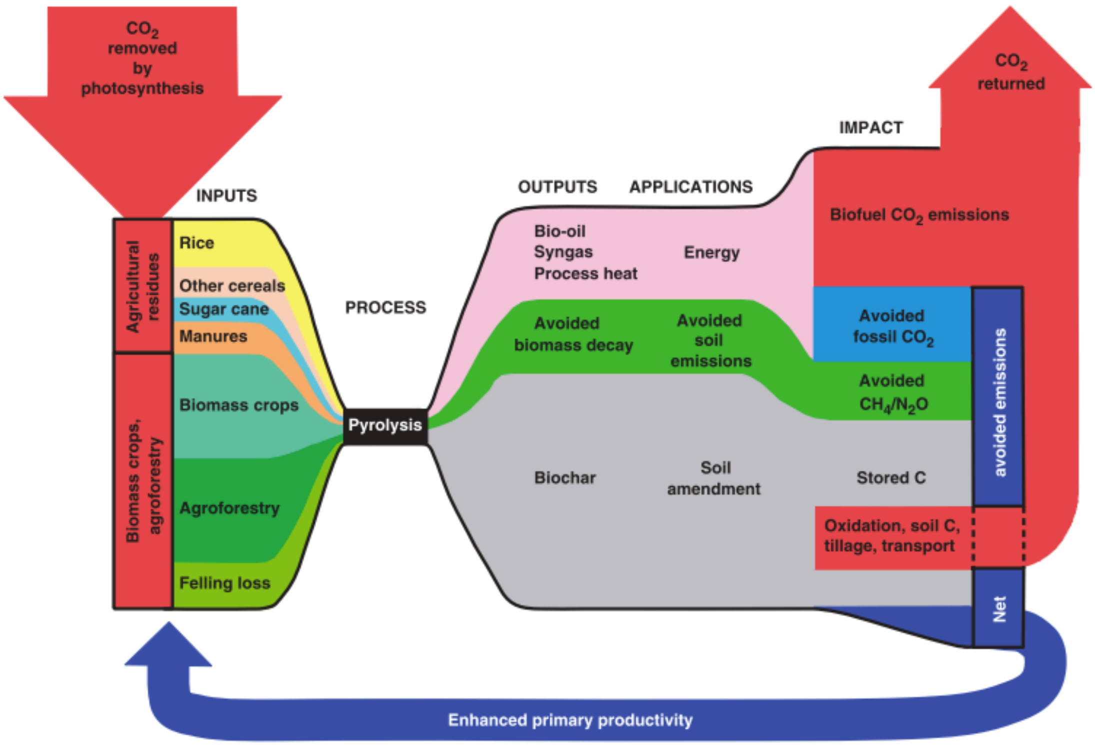


**Figure 6: Biochar inputs, outputs and impacts. Source:** Woolf et al. (2010)

## Biochar effects on soil properties

Biochar is mostly distinctive from other soil organic matter in its porous structure and resulting large specific surface area. The large surface area of biochar is also associated with its ability to retain more nutrients and water than other soil organic matter.

Besides increasing crop yields, greater nutrient and water retention decreases the amount of nutrient rich effluent leakage into water bodies. The porous structure of biochar apparently enables high microbial activity – an aspect that further enhances soil fertility. Biochar application to soil also leads to carbon storage. The effectiveness of storing carbon in ground depends on its stability in soil. Radiocarbon dating of biochar found in Terra Preta, estimates its age from hundreds to thousands of years. These aspects differentiate biochar from other soil amending techniques.

The following paragraphs will present the main effects on soil properties that make biochar an appealing soil amending method.

### High specific surface area

Soil surface area influences all of the essential functions for fertility – this includes water, air, nutrient cycling and microbial activity (Downie et al., 2009). Increasing soil surface area enables soil particles to retain and supply more nutrients and water for plant uptake (University of Hawaii, 2012). Biochar significantly alters soil physical properties and in doing so potentially enables better nutrient management and increases air and water availability within the soil root zone (Downie et al., 2009).

Biochar is produced by heating feedstock in an oxygen strived environment. Research has indicated that biochar's surface area mostly depends on the highest treatment temperature. (HTT) where the surface area increases with increasing the treatment temperature (Downie et al., 2009). The feedstock material mostly develops micropores that are responsible for biochar's absorptive capabilities (Rodriguez, 2010). Macropores on the other hand develop in lesser extent. However, these are very important for providing habitat for microorganisms that are in part responsible for the positive effects of biochar on soil (Downie et al., 2009).

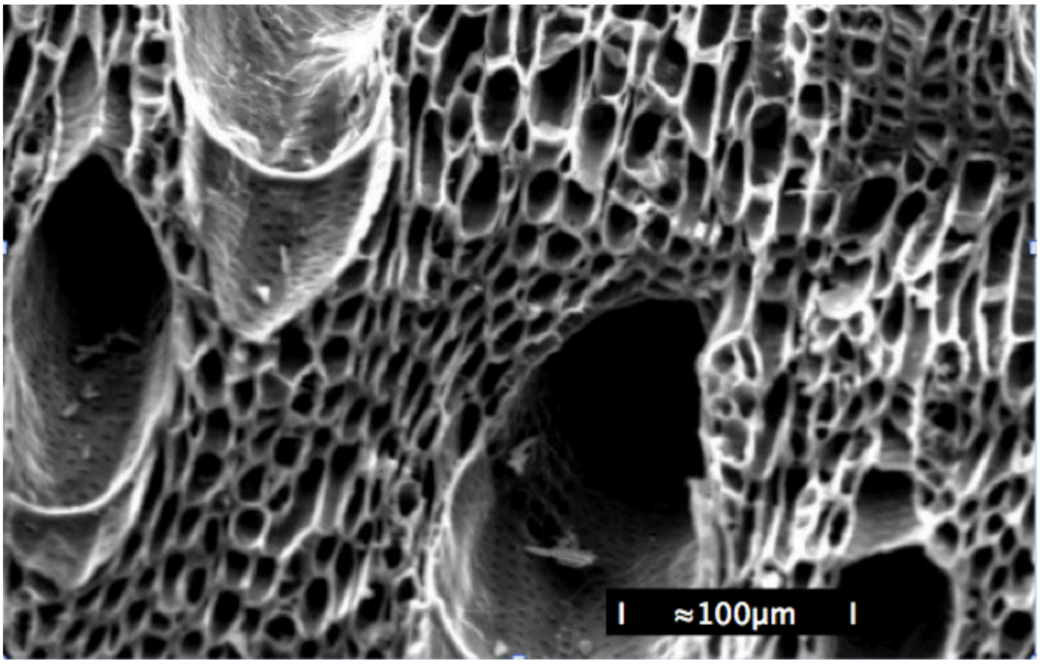


**Figure 7: Macroporosity of a wood-derived biochar produced by "slow pyrolysis". Source: Best Energies**

### Nutrient retention

Biochar soil conditioning leads to increased nutrient availability in two basic ways: a) directly through the nutrients contained in the biochar structure itself and b) indirectly through improving nutrient retention (Chan & Xu, 2009).

Biochar in itself is not a major source of nutrients, although its chemical structure largely depends and varies with the feedstock used and processing conditions (Amonette & Joseph, 2009).

The biochar particle comprises of two main structural fractions, and these are stacked crystalline graphene sheets and randomly ordered amorphous aromatic structures. The later contain hydrogen, oxygen, nitrogen, phosphorus and sulfur and these are though to be of great relevance for the highly heterogenous surface chemistry and reactivity of biochar (Verheijen et al., 2009) .

Table 5 summarizes the total elemental composition and pH ranges of biochar's from a variety of feedstock's and pyrolysis conditions used in various studies. The differences in biochar chemical (and physical) composition imply that each individual soil application needs to be preceded by an assessment of biochar properties.

**Table 3: Summary of total elemental composition and pH ranges and means of biochar's from a variety of feedstock's and pyrolysis conditions. Source:** Verheijen et al. (2009)

| | | pH | C $(g\ kg^{-1})$ | N $(g\ kg^{-1})$ | N $(NO_3^{-1} + NH_4^{-1})$ $(mg\ kg^{-1})$ | C:N | P $(g\ kg^{-1})$ | Pa $(g\ kg^{-1})$ | K $(g\ kg^{-1})$ |
|---|---|---|---|---|---|---|---|---|---|
| Range | From | 6.2 | 172 | 1.7 | 0.0 | 7 | 0.2 | 0.015 | 1.0 |
| | To | 9.6 | 905 | 78.2 | 2.0 | 500 | 73.0 | 11.6 | 58 |
| Mean | | 8.1 | 543 | 22.3 | - | 61 | 23.7 | - | 24.3 |

## Water retention

Agronomic benefits of biochar are often attributed to improved water retention. Water retention in soil is determined by the distribution and connectivity of pores in the soil medium. This is largely regulated by soil particle size and structural characteristics of soil organic matter.

Biochar is a highly porous material with a great surface area and its application to soil increases water retention. The improvements stemming from biochar additions, however, depend on the initial soil texture. A draw back is the large volume of biochar that needs to be added before it increases soil water retention (Verheijen et al., 2009).

Besides the apparent positive effects for plant growth, biochar also purifies runoff water from nutrients. The increase in water quality could decrease eutrophication[2] impacts of modern agriculture.

## Soil microbial activity

Biochar‘s large internal surface area and its ability to absorb soluble organic matter, gasses and inorganic nutrients provide a favorable habitat for microbes to colonize, grow and reproduce. These are sheltered by the pores in biochar that protect them

[2] Eutrophication refers to algae growth induced by excessive nutrient concentration in water. When this happens, water oxygen levels are depleted leading to dying of other water organisms

form predation and desiccation. Biochar pores act as a refuge site for colonizing microbes (Figure 8) and provide for many diverse carbon, energy and mineral nutrient needs (Thies & Rillig, 2009).

Increased microbial activity favors soil fertility because of the ecosystem services that these perform. Soil microorganisms decompose organic matter, cycle and immobilize inorganic nutrients, filter and bioremediate soil contaminants, suppress and cause plant disease, produce and release GHG, and improve soil porosity, aggregation and water infiltration (Thies & Rillig, 2009).

Biochar alters the chemical and physical environment of the soil, which in turn affects the behavior and characteristics of soil microorganisms. Differing biochar materials will alter the availability of soluble organic matter, mineral nutrients, pH, soil aggregation and the activity of extracellular enzymes. This affects the abundance and distribution of soil microbes, particularly bacteria, actinomycetes and arbuscular mycorrhizal fungi. Bacterial abundance, diversity and activity are mostly influenced by moisture, temperature and pH – all of these can be affected by biochar (Rodriguez, 2010).

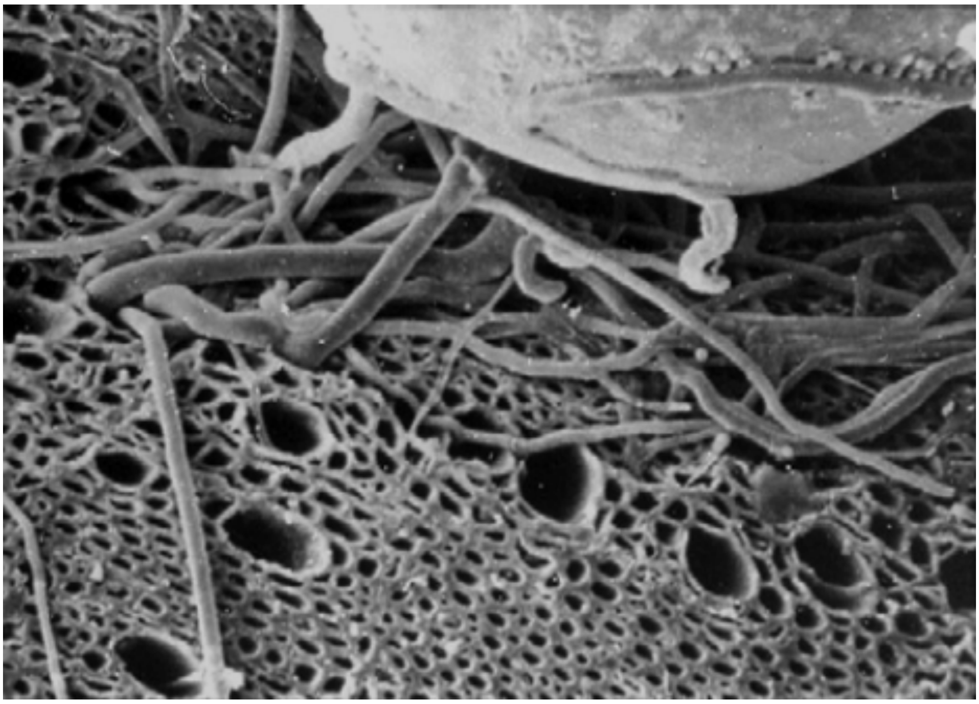

**Figure 8: Interaction of arbuscular mycorrhiza with a piece of porous wood charcoal. Source:** Ogawa & Okimori (2010)

### Stability of biochar in soil

Biochar is one of the most stable forms of carbon in soil. Unlike other organic matter that oxidizes after a short time period, biochar stays stable on a millennial scale. Radiocarbon dating of biochar, found in Terra Preta, indicates to an origin dating back from 500 up to 7000 years BC (Lehmann et al., 2009).

Stability of biochar in soil is crucial for these reasons (Lehmann et al., 2009):

1) Viability of biochar strategies to mitigate climate change. Retention of carbon in a stable form in soil will depend on the rate of biochar oxidation. Longer biochar retention times will yield greater benefits in terms of reducing the levels of atmospheric carbon dioxide
2) Length of time biochar exhibits positive effects on soil properties, crop growth and water quality. Longer retention in soil will create greater benefits for the local environment

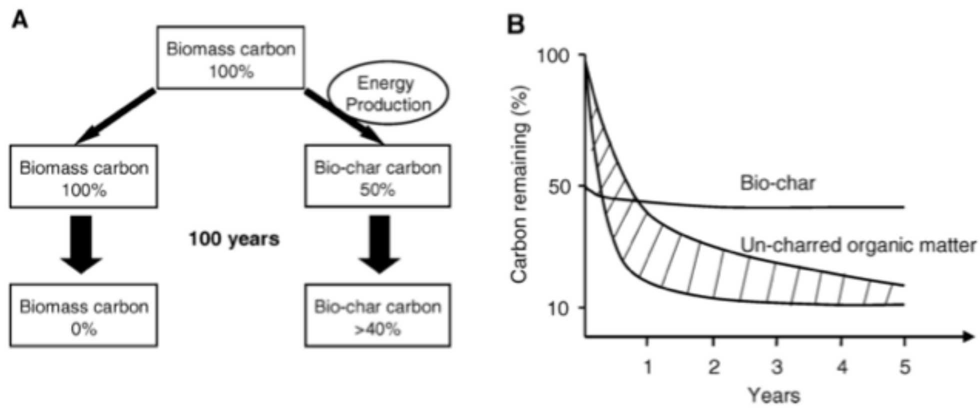


**Figure 9: Schematics for biomass or biochar remaining after charring and decomposition in soil.**
**Source:** Lehmann et al., (2006)

Strategies to apply biochar to soil rely on the assumptions described in Figure 9 (Lehmann et al., 2006).:

1) Adding biomass directly to soil will result in a complete decrease of its carbon content over a period of one hundred years
2) Charring the same biomass will induce a loss of at least 50% of the biomass carbon. The other half will be retained in the form of stable biochar residue

3) The biomass that is not retained as biochar, but is converted into heat and gas, can be used for electricity and bio oil generation

However a great deal of scientific uncertainty exists regarding biochar stability in soil. The main areas of concern are given bellow:

1) Biochar is applied to different soil types and environments. Many different feedstocks from which it can be produced as well as production processes, add to the variability of biochar properties and responses in soils.

2) There are many mechanisms through which biochar can decay or be transported in soil. Research indicates that biotic decomposition of biochar fractions is the most significant mechanism that contributes to its decay. This refers to biochar decomposition by microorganisms (Lehmann et al., 2009). On the other hand, soil erosion is the most significant transport mechanism of biochar.

The great number of mechanisms by which biochar could decay indicate to the big uncertainties associated with using biochar as a strategy to mitigate climate change. Applying biochar on a massive scale could generate negative feedbacks if that same biochar mineralizes much more quickly than what was initially expected. This event could cause a potentially large release of carbon back to the atmosphere. Therefore, estimating biochar stability is of great significance for its application to soil.

### *Estimating biochar stability*

Currently there is no established methodology that can be used to estimate the stability of biochar with great precision. Radiocarbon dating of biochar gives results that could be off track in the range of hundreds of years (Lehmann et al., 2009).

Gaps in soil science prevent the full understanding of biochar stability and decay. It remains largely unknown why some soil organic matter persists for millennia while other decomposes readily (Schmidt et al., 2011). Likewise, there is no agreed methodology for estimating the stability of biochar.

Strategies to use biochar for environmental management often cite that biochar is stable on a millennial scale. However, these estimates are based on research on Terra Preta soils. This differs from research on freshly produced biochar, where some results indicate to a significant mass loss in a matter of years (Sohi et al., 2009).

Unknowns related to biochar stability are one of the main reasons why biochar environmental management hasn't been applied on a wider scale. Research on biochar effects on crop yields is under review as well.

## Effects of biochar on crop yields

Results of biochar application to soil are subject to variability and there is no clear understanding under what climatic conditions and plant species high or low yields can be expected.

Sohi et al. (2009) propose three main mechanisms that explain how biochar might effect crop production:

1) Direct modification of soil chemistry through its elemental and compositional make up
2) Provision of chemically active surfaces that modify the dynamics of soil nutrients or catalyze useful soil reactions
3) Modification of the physical character of soil in a way that benefits root growth and/or nutrient and water retention and acquisition

According to the authors the first mechanism can result in a temporary change in crop productivity, and this depends on biochar nutrient content and weathering over time. The second and third mechanisms depend on long-term biochar persistence in soil and, therefore, their effects might be finite.

Sohi et al. (2009) compile a list of biochar experiments assessing the impact of biochar additions on crop yields (Table 4). The compiled studies were made on a variety of different soil types and using a multitude of feedstock materials. Most of the presented results show that biochar had a positive effect on crop growth.

However, the majority of currently published studies are small scale, short term and sometimes conducted in pots where environmental fluctuations are removed (Sohi et al., 2009). Most of the field trials are conducted in tropical climates, leaving little evidence of biochar effects in temperate climates (Brownsort et al., 2010).

Deriving conclusions about the potential effects of biochar on crop growth is impossible without further understanding of the soil processes associated with its application. Biochar applications in individual regions should be preceded by experiments on the effects of biochar on local soils.

