Analyzing Transactions in Linked Value Chains of Wastewater Treatment and Crop Production

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Erklärung:

Hiermit erkläre ich, die Dissertation selbstständig und nur unter Verwendung der angegebenen Hilfen und Hilfsmittel angefertigt zu haben.

Declaration:

I hereby declare that I completed the doctoral thesis independently based on the stated resources and aids.

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Abstract (English)

The increasing depletion of the natural phosphate reserves and the limited availability of freshwater in many regions challenge crop production across the world. Recovering phosphorus (P) in wastewater treatment and reusing wastewater in agriculture may help and lead to linked regional value chains which bring about cost savings and higher added-value. The study at hand explores the impact of transactions for reusing nutrients and treated municipal wastewater on the value chains of wastewater treatment and crop production. It aims to analyze what costs and benefits and what added-value can result from transactions in linked value chains of wastewater treatment and crop production. Furthermore, it aims to analyze how transactions and interdependences between actors in linked value chains shape the governance structures for reusing treated wastewater at the local level. The study consists of three research papers which shed light on the subject from a cost-benefit and an institutional point of view. The first paper analyzes the cost-benefits and the added value of recovering phosphorus via struvite precipitation and its use as fertilizer in crop production. The second paper investigates the cost-benefits and the added value of reusing treated wastewater and sludge in crop production. The third paper explores the interplay of transactions and interdependences between actors with the institutions and governance structures for reusing treated wastewater.

This research is mainly guided by the value chain concept, the concept of the circular economy and the theory of transaction costs economics. A combination of different methods including cost-benefit analysis, value chain analysis and transaction cost analysis is used to investigate two case studies located in Germany: (1) the precipitation of struvite (magnesium ammonium phosphate) in the wastewater treatment plant in Waßmannsdorf and its application as fertilizer in Berlin-Brandenburg, and (2) the agricultural wastewater reuse scheme of the Wastewater Association Braunschweig. Primary data about the cases was collected by written questionnaires and semi-structured in-depth interviews with operators of wastewater treatment facilities, farmers, employees of agricultural wastewater reuse schemes as well as representatives of local water authorities.

The results show that transactions for reusing nutrients and treated wastewater can lead to linked regional value chains which contribute to preserving natural resources of phosphate and water and which generate cost reductions and higher added-value. In detail, the results show that phosphorus recovery via struvite precipitation and its use as fertilizer leads to the development of an innovative value chain for nutrient recycling with added-value gains for wastewater treatment facilities and farmers. In wastewater treatment, struvite precipitation reduces operating costs and generates additional revenues through struvite sales. In crop production, fertilization costs are reduced by substituting struvite for mineral P-, N- and Ca-fertilizers. However, the distribution of the added-value in the struvite value chain depends on the marketing modalities for struvite. Farmers can obtain a higher share of added-value if struvite is marketed via direct sales. Moreover, the results show that the reuse of treated wastewater and sludge results in the development of linked regional value chains

with lower costs of wastewater treatment and sludge disposal, higher profitability and added-value in crop production, and a high share of regional added-value. The benefits in wastewater treatment result from savings in wastewater fees and the reduced costs for dewatering and incinerating sludge. The benefits in crop production result from savings in the cost for irrigation and fertilization. However, the results also highlight that the reuse of wastewater and sludge can lead to restrictions (e.g., cultivation bans on certain crops), crowding out effects and changes in the distribution of the added-value. Furthermore, the results suggest that different governance structures are needed to match the different properties of the transactions between the value chains of wastewater treatment and crop production. Interdependences resulting from transactions between wastewater providers and farmers increase the need for hybrid and hierarchical elements in the governance structures for reusing wastewater. Last but not least, the results indicate that aligning governance structures with transactions and interdependences contributes to efficiently governing transactions and interdependences between linked value chains of wastewater treatment and crop production.

The results obtained from this research are useful for operators of wastewater treatment facilities, farmers and municipalities since they provide decision-relevant knowledge and information on the costs and benefits of reusing nutrients and treated wastewater at the local level. In addition, the findings provide important information on how to coordinate transactions between linked and interdependent value chains efficiently. This knowledge can be used to promote alternative value chains of wastewater treatment and crop production, and thus makes an important contribution to the development of circular economies.

Abstract (deutsch)

Die Abnahme der natürlichen Phosphorreserven und die begrenzte Verfügbarkeit von Süßwasser in vielen Regionen stellen die Pflanzenproduktion weltweit vor Herausforderungen. Die Rückgewinnung von Phosphor (P) in der Abwasserbehandlung und die Wiederverwendung von Abwasser in der Landwirtschaft können möglicherweise bei diesen Problemen helfen und zu verknüpften regionalen Wertschöpfungsketten mit Kosteneinsparungen und höherer Wertschöpfung führen. In der vorliegenden Arbeit wird der Einfluss von Transaktionen zur Wiederverwendung von Nährstoffen und gereinigtem kommunalen Abwasser auf die Wertschöpfungsketten der Abwasserbehandlung und Pflanzenproduktion untersucht. Ziel ist es, Kosten und Nutzen sowie die Wertschöpfung von Transaktionen in verknüpften Wertschöpfungsketten der Abwasserbehandlung und Pflanzenproduktion zu analysieren. Darüber hinaus wird untersucht, wie Transaktionen und Interdependenzen zwischen Akteuren in verknüpften Wertschöpfungsketten die Governance-Strukturen für die Wiederverwendung von gereinigtem Abwasser auf lokaler Ebene beeinflussen.

Die Studie besteht aus drei Artikeln, die das Thema aus Kosten-Nutzen-Sicht sowie institutionellem Blickwinkel beleuchten. Im ersten Artikel werden Kosten und Nutzen sowie die Wertschöpfung durch Rückgewinnung von Phosphor mithilfe der Struvit-Fällung und dessen Verwertung als Dünger in der Pflanzenproduktion untersucht. Im zweiten Artikel werden Kosten und Nutzen sowie die Wertschöpfung durch Wiederverwendung von gereinigtem Abwasser und Klärschlamm in der Pflanzenproduktion betrachtet. Im dritten Artikel wird das Zusammenspiel von Transaktionen und Interdependenzen zwischen Akteuren mit den Institutionen und Governance-Strukturen für eine Wiederverwendung von gereinigtem Abwasser analysiert.

Diese Forschungsarbeit wird hauptsächlich durch das Wertschöpfungskettenkonzept, das Konzept der Kreislaufwirtschaft und die Theorie der Transaktionskostenökonomie geleitet. Mit einer Kombination verschiedener Methoden, wie der Kosten-Nutzen-Analyse, der Wertschöpfungskettenanalyse und der Transaktionskostenanalyse, werden zwei Fallstudien in Deutschland untersucht: (1) die Fällung von Struvit (Magnesium-Ammonium-Phosphat) in der Kläranlage Waßmannsdorf und dessen Verwendung als Dünger in Berlin-Brandenburg und (2) das Modell der landwirtschaftlichen Abwasserwiederverwendung des Abwasserverbandes Braunschweig. Die Primärdaten zu den Fallbeispielen wurden mit Hilfe von schriftlichen Fragebögen sowie semi-strukturierten Tiefeninterviews mit Betreibern von Abwasserbehandlungsanlagen, Landwirten, Mitarbeitern von landwirtschaftlichen Abwasserwiederverwendungssystemen und Vertretern von lokalen Wasserbehörden erhoben.

Die Ergebnisse zeigen, dass Transaktionen zur Wiederverwendung von Nährstoffen und gereinigtem Abwasser zu verknüpften regionalen Wertschöpfungsketten führen können. Diese können zur Erhaltung der natürlichen Phosphor- und Wasserressourcen beitragen und zu Kostensenkungen sowie einer höheren Wertschöpfung führen. Im Detail