**Table 4: List of experiments assessing the impact of biochar addition on crop yield. Source: Adopted from Sohi et al. (2009)**

| Authors | Study outline | Result summary |
|---|---|---|
| Iswaren et al (1980) | Pea, India | 0.5 Mgha-1 char increased biomass 160% |
| Iswaren et al. (1980) | Mung bean, India | 0.5 Mgha-1 char increased biomass 122% |
| Kishimoto & Sugiura (1985) | Soybean on volcanic ash loam, Japan | 0.5 Mgha-1 char increased yield 151 %<br>5 Mgha-1 char decreased yield to 63%<br>15 Mgha-1 char decreased yield to 29% |
| Kishimoto & Sugiura (1985) | Sugi trees on clay loam, Japan | 0.5 Mgha-1 wood charcoal increased biomass 249%<br>0.5 Mgha-1 bark charcoal increased biomass 324%<br>0.5 Mgha-1 activated charcoal increased biomass 244% |
| Chidumayo (1994) | Bauhinia trees on alfisol/utisol | Charcoal increased biomass by 13% and height by 24% |
| Glaser (2002) | Cowpea on xanthic ferrasol | 67 Mgha-1 char increased biomass 150%<br>135 Mgha-1 char increased biomass 200% |
| Lehman (2003) | Soil fertility and nutrient retention. Cowpea was planted in pots and rice crops in lysimeters at the Embrapa Amazonia Ocidental, Manus, Brazil | Bio-char additions significantly increased biomass production by 38 to 45% (no yield reported) |
| Oguntunde (2004) | Comparison of maize yields between disused charcoal production sites and adjacent | Grain yield 91% higher and biomass yield 44% higher on charcoal site than control |

| | | |
|---|---|---|
| | fields. Kotokosu watershed, Ghana | |
| Yamato (2006) | Maize, cowpea and peanut trial in area of low soil fertility | Acacia bark charcoal plus fertilizer increased maize and peanut yields (but not cowpea) |
| Chan (2007) | Pot trial on radish yield in heavy soil using commercial green waste biochar (three rates) with and without N | 100 t $ha^{-1}$ increased yield x3; linear increase 10 to 50 t $ha^{-1}$ - but no effect without added N |
| Rondon (2007) | Enhanced biological N-2 fixation (BNF) by common beans through biochar additions. Colombia | Bean yield increased by 46% and biomass production by 39% over the control at 90 and 60 g kg (-1) biochar, respectively |
| Steiner (2007) | Four cropping cycles with rice and sorghum | Charcoal amended with chicken manure amendments resulted in the highest cumulative crop yield (12.4 Mgha-1) |
| Kimetu et al. (2008) | Mitigation of soil degradation with biochar. Comparison of maize yields in degradation gradient cultivated soils in Kenya | Doubling of crop yield in the highly degraded soils from about 3 to 6 t/ha maize grain yield |

## Terra Preta Nova production systems

Terra Preta Nova (TPN) is a term describing a soil conditioner that resembles ancient Terra Preta in its composition and effects on soil properties. TPN is a product of high-end waste management, where regional waste resources are employed to the highest measure. The feedstock materials that enter the composition of TPN are biochar (any feedstock) and composted organic waste.

TPN is mostly a theoretical concept and there are almost no scientific papers published on the topic of reproducing ancient Terra Preta soils (exception being Kern et al., (2009) and Fischer & Glaser, (n.d.) ). However, some private companies have attempted in doing so. This thesis is among the first efforts to document the possibilities of producing Terra Preta Nova. The focus of the thesis is on large-scale regional production.

Terra Preta Nova production systems are systems in which TPN feedstock is collected and used for TPN production. These systems are circular, meaning that they rely on recycling of waste materials. Introducing these systems would require fundamentally rethinking conventional economic systems that rely on linear resource use.

The linear approach assumes that at one end of the system there is an unlimited supply of energy and raw materials, while at the other the environment has an infinitive capacity to absorb pollution and waste. The result of this is resource shortage on the one hand and negative environmental impact on the other (Pimbert, 2012).

Circular systems rely on local waste materials as input feedstock into production processes. Terra Preta Nova is a product of circular economic design. Managing such systems is more complex than operating a liner system. Instead of disposing of material streams in landfills, circular economies streamline them into productive purposes.

## Existing Terra Preta Nova and biochar systems

Germany hosts a demonstration-scale Terra Preta Nova facility that is based on established waste management systems. This pilot plant utilizes green waste, dung, manure and the solid fraction of the digestate from biogas production. Biochar feedstock is not explained in the literature (Palaterra, n.d.). Constant flow of input materials into the plant depends on streamlined regional logistics systems. Waste management is therefore essential for potential large scale TPN production.

Small-scale systems have also been developed. Terra Preta sanitation refers to sanitation systems based on urine diversion and addition of charcoal. Natural processes like lacto-fermentation and vermicomposting converts fecal material into Terra Preta like soils (Gensch, 2010).

Apart from Germany, attempts to create Terra Preta Nova have been rare. A TPN experiment in the Municipality of Tailândia in Brazil has used as feedstock a combination of charcoal, sawmill and butchery residues (Kern et al., 2009). This experiment utilized the local waste streams from the wood industry that is prevalent in the region.

Terra Preta Nova systems are not clearly defined in the literature. Often these are confused with biochar systems, where biochar was supplemented with some form of organic waste. This includes materials like human and animal manure, compost, urine etc.

The International Biochar Initiative surveyed biochar projects and yielded 154 responses from 43 countries. Most of the projects are located in India, Indonesia and China. Around one third of the projects mixed organic waste with biochar (Wilson, 2011). Abiding by the definition of TPN given in the previous segments, these projects could be counted as small scale Terra Preta Nova systems.

## Feedstock for Terra Preta Nova development

Creating a viable TPN plant is mostly determined by the availability of local waste feedstock materials. These will be examined in more detail in the following segments.

### Feedstock materials

Terra Preta Nova proposed in this thesis would mainly comprise of composted organic waste and biochar, while materials like ash and urine would be added as amendments (Figure 10 and 14). Since biochar and compost are among the most important segments, their utilization and feedstock materials will be discussed in more detail. Production technologies are presented in Appendix 3.

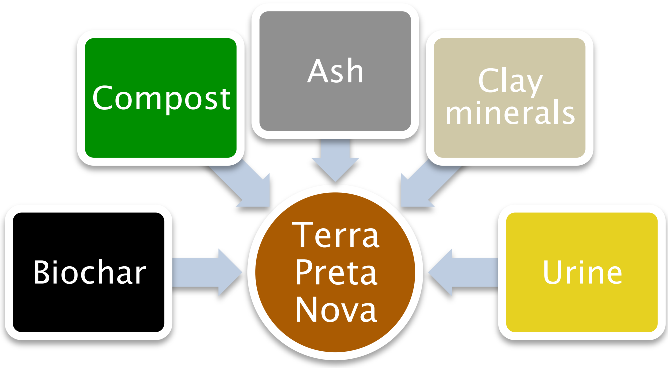


Figure 10: Terra Preta Nova feedstock streams. Source: Author

### Biochar

High quality biochar feedstock is usually a woody waste material, like waste wood or coconut shells. Despite their suitability for biochar production, these materials could also be used for energy production. Waste wood could for instance be incinerated to derive electricity. Biochar feedstock therefore runs into the alternatives-problem.

Lehman and Joseph (2009b) outline the feedstock materials that were used in biochar field trials (Table 5). Many of these are, however, suitable for bioenergy production and biochar should only be considered as a second option. Green waste is a material that is for instance well suited for composting, biogas production etc. Whether or not this is used for biochar production, depends on regional energy and materials demand analysis.

Large differences exist between the biochar resource base in urban, industrial and rural areas and to some extent between developing and developed countries. Feedstock materials are also variable in quality. Agricultural and forest residues often contain rock and soil that decrease efficiency of biomass conversion or damage equipment. Urban and industrial areas often have feedstock contamination problems. Many resources coming from these sources are available during the entire year but contain heavy metals, sewage sludge being a prime example (Lehmann & Joseph, 2009b). Industrial sources, like the paper industry, generate large quantities of waste that can be utilized for biochar production (Van Zwieten et al., 2010).

Seasonality of feedstock will be of great importance as well. Sources like paper mills and sewage sludge provide a steady all-year flow of input materials. Energy crops on the other had are available only in harvest periods. Their availability also depends on the yields, which vary with climate conditions.

Individual feedstock will also differ in transportation distances. The economics of transportation will vary with the moisture content of feedstock and transportation type. Input materials with large water content will be more uneconomical to transport. Such feedstock will also be more costly to treat. High moisture feedstock will require additional drying, before being pyrolyzed for biochar production. Transporting the feedstock with trains and boats will be more economical that truck transport, because of the higher energy efficiency (Lehmann & Joseph, 2009b).

Table 7 provides a comprehensive summary of biochar feedstock input. The materials are divided based on source (urban, rural and industrial), global region (developed and developing countries), moisture content (low, high and medium) and transportation (high and low transportation distances).

**Table 5: Different biochar feedstock according to various quality factors. Source: Adapted from** Lehmann & Joseph, (2009b)

| Resource base | Location | Global region | Moisture | Transportation |
|---|---|---|---|---|
| Green waste from households, parks, gardens and construction clearing | U, (R) | DD | L-M | H |
| Source separated organic waste (animal, grease-trap waste) | U | DD | H | L-H |
| Waste from wood-and paper-processing industries | I.R | (DG) DD | L-H | L-H |
| Source-separated commercial and industrial waste with low heavy-metal contents | U,I, (R) | DG, DD | L-H | L-H |
| Sewage sludge with low levels of contaminants | U,I | DG, DD | H | L |
| Residues from food crops | R | (DG), DD | L | L-H |
| Manure from confined animal operations | R | DD | H | L-H |
| Purpose-grown feedstock | R | DD | L | H |
| Forest thinning's and residues of timber production | R | (DG), DD | L | H |
| Residues from food-and crop processing facilities | U,I,R | (DG), DD | L-H | L |
| Residues from the clearing of land mines | R | DG, DD | L | L-H |

Notes:
1. Location where the feedstock is most abundant: R = rural; U = urban
2. Global region where the feedstock is most abundant: DG = developing; DD = developed countries
3. H = high moisture content; L = low moisture content
4. H = high transportation distances; L = low transportation distances, both with and without cogeneration of energy
5. Brackets indicate low importance

### *Compost*

Compost is a material consisting of degraded organic waste that has been conditioned to make it suitable for land application. Organic waste originates from municipal, agricultural and industrial sources. Before being used in agriculture in any form, these materials should be composted.

> *Composting is the biological decomposition and stabilization of organic substrates, under conditions that allow development of theomorphic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land.*
>
> *Taken form Haug (1993)*

Composting essentially stabilizes waste and in doing so it decreases the waste volume and eliminates any harmful pathogens and plant seeds.

Under natural conditions, earthworms, nematodes and soil insects break down most of organic material into smaller particles, increasing their exposure to microbial degradation. When compost is produced for waste management purposes, organic waste is broken down into smaller particles mechanically (Chen et. al. 2011). Besides this, the degradation process is controlled to maximizes the production of humus and minimize the creation of unwanted substances like methane.

Achieving the appropriate carbon to nitrogen ratio is one of the most essential elements of composting. This represents the relative proportion of these two elements. Organic waste materials differ in the amounts of carbon and nitrogen, which necessitates achieving a right compost mix.

Woody materials will mostly have higher amounts of carbon, while residues like grass cuttings and leaves have higher nitrogen amounts. The best carbon to nitrogen ratio is believed to be between 40:1 and 25:1. For normal functioning, the microorganisms also require appropriate moisture (50 to 60% by weight), oxygen availability (>10%), pH levels (6.5 to 8.0) and process temperature (55 to 65 $^{o}C$) and particle size (<2.5 cm) (Chen et. al. 2011).

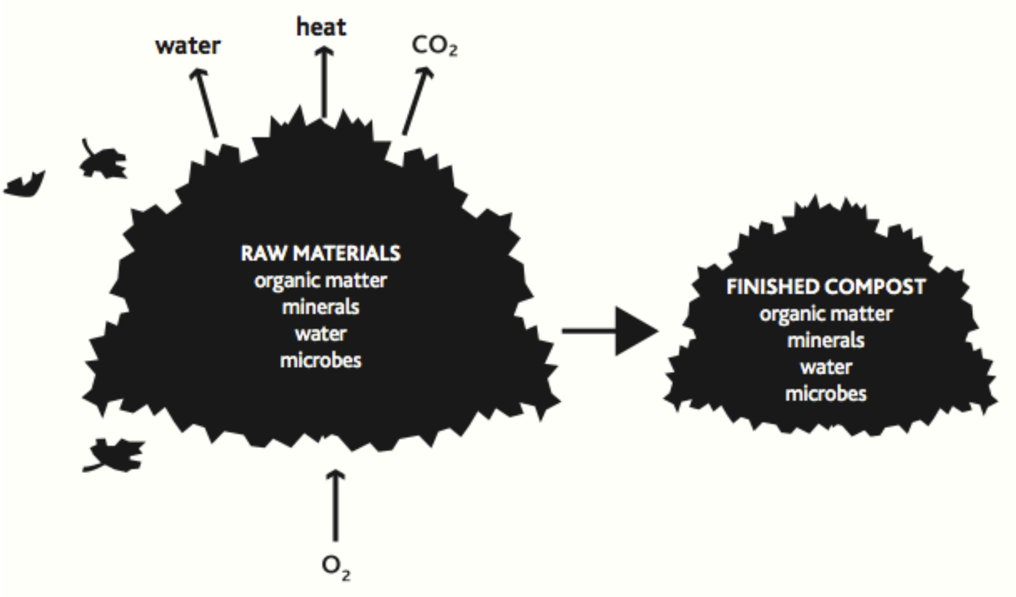


Figure 11: The composting process. Source: Chen et al. (2011)

## The composting process

Composting is a process requiring oxygen and water, where microorganisms harness the chemical energy contained in the bonds of the substrates being degraded. Results of the process are heat and $CO_2$ and humus (carbon skeletons and recalcitrant humic substances), which is largely responsible for the soil-amending ability of compost (Figure 12). This process consists of three basic stages and these are (Seyedbagheri, 2010):

1) Initial mesophilic stage – population of microbes increases exponentially as these are readily available food sources, contained in the feedstock. This increases the temperature of the compost pile from ambient temperature to around $40\,^oC$.

2) Second thermophilic phase – occurs during the second or third week of composting when temperatures in the pile reach 60 to $70\,^oC$. Maintaining the process requires constant watering and turning of the pile in order to ensure adequate levels of oxygen. This phase continues until most of the nutrient and energy-containing materials within the pile have been transformed. The high temperatures kill pathogens and weed seeds and break down phytotoxic compounds (toxic to plants) (Chen et. al. 2011).

3) Final mesophilic phase – composting slows down and the compost becomes relatively stable. During this phase, soil microbes recolonize the pile and the formation of humic substances increases. The composting process stops when the pile reaches ambient temperatures.

Composting leads to the formation of humus and this is a stable substrate, free of pathogens and plant seeds, which can be beneficially applied to land for the purpose of fertilizing and soil amending.  The main aim of applying compost to ground is increasing and maintaining the level of soil organic matter. Soil organic matter improves soil water holding capacity, root density and cation exchange capacity. It also improves other physical, chemical and biological soil properties that will not be discussed in this thesis (Cecil & Jolin, 2005).

### Compost feedstock

Compost can be made from the following waste streams that differ in nitrogen and carbon content (Cecil & Jolin, 2005):

1) Green waste or yard waste – landscape or plant trimmings, leaves and grass. This is usually nitrogen rich
2) Wood waste – includes woody debris, branches, twigs, stumps and sawdust. These are carbon rich
3) Food waste – food material resulting from the processing, storage, preparation, cooking, handling or consumption of food. This includes industrial, commercial and residential sources. It includes pre-consumer (kitchen trimmings) and post-consumer (off the trimmings) waste.
4) Other organic waste – includes manure, agricultural crop residue and other miscellaneous compostable organic materials. Manure is more nitrogen-rich and crop-residues are more carbon rich.

## Carbon use efficiency

Due to its positive effects on the physical, chemical and biological soil properties, compost contributes to greater and more stable crop yields. However, composting is limited in terms of carbon use efficiency and long-term carbon sequestration. Large amounts of carbon are lost through oxidation of organic matter. Figure 12 shows that the average carbon losses during the rotting process, due to $CO_2$ emissions, ranged from 35% to 55% (Fischer & Glaser, n.d.).

| | Fresh compost from bio-waste | | | Mature compost from bio-waste | | | Mature compost from yard + parc waste | | |
|---|---|---|---|---|---|---|---|---|---|
| | Processing | CO2 emission | Screening | Processing | CO2 emission | Screening | Processing | CO2 emission | Screening |
| Feedstocks | 100 | | | 100 | | | 100 | | |
| loss during rotting process | | 35 | | | 55 | | | 55 | |
| compost, not sieved | 65 | | | 45 | | | 45 | | |
| compost, sieved | 43 | | | 25 | | | 16 | | |
| Screening remains | | | 22 | | | 20 | | | 29 |

**Figure 12: Relative carbon balance in percent of initial carbon input based on composting facilities in Germany. Source: Fischer & Glaser (n.d)**

### *Biochar and compost mixture*

**Note**

This segment is based in the research done by Fischer and Glaser (n.d), a research paper on mixing biochar and compost.

Efficiency of carbon use in compost could be enhanced with Terra Preta Nova technologies. Adding biochar to compost would increase the amount of stable carbon in the mixture. However, the overall amount of organic matter in the mixture will be variable and might even decrease. Mixing compost with biochar might induce more rapid mineralization of organic matter in the compost. Biochar science refers to this as the biochar priming effect.

Fischer and Glaser (n.d) indicate that positive priming effects occurred when biochar constituted 1% of the biochar-compost mixture. However, a significantly negative priming effect occurred when biochar composed 50% of the mix. These results indicate that biochar-compost mixtures increase the stable carbon fraction and overall organic matter content, when biochar is added in larger amounts. The results are based only on one experiment so any generalizations about biochar-compost mixtures cannot be made.

Adding biochar to compost could have the following positive effects on the composting process:

1) Biochar surface oxidation enhances the capacity of biochar to chemisorb nutrients, minerals and dissolved organic matter. Overall reactivity of biochar surfaces increases with composting
2) Biochar as a bulking agent improves oxygen availability and stimulates microbial growth and respiration
3) Biochar increases moisture retention that will have a positive effect on composting
4) Biochar enhances the rotting process due to its functions as a matrix for the involved aerobic microorganisms probably increasing decomposition speed.

Positive effects of biochar application to compost have been demonstrated in a greenhouse experiments on sandy and loamy soil in temperate climate conditions (Figure 13). Biochar-compost mixtures increased crop yields more than individual biochar and biochar-fertilizer applications (10kg of biochar per one tonne of compost material). However, best yields were observed when compost was applied individually.

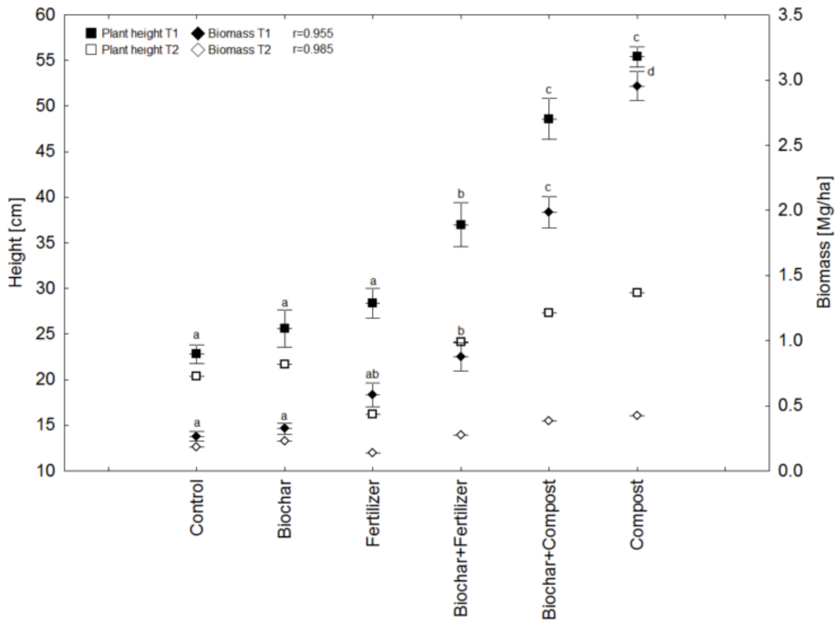


**Figure 13: Crop response in relation to different biochar and compost application. Source: Fischer & Glaser (n.d)**

Figure 14 shows the material flows that could be considered in making Terra Preta Nova. The materials are presented according to availability of individual nutrients and degradability. The graph does not include digestate from biogas production. This material is rich in nutrients and is usually used in agriculture for fertilization. Using digestate for TPN production is welcomed in regions that have great numbers of biogas plants and lack of agricultural fields.

Fischer and Glaser (n.d) note that nitrogen rich materials, like leaves, could work to promote a rapid rotting process. On the other hand, ligneous carbon rich materials could provide a stable organic matter pool with long term benefits for soil amelioration, carbon sequestration and humus reproduction. Biochar could serve as a medium to retain water and nutrients, guaranteeing long-term positive effect on crop yields. Adding clay minerals could additionally enhance cation exchange capacity and water holding capacity due to its high adsorption or swelling capacity.

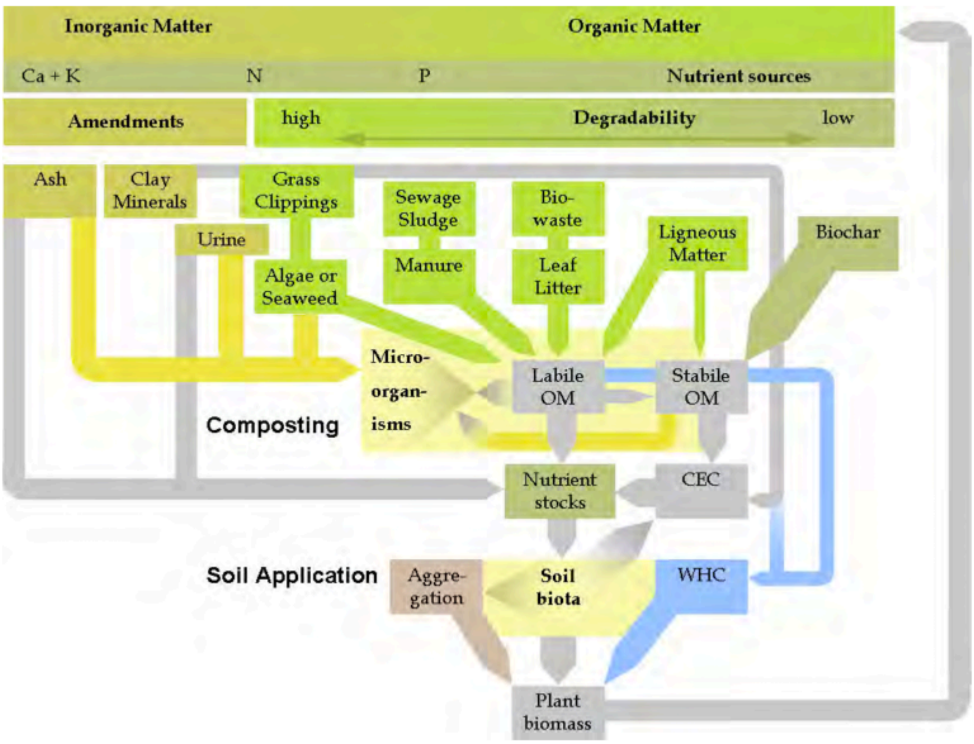


Figure 14: Material Flows for Terra Preta Nova. Source: Fischer & Glaser (n.d)

## Material Flow Management for Terra Preta Nova

Material Flow Management (MFM) is a resource management approach used to design new efficiency strategies needed to manage industrial and urban metabolisms in a sustainable way.

> *Material-Flow Management (MFM) means the goal oriented, responsible, integrated and efficient influencing of material systems. The goals are given by ecological and economical areas and by observing social aspects.*
>
> *Taken from* Hongyan (2005)

The scope of MFM are regions, municipalities and individual companies. These are seen as systems where material and energy flows underline normal economic activity. Because every material has energy embedded in it – like energy from the Sun in biomass – energy and material flows are viewed as a single entity.

Material and energy flows in current systems are unorganized. Single parts of a system, like household, industry and public buildings, are seen as individual subsystems. Each consumes materials and energy and produces low quality waste. Modern economic systems treat this waste in the simplest and financially cheapest way. Solid waste is transported to a landfill or discarded in nature, while wastewater is untreated and discharged in water bodies. Low energy efficiency of the current system creates energy losses, while waste heat is not utilized.

Material Flow Management creates circular material and energy flows. Consumed materials and energy that would otherwise be treated as waste, are regarded as locally generated resources that can be reused. Instead of discharging wastewater into water bodies and landfilling solid waste, clean technologies are employed to restore the value embedded in these consumed resources. Clean technologies optimize system material and energy flows and create regional added value

MFM constantly improves the efficiency of existing systems by using integrated technologies. Integrated refers to using diverse technologies that achieve full material and energy cycles in the sphere of waste and wastewater management, energy production and land management.

MFM measures are based on sound economic analysis. Decisions to invest into clean technologies are made after careful financial considerations. But unlike conventional decision making, where investment decisions are made strictly taking into account the expected financial performance – like time needed for the investment to pay back itself or return on investment – MFM investment decisions are also guided by regional added value creation.

Regional added value is a term describing any non-monetary value created by an investment decision. This refers to job creation, information exchange, local business network creation, enhanced environmental quality etc. In economics, cost-benefit analysis values these additional project benefits.

Instead of purely seeking projects with best returns on investment, the MFM ventures are based on sustainability criteria. Projects that decrease environmental degradation and improve the social livelihood of local communities will have a greater attractiveness than the most profitable business ventures.

This segment will describe the MFM methodology and its application for regional Terra Preta Nova development. The first segment will focus on the methodology itself, while the second segment will investigate the viability of developing TPN using this methodology. Main risks of using this methodology will be presented using a case study. The findings of this thesis can be used as a framework for developing TPN through regional MFM optimization[3] strategies.

## MFM methodology

MFM starts with Material Flow Analysis (MFA) – a detailed analysis of material and energy flows on a regional or municipal level. This exercise looks into the inefficiencies of the current system and seeks to identify optimization potentials. In terms of Terra Preta Nova, this would include looking into organic waste accumulation. The MFA evaluates if it makes sense to establish a Terra Preta Nova system from a feedstock point of view. This exercise provides the basic data, upon which detailed economic and technical analysis can be performed.

Implementing any MFM optimization is dependent on clear political will from the local government and participation of the local population. MFM seeks to establish cooperation with local decision makers through detailed stakeholder analysis. Participation of the local population is assured by appointing local MFM officers in charge of the MFM project implementation. Inclusion of the local population is further assured through creating a local MFM business unit. The business unit facilitates the development of all MFM projects through supervision, marketing, financing and capacity building.

The segments bellow will outline the main elements of the MFM methodology (Figure 15) in the order of execution. Relevant segments will be discussed in terms of developing Terra Preta Nova.

---

[3] MFM optimization is defined as measures taken in odred to organize material flows in a higjly efficidnct way. The technologies used in the process are capable of revaliung waste streams, in such a way that maximum potential is achieved

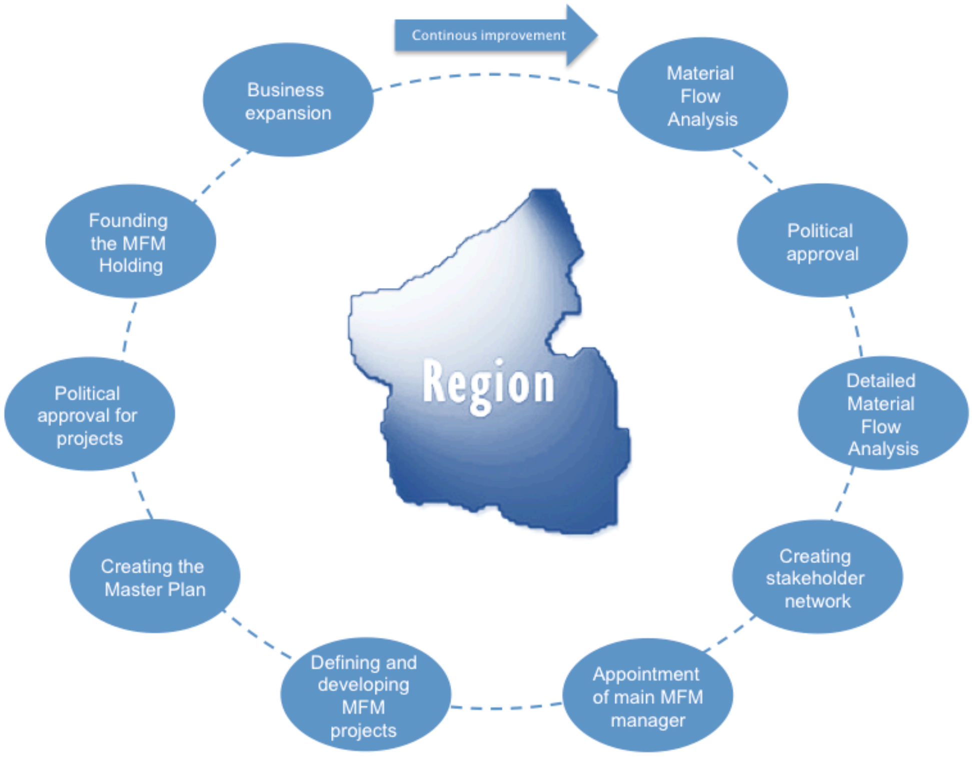


**Figure 15: MFM Methodology. Source: Developed from Heck (2011)**

## Material Flow Analysis

Material Flow Analysis (MFA) in its technical meaning is a systematic assessment of the flows of stocks of materials within a system defined in space and time. MFA scans the region or municipality (scope of MFM) in question for optimization potentials, such as accumulations of waste in a landfill. When such an accumulation of materials is identified in the adequate quality and quantity, MFM optimization can be initiated.

MFA connects the sources, the pathways, and the intermediate and final sinks of a material. Through balancing inputs and outputs, the flows of waste and environmental loading become visible, and their sources can be identified (Brunner & Rechberger, 2004). This is done based on this simple equation:

$$\mathrm{I} = \mathrm{O} + \Delta, \Delta t \qquad (1)$$

In equation (1) the inputs of a system (I) are equal to the outputs (O) and accumulation of goods and substances (Δ). MFA is used for evaluating the trends of accumulation/depletion of a stock and finding sustainable solutions. In terms of Terra Preta Nova, this can include looking at accumulations of organic waste for composting or ligneous materials for biochar production.

The MFM methodology expands on this and includes in the MFA a demand side analysis and key decision makers identification. Demand side analysis identifies if there is demand for the products of optimizing material and energy flows. This can include looking into potential markets for Terra Preta Nova. Identifying key decision makers, on the other hand, maps out individuals and institutions with which MFM optimization has to seek cooperation. The results of this analysis are a deeper understanding of regional material flow systems, limitations, inefficiencies, real costs and potentials.

MFA is closely linked to Life Cycle Assessment (LCA) but there are major differences. MFA is based on creating a balance between inputs and outputs of materials flowing in a system[4]. On the other hand, the main goal of LCA is to determine the environmental impact of an activity (production of a good) by presenting its ecological footprint. The interaction of these concepts is given in figure 16.

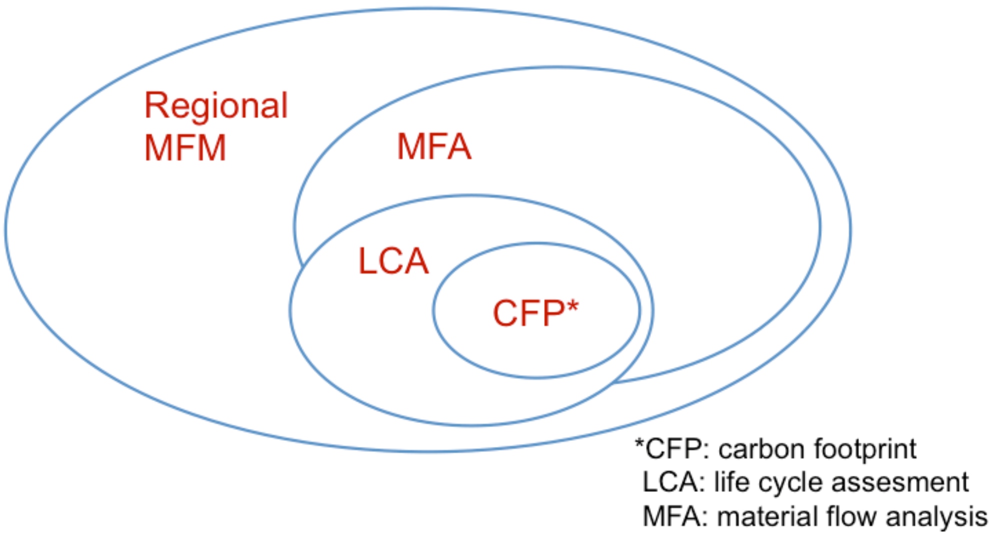


**Figure 16: Interaction of MFA and MFM related concepts. Developed from Avadi (2011)**

[4] MFM expands on this and includes the demand side anlysis and key decision makers analysis

Regional MFM is seen in the context of MFA, LCA and CFP. In effect, the MFA is like an inventory of material and energy flows that can be used to calculate the carbon footprint with an LCA.

Figure 17 presents the steps of MFM methodology in conducting the Material Flow Analysis. Conventional thinking about MFA, discuses this method only in terms of the first three steps, where the main result is a diagram showing the material flows. Results of drawing a material and energy system in MFA software are used to make recommendations for optimizing the material and energy flows of a system.

Material Flow Management applies a more practical approach, which is why demand side analysis and key person analysis are included.

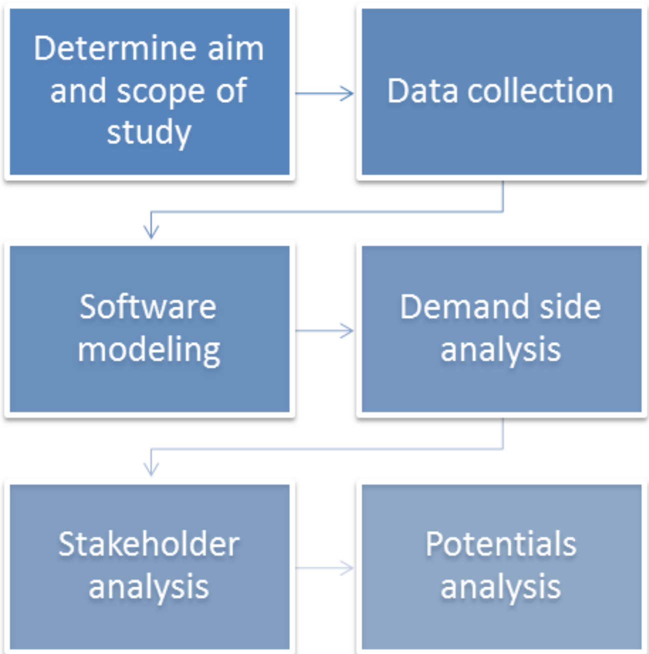


**Figure 17: Material Flow Analysis in the MFM approach. Source: Author**

The goals of the MFA within the MFM methodology are:

1. Study the current system
    a. Material and energy flows
    b. Demand for resources like electricity, heat, synthetic fertilizer etc.
    c. Identify key decision makers

2. Study optimization potentials
    a. Locate opportunities to optimize the system
    b. Define clean technologies that can be used
    c. Identify the potential results (possible amount of energy produced from biogas etc.)

### *MFA for Terra Preta Nova*

The following paragraphs will describe the MFA process in more detail and will link this to Terra Preta Nova development.

#### Determine aim and scope of study

Defining an aim narrows down the entire MFA. Instead of looking at all material and energy flows within a system, an MFA can focus on just the flows that are relevant for the project in question. A scope follows directly from the aim. This refers to the boundaries of the study. Having a well-defined scope assures that the analysis will not grow beyond manageable means.

**TPN:** The aim of an MFA for Terra Preta Nova would be to identify all material flows that are usable as feedstock. It is recommended to take a political region as the main scope of the study. Setting such a boundary facilitates data collection. This is because most of the statistical data is compiled for political regions. Moreover, the political approval to conduct MFM optimization would have to be obtained only from the selected region.

#### Data collection

Data can be collected using the following methods:

1) On site visits
2) Interviews
3) Questionnaires
4) Official statistical data
5) Internet search for similar case studies

6) Consultation with experts

**TPN:** Having the aim and the scope of the study defined, it is easier to determine the data that needs to be collected. In terms of Terra Preta Nova development, the main interest would be to see if there is sufficient feedstock for production. The materials that constitute the object of investigation would include organic waste rich in nitrogen and carbon.

The feedstock would have to be evaluated according to its quality, quantity and source. In some instances there might be enough waste, but its location makes it uneconomical to transport and process into Terra Preta Nova. The economics of extracting a certain waste stream would in large extent depend on the existing logistical infrastructure. Regions with well established waste collection and management schemes would find it easier to collect the feedstock.

The result of the data collection will be used in the following step, where the collected data is inserted into a computer program that makes it easier to visualize the material and energy flows.

### Software modeling

The data collected in the previous step is analyzed and sorted using software applications. These are used mainly to support and facilitate procedures and calculations that would otherwise be time consuming (Brunner & Rechberger, 2005).