zeigen die Ergebnisse, dass die Rückgewinnung von Phosphor durch Struvit-Fällung und dessen Nutzung als Dünger die Entwicklung einer innovativen Wertschöpfungskette mit Wertschöpfungsgewinnen für Kläranlagenbetreiber und Landwirte zur Folge hat. In der Abwasserbehandlung reduziert die Struvit-Fällung die Betriebskosten und generiert zusätzliche Einnahmen durch den Struvit-Verkauf. In der Pflanzenproduktion werden die Düngekosten durch die Substitution von mineralischen P-, N- und Ca-Düngern gesenkt. Die Verteilung der Wertschöpfung in der Struvit-Wertschöpfungskette hängt jedoch von der Vermarktungsstrategie des Struvits ab. Landwirte können einen höheren Anteil an der Wertschöpfung erzielen, wenn dieses im Direktverkauf vertrieben wird. Des Weiteren zeigen die Ergebnisse, dass die Wiederverwendung von gereinigtem Abwasser und Klärschlamm zur Entwicklung verknüpfter regionaler Wertschöpfungsketten bei geringeren Kosten für Abwasserbehandlung und Klärschlammentsorgung, zu höherer Rentabilität und Wertschöpfung in der Pflanzenproduktion und zu einem hohen Anteil an regionaler Wertschöpfung führt. Der Nutzen in der Abwasserbehandlung ergibt sich aus den reduzierten Kosten für die Abwasserabgabe sowie für die Entwässerung und Verbrennung von Klärschlamm. Der Nutzen in der Pflanzenproduktion resultiert hauptsächlich aus Einsparungen bei den Kosten für Bewässerung und Düngung. Die Ergebnisse verdeutlichen aber auch, dass die Wiederverwendung von Abwasser und Klärschlamm zu Einschränkungen (z.B. Anbauverbote für bestimmte Kulturen), Verdrängungseffekten und Veränderungen in der Verteilung der Wertschöpfung führen kann. Des Weiteren weisen die Ergebnisse daraufhin, dass differenzierte Governance-Strukturen erforderlich sind, um den unterschiedlichen Eigenschaften der Transaktionen zwischen den Wertschöpfungsketten der Abwasserbehandlung und der Pflanzenproduktion gerecht zu werden. Interdependenzen, die sich aus Transaktionen zwischen Abwasseranbietern und Landwirten ergeben, erhöhen den Bedarf an hybriden und hierarchischen Elementen in den Governance-Strukuren für die Wiederverwendung von Abwasser. Nicht zuletzt zeigen die Ergebnisse, dass die Ausrichtung der Governance-Strukturen an den Transaktionen und Interdependenzen dazu beiträgt, Transaktionen und Interdependenzen zwischen verknüpften Wertschöpfungsketten der Abwasserbehandlung und der Pflanzenproduktion effizient zu koordinieren.

Die Ergebnisse der Studie stellen für Kläranlagenbetreiber, Landwirte und Kommunen entscheidungsrelevantes Wissen und Informationen zu Kosten und Nutzen der Wiederverwendung von Nährstoffen und gereinigtem Abwasser dar. Darüber hinaus liefern die Ergebnisse wichtige Hinweise darauf, wie Transaktionen zwischen verknüpften und interdependenten Wertschöpfungsketten effizient koordiniert werden können. Dieses Wissen kann für die Förderung von alternativen Wertschöpfungsketten der Abwasserbehandlung und der Pflanzenproduktion genutzt werden und somit einen wichtigen Beitrag zur Entwicklung der Kreislaufwirtschaft leisten.

List of Publications

The research presented here is based on the following three papers which are referred to in the text by their roman numbers (I-III). All papers are reprinted with the permission of the publishers.

Paper I

Maaß, O.; Grundmann, P.; von Bock und Polach, C., 2014. Added-value from Innovative Value Chains by Establishing Nutrient Cycles via Struvite. *Resources, Conservation and Recycling* 87, 126-136. *doi:10.1016/j.resconrec.2014.03.012*

Paper II

Maaß, O.; Grundmann, P., 2016. Added-value from Linking the Value Chains of Wastewater Treatment, Crop Production and Bioenergy Production: A Case Study on Reusing Wastewater and Sludge in Crop Production in Braunschweig (Germany). *Resources, Conservation and Recycling* 107, 195-211. *doi:10.1016/j.resconrec.2016.01.002*

Paper III

Maaß, O.; Grundmann, P., 2018. Governing Transactions and Interdependences between Linked Value Chains in a Circular Economy: The Case of Wastewater Reuse in Braunschweig (Germany). *Sustainability* 10 (4), 1125. *doi:10.3390/su10041125*

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List of Abbreviations

a	Anno
ABWV BS	Abwasserverband Braunschweig
As	Arsenic
Ca	Calcium
CaO	Calcium oxide
Cd	Cadmium
Cr	Chromium
CSB	Chemical Oxygen Demand
Cu	Copper
d	Day
DAP	Diammonium Phosphate
DM	Dry matter
DU	Damage unit
DüMV	Verordnung über das Inverkehrbringen von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln (Düngemittelverordnung)
DWA	Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall
ELaN	Entwicklung eines integrierten Landmanagements durch nachhaltige Wasser- und Stoffnutzung in Nordostdeutschland
€	Euro
FAO	Food and Agriculture Organization
EBT	Earnings Before Taxes
EAT	Earnings After Taxes
EU	European Union
h	Hour
ha	Hectare
IAD	Institutional Analysis and Development Framework
IP	Interest payments
K	Potassium
K_2O	Potassium oxide
Kg	Kilogram
LELF	Landesamt für Ländliche Entwicklung, Landwirtschaft und Flurneuordnung
LWK H	Landwirtschaftskammer Hannover
LWK NS	Landwirtschaftskammer Niedersachsen
m^3	Cubic meter
MAP	Magnesium Ammonium Phosphate
Mg	Magnesium
Mg^{2+}	Magnesium
MgO	Magnesium oxide
MIL	Ministerium für Infrastruktur und Landwirtschaft des Landes Brandenburg

min.	Minutes
Min.	Minimum
Max.	Maximum
mm	Millimeter
Mn	Manganese
N	Nitrogen
NAV	Net Added-Value
NH_4^+	Ammonium
Ni	Nickel
$N_{inorg.}$	Inorganic nitrogen
NLWKN	Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz
NWP	Net wage payments
OECD	Organization for Economic Co-operation and Development
P	Phosphorus
P_2O_5	Phosphorus pentoxide
PAT	Profits after taxes
Pb	Lead
p.e.	Population equivalent
PO_4^{3-}	Orthophosphate
PT	Payments of taxes
S	Sulfur
SUP	Superphosphate
t	Ton
t	period of time
TSP	Triple superphosphate
UBA	Umweltbundesamt
VAT	Value-Added Tax
y	Year
Zn	Zinc

1 General Introduction

1.1 Background

1.1.1 Increasing Depletion of Phosphate Reserves and Limited Availability of Water

The increasing depletion of the natural phosphate reserves is a significant challenge for securing the productivity of crop production across the world. Phosphorus (P) is a life-sustaining nutrient which is essential for optimal plant growth (Cordell and White, 2014; Schachtman et al., 1998). The nutrient phosphorus is a non-renewable resource which is mainly obtained from mined phosphate rock located in a few countries, primarily Morocco and Western Sahara (USGS, 2018). As a consequence, all countries which lack their own natural reserves are dependent on the import of phosphate and are vulnerable to supply shortages and price volatility. Phosphorus has no substitute in crop production and today about 90% of the phosphorus derived from mineral phosphate rock is used as fertilizer (Brunner, 2010; Cordell, 2010). Estimates on the global phosphate reserves vary considerably and there is no agreement about when the reserves will be depleted. Some studies claim that economically minable phosphate reserves could be exhausted within 50-100 years (Cordell, 2010; Schröder et al., 2010; Smit et al., 2009), while other studies state that deposits may last 300-400 years (Cooper et al., 2011). Regardless of the different estimates there is a general consensus that the quality and accessibility of the remaining deposits is decreasing and production costs will increase (Cordell and White, 2011). In addition, researchers agree that the price of phosphate rock will increase in the long-term (Cordell et al., 2009; Horn and Satorius, 2009), with significant implications for farmers and food production systems (Cordell and White, 2011; Mew, 2016).

Another significant challenge for securing the productivity of crop production is the limited availability of freshwater. Freshwater represents just 2.5% of the Earth´s water and of this water only one-third occurs in liquid form (Shiklomanov, 2000). The global reserves of freshwater are distributed unevenly among countries and regions (FAO, 2003). While some regions have sufficient reserves available to satisfy demand, many others experience situations of extreme water scarcity (Mekonnen and Hoekstra, 2016). Water scarcity varies with local conditions and describes a "situation of long-term water imbalance, where water demand exceeds the level of water resources available" (EC, 2007: p. 6). Presently, about "two-thirds of the global population (4.0 billion people) live under conditions of severe water scarcity at least 1 month of the year" (Mekonnen and Hoekstra, 2016: p. 1). Although, at the global level there is sufficient freshwater available to meet future demand (Mekonnen and Hoekstra, 2016), a growing number of regions are expected to face increasing water scarcity due to population growth, climate change, economic development and urbanization (Alcamo et al., 2007; Distefano and Kelly, 2017; Sophocleous, 2004). Agriculture depends crucially on water availability. Today, irrigated crop production accounts for 70% of the total freshwater abstraction worldwide (WWAP, 2014). Furthermore, irrigated crop production represents 16% of the total area under cultivation and constitutes 44% of global food production (Alexandratos and Bruinsma, 2012).

The Food and Agricultural Organization of the United Nations (FAO) estimates that compared to 2005/2007 about 60% more food will be needed by 2050 to satisfy the food demand of a growing global population (Alexandratos and Bruinsma, 2012). Increased food production will increase the demand for P and freshwater in agriculture. It is expected that global water demand from agriculture will grow by 20% by 2050 (WWAP, 2012). At the same time, agriculture will face increasing competition for water from industrial production and the energy sector (Strzepek and Boehlert, 2010; Ziolkowska and Peterson, 2017).

It is apparent that a deficit in P and water in agriculture would severely restrict crop yields and the food security of the world´s increasing population (Cordell et al., 2009; Fereres et al., 2011; Koning et al., 2008; Rosegrant et al., 2009). Therefore, there is an urgent need to use P and water more efficiently (Roberts and Johnston, 2015; Wallace, 2000) and to seek alternative sources of P and water supply (Peng et al., 2018).

One alternative source of P and water supply which has received increasing attention is municipal wastewater (Pollice et al., 2004; Qadir et al., 2007; Schoumans et al., 2015). Municipal wastewater is produced constantly and usually contains high concentrations of P and other nutrients (e.g., nitrogen and potassium) (Peng et al., 2018). Estimates indicate that P recovered from municipal wastewater could theoretically meet 15-20% of the global demand for P (Peng et al., 2018; Yuan et al., 2012). Furthermore, researchers agree that there is a significant potential for reusing treated wastewater in irrigated agriculture (Norton-Brandão et al., 2013). Awareness of the potential role of municipal wastewater as an alternative source of P and water supply has encouraged intensive research on the recovery of nutrients in wastewater treatment and the reuse of wastewater in agriculture.

1.1.2 Phosphorus Recovery in Wastewater Treatment and Wastewater Reuse in Agriculture

Nutrient recovery is the "practice of recovering nutrients such as nitrogen and phosphorus from used water streams that would otherwise be discarded and converting them into an environmental friendly fertilizer used for agricultural purposes" (Haddaway, 2015). Numerous techniques have been developed to recover P at different steps of wastewater treatment (Cieślik and Konieczka, 2017; Egle et al., 2015; Egle et al., 2016; Mehta et al., 2015; Melia et al., 2017; Peng et al., 2018). However, most of these techniques are problematic since they "produce low-quality products, have high costs, or are operationally complex" (Peng et al., 2018: p. 769). Currently, only a few techniques have potential for full-scale implementation (Egle et al., 2015). One technique for P recovery, which is already used on a commercial scale, is struvite precipitation. Struvite (magnesium ammonium phosphate or MAP) is a white crystalline substance which can be precipitated from various types of wastewater (Doyle and Parsons, 2002; Kataki et al., 2016; Le Corre et al., 2009). It consists of magnesium, ammonium and phosphate and has the potential to be used directly as a slow-release fertilizer in agriculture (Rahman et al., 2014; Talboys et al., 2016). The main advantage of using struvite in agriculture is its slow nutrient release which can increase the efficiency of fertilization and reduce the risk of leaching and damaging plant roots in case of high application rates (Le Corre et al., 2009; Rahman et al., 2014; Talboys et al., 2016). Furthermore, the heavy metal content of struvite is generally lower than that of mineral fertilizer which presents another advantage of struvite fertilization (Kern et al., 2008; Ueno and Fujii, 2001).

Wastewater reuse involves "treating wastewater to an appropriate standard so it can be used again as non-potable or potable water rather than being discharged into the sea, a river or other water body" (Jeffrey et al., 2017). Reusing treated wastewater in agriculture includes the irrigation of non-food crops, such as fodder and fiber, nurseries, sod farms and pastures. High-quality water can be used for irrigating food crops (Levine and Asano, 2004). In safe conditions, the agricultural reuse of treated wastewater can provide many economic, social and environmental benefits (Jaramillo and Restrepo, 2017). It can conserve natural freshwater sources, increase water availability and reduce the amount of wastewater discharged into surface water bodies (Aiello et al., 2007). Furthermore, it can reduce purification levels and wastewater treatment costs since soil and crops act as natural filters (Haruvy, 1997; Rosenqvist and Dawson, 2005). Last but not least, wastewater reuse can supply nutrients which contribute to increasing crop yields (Aiello et al., 2007; Bedbabis et al., 2015; Dimitriou and Rosenqvist, 2011; Singh et al., 2012; Zema et al., 2012) and saving mineral fertilizer (Paranychianakis et al., 2006). However, depending upon its source and treatment, wastewater may contain pathogens (e.g., bacteria and viruses) and hazardous substances (e.g., heavy metals, anthropogenic trace contaminants) which can create serious risks for humans and the environment (Christou et al., 2017; Fatta-Kassinos et al., 2011; Khan et al., 2008; Mapanda et al., 2005; Pedersen et al., 2005; Toze, 2006). Careful management, including the application of proper treatment levels, regular monitoring of crop and soil properties, as well as suitable irrigation and cultivation practices, is indispensable to the minimizing of potential risks to humans and the environment (Aiello et al., 2007; Muyen et al., 2011; Qadir et al., 2010; Rusan et al., 2007).

1.1.3 Current Status of Phosphorus Recovery and Wastewater Reuse in Europe

Researchers agree on the significant potential for implementing P recovery and wastewater reuse in Europe (Angelakis and Gikas, 2014; Egle et al., 2016; Hochstrat et al., 2006; Kern et al., 2008; Raso, 2013; Schoumans et al., 2015; Wintgens and Hochstrat, 2006). However, despite its potential, the implementation of P recovery and wastewater reuse remains underdeveloped at EU level (Kabbe, 2018; Kirhensteine et al., 2016; Raso and Seiz, 2012). Techniques for P recovery such as struvite precipitation are still at the early stages of the implementation process (Boer et al., 2018). Struvite precipitation systems operating at full-scale and producing fertilizer for agriculture have only been implemented in some wastewater treatment plants in the Netherlands, Denmark, Germany, Italy and in the United Kingdom (Heinzmann and Engel, 2006; Kleemann et al., 2015; Schoumans et al., 2015). The amount of P recovered in these treatment plants is certainly negligible when compared to the

1.16 million tons of pure phosphorus consumed in the form of mineral fertilizer in the European Union in 2016 (EUROSTAT, 2018).[1]

Presently, wastewater reuse for agricultural purposes occurs predominantly in the semi-arid regions of southern Europe (Angelakis and Gikas, 2014; Raso and Seiz, 2012). In 2006, the total volume of reused treated wastewater in Europe was 964,000,000 m^3 a^{-1}, which accounted for only 2.4% of the total treated municipal wastewater effluents (Wintgens and Hochstrat, 2006) and less than 0.5% of the annual freshwater abstraction in the European Union (Kirhensteine et al., 2016).[2] The largest users of wastewater were Spain and Italy which jointly accounted for about 60 % of the wastewater volume reused in Europe in 2006 (Kirhensteine et al., 2016). There are significant differences between European countries regarding their wastewater reuse rates. Malta, for instance, reuses approximately 60% of its wastewater, whereas other countries such as Greece, Italy and Spain reuse only between 5% and 12% of their wastewater (Raso and Seiz, 2012). So far, the reuse of treated wastewater contributes only marginally to the countries´ water supply. In most European countries, including Germany, the amount of reused wastewater is less than 1% when compared with the countries´ total water abstraction (Raso and Seiz, 2012).

1.1.4 Barriers for Phosphorus Recovery and Wastewater Reuse

Several economic, social and institutional barriers hamper the widespread implementation of P recovery and wastewater reuse in Europe. A significant barrier for P recovery via struvite precipitation is the high investment costs with an uncertain return on investment (Boer et al., 2018). Furthermore, for technical and economic reasons, struvite precipitation is currently only applicable in large wastewater treatment plants which use enhanced biological phosphorus removal (Melia et al., 2017). Barriers for using struvite in agriculture include the different and often unclear characteristics of struvite compared to conventional P fertilizer, the limited availability to farmers, and the lack of communication on the applicability and benefits of struvite fertilization (Boer et al., 2018; Le Corre et al., 2009; Shu et al., 2006). Last but not least, the low market price of phosphate ore is generally seen as an impediment for P recovery (Molinos-Senante et al., 2011b; Roeleveld et al., 2004) and for the development of a struvite value chain (Boer et al., 2018; Kabbe et al., 2015).

A basic driver of the reluctance to reusing wastewater is the fact that water reuse is complex and often more costly than freshwater abstraction due to treatment costs and infrastructure needs for treated water (e.g., facilities for distributing and storing wastewater) (Kirhensteine et al., 2016). In addition, stakeholders fear potential environmental and health risks and are often not aware of the benefits of wastewater reuse (Alcalde-Sanz and Gawlik, 2014; Mudgal et al., 2015; Saliba et al., 2018). Another significant obstacle to a greater uptake

[1] The exact amount of P recovered in the treatment plants could not be specified due to a lack of data at the treatment plants. Presently, no comprehensive data exists on the total quantities of P recovered from wastewater in Europe.