Software applications are not a must in conducting the MFA. The Institute for Applied Material Flow Management, a leader in the field of practical MFA, often does not use any software applications. However, using these has several advantages:

1) Information is presented in an easily understandable way using diagrams. These clearly show the quantities and directions of material and energy flows in a system

2) Using MFA software gives the studies a scientific value. The software's are accepted in the scientific community as a method to communicate MFA results
3) Presenting the MFA results with standardized diagrams enables comparison of results from multiple studies

There are several criteria that define the value of using an MFA software (these are not exclusive). The criteria take into account that individuals with inadequate experience in MFA might use the software. These criteria are the following (Brunner & Rechberger, 2005):

1) **Documentation** – there is comprehensive documentation that is easily available, comprehendible and easy to understand. This must involve an installation guide, a user manual with examples of MFA models (and guidance on how to make them) and on-line help.
2) **User friendliness** – the user interface is easy to understand and intuitive. The programs can be used in widely present operation programs such as Windows and are available in local languages.
3) **Support and maintenance** – there is a support network to aide users and this is available at any time. Product maintenance is guaranteed by the software producer
4) **Stability** – the program is stable and reliable. There are no crashes of the program and the bugs have been fixed
5) **Cost benefit** – the price is reasonable in relation to the benefits of using the software. There is a free test version available
6) **Calculation speed and accuracy** – the program generates accurate calculations within an acceptable time span

Some of the most commonly used software for Material Flow Analysis are *STAN - Substance flow analysis* and *Umberto for Carbon Footprint*. MFA modeling in these programs will be described in more detail in Appendix

### *STAN - Substance flow analysis*

STAN is a MFA software that was developed by Technical University of Vienna for application in waste and wastewater management. It enables the user to graphically model a system of substance and good flows within a predefined system and time period. STAN is for instance used in tracking the sources, flows and sinks of phosphorus in rural and urban settings (Moore et al., 2011).

Substance is defined as any chemical element or compound of uniform units. All substances are characterized by a unique and identical constitution and are homogenous. For instance, drinking water is not a substance itself. Instead, it is composed of substances like pure water, calcium and many trace elements. On the other hand, goods are defined as economic entities of matter with a positive or negative value. These are drinking water, fuel, solid waste, sewage etc. (ComponentOne LCC, n.d.).

STAN presents the flows of goods and substances in Sankey diagram format. Sankey diagrams are a specific type of flow diagram, in which the width of the arrows is shown proportionally to the flow quantity. They are typically used to visualize energy and material transfers between processes within a system. STAN user interface with such a diagram is shown in Figure 18.

Modeling in STAN is preceded with aim and scope determination as well as data collection. After conducting these steps, a graphical model of the analyzed system can be constructed. This model consists of processes, flows, system boundaries and text fields.

Each flows is defined with data that was previously collected. Mass flows and stocks, volume flows and stocks, concentrations and transfer coefficients are imported into each flow connecting two processes. A transfer coefficient defines the percentage of a substance or good in an overall mass flow (% of phosphorus in wastewater flow).

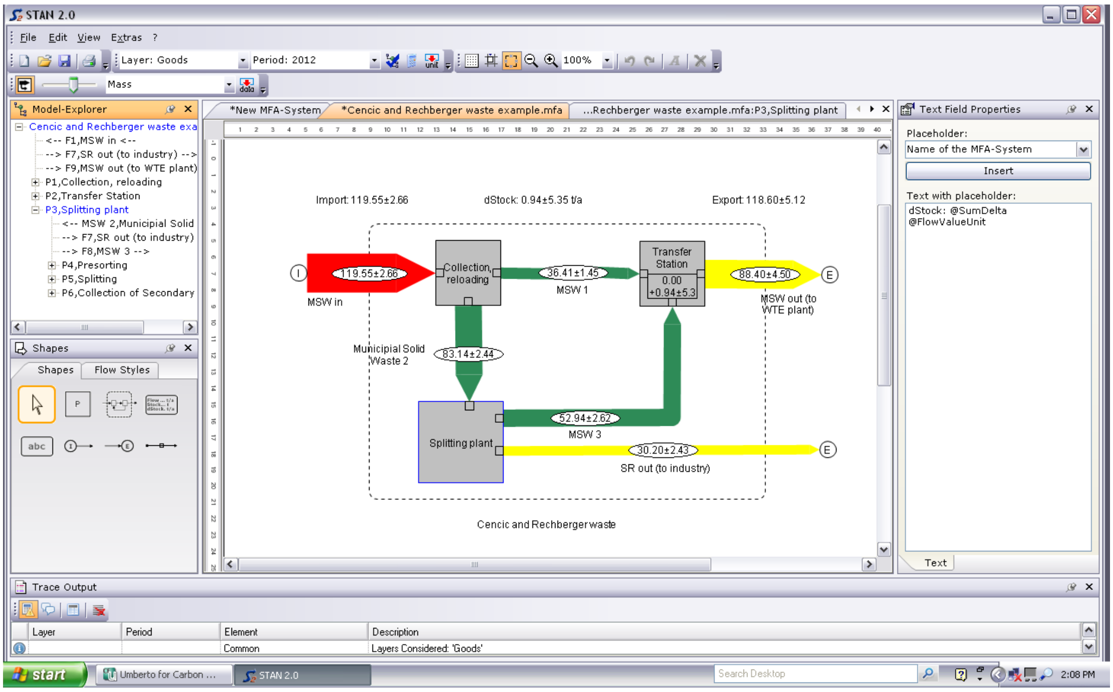


**Figure 18: STAN user interface. Source: Component One (n.d)**

**TPN:** STAN can simultaneously track multiple substance or good flows within a system. The same graphical model, consisting of processes and flows, can have multiple variations, depending on the flows that the user wants to present. These different variations of the same model are called layers.

Modeling Terra Preta Nova in STAN would require having multiple layers. Each layer would present one material flow. Directions and quantities of the material flows would be presented for the processes that were defined for the system.

This system would be defined in space and time by a predetermined border. The model could be calculated for a time period of one year. Multiple years could be modeled at the same time and this allows tracking the historical trends in material flows.

A simplified version of a Terra Preta Nova model is given in Figure 19. The figure emphasizes that each MFA model, developed in STAN, has multiple layers of material flows. These are examined for the same model – same processes (segments) of a system.

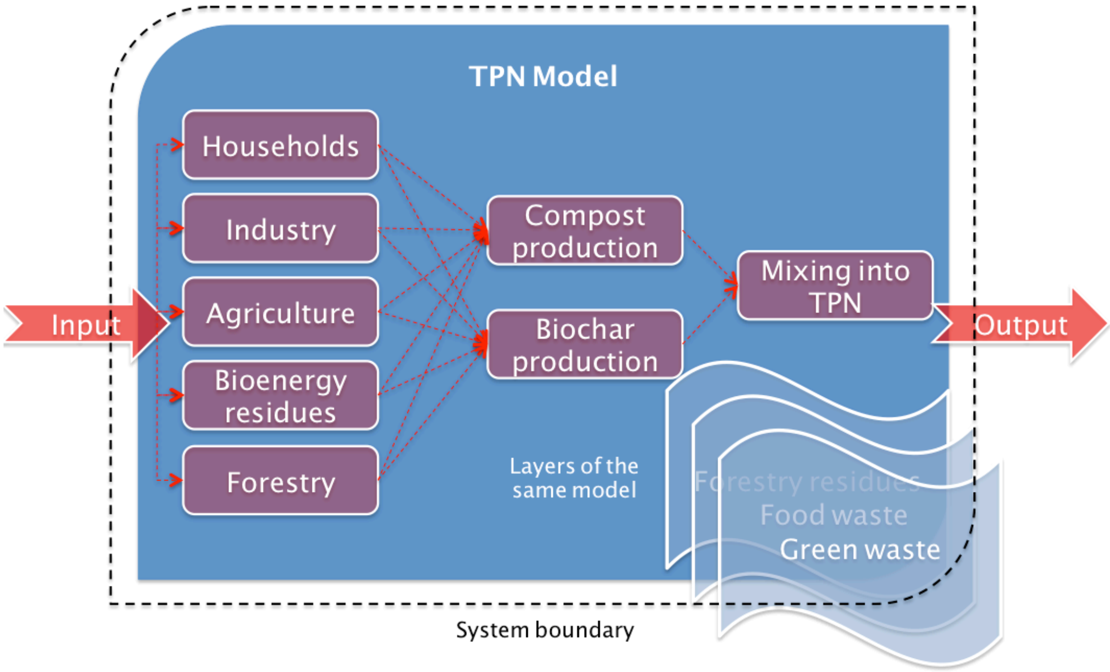


**Figure 19: Layer TPN model in STAN - simplified version. Source: Author**

### *Umberto for Carbon Footprint*

Umberto for Carbon Footprint is a program primarily developed for calculating the carbon footprint of a product (LCA). The GHG emissions are calculated according to a pre defined functional unit. For instance, LCA could calculate the GHG emissions of 1t of Terra Preta Nova. The ecological footprint and other environmental indicators are scaled to this functional unit.

Since the MFA is like an inventory of material and energy flows, used to calculate the carbon footprint with an LCA, using Umberto will yield both an MFA and LCA.

Umberto uses graphical modeling of the life cycle of the product and allows analyzing, assessing and visualizing the emissions of greenhouse gases (GHGs) that contribute to climate change. Apart from GHG emissions as well as material and energy flows of systems, Umberto can calculate other environmental impact categories such as eutrophication, ozone depletion, ecotoxicity, or abiotic resources depletion.

Umberto relies on the *ecoinvent* database, where the users can find Life Cycle Inventory (LCI) data with more than 4000 LCI datasets in the areas of agriculture, energy supply, transport, biofuels etc. This mainly relates to $CO_{2eq}$ emissions related to the production of individual materials (1kg of plastics) or performing a process (transport of 1kg of plastic via lorry etc.).

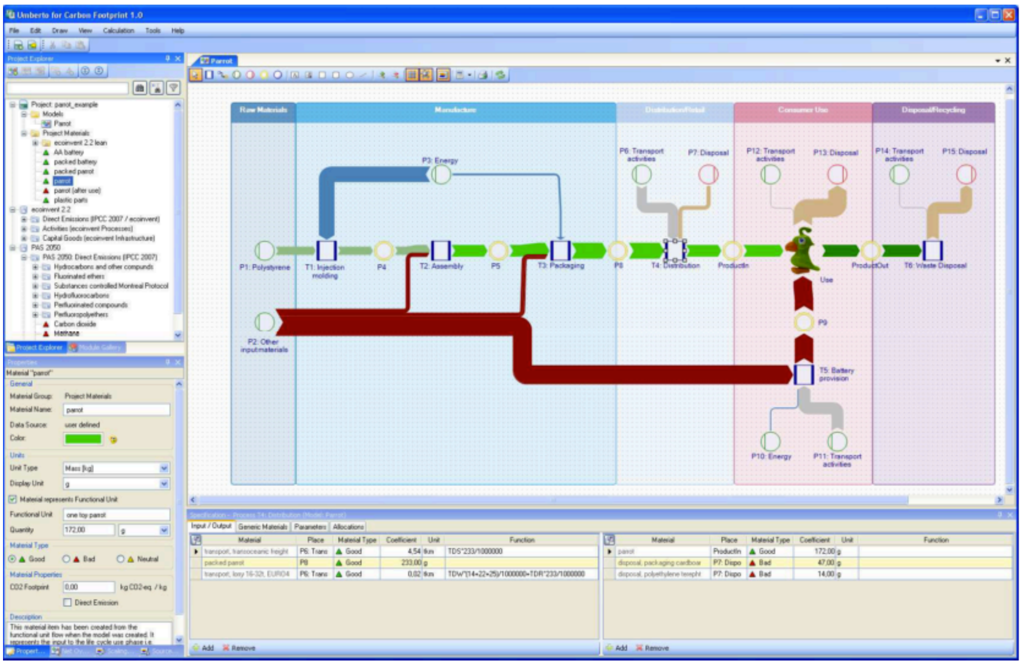


Figure 20: Umberto for Carbon Footprint user interface. Source: ifu Hamburg (2012)

**TPN:** Umberto does not function on the basis of layers, which is the case with STAN. Each process in Umberto (segment of the system, like composting in TPN systems) has a defined set of input and output materials. This is shown in Figure 21, on the example of flour production (ifu Hamburg, 2012).

Material and energy flows are tracked jointly. Sankey diagrams in Umberto cannot separate between the materials; instead the flows are aggregated and shown as a total..

Using Umberto for MFA in Terra Preta Nova systems would enable the user to calculate the ecological footprint of TPN and compare it to a system without it. Carbon savings could be a basis for claiming carbon credits and these could be used to finance the TPN investment.

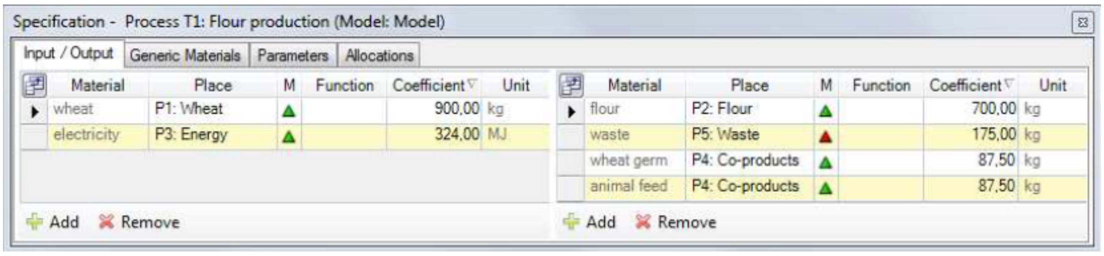


**Figure 21: Example input/output table in Umberto. Source: ifu Hamburg (2012)**

### *Comparison of Umberto for Carbon Footprint and STAN*

Umberto and STAN both have advantages and disadvantages and their usefulness will depend on the primary aim of the research project.

STAN is a simpler program and more straightforward than Umberto. It primarily balances the material flows in a system. The user can easy see the amounts and types of flows as well as determine the accumulations of materials.

On the other hand, Umberto does not allow the user to see the accumulation of materials. Instead its main benefits are in its ability to show the flows of GHG emissions. Umberto requires more detailed data input and, as a result, there is a higher chance of making an error. When this occurs the user needs to manually trace the error and fix it before the calculation can be completed.

Fixing such errors is often time consuming and STAN avoids this with data reconciliation. The program equalizes the input and output amounts to create a mass balance. Another major advantage of STAN is in its cost benefit. While one copy of Umberto costs around 10000 EUR, STAN is free of charge. This also explains why private companies mainly use Umberto, while public institutions and research organizations are the most frequent users of STAN.

Characteristics of both programs are outlined in Table 6, while Table 7 presents their main advantages and disadvantages. Choice of the program will depend on the final aim of the project, level of computer literacy of the users, project budget etc.

**Table 6: Comparison of Umberto and STAN. Source: Author**

| Software/developed by | Description |
|---|---|
| UMBERTO<br>Ifu Hamburg<br>www.umberto.de | • Modeling on the basis of material flow networks<br>• Variety in application, high flexibility<br>• Management of comprehensive data bases<br>• Company-related (Process optimization, Material efficiency) and product-related (Life Cycle Assessment)<br>• Calculates GHG emissions and other environmental impacts (eutrophication, ecotoxicity etc.)<br>• Presentation of results in Sankey diagrams<br>• Calculates cumulative energy and material flows |
| STAN<br>Technical University of Vienna, Austria<br>www.iwa.tuwien.ac.at | • Freeware, specifically developed for application of MFA in waste and waste water management<br>• Import/export with Excel data bases<br>• Purely based on input/output calculation<br>• Enables tracking flows of multiple substances/materials at the same time<br>• Tracks flows in time period<br>• Presentation of results in Sankey diagrams<br>• Calculates individual flows of goods and substances |

**Table 7: Advantages and disadvantages of Umberto and STAN. Source: Author**

| STAN | UMBERTO |
|---|---|
| **Advantages** | |
| • Developed for MFA in waste management<br>• Free of charge<br>• Simple and purely for input/output flows<br>• Training programs available at TU Vienna | • Calculation of Life Cycle Assessments, but could also be used for MFA<br>• Draws data on material carbon footprint from extensive databases<br>• Can calculate cost flows<br>• Calculates in great detail<br>• Great support network<br>• Frequently available training programs<br>• Good user manual and practice examples |
| **Disadvantages** | |
| • Calculating GHG emissions and energy flows is more difficult<br>• Data gathering for all materials. Is not supported with a materials database (like Umberto)<br>• Help desk is poor<br>• Training programs not available frequently<br>• Basic user manual with no practice examples | • High cost of program and low cost benefit if used only for MFA<br>• Great detail creates high complexity<br>• Calculations often yield errors<br>• Solving errors time consuming<br>• |

## Demand side analysis

MFM technologies will only be implemented successfully if there is demand for the services they produce. In the case of TPN production, this includes researching if there is market potential and demand for organic fertilizer/soil conditioner. Demand side analysis, therefore, involves market research and demand estimation.

In economics demand refers to quantities of goods that consumers are willing and able to purchase at various prices during a given period of time. There is a distinction between the willingness and ability of consumers to buy a good. While a consumer can be willing to buy an item, she or he might not be able to afford it. For instance, many consumers would be willing to but a BMW but they do not have the money. In demand side analysis, research is only interested in effective demand - the goods that the consumers are both willing and able to purchase (Mote et. al., 2003).

Demand for each good is determined with a demand function. This sets out the variables, which are believed to have an influence on the demand for any product. The demand function can be written as:

$$Qd = f(Po, Pc, Ps, Yd, T, A, CR, R, E, N, 0) \qquad (2)$$

Products differ in the variables that affect their demand. But the most common ones are given in equation (2) and these are (Mote et. al., 2003):

1) $Po$ - Price of the product: the higher the price the lower the demand, and the lower the price the higher the demand. This inverse relationship between price and quantity consumers will buy is called the *law of demand*.

2) $Pc$ - Price of complements: complements are goods like hot dogs and hotdog buns. If the price of hotdog buns increases, the price of hotdogs will increase as well leading to a decreased demand for hotdogs. Complements are, therefore, goods that have a direct relationship with one another in terms of price movement and demand response.

3) $Ps$ - Price of substitute: substitutes are goods that substitute each other (consumers can obtain the same utility by purchasing either good A or B). When the price of a good A increases the demand for good B will increase as well. When the price of a Taxi Service A increased, the demand for Taxi Service B will increase in response.

4) $Yd$ - Disposable income: this relates to the amount of money available to people for spending. The greater the level of disposable income, the more people can afford to buy and the higher the demand for a product.

5) $T$ - Tastes: Demand for an individual product will be determined by the tastes of consumers. Over time tastes may change considerably and this incorporates many factors. For instance, increasing environmental degradation might increase the demand of consumers for better environmental services.