[2] No comprehensive and up-to-date quantitative data is available on the volumes of reused treated wastewater in Europe (Kirhensteine et al., 2016) . The figures presented here refer to the latest data provided by a survey conducted in the AQUAREC research project (http://www.aquarec.org).

of water reuse lies in the difficulties in designing appropriate institutions and governance structures for wastewater reuse (Alcalde-Sanz and Gawlik, 2014; Frijns et al., 2016; Khatib et al., 2017; Saldías et al., 2015; Saldías et al., 2016). At the EU level, no common standards or quality guidelines for wastewater reuse have been implemented yet (Alcalde-Sanz and Gawlik, 2014; Fawell et al., 2016). Only a few countries including Spain, Portugal, France, Italy, Greece and Cyprus have introduced national standards for water reuse (Alcalde-Sanz and Gawlik, 2014). In countries where no reuse standards exist (e.g., Germany) "there is a lack of clarity in the regulatory framework to manage health and environmental risks, and a lack of confidence in the health and environmental safety of water reuse practices" (European Commission, 2015: p. 3). By contrast, in countries where national standards have been implemented, they are often very strict, which decreases the economic attractiveness of water reuse for potential investors (European Commission, 2015; Mudgal et al., 2015). Particular barriers for reusing wastewater in agriculture include the lack of public acceptance due to the negative perception of the quality of the water and the fear of potential trade barriers for crops irrigated with wastewater (Kirhensteine et al., 2016; Mudgal et al., 2015).

1.1.5 Phosphorus and Wastewater Reuse in Linked Value Chains

Reusing phosphorus and wastewater is characterized by transactions between the value chains of wastewater treatment and crop production, like the spreading of struvite or the irrigation of wastewater for cultivating crops. Transactions for reusing phosphorus and wastewater may create linkages and interdependences between the value chains of wastewater treatment and crop production when actors or actions are affected by or depend on each other´s actions (Johnson and Johnson, 1989; Paavola, 2007). The linkages and interdependences may develop due to shared resources (e.g., land for releasing wastewater and cultivating crops), input-output relations (e.g., water and nutrients), and interdependences between activities and actors (e.g., interdependences between wastewater treatment and cultivation practices and the respective providers and users of resources). As a result of the linkages and interdependences linked regional value chains may develop. Moreover, these linked regional value chains may bring about cost savings and a higher added-value.

1.2 Research Gaps

Economic studies including cost-benefit analyses are of high importance when assessing the feasibility of techniques for recovering nutrients and reusing wastewater. They can assist practitioners and stakeholders in decision-making and provide a "basis for rational thinking about the monetary losses and gains subjected to decisions" (Garcia and Pargament, 2015: p. 155). However, economic studies are underrepresented in the body of literature on P recovery and wastewater reuse and leave significant research gaps regarding the economic impact of P recovery and water reuse on the value chains of wastewater treatment and crop production.

The research on P recovery via struvite precipitation has mainly focused on the technical matters of the precipitation process (Le Corre et al., 2009; Rahman et al., 2014). Only a few studies have analyzed the economic aspects of struvite precipitation (Gaterell et al., 2000; Jaffer et al., 2002; Münch and Barr, 2001; Shu et al., 2006; Ueno and Fujii, 2001). These studies have discussed the costs and benefits for wastewater treatment but have not taken into account the costs and benefits of struvite fertilization in crop production. Moreover, none of the existing studies have analyzed the added-value from the precipitation of struvite and its use as an agricultural fertilizer.

The research on reusing wastewater in agriculture has tended to focus on the suitability of treated wastewater for irrigation, and on the ability of particular techniques to meet specific parameters of the irrigation water quality (Norton-Brandão et al., 2013). Some studies provide insights into the monetary costs and benefits of wastewater reuse (Garcia and Pargament, 2015; Haruvy, 1997; Hernández et al., 2006; Hernández-Sancho et al., 2010; Molinos-Senante et al., 2011a; Rosenqvist and Dawson, 2005). However, these studies have concentrated on analyzing the costs and benefits for farmers and operators of wastewater treatment facilities. The research has neglected to analyze the added-value resulting for other stakeholders including employees, creditors and the state. In addition, the distribution of the added-value among the stakeholders and the value chains of wastewater treatment and crop production has not been investigated yet. Lastly, little attention has been paid to the impact of wastewater reuse on local economic development.

Another issue which has not been thoroughly investigated yet is the governance of wastewater reuse at the local scale. Most of the research has focused on studying the institutional challenges for water reuse at higher levels of governance, including regulatory and legislative issues at national and international levels (Alcalde-Sanz and Gawlik, 2014; Angelakis et al., 1999; Fawell et al., 2016; Frijns et al., 2016; Kellis et al., 2013; Lavrnić et al., 2017; Sanchez-Flores et al., 2016). Only a few studies have scrutinized the institutional arrangements for reusing wastewater at the local level (Khatib et al., 2017; Saldías et al., 2015; Saldías et al., 2016). The body of literature is lacking in the characterization of the specific transactions between the value chains of wastewater treatment and crop production according to their properties, the analysis of the governance structures regarding their features and the consideration of the interdependences between the actors involved.

Therefore, the understanding of the governance structures for coordinating the specific transactions that create linkages and interdependences between the value chains of wastewater treatment and crop production is insufficient. In particular, the question of how transactions and interdependences between wastewater providers and crop producers shape the governance structures for wastewater reuse and how the alignment between governance structures with the transactions and interdependences can facilitate reusing wastewater has not been analyzed yet.

This dissertation is an attempt to address the gaps by looking at P recovery and municipal wastewater reuse from a value chain perspective, analyzing costs and benefits including the added-value, as well as the interplay between the associated transactions and governance structures. By focusing on the value chains of wastewater treatment and crop production, the dissertation introduces a novel viewpoint in the discussion of nutrient recovery and wastewater reuse at the local level.

1.3 Research Objectives, Research Questions and Structure of the Thesis

The general objective of this study is to understand and explain the impact of transactions for reusing nutrients and wastewater on the value chains of wastewater treatment and crop production. In particular, the study aims to analyze what costs, benefits and added-value can result from transactions in linked value chains of wastewater treatment and crop production. Furthermore, the study aims to analyze how the added-value is distributed among linked value chains and stakeholders. Finally, the study aims to scrutinize how transactions and interdependences between actors in linked value chains shape the governance structures for reusing wastewater at the local level.

The analysis is based on three research papers which approach the subject from two perspectives: On the one hand, from a cost-benefit point of view focusing on costs and benefits including the added-value, and on the other hand, from an institutional point of view concentrating on the characteristics of actors, transactions, institutions and governance structures (Figure 1-1). The cost-benefit analysis of transactions in linked value chains refers to the agricultural reuse of phosphorus recovered via struvite precipitation (Paper I) and the agricultural reuse of treated municipal wastewater and sludge (Paper II). The institutional analysis refers to the agricultural reuse of treated municipal wastewater (Paper III). The main research objectives pursued in the three papers are:

1) Analyzing the economic impact of recovering phosphorus (P) and its reuse as agricultural fertilizer on the value chains of wastewater treatment and crop production (Paper I)

Paper I seeks to contribute to the research gap regarding the added-value of nutrient-cycling in wastewater treatment and crop production. It aims to analyze the recovery and reuse of phosphorus as a fertilizer from an added-value-perspective. Referring to the case of struvite precipitation, I investigate in this paper the theoretical assumption that innovations for feeding nutrient cycles are conducive to the emergence of innovative value chains with a higher added-value. The specific research objectives pursued in this paper are:

a. To analyze what techno-economic changes occur in the value chains of wastewater treatment and crop production due to the precipitation of struvite and the substitution of struvite for mineral P-fertilizer.

b. To determine the monetary costs and benefits from establishing a P nutrient cycle via struvite precipitation and its use as agricultural fertilizer.

c. To examine how the added-value of struvite is distributed along the struvite value chain.

2) Analyzing the economic impact of reusing wastewater and sludge on the value chains of wastewater treatment and crop production (Paper II)

Paper II seeks to contribute to the research gaps regarding the impact of reusing wastewater and sludge on added-value and local economic development. In this paper, I investigate the theoretical assumption that the reuse of treated municipal wastewater and sludge is conducive to the development of linked regional value chains which bring about cost reductions and higher added-value. In this context, I present a methodological approach for comparing alternative systems of wastewater treatment and crop production with conventional ones from a regional economic point of view. The specific objectives of the paper are:

a. To determine the monetary costs and benefits from reusing wastewater and sludge in crop production.

b. To determine what additional added-value can be generated from the agricultural reuse of wastewater and sludge in the value chains of crop production.

c. To analyze the distribution of the added-value among the value chains and stakeholders.

d. To assess the impact of the linkage of natural-resource-based value chains on the added-value of local economies.

3) Analyzing the impact of transactions and interdependences between actors on governance structures for reusing wastewater at the local level (Paper III)

Paper III complements the economic analysis of Paper II and introduces the perspective of transaction cost economics on reusing wastewater. The paper seeks to contribute to the research gap regarding the specific characteristics of the transactions and governance structures for reusing treated wastewater at the local level. In particular, the paper aims to analyze the interplay of transactions and interdependences between actors with the institutions and governance structures for reusing wastewater. The specific objectives of this paper are:

a. To analyze how the properties of the transactions and the interdependences between actors shape the governance structures for reusing wastewater at the local scale.

b. To scrutinize how the alignment of governance structures with the transactions and interdependences contributes to the smooth operation of agricultural wastewater reuse schemes.