6) $A$ - Advertising: This represents the level of own product advertising as well as complementary and substitute good advertising. The higher the level of own advertising of a good, the higher the demand, other things being equal.

7) $CR$ - Availability of credit: Credit will have importance when we consider buying goods that have high upfront costs. This can, for instance, relate to technological investments, like biogas plants etc. The easier it is to obtain credit, the higher the demand for a product.

8) $R$ - Rate of interest: Credit will be more affordable if the rate of interest is lower. That being said, lower the rate of interest, higher the demand for a good.

9) $E$ - Expectations: This mainly includes expectations about price and income changes. If the consumers expect the price of a good to increase in the future, they will stock up on that good now. Income levels have similar effects. When consumers expect their incomes to increase in the future, they will buy more goods.

10) $N$- Number of potential customers: Every product can expect to have a certain share of a market. Knowing the number of potential customers will depend on market research.

11) $O$ - Unexpected variables

Demand can be assessed in two basic ways (Mote et. al., 2003):

1) Quantitative analysis – Regression analysis is the main form of quantitative analysis. This is a statistical method that determines the effects of a series of independent variables on one depended variable. For instance, the effects of a price of a product on the quantity consumed. This method can, for instance, be used to determine the demand for electricity in relation to a number of variables such as available income, GDP growth, population growth etc.

2) Qualitative or marketing analysis

   a. Expert opinion – Insights of individuals closely connected to an industry can be of great value in forecasting. One of the most well known methods in assessing expert opinion is the Delphi technique.

**Delphi technique**

Multiple experts in the given field are asked to produce an estimate of future demand in terms of percentage increase/decrease. After the first series of estimates, the experts are presented with all the results. In most cases, the experts produce differing estimates. After the experts have reviewed each other's results, they are asked to make new estimation. The expectation is that the experts will revise their estimates once they have been influenced by the estimates of their peers. This will continue until the experts reach an agreement regarding future demand estimates.

   b. Survey – Quality of obtained results will largely depend on the precision and meaningfulness of the questions that were asked. This method does not always leads to the most precise estimates and has to be complemented with other methods.

c. Market Experiments – Surveys produce results, which might not transfer to actual action from the side of a consumer. Consumers do not necessarily do what they say they are going to do. Market experiments test a product in a selected market. The product is evaluated in terms of consumer perception etc.

**TPN:** Variables that effect the demand for TPN will differ depending on regional and country conditions. Developed countries have a higher GDP per capita and overall level of development. This will of course facilitate the development of TPN, in terms of higher disposable income, educational level and awareness of environmental problems etc. These relevant variables from equation (2) might effect TPN development:

1) $Po$ - Higher the price of TPN, lower the demand and lower the price of TPN, higher the demand.

2) $Pc$ - Compost and biochar are complements of TPN (direct input materials). Demand for TPN will therefore largely be a reflection of the price of these two input streams.

3) $Ps$ - Synthetic fertilizer is the main substitute to Terra Preta Nova. Price developments of synthetic fertilizer depend on many variables among which the most important ones are global population increase, increased global consumption of phosphate and potassium etc. (Huang, 2009).

4) $Yd$ - Regions with higher disposable income are more likely to have a greater demand for TPN. This is because individuals will have a higher ability to finance the investment into TPN production facilities and logistical network for feedstock collection (directly or indirectly through taxation etc.)

5) $A$ - Educational campaigns might have the greatest overall weight in terms on TPN advertising and marketing. TPN contains charred material – some schemes even envisage charring sewage sludge into biochar. People might be skeptical regarding using these materials in their gardens and fields. Even organic waste contained in compost, might be a source of resistance. This is why education is crucial

6) $CR$ - TPN is a high-end technology that still has not achieved market potential. Starting a TPN production facility will require credits lines with favorable interest rates. Investments by venture capitalists might be of use in jump-starting TPN production.

7) $N$ - The number of potential customers for TPN will be higher in developed agricultural regions with higher awareness of environmental problems on the local level (water quality, soil organic carbon content etc.) and global level (climate change induced by GHG emissions etc.)

## Stakeholder analysis

Stakeholder analysis (SA) determines the individuals or organizations that need to be considered during project planning and implementation, and who can have a positive or negative effect on the final outcome of the project.

A stakeholder can be defined as and individual or group who has a vested interest in the project area and who can potentially be affected by project activities and have something to gain or loose if conditions change or stay the same (Golder & Gawler, 2005). The goal of SA is to identify the direction, relationship and extent of influence of multiple stakeholders relevant for the project success.

Benefits of using stakeholder analysis are (Thompson, 2012):

1) Opinions of the most powerful stakeholders can be used to shape a project in its early stage. This makes it more likely that they will support the project but also improve its quality.

2) Gaining support from powerful stakeholders can help the project win more resources
3) Early and frequent communication with stakeholders can ensure that they understand the intentions of the project and are in agreement with them
4) Anticipation of people's reactions to the project

Stakeholder analysis can be performed in many ways, but most methodologies have these features in common (Thompson, 2012):

1) Identifying key stakeholders by brainstorming, with the project group, who the main stakeholders are.
2) Prioritize the stakeholders by mapping them on a Power/Interest Grid (Figure 22). This places the identified stakeholders in the context of the project. The grid tells the project managers in what way should individual stakeholders be managed. The ones with a high interest and power should be managed closely, while the ones with only low power and interest should only be monitored. Knowing this will help the project guide efforts towards securing support of the most important decision makers.
3) Understand key stakeholder by analyzing their importance, through desktop analysis, interviews, expert consultation etc.

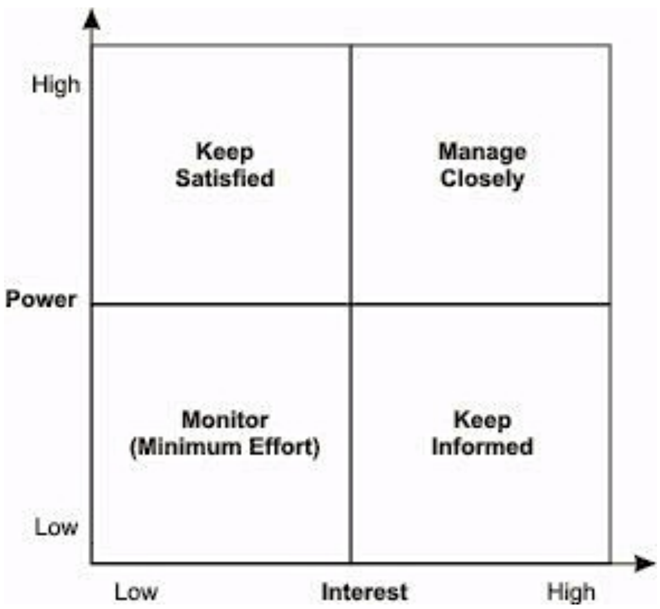

**Figure 22: Power/Interest Grid. Source:** (Thompson, 2012)

### Potentials analysis

After detailed supply and demand considerations, undertaken in the previous steps, MFM defines possible optimization potentials. This relates to choosing the projects will the highest probability of having positive economic and technical feasibility. This appraisal is based on the conclusions made in the MFA. The selected projects are analyzed in more detail in steps following the MFA – technical and economic feasibility studies.

## *Economic and Technical Feasibility*

### Economic feasibility

Economic feasibility mainly examines whether the projects achieve economic profitability and what is the time in which they repay the initial investment. Economic profitability is defined with financial indicators such as:

1) Net present value
2) Internal rate of return
3) Payback period

These indicators are calculated using Discounted Cash Flow Analysis (DCFA) - a method that compares all envisaged cash flows from a project. This includes both positive and negative cash flows that are examined for a future time frame (most studies look at a 20 year time period).

DCFA is based on assumptions about future cash flows. This being the case, many of these assumptions might not materialize themselves. For instance, DCFA might assume the revenues of a venture will increase 5% each year. This might change due to a number of factors, such as macroeconomic (in) stability. For these reasons, the results of DCFA are tested using Sensitivity analysis.

Sensitivity analysis tests the sensitivity of projects profitability to sudden changes in the project cash flows. Cash flows can change due to a number of reasons including interest rate changes, product price changes etc. Through changing the variables that contribute to positive or negative cash flows, the projects overall sensitivity to changing circumstances can be evaluated. Variables that affect the project the most can be singled out, enabling the project managers to focus their attention to those factors.

### Technical feasibility

Environmental problems require various technological solutions. Not every technology is applicable to each problem. Technical feasibility examines if a proposed technological solution is practical, applicable and available. In other words it answers these questions:

1) Is the proposed technology or solution practical?
2) What kind of technology do we need?
3) Is the required technology available?

**TPN:** This thesis proposes developing Terra Preta Nova from biochar, composted organic waste and other amendments like urine and ash. Compost and biochar are the main elements of this feedstock mix, without which TPN systems would not be possible. Compost and biochar production technologies are examined in Appendix 2, in line with the above stated questions. Due to lack of data, the thesis does not discuss the actual feedstock mixing and processing into Terra Preta Nova.

## MFM Master Plan

The MFM master plan refers to a strategy for conducting MFM optimization, through implementing a series of technologies that improve material and energy flows in a region and have been identified as economically and technically viable.

Regional MFM optimization is here defined as any MFM measure that leads to the improvement of regional material and energy flows, in such a way that sustainable benefits are created. Usually this involves integrating technologies that combine waste management and water management with energy production, agriculture and land management. Figure 23 shows exemplary projects that could constitute the outcomes of regional MFM optimization.

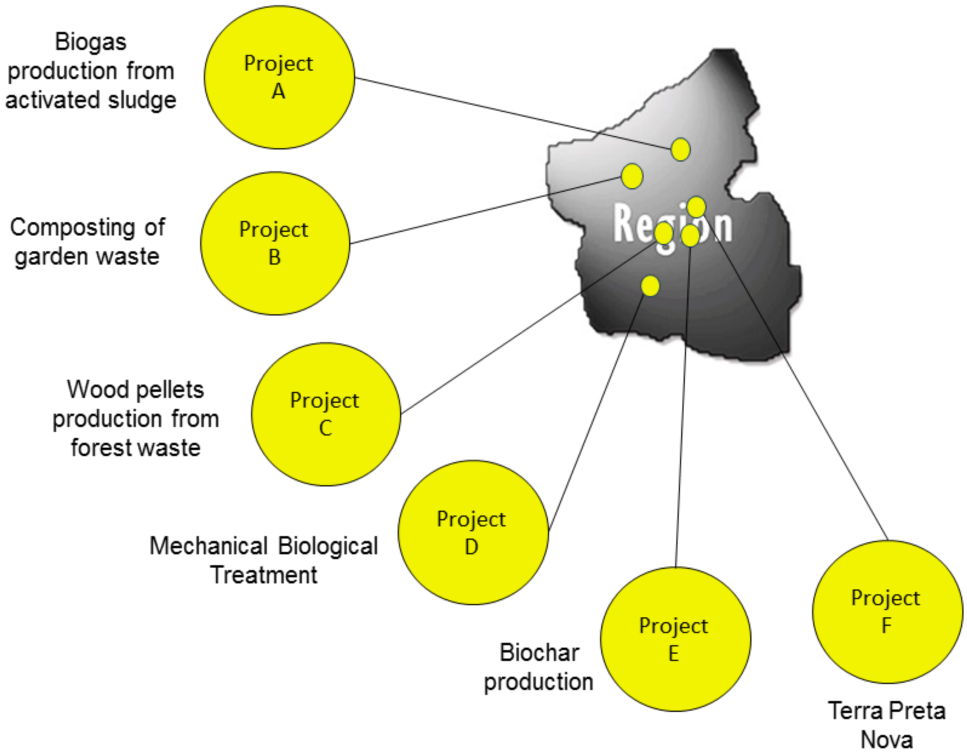


Figure 23: Exemplary regional MFM Master Plan. Source: Author

### *Levels of MFM optimization*

Terra Preta Nova is a product of high-end regional material flow management. Development of TPN as described in this thesis could then be achieved only if more basic MFM optimization measures are conducted first (Figure 24). However, there are exemptions to this:

1) Grassroots movements can develop simple Terra Preta Nova technologies that do not require high-end regional MFM optimization. These are for instance Terra Preta Toilets, where biochar is mixed with human urine and feces

In regions with undeveloped waste and wastewater management, material flows are in the state of chaos. Organic waste is being discarded in uncontrolled landfills, while wastewater is discharged in nature. Germany is the most developed country in the world when it comes to waste management and its progress from chaos to integrated material flows (still in the process of transitioning) lasted from the end of second word war until today. Terra Preta Nova is developed in just one pilot plant, indicating how complicated it is to integrate material flows in such high-end ways. This however, does not mean that developing countries will need the same time period to integrate their material flows. What was done in Germany was experimental and this process and know how can be implemented faster in other countries.

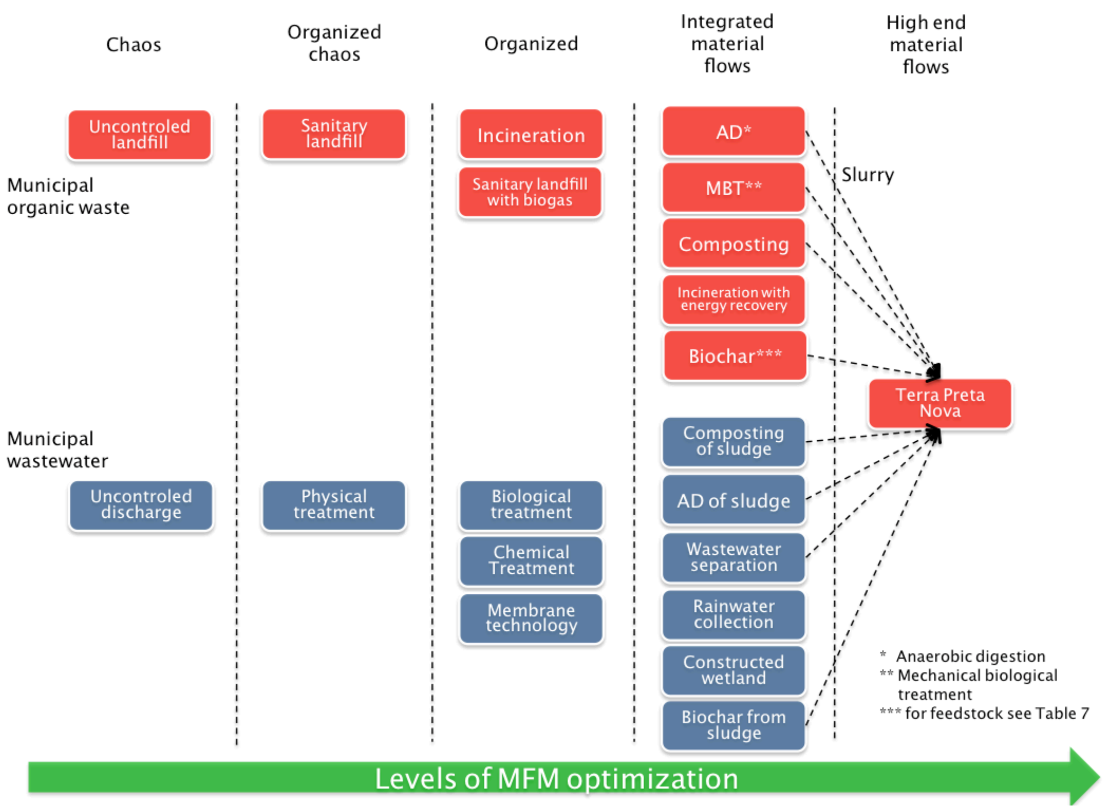

Figure 24: Levels of regional MFM optimization. Source: Author

Countries with undeveloped material and energy flows, can actually achieve the same level of progress in a much shorter time frame. Instead of developing old technologies first – like landfilling – and replacing them later with MFM technologies – like MBT or AD – they can install these high-end technologies right away. This is also called technological leapfrogging and it is possible when there exists a knowledge base. Waste management improvements in developed countries have built up the knowledge and expertise. These can now be transferred to less developed countries, in terms of waste and wastewater management.

## MFM Holding

The MFM Holding is a regional organization, created with the aim of streamlining the regional MFM optimization process (Figure 25). Using MFA and economic and technical feasibility studies, described in the previous segments, the MFM methodology has identified the projects that can be feasibly implemented. After the projects have been approved politically, from local or national governing bodies, the MFM optimization can commence in practice.

The MFM Holding aids in developing the selected projects, through providing a set of services. These include project management, capacity building, investment promotion, marketing, public relations etc.

Moreover, the holding assigns responsible personnel for each project made up of people from the local community. These can for instance be employees in a municipality that show interest in the projects, or anyone local skilled to manage a project. These individuals would are trained in managing such projects and external consultants would do this. Doing so transfers knowledge towards the local community and creates long-term social benefits.

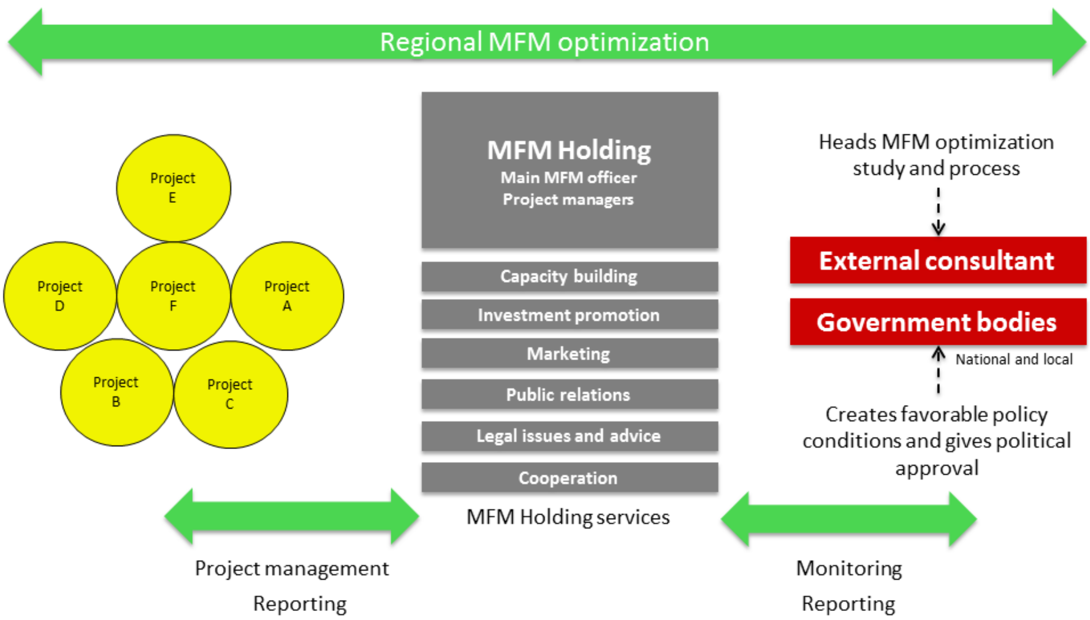

Figure 25: MFM Holding in context of regional MFM optimization. Source: Author

The local community would ideally install the MFM technologies. These people would have to be trained in their maintenance and technicalities, creating additional skills transfer. An external consultant with expertise in regional MFM planning would head the entire MFM optimization process. After the initial projects have been completed, the MFM holding would seek new optimization potentials and monitor the existing implemented technologies.