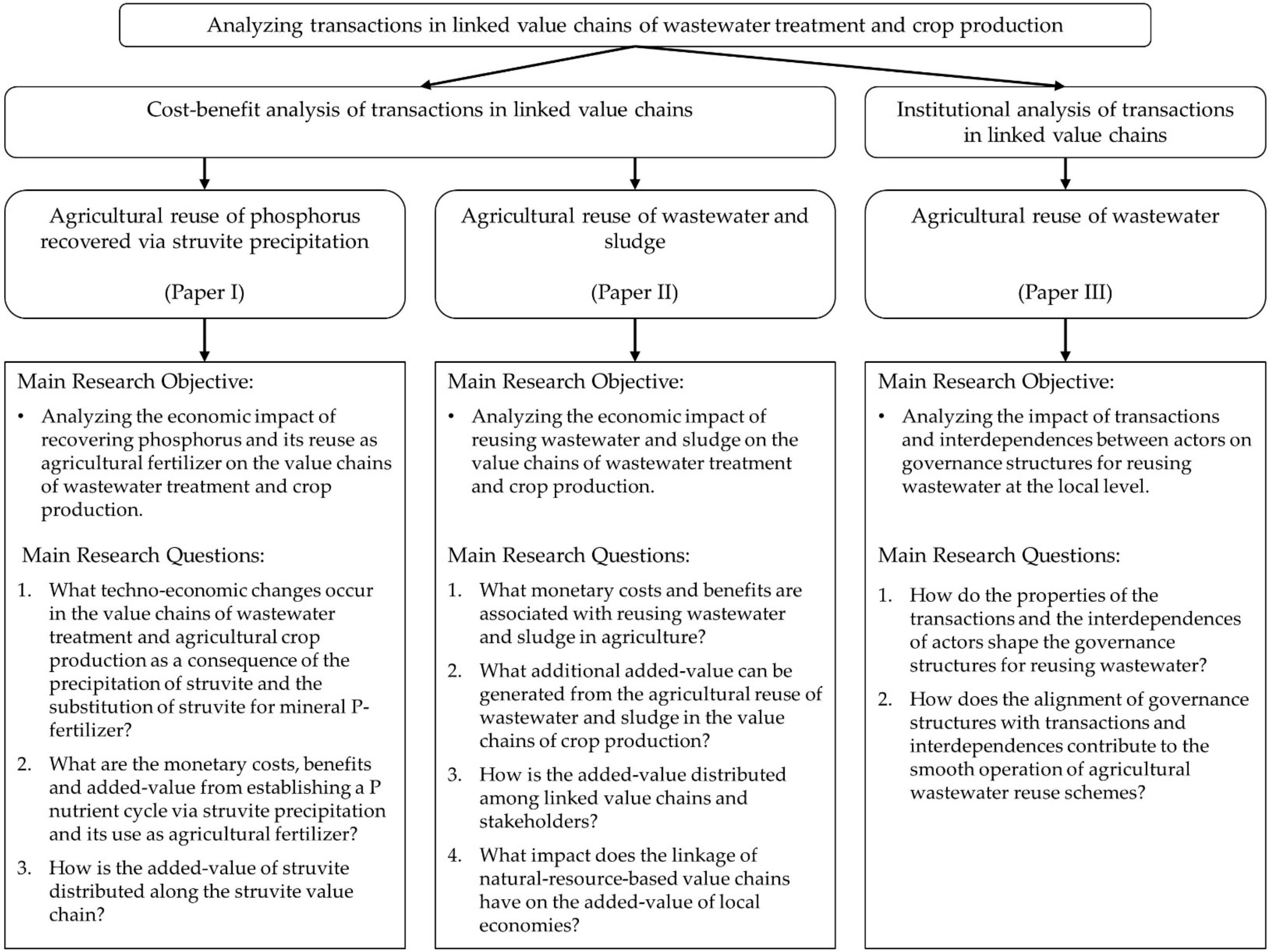

Figure 1-1: Overview of the research objectives and research questions of the three papers integrated in the thesis.

1.4 Conceptual and Theoretical Framing

The conceptual and theoretical framing of this study is based on several concepts and theories, including the concept of linked and interdependent value chains in a circular economy, the related concepts of transactions, institutions, and governance structures in action arenas and action situations, as well as the theory of transaction cost economics. The following section is mainly adapted from Paper III and provides a general overview of the conceptual and theoretical framing of this study. More detailed information on the different concepts and the theory of transaction cost economics is presented in the papers.

"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations" (Kirchherr et al., 2017: pp. 224-225). The circular economy "goes beyond the pursuit of waste prevention and waste reduction to inspire technological, organizational and social innovation across and within value chains" (European Commission, 2014: p. iv). Transferring the thinking of the circular economy to water means to convert the conventional linear water use model—which is based on extracting, treating, distributing, consuming, collecting, treating, and disposing of water—to a circular water use model (Voulvoulis, 2018). In such a model, "wastewater is not considered as waste but rather as a valuable non-conventional resource" (Abu-Ghunmi et al., 2016: p. 229) that can create additional added-value (Maaß et al., 2014; Maaß and Grundmann, 2016), and that should be circulated to preserve natural resources of water and nutrients such as phosphorus (Abu-Ghunmi et al., 2016).

The approach chosen for analyzing the reuse of phosphorus and wastewater in the circular economy draws on the concept of value chains, and focuses on the transactions between the value chains of wastewater treatment and crop production. Value chains include "the full range of activities which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use" (Kaplinsky and Morris, 2001: p. 4). In the case of reusing phosphorus and wastewater in agriculture, several goods and services are produced and provided. The goods produced include phosphorus, treated water and crops. The services provided include treating wastewater as well as irrigating and fertilizing crops. Usually, these goods and services pertain to separate value chains. However, in the case of reusing phosphorus and wastewater in agriculture, the production of phosphorus, treated water, crops and the associated services go together. This leads me to assume linkages and interdependences between the value chains of wastewater treatment and crop production in the studied case. Furthermore, I assume that the linkages and interdependences between the value chains emerge from different physical and social processes occurring in distinct action situations located in various action arenas[3]. An action arena refers to the "conceptual space in which actors [...] make decisions, take action, and experience the consequences of these actions" (Polski and Ostrom, 1999: p. 20). The action arena involves one or multiple action situations and the actors who interact in the action situation regarding activities and/or transactions (Polski and Ostrom, 1999). The action situation is defined as the "social space where participants […] interact, exchange goods and services, solve problems, dominate one another, or fight (among the many things that individuals do in action arenas)" (Ostrom, 2005: p. 14).

In this research, the agricultural reuse of phosphorus and wastewater is conceptualized as an action arena which consists of three sub-arenas: (1) the provision of phosphorus and wastewater through the value chain of wastewater treatment; (2) the use of phosphorus and wastewater as input in the value chain of crop production; and (3) the transference of phosphorus and wastewater between both value chains. The actors in the sub-arenas participate in multiple action situations. Action situations related to the reuse of wastewater in agriculture involve, for instance, provision situations in which actors provide resources and services (e.g., land, water or irrigation services), distribution situations where actors define the allocation of resources (e.g., distribution of wastewater between farmers and plots) and appropriation situations in which actors make use of resources (e.g., use of wastewater and land for cultivating crops).

The theory of transaction cost economics is used as the theoretical framework for understanding the alignment of transactions and governance structures in linked value chains. Analyses based on the transaction cost theory traditionally aim to assess the relative efficiency of organizing transactions while assuming that actors are rationally bound and tend to behave opportunistically (Williamson, 1991). The basic unit of analysis is the transaction defined as "an exchange which occurs between two stages of the production/distribution chain as the product changes in form and/or in ownership rights" (Hobbs, 1996: p. 17). As explained in section 1.1.5, transactions may create interdependences between value chains, when actors or actions are affected by or depend on each other's actions (Johnson and Johnson, 1989; Paavola, 2007). Transactions and interdependences between value chains or actors may result "in either conflicts to be solved or opportunities for cooperation" (Hagedorn, 2008: p. 363). In order to alleviate conflicts and to realize benefit from cooperation, actions and transactions causing interdependences need to be regularized by institutions and governance structures (Hagedorn, 2008). "Institutions are the rules of the game of a society or, more formally, are the humanly devised constraints that shape human interaction" (North, 1990: p. 3). Governance structures are conceptualized as "organizational solutions for making institutions effective, i.e., they are necessary for guaranteeing rights and duties and their use in coordinating transactions" (Hagedorn, 2008: p. 360). How institutions

[3] The terms "action arena" and "action situation" originate from the Institutional Analysis and Development framework (IAD) developed by Ostrom (2005). I adopt the terms and related definitions for this research but do not further refer to the IAD framework.

and governance structures are socially constructed depends, among others factors, on the specific properties of the transactions and the characteristics of the actors involved in the transaction (Beckmann, 2000; Hagedorn, 2008; Hagedorn, 2013; Williamson, 1991; Williamson, 1996).