**TPN:** The previous segments have shown that Terra Preta Nova is a product of high-end regional MFM optimization. This means that its development would be preceded with projects that optimize regional waste management. The MFM Holding would be in charge of the entire regional optimization process. Here are the most relevant benefits it could provide towards developing TPN:

1) Capacity building
    a. Upskilling of local labour: education on waste management and TPN related jobs
    b. Awareness raising: education of the general population on the benefits of developing alternative agriculture and using TPN and importance of waste separation

2) Investment promotion – TPN as a regional showcase that could attract investment in TPN development or other activities in the region

3) Marketing – developing a market for TPN, through regional advertising targeted at focus groups such as gardeners, farmers etc. This could also include TPN demonstration activities, such as tours through the TPN production facility. TPN effectiveness in stimulating plant growth could be demonstrated by comparing existing field trials, where the yield effects of TPN are compared to the yield effects of synthetic fertilizer etc.

4) Cooperation – aligning the interests of local and national government bodies with regional stakeholders

## Regional added value creation

Terra Preta Nova production is a complex system that relies on linking multiple circular material flows. Regional value added creation is among the greatest benefits of creating such systems.

Added value is a term describing all monetary and non-monetary benefits stemming from applying MFM measures. This includes job creation, new business opportunities, regional marketing value, increase in the quality of the environment, knowledge transfer etc.

TPN production would generate the highest value added when produced from local waste materials. Monetary value is in such instances added to waste and it becomes a resource. Under these conditions, the economics of waste management improve. Local stakeholders have an incentive to engage in waste management and overall material flows become more organized. Bioenergy is another value added that develops with Terra Preta Nova production. This renewable energy source could be obtained as a byproduct of biochar production; under the condition that proper technology is employed.

The full list of potential value added from developing TPN is given in Table 8.

| Environmental |
|---|
| • Soil improvements similar to biochar application<br>  o Increase in nutrient and water retention, microbial activity and organic matter content<br>  o Decrease of nutrient runoff from croplands<br>  o Positive effects on cation exchange capacity and pH<br>• Decrease in landfilling of organic waste, which has the following benefits<br>  o Reduced GHG emissions. Organic waste decomposition emits methane gas, that has a 21 times greater warming potential than carbon dioxide<br>  o Decrease in bad odors that affect local living conditions<br>  o *Decrease of leachate emissions, which can contain heavy metals and reach water bodies. Consuming water that has been contaminated with leachate increases the rate of cancer and birth defects (Health Protection Agency, 2011).<br>  * This depends on the type of landfill |
| **Economic** |
| • Revaluation of local waste streams would create incentives to develop waste management systems<br>  o Waste becomes a commodity<br>  o Increase in economic activity due to organized waste management<br>  o Local job creation for waste management logistics<br>• Bioenergy development from biochar production<br>  o Decrease in fossil fuel imports decreases the amount of income being spent on imported energy<br>• Organic agriculture development<br>  o Potential for new product placement on market<br>  o Substitution of mineral fertilizer use<br>• Technology transfer and development of a local skills base for operating and maintaining the waste management and bioenergy technologies |
| **Social** |
| • Involvement of local communities in waste collection<br>• Awareness raising of environmental issues associated with waste impact on the environment, sustainable agriculture issues and energy production from sustainable sources |

**Table 8: Regional added value from TPN production. Source: Author**

## Risks of developing TPN with MFM methodology

The MFM methodology is not a “copy-paste” method that could be used anywhere, in the manner it was described in this thesis. Each region is unique, in the sense that it has distinctive material and energy flows, different stakeholder relations and legal as well as institutional structure.

Developing Terra Preta Nova might come across a number of obstacles that would require adjusting the MFM methodology. TPN is a high-end product of material flows management, and its development would require creating an entire infrastructure of waste (and wastewater) management (large scale systems). There are numerous variables that could go wrong, which largely depend on the level of economic and social development of the region in question. This segment will outline the risks associated with developing TPN within the administrative borders of the Republic of Serbia.

The scope of the case study is defined on a country level because the author does not have any region specific data. Serbia is chosen as a case study due to availability of data[5].

### General risks of the MFM methodology

Risk is not evenly distributed along the MFM optimization process. This thesis has ranked the risks according to strength and in relation to developing TPN in Serbia. The ranking was done based on literature review. The individual segments of the MFM methodology are colored differently, signifying the risk levels (Figure 26). The thesis assumes that the MFM optimization is performed by a consultant, development organization, research institute, government body and alike.

[5] The author is at the period of writing placed with the German Development Cooperation in Belgrade, working on a project dealing with municipal waste and wastewater management in Serbia.


**Figure 26: Risks associated with developing TPN with MFM methodology. Source: Author**

The methodology can be divided into three main phases. These can be applied to projects other than developing TPN. The phases are:

1) Selling phase (middle to high risk): MFM systems consists of individuals and organizations that have become accustomed to the status quo. The status quo is the linear resource management system, where high quality resources and energy are processed, turned into waste that is then discarded. Developing a circular economy requires rearranging the thinking and functioning of the conventional linear system. The main decision makers/stakeholders in any region are municipality heads, members of the municipality assemblies and prominent business people. These have the power and influence to move the system - consisting of people, businesses, institutions etc. – towards accepting the idea of circular economy. Selling, in the marketing meaning of the word, the MFM approach to them is crucial in MFM optimization. In practice this consists of these steps:

   a. *MFA:* preliminary study that shows the region has potential in terms of creating resources from waste flows, lowering energy consumption etc.

b. *Political approval:* the results of MFA are presented to the main stakeholders that approve a more detailed study. The political head gives (or does not) the approval to continue with MFM optimization. Considering the influence other stakeholders have on the political head, getting them to believe in MFM is crucial

c. *Detailed MFA:* described in previous segments. This yields a list of feasible optimization potentials.

2) Planning phase (low risk): This phase involves detailed planning and analysis. The building blocks of this phase are the results of the MFA. The most promising projects are studied in detail and included in the regional master plan. Regional MFM officers are named and they help streamline the process. This phase involves mainly intellectual work of the MFM Consultant and communication between the MFM officers and stakeholders. Creation of a stakeholder network (formal or informal) strengthens the process further.

3) Ending phase (high risk): the previous phases, starting with the MFA and ending with an elaborated Master plan, could have taken several years to conduct. Considering this, there are high chances that the MFM optimization process overlaps with local elections. Chances of having the Master plan rejected by the new government are high. This considerably increases the risks associated with this last phase.

## Case study: Republic of Serbia

### Country context

Serbia is a transitional economy and is among the least developed countries in Europe. The Republic of Serbia is located in South-Eastern Europe in the heart of the Balkan Peninsula. Northern Serbia is mainly flat, while central parts are highlands. Going to the south, the hills gradually turn into mountains.

The total population is around 7.5 million inhabitants, where 57% of the population lives in urban areas. The ethnic composition of Serbia is diverse, which is a result of the countries turbulent past. Majority of the population is comprised of Serbs, but there are 37 other ethnic minorities, among which the Roma comprise a major share.

Serbia is mostly a market economy, although the state sector remains large. The economy relies on manufacturing and export (CIA, 2012). Some of the greatest economic sectors are the processing industry, metallurgical and chemical industry etc. The most significant agricultural areas are in Vojvodina, where cattle, sheep and pig farming dominates (GIZ, 2012a).

GDP growth in 2011 was 2.0%, following a modest increase in 2010 and 3.5% contraction in 2009. High unemployment and stagnant household income are ongoing political and economic problems (CIA, 2012). Budget environmental protection spending amounted to only 0.35% of GDP in 2008. The National Investment Plan allocated only 5.6 million EUR[6] for environmental protection in 2008, out of which 3.3 million EUR (60%) was allocated for regional waste management activities (GIZ, 2012a).

### Risks for TPN development in Serbia

The risks of developing TPN in Serbia can be divided into two basic groups:

1) Show-stoppers: circumstances that would stop the TPN development process in tracks
2) Controllable risks: circumstances that hinder the MFM optimization process, but can be managed

This list of risks is shown in Table 9.

[6] Historican exchange rate for 1st July 2008

Table 9: Risks of developing TPN in Serbia. Source: Author

| Show-stoppers |
| --- |
| **R1:** Regional feedstock material not adequate or too expensive to obtain<br>**R2:** The political head does not give approval for further research in the selling phase<br>**R3:** Results of detailed MFA show that TPN is not economically and/or technically viable<br>**R4:** The political head that gave the go-ahead in the selling phase is replaced and the new leader does not approve of the master plan and MFM approach in general<br>**R5:** Financing stops or the price of financing increases considerably<br>**R6:** TPN does not demonstrate positive benefits for plant growth |
| **Controllable risks** |
| **R7:** Length of MFM optimization process<br>**R8:** Inadequate local skills base required to run the MFM Holding<br>**R9:** Technical problems with implementation of MFM technologies |

## Discussion

This segment discusses the risks presented in Table 9. Many of the above named risks are self-explanatory and will not be included in this discussion.

### *R1: Regional feedstock material not adequate or too expensive to obtain*

Waste quantities and qualities are the least problem of developing TPN in Serbia. The biggest obstacle is in the lack of proper waste management practices and infrastructure. Considering this, MFA might indicate that organizing feedstock collection to produce Terra Preta Nova is too costly. Exceptions do exist but are very rare – source separation of organic municipal solid waste (OMSW) is conducted only in the city of Čačak, where a portion of the municipal solid waste is separated into "dry" and "wet" fractions. The wet fraction is composed of biodegradable waste, while everything else is being classified as dry (GIZ, 2012a).

Here are general conclusions about waste potentials for developing TPN in Serbia. Background information, graphs and diagrams can be found in Appendix 4.

### Organic Municipal Solid Waste

- Main use: compost for Terra Preta Nova
- Alterative use: incineration, anaerobic digestion (AD) for biogas production and landfilling.
- Info: biodegradable waste composes some 40% of MSW while garden waste makes around 12%. Serbia produces 3.7 million tons of organic waste per year. There are currently 164 official registered landfills and over 4000 unregulated landfills across the country. Waste collection systems exist but lack proper machinery. It was assessed that collection of 60% of municipal waste in Serbia is organized. Urban areas are much more organized than rural areas that receive significantly less waste collection coverage (GIZ, 2012a).

### Forest waste

- Main use: biochar for TPN
- Alternative use: incineration and natural decomposition
- Info: Unutilized parts of the tree after cutting include a) bark b) thin branches and c) stumps. These amount to about 42% of the total tree volume. According to present statistical data, this generates 1,1 million m3 of wood waste (Energy Saving Group, n.d.). Forest in the north part of the country, located in plains, are easier to access and almost 100% of waste wood can be recovered. But forests in mountainous regions in the south have very steep slopes and less developed infrastructure. Collecting waste wood in these regions would be very challenging

### Wood waste in wood processing industry

- Main use: biochar for TPN
- Alternative use: incineration, wood pallet production and landfilling
- Info: The wood processing industry produces three main types of wastes in different sizes: a) bark b) coarse waste (from cutting round wood) and c) fine waste (wood chips, sawdust, and wood dust). In 2006 wood wastes in

sawmills amounted to 480 000 m3. Most sawmills have a small installed capacity. Assuming that small sawmills process about 50% of all wood material, the waste quantities would be as follows (Energy Saving Group, n.d.):

- Wood chips – 68 000 m3
- Sawdust – 30 000 m3
- Coarse wood waste – 91 000 m3
- Bark – 51 000 m3

### Sludge from wastewater treatment

- Main use: biochar or compost for TPN
- Alternative use: incineration, cement production, anaerobic digestion for biogas, soil amender (if no heavy metals in material) and landfilling
- Info: Only half of the households in Serbia are connected to a public sewage system (1.3 million connections) and barely 15 percent of wastewater is treated (51 million $m^3$and mostly only to primary standards) (GIZ, 2012b). According to available data, there is no activated sludge treatment in Serbia. There are plans to develop facilities in the future.

### Agricultural waste

- Main use: compost for TPN
- Alternative use: anaerobic digestion for biogas and landfilling. This largely depends on the type of agricultural waste.
- Info: there are no reliable data sources on this issue

### *R6: TPN does not demonstrate positive benefits for plant growth*

Using TPN could run in the risk of failing to benefit soil quality and plant growth. Here are the main reasons behind this risk:

1) The effects of Terra Preta Nova on soil quality and plant growth have not been determined. Effects of biochar applications alone, an area that has been investigated in much greater extent than TPN, still remain unknown.
2) There are multiple combinations of feedstock materials that could be used in producing TPN. The great variability in these mixtures, does not allow for any generalizations on TPN effects on soil and plant growth.

Failure to generate positive effects on plant growth would create an aversion towards TPN from users.  Conducting field trials that would test the best mixtures could minimize this risk.

## Conclusions

Modern agriculture relies on consuming finite resources and in doing so creates environmental degradation and food insecurity.

Agriculture has been both a source of rise and decline of societies during history. Ancient Mesopotamia and Greece provide historic examples of the negative implications of intensive farming.

Soil salinization in the Fertile Crescent, caused in part by intensive irrigation, was among the main causes of the decline of the Mesopotamian civilization. Steady declines in barley production, which correlated with the demise of Mesopotamian power, document this.

Historical records also speak of intensive soil erosion in Ancient Greece, that lead to a decrease in local wheat production. This is certainly not the main reason for the demise of the Greek civilization. But it made the Greeks more vulnerable by forcing them to rely on trade for food.

Modern history testifies to the Dust Bowl in US and decline of the Aral Sea. Both of these examples confirm the destructive forces of modern agriculture. Intensive cultivation in the US depleted topsoil and induced desertification. The effects of this were clearly visible, when dust storms buried entire human settlements. On the other hand, the declining shorelines of the Aral Sea and a staggering increase in human illness (Table 1), demonstrate to the destruction caused by intensive Soviet farming.

Learning from these examples enables future generations to develop sustainable agricultural systems. These are characterized by circular material and energy flows, which are based on reusing local waste streams.

Terra Preta Nova is a product of circular flow design. Composted organic waste from municipalities and agriculture is combined with charred woody feedstock or biochar, to create a terra-preta-like soil amender. This replicates Amazonian dark earths that are composed of large amounts of charred material (70 times higher than surrounding soil) and residues of vegetal and animal origin. Findings of pottery on the grounds of terra preta incline that this fertile land might have been produced purposefully by an ancient Amazonian civilization.

The implication that this primitive society (in comparison to todays modern technologies) could have developed sustainable agriculture in otherwise infertile Amazonian soil implies that terra preta could be replicated in modern times and used to improve degraded land. This created a plethora of research on biochar and TP. The large majority of studies have focused on biochar, because this is considered to be the key to TPs fertility. Biochar is likely responsible for the high nutrient retention and water holding capacities of Terra Preta. This along with increased microbial activity gives biochar unique properties.

Field trials on biochar have produced variable results, mostly but not exclusively indicating to positive plant responses. Biochar soil science is highly complex because it involves multiple feedstock, production processes and soil application measures. Uniform conclusions about biochar effects on soil properties and plant growth do not exist. This lack of scientific certainty disables biochar to be applied on a wider scale.

Other major areas of uncertainly include biochar stability in soil and effects on other soil organic matter (priming effect). Biochar found in Terra Preta is of ancient origin, indicating to its resistance to mineralization. The high stability of biochar arguments that charring biomass could help stabilize carbon in ground and reduce atmospheric GHG levels. Studies indicate that biochar soil conditioning could sequester 12% of current anthropogenic GHG emissions. But modern biochar is produced in conditions different from those in ancient Amazonia. Field trials show variable results in regards to its stability in soil. Using biochar for environmental management on a global scale could backfire, leading to a rapid return of large amount of GHG to the atmosphere.

What are the implications of this for Terra Preta Nova?

The scientific uncertainty around biochar, and biochar mixing with compost, could hinder the development of Terra Preta Nova. Field trials on the effects of biochar on compost are limited. The variety of compost and biochar feedstock, as well as the numerous permutations of the two, could create thousands of versions of Terra Preta Nova version globally. While some versions, might be successful in restoring and increasing soil fertility, other might fail and even induce economic and social losses to the local community. Before developing Terra Preta Nova on a wider scale, science should classify the safe feedstock combinations.

Individual companies are already experimenting with feedstock's for Terra Preta Nova. A German holding is producing TPN from green waste, dung, manure and the solid fraction of the digestate from biogas production. The company has by far only developed a pilot plant. Reasons why their products are not marketed are unknown due to lack of data.

Developing Terra Preta Nova on a regional level would be highly complex. This would require a steady stream of input materials, meaning that waste management systems would have to be in place. Terra Preta Nova is a product of high-end material flow management (Figure 24).

Material Flow Management is a holistic resource management approach that optimizes material and energy flows across the economic sector. This includes integrating technologies that process low quality waste from households, industries, agriculture etc. into high quality resources. Developing Terra Preta Nova with the Material Flow Management methodology would facilitate the complexity involved.

MFM analyzes material and energy flows in a system through Material Flow Analysis. Quantities, qualities and directions of the flows are documented and displayed in Sankey diagram format. This enables decision makers to identify the most relevant optimization potentials and employ appropriate technologies.

Following this, MFM creates regional stakeholder networks to facilitate the process. Detailed economic and technical feasibility studies, analyze the most relevant projects. These are included in a regional Master plan that is developed with the aid of a newly established MFM Holding.

The MFM methodology suffers from several risks that might hinder Terra Preta Nova development (Table 9). This thesis has examined these on a case study. Serbia was chosen because of data availability. The biggest risk lies in getting and maintaining the political approval for MFM optimization projects from local decision makers. Other major risks include the potential danger of TPN failing to demonstrate positive effects on crop growth and soil properties.

People in general are highly skeptical of new things, so developing Terra Preta Nova in Serbia would require an intensive education campaign.

In conclusion, here is a summary of the answers to the key questions raised by this thesis:

Q1: Is Terra Preta Nova a viable solution for sustainable agricultural systems?

A1: Terra Preta Nova is viable solution under the condition that its effects on crop growth and soil properties are examined before widespread application. Since each region would produce TPN from different feedstock materials, individual trials have to be conducted.

Biochar and biochar-compost mixtures have demonstrated positive results for crop growth in most cases. But negative results of biochar field trials exit and soil science is not in agreement regarding their cause. Biochar and TPN have not been tested enough in order to generalize about the potential impacts on crop growth. Regarding environmental impacts, TPN could reduce the negative effect of agriculture, through greater nutrient retention, substitution of synthetic fertilizer, decrease in GHG emissions, improved soil quality, decentralization of food systems etc.