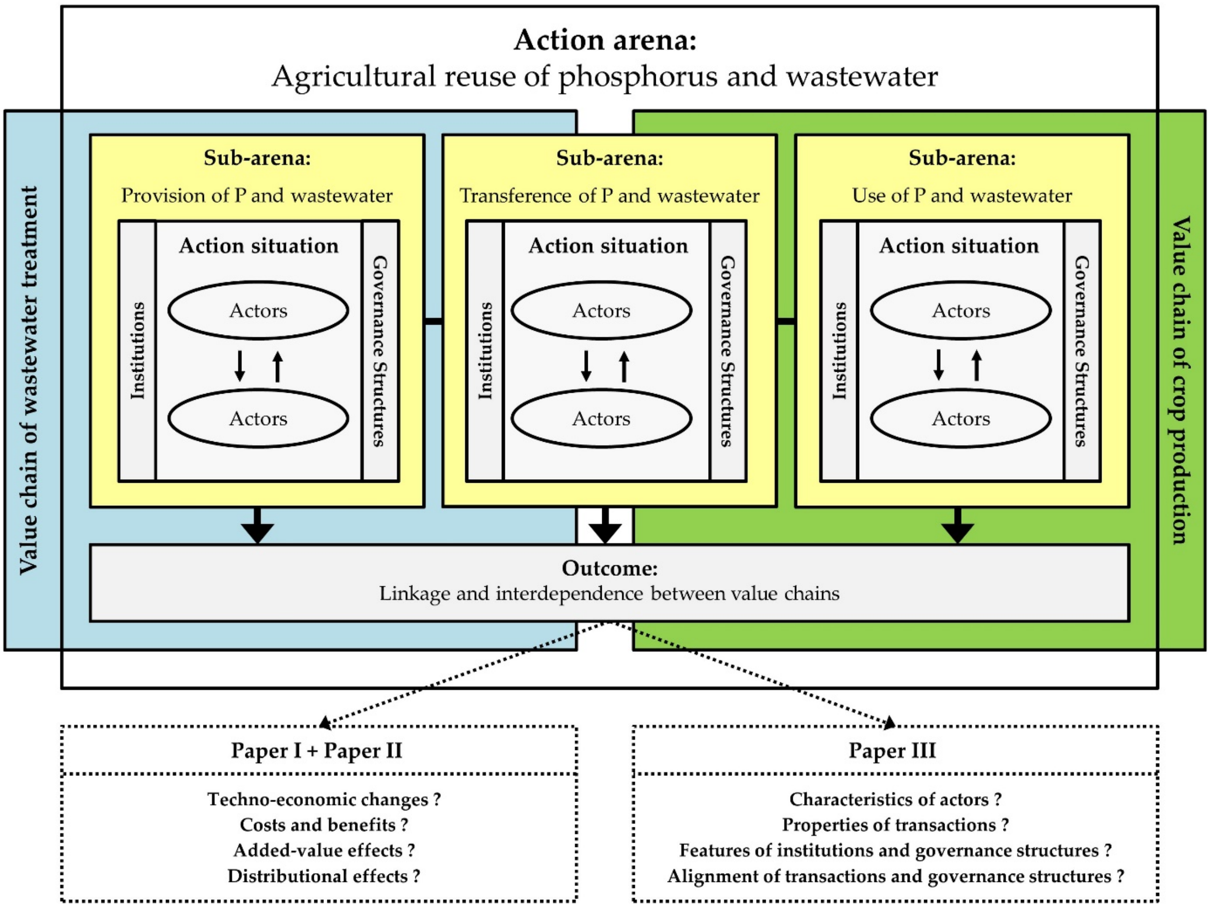

Figure 1-2: Conceptual framework for analyzing transactions in linked value chains of wastewater treatment and crop production (adapted from Maaß and Grundmann, 2018: p. 4-9).

Figure 1-2 illustrates the conceptual framework for analyzing transactions in linked value chains of wastewater treatment and crop production. The figure shows the different arenas and situations within and between the value chains of wastewater treatment and crop production. Furthermore, it shows the outcome of the physical and social processes in the arenas and situations which is the linkage and interdependence of the value chains of wastewater treatment and crop production. The boxes in the bottom part of the figure indicate the main research issues analyzed in the single papers of this study.

1.5 Methodological Overview

The focus of the analysis regarding the study area is on reusing phosphorus and wastewater in North-East Germany. The focus was set by the project ElaN in which the research was carried out. [4] The methodological approach selected for answering the research questions combines case study research (Gerring, 2004; Stake, 1995; Yin, 2014) with cost-benefit analysis (Boardman et al., 2017; Nas, 2016; Quah and Toh, 2012), value chain analysis (Haller, 1997; Kaplinsky and Morris, 2001) and transaction cost analysis (Williamson, 2000).

Case study research is a method which allows researchers to study complex social phenomena in-depth and within their real-world context (Yin, 2014). The social phenomenon studied in this research is the linkage of wastewater treatment and agricultural value chains based on transactions for reusing phosphorus and wastewater. This phenomenon is observed only rarely in the water and agricultural sector of Germany. Researchers who use case studies as a method for analyzing social phenomena can adopt either a single-case or a multiple-case design. In general, the evidence and conclusions drawn from a multiple case study are regarded as more compelling and robust than those coming from a single case study (Herriott and Firestone, 1983; Stake, 1995; Yin, 2014). However, the conduction of a multiple case study requires a number of suitable cases available for the analysis. Moreover, scrutinizing multiple cases in-depth may require extensive resources and time (Yin, 2014). The study at hand adopted a single-case design since the number of cases available for studying large-scale agricultural applications of struvite and wastewater in the study area was limited. The single cases studied in the thesis were:

1) The precipitation of struvite in the wastewater treatment plant in Waßmannsdorf and its application as fertilizer in Berlin-Brandenburg (Paper I).

2) The agricultural wastewater reuse scheme of the Wastewater Association Braunschweig (Paper II; Paper III).

Both cases represent large-scale applications of struvite and wastewater in agriculture. They were selected for the analysis due to the research assignments from the project ElaN.

Cost-benefit analysis is a method which has been used by many researchers in various case studies to compare the costs and benefits among alternative technologies, activities and policy actions (Benis et al., 2018; Haruvy, 1997; Ito and Managi, 2015; Liu et al., 2018; Molinos-Senante et al., 2010; Molinos-Senante et al., 2011a; Papendiek et al., 2016; Zhou et al., 2015). In this research, cost-benefit analysis was applied to the cases of Waßmannsdorf and Braunschweig in order to assess in detail the monetary costs and benefits from transactions for reusing phosphorus and wastewater. The analysis focused on the steps in the value chains of wastewater treatment and crop production that were affected directly by the reuse of phosphorus and wastewater, i.e. the analysis focused on the treatment of wastewater and

[4] Detailed information on the project ElaN will be presented in section 1.6.

the irrigation and fertilization of crops. The assessment was based on a comparative cost–analysis for different scenarios of wastewater treatment and crop production. Benefits from producing and using struvite were found by determining the cost savings in wastewater treatment and the fertilization costs when struvite is substituted for conventional mineral fertilizer (Paper I). Benefits from reusing wastewater were assessed by comparing the costs of wastewater irrigation with conventional disposal options (i.e., the discharge of treated wastewater into surface water bodies), as well as by comparing the costs of irrigation and fertilization with treated wastewater to groundwater irrigation and mineral fertilization (Paper II).

Cost-benefit analysis can provide important insights into the monetary costs and benefits of transactions for reusing phosphorus and wastewater. However, cost-benefit analysis says little about the value creation within linked value chains and the economic and social relations between the actors involved. This motivated me to combine cost-benefit with value chain analysis in order to obtain a deeper understanding of the economic performance and organization of linked value chains.

Value chain analysis is an analytic tool which helps to identify and analyze the different actors, steps and linkages in a value chain and to assess their economic performance (Kaplinsky and Morris, 2001; Macfadyen et al., 2012). Researchers and practitioners have studied costs, margins and the added-value at different steps of value chains to make competitive comparisons and to improve the efficiency and effectiveness of processes in value chains (Brown, 2009; El-Sayed et al., 2015; Jaligot et al., 2016; Kogut, 1985; Rosales et al., 2017; Taylor, 2005). Furthermore, value chain analysis has been used to scrutinize issues of upgrading and governance in value chains (Gereffi et al., 2005; Giuliani et al., 2005; Grundmann and Ehlers, 2016; Ponte et al., 2014; Villamayor-Tomas et al., 2015). In this research, value chain analysis was used to get an overview and a better understanding of the value creation within linked value chains of wastewater treatment and crop production, and the exchange of resources, services and information between the actors involved. In addition, value chain analysis was used to learn about the distribution of the added-value among the stakeholders (i.e., equity providers, creditors, employees, state) and the value chains of wastewater treatment and crop production.

The value chain analysis conducted in this research started with the mapping of the value chains in the cases of Waßmannsdorf and Braunschweig. The mapping of value chains is a common element of value chain analysis and means drawing a visual representation of the major production steps, product flows and actors in the studied value chains. Value chain maps help to "reduce the complexity of economic reality with its diverse functions, multiple stakeholders, interdependencies and relationships to a comprehensible visual model." (GTZ, 2008: p. 55). The chain maps of the studied cases were used to uncover (1) the boundaries of the investigation, (2) the physical activities and transactions for reusing phosphorus and wastewater, (3) the actors and resources involved, and (4) the links within and between the studied value chains.

Researchers frequently measure the economic value created in value chains by using the added-value as a success indicator (Heinbach et al., 2014; Hoffmann, 2009; Kosfeld and Gückelhorn, 2012). The added-value indicates the increase of value created by economic activities along every step of the value chain. It is the difference between the market value of a good or service and the value of the inputs required for producing and delivering that particular good or service (Haller, 1997). At the same time, the added-value represents the disposable income for remunerating all those stakeholders who have contributed to the created value (i.e., the equity providers, the employees, the creditors and the state) (Coenenberg et al., 2012; Haller, 1997; Möller, 2006). Thus, the added-value can also be used for analyzing the social and distributional impact of transactions on value chains. The added-value was used in this research to gauge the economic performance of reusing phosphorus and wastewater in linked value chains (Paper I; Paper II). Furthermore, the added-value was used to assess the impact of reusing wastewater on the local economy by determining the share of the added-value which remains in the local economy (Paper II). Other success indicators like EBT (earnings before taxes) or EAT (earning after taxes) were considered to be less suitable for this research, since they solely reflect cash flows and earnings of business owners (e.g., farmers or operators of wastewater treatment facilities) and do not take into account the cash flows and earnings of the employees, the creditors and the state.

Transaction cost analysis is an analytic tool which helps to explain the rationale behind the choice of governance structure for certain transactions. Transaction cost analysis has often been used by researchers to analyze transactions and institutional arrangements in agricultural value chains (Hobbs, 1996; Verhaegen and VanHuylenbroeck, 2002; Vinholis et al., 2014). In this research, I used the insights from the transaction cost theory to analyze the specific transactions and governance structures for reusing wastewater at the local scale (Paper III). The qualitative analysis included a detailed characterization of the actors, transactions and governance structures of the agricultural wastewater reuse scheme in Braunschweig according to their features and an analysis of the discriminating alignment of transactions and governance structures as suggested by Williamson (2000).

The main tools used for collecting primary data on the studied cases included written questionnaires (Foddy, 1993; Gillham, 2008) and semi-structured in-depth interviews (Bogner et al., 2009; Flick, 2014; Gläser and Laudel, 2010) with operators of wastewater treatment facilities, farmers and employees of agricultural wastewater reuse schemes, and representatives of local water authorities. The questionnaires were used mainly to collect quantitative information on technical and economic aspects of P recovery and wastewater reuse (e.g., quantities of wastewater treated, quantities of P recovered, costs and revenues of recovering P and reusing wastewater). This information was used for the analysis of the cost-benefits and the added-value from reusing phosphorus and wastewater. Although written questionnaires are helpful in collecting quantitative information on transactions and value chains, they are less suitable for gathering detailed information about the actors´ personal experiences as well as the organizational and institutional setting of value chains. Therefore, I used semi-structured face-to-face and telephone interviews to complement the information from the questionnaires and to obtain a deeper understanding of the studied cases. In particular, I used the interviews to accumulate detailed information about the characteristics of the transactions, actors and governance structures in the studied cases. Furthermore, I used the interviews to identify and describe the different perceptions, attitudes and motivations that underlie and influence the behavior of the actors involved. All interviewees were experts who were carefully selected according to their roles and expertise in legal and practical matters of reusing phosphorus and wastewater. Table 1-1 provides an overview of the main sources of data used for the cost-benefit and institutional analysis of transactions in linked value chains of wastewater treatment and crop production.

Table 1-1: Overview of the main sources of data used for the cost-benefit and institutional analysis of transactions in linked value chains.

	Paper I	Paper II	Paper III
	Cost-benefit analysis of transactions in linked value chains	Cost-benefit analysis of transactions in linked value chains	Institutional analysis of transactions in linked value chains
Cases	Precipitation of struvite in the wastewater treatment plant in Waßmannsdorf and its application as fertilizer in Berlin-Brandenburg	Agricultural wastewater reuse scheme of the Wastewater Association Braunschweig	Agricultural wastewater reuse scheme of the Wastewater Association Braunschweig
Sources of primary data	• 1 written questionnaire • letter survey (N=146) • 4 face-to-face interviews	• 1 written questionnaire • 3 face-to-face interviews • 3 telephone interviews	• 1 written questionnaire • 7 face-to-face interviews • 5 telephone interviews
Sources of secondary data	• (Federal Statistical Office Germany, 2012) • (LELF, 2010) • (MIL, 2012) • (MIL, 2010)	• (ABWV BS, 2012) • (LWK H, 2000) • (LWK NS, 2011)	• (ABWV BS, 2008) • (Bezirksregierung Braunschweig, 2001) • (NLWKN, 2015)

For Paper I, a written questionnaire was sent to the operators of the Waßmannsdorf treatment plant to collect data on the monetary costs and benefits of struvite production in Waßmannsdorf. The information from the questionnaire was complemented by a letter survey of 146 farmers located in Brandenburg and four face-to-face interviews with the operators of the treatment plant and a farmer. The survey was based on standardized questionnaires and collected information about the crops cultivated in Berlin-Brandenburg and the willingness of farmers to substitute struvite for conventional mineral fertilizer. The face-to-face interviews were used to obtain information about the value chains of wastewater treatment and crop production, the production and marketing of struvite and its application as a fertilizer. Additional information about agricultural production methods in the study region (e.g., fertilizer needs of crops, prices of conventional mineral fertilizer) was collected from secondary data.

For Paper II, a written questionnaire was sent to the management of the agricultural wastewater reuse scheme in Braunschweig to collect information on the monetary costs and benefits of reusing wastewater and sludge. In addition, three face-to-face interviews and three telephone interviews with farmers and employees of the scheme were used to gather detailed information on the organizational setting of the reuse scheme, the operations and links between the value chains of wastewater treatment and crop production, and the responsibilities of the actors involved. The information obtained from the questionnaire and interviews was complemented by secondary data on agricultural production methods in the study region. Furthermore, data from the financial accountings of the Wastewater Association Braunschweig was used to increase information on the monetary costs and benefits of the reuse scheme.

For Paper III, a written questionnaire was sent to the management of the wastewater reuse scheme in Braunschweig to collect data on the information exchange, communication, contracting, monitoring, and adaptation between the actors involved in the scheme. In addition, seven face-to-face interviews and five telephone interviews with representatives of the scheme and the local water authority were conducted to obtain detailed information about the characteristics of the actors (e.g., ownership and decision rights), the properties of the transactions (e.g., asset specificity, uncertainty, frequency), and the features of the governance structures of the wastewater reuse scheme in Braunschweig (e.g., incentive intensity, administrative control, adaptation, contract law). The information acquired from the questionnaire and interviews was supplemented by secondary data on the official permit and statuary regulations for reusing wastewater in the study area. Detailed information on the data collection and analysis is presented in the methodology section of each paper (see section 2.3, section 3.3, section 4.3).

1.6 The Project ElaN

The thesis is conducted as part of the joint research project ElaN ("Development of an integrated land management through sustainable water and materials use in north-east Germany”) funded by the German Federal Ministry of Education and Research (grant no. 033L025B).

The starting point for ELaN is the current practice of discharging treated wastewater into surface water bodies, which means the water and the nutrients contained in the water are lost for landscape and agricultural purposes. The main hypothesis of ElaN is that reusing treated municipal wastewater can contribute to more sustainable land and water management. The aim of ELaN is to combine technological innovations for water and nutrient management with organizational innovations for sustainable land use management. In addition, the project aims to clarify the political and legal conditions for reusing wastewater and to analyze how wastewater reuse can promote regional value chains. The study focus of ElaN is on selected regions in north-east Germany which are characterized by increasing drought periods and sinking ground water levels. In these regions the reuse of treated wastewater may contribute to stabilizing the regional water balance and preserving wetlands for biomass production. In addition, the nutrients contained in the wastewater can be recovered and used as fertilizer in the region. The technological innovations studied in the project are the recovery of nutrients via struvite precipitation and the irrigation of treated municipal wastewater for landscape and agricultural purposes. The project pursues an interdisciplinary approach and consists of different subprojects which are concerned with the technological, environmental and socioeconomic aspects of recovering nutrients and reusing wastewater (ELaN, 2018).

The thesis at hand contributes to the project by analyzing the economic impact of struvite precipitation and wastewater reuse on the value chains of wastewater treatment and crop production on the local scale.