Q2: Could Terra Preta Nova be used on a global level or is it just suitable for particular regional conditions?

A2: Terra Preta Nova could be produced from various streams of input materials. TPN would therefore differ across regions in composition, which would create variable results in crop growth. Moreover, regions differ in soil properties and climate conditions making potential TPN effects even more variable. TPN is therefore not a global solution. Instead it should be applied regionally, where proper conditions exist – both for its production and application.

Besides TPN, there are many other alternative agricultural solutions. Developing sustainable agriculture globally would require using all of these technologies in combination, depending on local circumstances. Terra Preta Nova is therefore, just one solution among many possible options.

Q3: What are the obstacles of creating Terra Preta Nova systems?

A3: The main obstacles are in gaining the political approval for regional TPN development and MFM optimization from the local decision makers. Other major risks include demonstrating positive effects on crops and soil and securing a steady supply of waste feedstock.

## Appendix 1: Biochar in the context of geoengineering strategies

Biochar application on a global scale classifies as a geoengineering method and as such can be compared to other similar solutions. The Royal Society (2009) examines the know geoengineering methods and compares them according to their costs, potential to remove carbon dioxide, general interference with ecosystems, social acceptability and ease of governance. The methods against which biochar is compared are presented in Table 10. Biochar has been rated rather low in comparison to some other methods. This is mainly because of these reasons:

1. The effects of adding large amounts of biochar to soil are still subject to uncertainty. Biochar can be produced from many different feedstock and various pyrolysis conditions leading to differing biochar qualities and effects on crop growth (Biofuelwatch, 2011). Effects of biochar application to soil will also largely depend on local soil and climate conditions. Most importantly, the stability of biochar in soil is not uniform as some biochar experiments indicated to a low residence time (Biofuelwatch, 2011). The sequestered carbon through biochar soil application could then be oxidized rather quickly leading to $CO_2$ returns to the atmosphere.
2. Low plant productivity, which poses a limitation in feedstock supply and consequently the overall amount of biochar produce
3. Conflicts over land use with food production. Massive biochar production and application could trigger its price to increase, or at least be higher than the price of food that would be produced on the same plot of land. Sustainable biochar production would then be possible only from waste materials.

**Table 10: Comparison of geoengineering methods. Source: The Royal Society (2009)**

| Geoengineering method | Description |
|---|---|
| Land use management | Afforestation and deforestation of land |
| Bio-energy with carbon sequestration | Using carbon capture and storage technologies to reduce $CO_2$ emissions arising from biofuel use. For instance, capturing and storing $CO_2$ form wood combustion. |
| Enhanced weathering of carbonate and silicate rock | Accelerating the rate at which silicate and carbonate rock react with atmospheric $CO_2$ |
| $\boldsymbol{CO_2}$ removal from ambient air | Adsorption of $CO_2$ to solids, highly alkaline solutions and moderately alkaline solutions with a catalyst |
| Ocean fertilization | Enhancing the rate at which surface ocean $CO_2$ is transported into the deep ocean, through means of the ocean biological pump. This involves fertilizing the ocean with nutrients that enhance surface algae growth (fixers of $CO_2$ that |

| | |
|---|---|
| | decompose and sink into ocean depths) |
| Surface albedo | Making the surface brighter so as to increase the reflection of solar radiation |
| Cloud albedo enhancement | Whitening clouds over parts of the ocean |
| Stratospheric aerosols | Releasing particles into the stratosphere with the objective of scattering sunlight back to space |
| Space based methods | Reducing the amount of solar radiation reaching the Earth by positioning sun-shields in space to reflect of deflect the solar radiation |

Looking at biochar as a strategy to alleviate global warming, in comparison with other geoengineering methods, places it into perspective. But what lacks in the Royal Society report is that it looks at each method as if its application would exclude the use of other methods. While biochar production may not pose a global solution, it could prove very effective when adopted in local settings.

## Appendix 2: Research gaps in biochar soil science

Research on biochar effects on soil is still in its infancy. Table 11 presents the current research gaps that need to be addressed. Unknowns related to biochar effects on soil indicate that its wider application would, at the present level of knowledge, pose risks concerning the local environment. Strategies to implement biochar soil conditioning would need to adopt a risk-based approach, where potential negative effects of biochar are evaluated beforehand.

**Table 11: Research gaps of biochar application to soil. Source: Various authors**

| Research gap | Explanation |
|---|---|
| Chemical and physical properties of biochar | Biochar will differ in properties depending on the choice of feedstock and production process condition - mainly temperature and time (Sohi et al., 2009) |
| Stability in soil | Biochar found in Terra Preta has been dated to be thousands of years old, resisting the rapid mineralization common to organic matter in tropic environments (Lehmann, 2007). But biochar from modern pyrolysis processes might be different to the one found on Terra Preta. Field trials need to establish the longevity of modern biochar in soils. |
| Effects on crop productivity | Different biophysical interactions and processes |

| | |
|---|---|
| | that occur when biochar is applied to soil are not well understood. Large number of studies has shown positive effects on crop productivity, while these are some that have shown negative effects. Models that enable extrapolation of biochar effects on soil are required (Sohi et al., 2009) |
| Safety of use in soil | The feedstock used may contain toxic elements (heavy metals). These will remain in the ash content of biochar. Care must be taken in the feedstock selection and the operation of the thermochemical conversion to ensure that the risks to the environment and human health are minimal and properly assessed (Brownsort et al., 2010). |
| Effects of biochar on interaction with soil microbial communities | Biochar is believed to increase soil microbial activity. Reasons behind this are still not understood precisely (Sohi et al., 2009). |
| Cation exchange capacity (CEC) | Applications of fresh biochar have been shown to increase CEC. But the processes that are instrumental in developing CEC over time are still not well understood (Sohi et al., 2009). |
| Water holding capacity | Studies indicate that biochar leads to better water holding capacity. There is little research evidence that indicates the reasons for this (Sohi et al., 2009). |
| Damage to soils | Research is mostly focusing on positive effects of large-scale biochar application. There might be some subtle negative effects on soil that have not been recognized (Brownsort et al., 2010). |
| Loss of soil organic matter (SOM) | One study found that charcoal additions to forest humus induced a loss in soil organic matter (Wardle et al., 2008). Studies of SOM in Terra Preta, on the other hand, found that charcoal induced its stability over millennial time ranges (Brownsort et al., 2010). |
| Loss of biochar due to erosion | Biochar can be lost from ground due to erosion. These processes complicate the calculations of biochar stability in soil. Further research in this is needed (Sohi et al., 2009). |

# Appendix 3: Composting and biochar technologies

This appendix discusses composting and biochar production technologies in more detail and in line with the questions proposed in the Technical feasibility segment of the MFM methodology for TPN section.

### *Composting*

*Is the proposed technology or solution practical?*

Composting reduces the volume of organic waste to more or less 50% its initial size. In doing so it reduces the energy required to transport the organic waste to agricultural fields. Moreover, it relies on natural processes, mainly aerobic decomposition, to eliminate pathogens and unwanted plant seeds.

Potentially, pest problem can occur (such as seagulls, rats, flies). Plant pathogens are easily spread if any of compost material is infected. This is often the case with the biodegradable fraction of municipal solid waste.

According to data from UNEP, composting is a waste management option with the highest number of failed facilities worldwide. The problems most often cited in the literature include: high operation and management costs, high transportation costs, low understanding of the composting process and the competitiveness of chemical fertilizers (Institute for Applied Material Flow Management, 2010).

*What kind of technology do we need?*

Composting can be divided in two categories, depending on the nature of the feedstock decomposition process (Misra et al. 2003):

1) Anaerobic: decomposition occurs in absence or limited availability of oxygen. Under these conditions, anaerobic microorganisms dominate and produce methane, organic acids and other substances. Many of these substances have strong odors and some of them are toxic to plants. Since anaerobic composting occurs at low temperatures, pathogens and weed seeds in the compost are not killed. This disables the use of the compost pile for agriculture

2) Aerobic: decomposition occurs in ample presence of oxygen and aerobic microorganisms break down organic matter and produce carbon dioxide, ammonia, water, heat and humus.

Aerobic composting is the type that every farmer strives for. However, anaerobic processes can occur if the feedstock is not managed properly (inadequate frequency of turning, aeration etc.)

Composting technologies can be divided into small scale and large scale. Small scale is applied in undeveloped rural settings or home applications. This thesis discusses Terra Preta Nova in terms of large-scale production, which is why small scale composting will not be discussed any further.

Composting techniques, irrespective of size, share these features:

1) Pile size – piles that are too big will develop anaerobic zones in the middle, slowing down the composting process. Small piles will however lose heat too quickly and may not achieve temperatures that kill off pathogens and weed seeds. Using porous materials will allow having piles of greater size, because the oxygen can penetrate the center of the pile more easily
2) Ventilation – multiple methods are available but the main point is in having the pile vented at right frequencies and quantities in order to optimize heat production, decomposition rates etc.
3) Turning – the pile has to be turned with the right frequency in order to avoid anaerobic zones in the middle and optimize aeration
4) Inoculation – compost piles are sometimes inoculated with microorganisms, like fungi, in order to enhance microbial activity
5) Supplemental nutrition – synthetic fertilizer is sometimes added in order to modify the C:N ratio
6) Shredding – this increases the surface area available for microbial action and provides better aeration

Here are the large scale composting technologies that are in use today (Misra et al. 2003):

*Wind-row composting* – consists of placing feedstock in long narrow piles called wind-rows that are ventilated either by turning the feedstock on a regular basis or through piping systems that deliver the air without the need for turning

1) Turned wind-rows – the rows are turned using specialized machinery, which reduces the time and labour involved. Turning ensures that the feedstock is receiving enough air, enabling the decomposition process to continue steadily. This method takes three to nine weeks to produce compost, depending on the nature of the material and the frequency of turning


**Figure 27: a) Turned wind-rows b) Passively aerated wind-rows. Source:** a) GroundGrocer, (n.d.) **and** Eco City Farms (2011)

2) Passively aerated wind-rows – air is supplied to the wind-rows through perforated pipes embedded in each wind row and this eliminates the need for turning. Air flows through the pipes and moves up the wind row, due to the chimney effect created by rising of the heat in the wind row pile: Since the feedstock is not mixed during the composting process, it has to be mixed thoroughly before being placed in the pile.

3) Aerated static pile – this method extends on the passively aerated technique by using a blower to supply the air to the composting pile. Using the blower provides direct control of the process and allows larger piles.

*In vessel composting* – the composting material is confined within a building, container or vessel. These techniques rely on a variety of forced aeration and mechanical turning techniques to accelerate the composting process.

1) Bin composting – feedstock is placed in bins consisting of concrete walls, with or without a roof. This method includes some means of forced aeration in the floor of the bin and little or no turning of the materials. The bins allow higher stacking of materials and better use of floor space than freestanding piles.

2) Rectangular agitated beds – the composting takes place between walls that form rows. A compost turning machine moves along the long rows and turns the composting material. The feedstock is aerated with a set of aeration pipes and an aeration plenum on the floor of the rows.  In addition to this, blowers are used. For reasons of protection from weather, the beds are placed in greenhouses or in warmer climates roofs cover them.

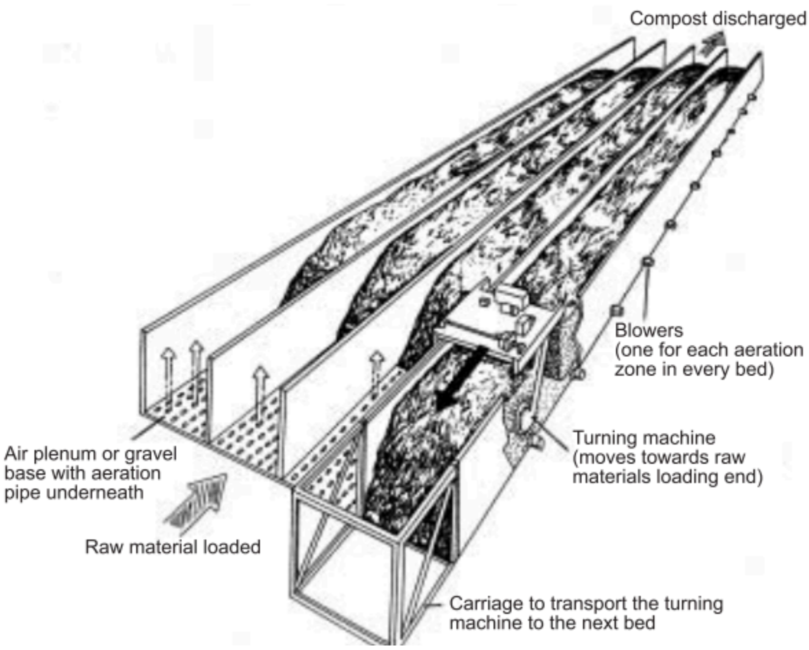


**Figure 28: Rectangular activated bed. Source:** (Misra et al., 2003)

3) Rotating drum – a horizontal rotary drum mixes, aerates and moves the material through the system. A drum of about 3.35 m in diameter and 36m long has a daily capacity of 50 tons with residence time of three days. Air is supplied through the discharge end of the drum and the material is aerated

while being rotated. The material nearest to the discharge point receives cool air, the material in the middle warmer air that keeps the degradation process going and the material at the very beginning receives the hottest air to initiate the composting process. The air is warmed as it passes through the drum, due to the heat emitted from the composting material.

4) Silo and transportable container – these methods will not be explained in more detail as they are used less frequently

*Vermicomposting* – this refers to the use of earthworms for composting organic residues. Earthworms consume any organic material and they consume their own body weight per day. Through consuming the feedstock, the worms excrete substrates rich in nitrate, available forms of P, K, Ca and Mg. Worm activity promotes growth of bacteria and actinomycetes, which are a specific group of bacteria responsible for decomposition of organic matter at elevated temperatures.

*Is the required technology available?*

Composting technologies are widely available and have been applied both in developed and developing countries. The above-described technologies are for large scale composting and will mainly be used in developed countries. They require more complicated logistics and machinery that may not be available in undeveloped regions. This thesis does not have the information about which of these systems is the most suitable for Terra Preta Nova production.

### *Pyrolysis for biochar*

*Is the proposed technology or solution practical?*

Biochar can be produced from waste materials, such as waste wood, coconut shells etc. This reduces the amount of waste to be landfilled. Modern systems can be adjusted to produce bioenergy from the off gasses and heat produced during pyrolysis. These are often make use of this energy for the purpose of heating the feedstock.

Pyrolysis technology for biochar is, however, still in the development phase. Improvements in the areas of its energy efficiency, pollution reduction, recovery of co-products, control of operating condition and feedstock flexibility need to be made (Brown, 2009).

*What kind of technology do we need?*

Biochar is produced from pyrolysis, the process of heating carbon bearing solid material under oxygen starved conditions. Char and charcoal are both produced in the same conditions, but not for the purpose of soil application, as is the case with biochar. Much of the knowledge about biochar production comes from what is known on producing char and charcoal.

Charcoal can be produced using various types of kilns and in many cases these do not have any control over the exhaust emission produced by the process. Modern biochar technologies can regulate the charring conditions in order to minimize the pollution. Moreover, the processing conditions can be regulated and monitored with the purpose of producing biochar with specific characteristics. The pyrolysis process could be adjusted to maximize the biochar surface area. But given the differences in feedstock used, there is no “one size fits all” solution.

Here are the biochar technologies that could be used for large-scale production (Brown, 2009):

1) The drum pyrolyser – moves biomass through an externally heated, horizontal, cylindrical shell using paddles. The drum is intentionally sealed of so not air can enter. The feed material is first dried and fed into the drum. As the material passes through the drum, it reacts to produce an off-gas (syngas), which is continuously removed from the kiln and utilized for its energy value. This system was developed by BEST energies and a fully operational demonstration plant has the capacity to take 300kg/h of biomass (BEST Energies, n.d.)

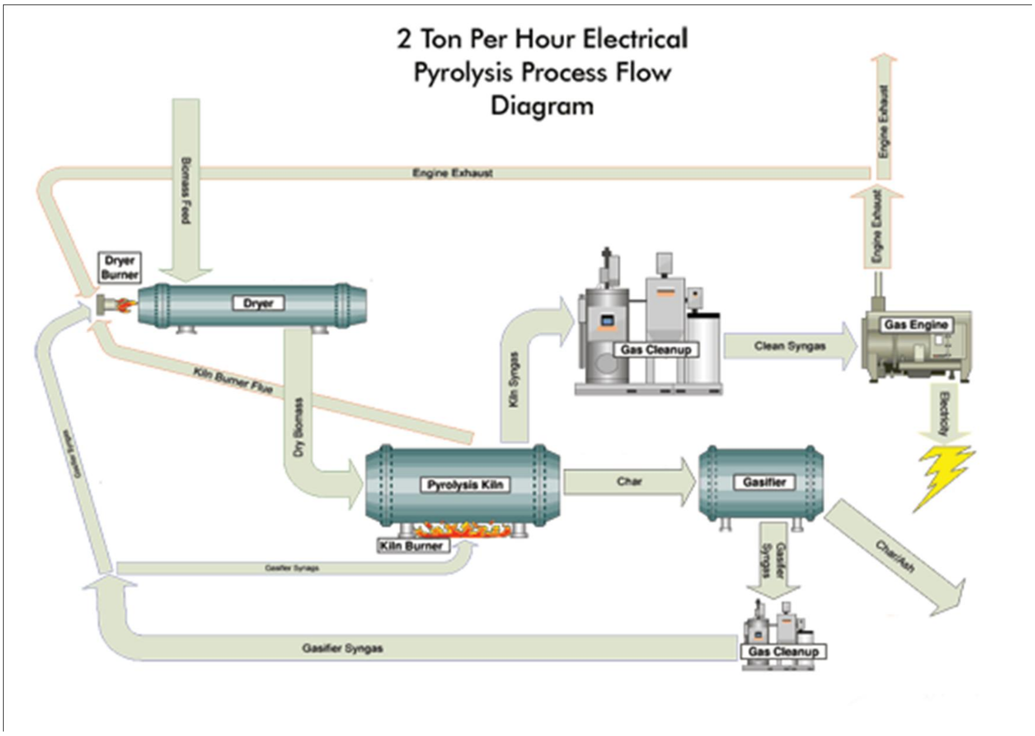


**Figure 29: BEST Energies slow pyrolysis process. Source:** (BEST Energies, n.d.)

2) Rotary kilns – these are similar to the drum pyrolyser because they as well employ an externally heated cylindrical shell. However, this is rotated at an angle to the horizontal, enabling gravity to move the biomass down the length of the kiln. The advantage over the drum pyrolyser is the absence of moving parts in the interior.

3) Screw pyrolyser – moves biomass through a tubular reactor by the action of rotating screw. While these are also externally heated, they can be adjusted to use a heat carrier instead, such as sand. This is mixed with the biomass as it passes through the screw.
4) The Flash Carbonizer – biochar production through the ignition of flash fire at elevated pressure. The reported fixed carbon yields are 100% of the theoretical limit in as little as 20 to 30 minutes.

5) Wood gas stoves – these are designed for efficient domestic cooking with wood in developing world. These stoves improve wood combustion by gasifying the wood into gas that is subsequently burned in a controlled manner (Roth, 2011). The carbon remaining at the end of biomass devolatilization can be burned in the stove to provide additional heat, but it can also be recovered

as biochar with yields of 20 to 25% by weight (Brown, 2009). The amount produced per batch is in the range of 150g, which disables any use in agriculture. But if this stove would be used by thousands of households in a region, the biochar collected could make significant amounts.

*Is the required technology available?*

Technologies for biochar production exist but they are not widely available. Most of the examples presented in the literature are demonstration scale, while there are some examples of larger biochar production. Review of the German literature, a leader in MFM, would have to determine the extent of actual production facilities in Germany. For further reference please consult the International Biochar Initiative[7].

[7] http://www.biochar-international.org/technology/production

## Bibliography


Amonette, J. E., & Joseph, S. (2009). Characteristics of biochar: microchemical properties. In Johannes Lehmann & S. Joseph (Eds.), *Biochar for environmental management science and technology* (pp. 33-52). Earthscan.

Avadi, A. (2010). Regional Material Flow Modelling and GHG Inventoring. Curitiba.

BEST Energies. (n.d.). *BEST Pyrolysis Technoogy: A sustainable solution to the greenhouse challenge*.

Bates, A. (2010). *The Biochar Solution: Carbon Farming and Climate Change. Carbon*. Gabriola Island: New Society Publishers.

Beck, D. A., Johnson, G. R., & Spolek, G. A. (2011). Amending greenroof soil with biochar to affect runoff water quantity and quality. *Environmental Pollution*, *159*(8-9), 2111-2118. Elsevier Ltd. doi:10.1016/j.envpol.2011.01.022

Blackwell, P., Riethmuller, G., & Collins, M. (2009). Chapter 12: Biochar application to soil. In J Lehmann & S. Joseph (Eds.), *Biochar for Environmental Management Science and Technology*. Earthscan.

Brown, R. C. (2009). Biochar Production Technology. (Johannes Lehmann & S. Joseph, Eds.)*Biochar for Environmental Management Science and Technology*, 127-146. Earthscan.

Brownsort, P., Carter, S., Cook, J., Cunningham, C., Gaunt, J., Hammond, J., Ibarrola, R., et al. (2010). *An assessment of the benefits and issues associated with the application of biochar to soil. Assessment*.

Bruinsma, J. (2009). *The resource outlook to 2050: By how much do land, water and crop yields need to increase by 2050?* Food and Agriculture Organization of the United Nations

Brunner, P. H., & Rechberger, H. (2005). Practical Handbook of Material Flow Analysis. Lewis Publishers.

Bruun, E. W. (2011). *Application of Fast Pyrolysis Biochar to a Loamy soil*. Technical University of Denmark, Risø National Laboratory for Sustainable Energy.

CIA. (2012). The World Fact book: Serbia. Retrieved from https://www.cia.gov/library/publications/the-world-factbook/geos/ri.html

Cassman, K. G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality and precision agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *96*(11), 5952-5959.

Cassman, K. G., Dobermann, A. R., & Walters, D. T. (2002). Agroecosystems, Nitrogen-use Efficiency, and Nitrogen Management. *Ambio*.

Cassman, K. G., Dobermann, A., Walters, D. T., & Yang, H. (2003). Meeting Cereal Demand While Protecting Natural Resources and Improving Environmental Quality. *Annual Review of Environmental Resources*. doi:10.1146/annurev.energy.28.040202.122858

Cecil, R., & Jolin, A. (2005). *Green waste, dark gold . . . commercial opportunities in organic wastes & soil buildings (a toolkit)*.

Chan, K. Y., & Xu, Z. (2009). Biochar: Nutrient Properties and Their Enhancement. In Johannes Lehmann & S. Joseph (Eds.), *Biochar for Environmental Management Science and Technology* (pp. 67-84). Earthscan, London, UK.

ComponentOne LCC. (n.d.). *STAN Operations Manual*.

Cooperband, L. (2002). *Building Soil Organic Matter with Organic Amendments. Agricultural Systems*. Madison.

Cordell, D., Drangert, J.-O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, *19*(2), 292-305. Pergamon. doi:10.1016/j.gloenvcha.2008.10.009

Diamond, J. (2002). Evolution, consequences and future of plant and animal domestication. *Nature*, *418*(August), 700 - 707.

Downie, A., Crosky, A., & Munroe, P. (2009). Physical Properties of Biochar. In Johannes Lehmann & S. Joseph (Eds.), *Biochar for Environmental Management* (pp. 13-32). Earthscan.

Eco City Farms. (2011). We Must Cultivate Our Garden. Retrieved from http://www.ecoffshoots.org/we-must-cultivate-our-garden/

Elser, J., & White, S. (2010). Peak Phosphorus, and Why It Matters. *Foreign Policy*. Retrieved from http://www.foreignpolicy.com/articles/2010/04/20/peak_phosphorus

Energy Saving Group. (n.d.). *Feasability study on wood waste utilization in Serbia*.

FAO. (2003). *World agriculture: towards 2015/2030. World Agriculture*. London.

FAO. (2011). *"Energy-Smart" Food for People and Climate*. Food and Agriculture Organization of the United Nations

Factura, H., Bettendorf, T., Buzie, C., Pieplow, H., Reckin, J., & Otterpohl, R. (2010). Terra Preta Sanitation: re-discovered from an ancient Amazonian civilisation - integrating sanitation, bio-waste management and agriculture. *Water Science & Technology*, 1-8.

Fischer, D., & Glaser, B. (n.d.). Synergisms between Compost and Biochar for Sustainable Soil Amelioration. Halle, Germany.

GIZ. (2012a). Municipal Solid Waste Management (MSW) in Serbia: General Framework Situation. Belgrade.

GIZ. (2012b). *Overview of the status of municipial wastewater treatment in small municipalities in Serbia*

Gensch, R. (2010). *Terra preta sanitation. Overview*.

Glantz, M. H. (1999). *Creeping environmental problems and sustainable development in the Aral Sea basin*. (M. Glantz, Ed.)*Sustainable Development and Creeping Environmental Problems in the Aral Sea Region* (p. 303). Cambridge University Press.

Glaser, B., & Birk, J. J. (2012). State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Indio). *Geochimica et Cosmochimica Acta*, *82*, 39-51. Elsevier Ltd. doi:10.1016/j.gca.2010.11.029

Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). The “Terra Preta” phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften*, *88*(1), 37-41. doi:10.1007/s001140000193

Golder, B., & Gawler, M. (2005). *Cross-Cutting Tool: Stakeholder Analysis*.

GroundGrocer. (n.d.). GroundGrocer - Compost Windrow Turners. Retrieved from http://www.groundgrocer.com/products/-Compost-Windrow-Turner.html

Haug, R. T. (1993). *The Practical Handbook of Compost Engineering*. Lewis Publishing.

Health Protection Agency. (2011). *Impact on Health of Emissions from Landfill Sites: Advice from the Health Protection Agency*.

Hillel, D. J. (1991). *Out of the earth: civilization and the life of the soil*. New York, Toronto, New York: Free Press, Collier Macmillan Canada, Maxwell Macmillan International,.

Ho, M.-W., Burcher, S., & Ching, L. L. (2008). *Food Futures Now: Organic, Sustainable, Fossil Fuel Free*. *Blueprint*. Institute of Sciences in Society, Third World Network.

Hongyan, L. (2005). *Forum für angewandtes systemisches Stoffstrommanagement*.

Huang, W.-yuan. (2009). *Factors Contributing to the Recent Increase in U.S. Fertilizer Prices, 2002-08*.

Institute for Applied Material Flow Management. (2010). *Pre-feasibility study for the construction of a plant for processing of the waste of the biological origin*. Birkenfeld.

International Biochar Initiative. (2012). What Is Biochar? Retrieved from http://www.biochar-international.org/biochar

Jacobsen, T., & Adams, R. M. (1958). Salt and Silt in Ancient Mesopotamia, *128*(3334), 1251 - 1258.

Kern, D. C., Ruivo, M. D. L. P., & Frazão, F. J. L. (2009). Terra Preta Nova : The Dream of Wim Sombroek. In W. I. Woods (Ed.), *Amazonian Dark Earths: Wim Sombroek's Vision* (pp. 339 - 349). Springer Science + Business Media B.V.

Laird, D., Fleming, P., Wang, B., Horton, R., & Karlen, D. (2010). Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*, *158*(3-4), 436-442. Elsevier B.V. doi:10.1016/j.geoderma.2010.05.012

Lavelle, P., Dugdale, R., Scholes, R., Asefaw, A., Carpenter, E., Codispoti, L., Izac, A.-marie, et al. (2005). Nutrient Cycling. In J. Etchevers & H. Tiessen (Eds.), *Ecosystems and Human Well-being: Current State and Trends, Volume 1* (pp. 331 - 353). Island Press.

Lehmann, J. (2007). Bio-energy in the black. *Frontiers in Ecology and the Environment*, *5*(7), 381-387.

Lehmann, J. (2009). Terra Preta Nova – Where to from Here ? In W. I. Woods (Ed.), *Amazonian Dark Earths: Wim Sombroek's Vision* (pp. 473-486). Springer Science + Business Media B.V.

Lehmann, Johannes. (2007). A handful of carbon. *Nature*, *447*, 143-144. doi:10.1002/jso.20705

Lehmann, Johannes, Czimczik, C., Laird, D., & Sohi, S. P. (2009). Stability of Biochar in Soil. In Johannes Lehmann & S. Joseph (Eds.), *Biochar for Environmental Management science and technology* (pp. 183-205). Earthscan.

Lehmann, Johannes, Gaunt, J., & Rondon, M. (2006). Bio-char Sequestration in Terrestrial Ecosystems – A Review. *Mitigation and Adaptation Strategies for Global Change*, *11*(2), 395-419. doi:10.1007/s11027-005-9006-5

Lehmann, Johannes, & Joseph, S. (2009a). Biochar for Environmental Management : An Introduction. (Johannes Lehmann & S. Joseph, Eds.)*Science And Technology*, *1*, 1-12. Earthscan Publications Ltd. Retrieved from http://www.biochar-international.org/images/Biochar_book_Chapter_1.pdf

Lehmann, Johannes, & Joseph, S. (2009b). Chapter 9 : Biochar Systems. In Johannes Lehmann & J. Stephen (Eds.), *Biochar for Environmental Management Science and Technology*. Earthscan.

Lehmann, Johannes, Pereira da Silva Jr, J., Steiner, C., Nehls, T., Zech, W., & Glaser, B. (2003). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin : fertilizer , manure and charcoal amendments. *Plant and Soil*, *249*, 343-357.

Lowenfels, J., & Lewis, W. (2010). *Teaming with Microbes: The Organic Gardner's Guide to the Soil Food Web*. London, Portland: Timber Press.

Manning, R. (2004). The oil we eat: Following the food chain back to Iraq. *Harpers Magazine*. Retrieved March 23, 2012, from http://www.harpers.org/archive/2004/02/0079915

Mcgreevy, S. R., & Shibata, A. (2010). A rural revitalization scheme in Japan utilizing biochar and eco-branding: The carbon minus project, Kameoka city. *Annals of Environmental Science*, *4*, 11-22.

Misra, R. V., Roy, R. N., & Hiraoka, H. (2003). *On-farm composting methods*. Rome.

Montgomery, D. R. (2007). *Dirt: The Erosion of Civilizations*. *Nature* (Vol. 447, p. 296). University of California Press. Retrieved from

Moore, S., Jakrawatana, N., Tungsubkul, N., & Cordell, D. (2011). Tracking the flow of phosphorus from agricultural use to disposal in cities.

Mor, S., Ravindra, K., Dahiya, R. P., & Chandra, A. (2006). Leachate characterization and assessment of groundwater pollution near municipal solid waste landfill site. *Environmental monitoring and assessment*, *118*(1-3), 435-56. doi:10.1007/s10661-006-1505-7

Mote, V. L. (2003). Managerial Economics. New Delhi: Indira Gandhi National Open University, School of Management Studies.

Ogawa, M., & Okimori, Y. (2010). Pioneering works in biochar research, Japan. *Australian Journal of Soil Research*, *1983*, 489-500.

Palaterra. (n.d.). *Let's make a green deal*.

Pfeiffer, D. A. (2006). *Eating Fossil Fuels*. *Agriculture*. New Society Publishers.

Pimbert, M. D. (2012). End of the line for the linear economy? *New Agriculturalist*. Retrieved from http://www.new-ag.info/en/view/point.php?a=2505

Pimentel, D. (2006). Soil Erosion: A Food and Environmental Threat. *Environmental, Development and Sustainability*, *8*(1), 119-137. doi:10.1007/s10668-005-1262-8

Pimentel, D., & Giampietro, M. (1994). Food, Land, Population and the US Economy. Retrieved from http://www.jayhanson.us/page55.htm

Qadir, M., Noble, A. D., Qureshi, A. S., Gupta, R. K., Yuldashev, T., & Karimov, A. (2009). Salt-induced land and water degradation in the Aral Sea basin: A challenge to sustainable agriculture in Central Asia. *Natural Resources Forum*, *33*, 134-149.

Rodriguez, M. (2010). *Biochar as a Stretegy for Sustainable Land Management, Poverty Reduction and Climate Change Mitigation/Adaptation? Carbon*. Vrije Universiteit, Amsterdam.

Roth, C. (2011). *Cooking with gas from biomass*. *GIZ REPORT*.

Salonius, P. (2008). Long term agricultural overshoot. Retrieved March 8, 2012, from http://www.theoildrum.com/node/6048

Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., Kleber, M., et al. (2011). Persistence of soil organic matter as an ecosystem property. *Nature*, *478*, 49-56. doi:10.1038/nature10386

Schröder, J. J., Smit, A. L., Cordell, D., & Rosemarin, A. (2011). Improved phosphorus use efficiency in agriculture: A key requirement for its sustainable use. *Chemosphere*, *84*, 822-831. doi:10.1016/j.chemosphere.2011.01.065

Scialabba, N. E.-H. (2007). *Organic agriculture and food security*. *Agriculture*.

Seyedbagheri, M.-M. (2010). *Compost: Production, Quality and Use in Commercial Agriculture*.

Shah, M., Xepapadeas, A., Emma, R., Haslberger, A., Jensen, F., Mirza, M. M. Q., Sartzetakis, E., et al. (2005). Food and Ecosystems. In A. M. Balisacan & P. Gardiner (Eds.), *Ecosystems and Human Well-being: Policy Responses, Volume 3* (pp. 173 - 210). Island Press.

Smil, V. (1991). Population Growth and Nitrogen: An Exploration of a Critical Existential Link. *Population and Development Review*, *17*(4), 569-601.

Smil, V. (2002). Nitrogen and food production: proteins for human diets. *Ambio*, *31*(2), 126-31. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12078001

Smil, V. (2011). Nitrogen cycle and word food production. *World Agriculture*, 9-13.

Sohi, S., Lopez-Capel, E., Krull, E., & Bol, R. (2009). *Biochar, climate change and soil: A review of research needs*. *Civil Engineering*

Steiner, C, Teixeira, W. G., Woods, W. I., & Zech, W. (2009). Indigenous Knowledge About Terra Preta Formation. In W. I. Woods (Ed.), *Amazonian Dark Earths: Wim Sombroek's Vision* (pp. 193-204). Springer Science + Business Media B.V.

Steiner, Christoph, Glaser, B., Geraldes Teixeira, W., Lehmann, J., Blum, W. E. H., & Zech, W. (2008). Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. *Journal of Plant Nutrition and Soil Science*, *171*(6), 893-899. doi:10.1002/jpln.200625199

Steiner, Christoph, Teixeira, W. G., Lehmann, J., Nehls, T., Macêdo, J. L. V., Blum, W. E. H., & Zech, W. (2007). Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and Soil*, *291*(1-2), 275-290. doi:10.1007/s11104-007-9193-9

Thies, J. E., & Rillig, M. C. (2009). Characteristics of Biochar: Biological Properties. In J Lehmann & S. Joseph (Eds.), *Biochar for Environmental Management Science and Technology* (pp. 85-105). Earthscan.

Thompson, R. (2012). Stakeholder Analysis - Project Management Tools from MindTools. *Mind Tools*. Retrieved from http://www.mindtools.com/pages/article/newPPM_07.htm

Tomczak, J. (2005). Implications of Fossil Fuel Dependence for the Food System. Retrieved from http://energybulletin.net/node/17036

University of Hawaii. (2012). Soil Texture and Soil Structure. Retrieved from http://www.ctahr.hawaii.edu/mauisoil/a_factor_ts.aspx

Vaccari, D. A. (2009). Phosphorus Famine: The Threat to Our Food Supply. *Scientific American Magazine*, (June).

Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., Joseph, S., et al. (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil*, *327*(1-2), 235-246. doi:10.1007/s11104-009-0050-x

Verheijen, F., Jeffery, S., Bastos, A. C., van der Velde, M., & Diafas, I. (2009). *Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*. *Environment* (p. 149pp.). Luxembourg. doi:10.2788/472

Wardle, D. a, Nilsson, M.-C., & Zackrisson, O. (2008). Fire-derived charcoal causes loss of forest humus. *Science*, *320*(5876), 629. doi:10.1126/science.1154960

West, T. O., & Post, W. M. (1997). *Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis* (pp. 1930-1946).

Wilson, K. (2011). IBI Developing Country Biochar Systems Survey: Methodology and Results. International Biochar Initiative.

Wood, S., Cassman, K. G., Sze, P., Cooper, H. D., Devendra, C., Dixon, J., Gaskell, J., et al. (2005). Cultivated Systems. In A. Balisacan & P. Gardiner (Eds.), *Ecosystems and Human Well-being: Current State and Trends, Volume 1* (pp. 745 - 792). Island Press.

Woods, W. I., & Denevan, W. M. (2009). Amazonian Dark Earths : The First Century or Reports. *Amazonian Dark Earths: Wim Sombroek's Vision* (pp. 1-14). Springer Science + Business Media B.V.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*(5), 1-9. doi:10.103/ncomms1053

Zafar, M., & Alappat, B. J. (2005). Landfill Surface Runoff and Its Effect on Water Quality on River Yamuna. *Journal of Environmental Science and Health, Part A*, *39*(2), 375-384. doi:10.1081/ESE-120027529

Zimmerman, A. R., Gao, B., & Ahn, M.-youn. (2011). Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry*, *43*(6), 1169-1179. Elsevier Ltd. doi:10.1016/j.soilbio.2011.02.005

ifu Hamburg. (2012). *Umberto for Carbon Footprint - User Manual*. Hamburg.