1.7 Outline of the Thesis

This study is structured as follows:

Chapter 1 introduces the thesis by providing background information on the research topic and providing information about the rationale and objectives of the study. Furthermore, the chapter provides a general overview of the conceptual and theoretical framing of the study and the methods used for the analysis.

Chapter 2 presents the findings from analyzing the monetary costs and benefits of recovering phosphorus via struvite precipitation and its reuse as a fertilizer in crop production.

Chapter 3 presents the findings from analyzing the monetary costs and benefits of reusing wastewater and sludge in crop production. Furthermore, it provides insights into the impact of wastewater reuse on the local economy.

Chapter 4 builds upon the analysis presented in Chapter 3 and provides the results from scrutinizing the specific characteristics of the transactions and governance structures for reusing wastewater in crop production. In particular, it explains how transactions and interdependences between actors shape the governance structures on the local scale. In addition, it shows how the alignment of the governance structures with the transactions and interdependences facilitates wastewater reuse.

Finally, in **Chapter 5**, the main findings are summarized and discussed, and conclusions are drawn. Furthermore, the research design is discussed and recommendations for future research are presented.

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2 Added-value from innovative value chains by establishing nutrient cycles via struvite

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Abstract

The establishment of nutrient cycles has been widely proposed as a strategy for an efficient management of nutrients such as phosphorus (P). Global reserves of phosphate rocks are limited and are being increasingly depleted. At the same time, P is disposed of via various substance-streams in wastewater treatment. Establishing nutrient cycles may solve these problems and lead to innovative added-value chains with a higher added-value. The objective of this paper is to assess the added-value of P-recovery from sewage sludge via struvite precipitation and its application as fertilizer in Berlin-Brandenburg (Germany). The added-value from struvite precipitation was determined by performing a cost/benefit analysis based on data from standardized questionnaires and interviews with operators of wastewater treatment facilities. Surveys of 146 farmers were used to ascertain what crops were cultivated in the study area and to gauge the willingness of farmers to substitute struvite for conventional mineral P-fertilizer. Benefits from using struvite were found by calculating the fertilizer costs when struvite is substituted for conventional mineral fertilizer. The results indicate that the precipitation of struvite and its use as fertilizer generates added-value gains for wastewater treatment facilities (416,000 €) and for crop producers (35,000€). In wastewater treatment, struvite precipitation reduces operating costs and yields additional revenues through struvite sales. In crop production, fertilization costs are reduced by substituting struvite for mineral P-, N- and Ca-fertilizers. The distribution of the added-value in the struvite value chain is determined by the marketing strategy of struvite. Farmers may obtain a higher share of added-value if struvite is marketed via direct sale.

Keywords: Added-value, Nutrient cycle, Wastewater treatment, Phosphorus, Phosphorus recovery, Struvite

2.1 Introduction

The cycle of elements in the biosphere is a life-sustaining feature of our planet. Some cycles, for example the phosphorus, calcium and magnesium cycles, continually sustain losses in biological systems due to erosion, and they ultimately land in the sea (Bormann and Likens, 1967: 424): "Acceleration of losses or, more specifically, the disruption of local cycling patterns by activities of man could reduce existing "pools", restrict productivity, and consequently limit human population."

Particularly in the case of phosphorus (P), there is growing concern about the worldwide depletion of this life-sustaining nutrient (Cordell et al., 2009; Déry and Anderson, 2007; Van Vuuren et al., 2010). Substantial P inputs are required for optimum plant growth and adequate food and fibre production (OECD/FAO, 2011). The nutrient P is produced completely from non-renewable resources, essentially from phosphate rocks. The geographical distribution of these phosphate rocks is extremely uneven. Just five countries, primarily Morocco, control about 91% of the global P reserves (USGS, 2012). Therefore, all importing countries are dependent on and vulnerable to shortages and price volatility. Today, about 90% of the phosphate rocks mined globally are processed into mineral fertilizer for agricultural production (Brunner, 2010; Cordell, 2010).

Estimates on the global P reserves vary greatly and are veiled by data availability and uncertainty (Schröder et al., 2010). Some studies state that phosphate rock reserves may be depleted within 50–100 years (Cordell, 2010; Schröder et al., 2010; Smit et al., 2009). Other studies indicate that total global reserves may last 300–400years (Cooper et al., 2011; USGS, 2012), but single countries will have depleted their reserves within 100 years (Cooper et al., 2011). Regardless of these estimates, it is evident that a deficiency in P in agriculture would severely restrict the crop yields and food security of the world's increasing population (Cordell et al., 2009; Koning et al., 2008). Other concerns about P are related to environmental and economic matters. P-pollution in the surface water can lead to problems with eutrophication. P-mining, processing and marketing are highly resource and emission-intensive (Ekardt, 2011). Another problem of P is soil contamination, due to its frequent combination with heavy metals, which could enter the entire food chain. The quality and accessibility of the remaining phosphate rocks are decreasing while production costs are increasing (Cordell and White, 2011). The price of phosphate rocks is expected to increase in the long term (Cordell et al., 2009; Von Horn and Sartorius, 2009), having significant consequences for farmers and food production systems (Cordell and White, 2011).

Simultaneously, P leaves the nutrient cycle due to the outflow of P in different streams of wastewater treatment. In Germany, for instance, estimates indicate a high potential of recoverable P from multiple streams of wastewater treatment and animal production (Table 2-1).

Table 2-1: P-recycling potential of different substance-streams in Germany (UBA, 2012).

Substance flow	Estimated potential of recoverable P in t $year^{-1}$
Wastewater (municipal)	54,000*
Wastewater (industrial)	15,000
Sewage sludge (municipal)	50,000*
Sewage sludge ash	66,000*
Manure	444,000
Animal by-products	20,000

* These potentials are not addable due to their competitive recycling paths.

Awareness of this potential has motivated research on the recovery of P from wastewater and its reinsertion into the nutrient cycle as agricultural fertilizer. Since recycling of P replaces mineral P-fertilizer, it may also contribute to easing the problems of dependency on P imports and depletion of stocks. Presently, the recovery and reuse of P is still far from being a main stream practice (Cordell et al., 2011). However, besides the option to use quality-assured sewage sludge on farmlands, there are already a variety of techniques for recovering P at wastewater treatment plants. These techniques differ by the origin of the used matter (wastewater, sludge, sludge liquor, sludge ash), the applied process (precipitation, wet chemical extraction, and thermal treatment) (Satorius et al., 2011), and the potential P-recovery rate (Cordell et al., 2011).

One of these techniques is struvite precipitation, which can be implemented in wastewater treatment plants that use enhanced biological phosphorus removal. Struvite (magnesium ammonium phosphate or MAP ($MgNH_4PO_4{\cdot}6H_2O$)) is formed by a basic precipitation reaction in different stages of the wastewater treatment process where magnesium (Mg_{2}^{+}), ammonium (NH_4^+) and orthophosphate (PO_4^{-3}) occur under weak alkaline conditions (Uludag-Demirer et al., 2005). Various techniques have been developed to precipitate struvite on both full and pilot scales. The majority of these techniques use sludge liquors, generated from anaerobic digesters as influent (Le Corre et al., 2009). Commercial large-scale struvite production plants which precipitate struvite from digested sludge liquors are operating in the USA, Canada (see Ostara, 2013; Britton et al., 2009) and Japan (Ueno and Fujii, 2001). While it is well known that the uncontrolled formation of struvite can cause operational problems in wastewater treatment plants, struvite has the potential to be used as fertilizer in agriculture (Parsons et al., 2001).

Present studies on struvite production and use have mainly focused on the techno-economical aspects of the precipitation process (Gaterell et al., 2000; Jaffer et al., 2002; Shu et al., 2006; Ueno and Fujii, 2001; Von Münch and Barr, 2001). Little attention has been paid to assessing the added-value of nutrient-cycling via struvite precipitation and its use as an agricultural fertilizer. This paper aims to complement the existing assessments of struvite precipitation and use in agriculture from an added-value-perspective. We aim to test the hypothesis that innovations for feeding nutrient cycles are conducive to the emergence of innovative value chains with a higher added-value. This hypothesis is tested in the case of P-recovery via struvite precipitation from digested sewage sludge and the substitution of mineral fertilizer in agriculture. In particular, the study will address the following research questions:

1 What techno-economic changes occur in the value chains of wastewater treatment and agricultural crop production as a consequence of the precipitation of struvite and the substitution of struvite for mineral P-fertilizer?

2 What are the monetary costs, benefits and added-value from establishing a P nutrient cycle via struvite precipitation and its use as agricultural fertilizer?

3 How is the added-value of struvite distributed along the struvite value chain?

2.2 Theoretical concepts

Several studies have argued that innovations in value chains, which lead to the completion of substances and energy cycles in a defined region, may contribute to increasing the added-value in the respective region (Baum, 2004; Bentzen et al., 1997; Fritsche, 2005; Hahne, 2006; Hillring, 2002; Lindenthal et al., 2004; Marsden et al., 2000; Tischer et al., 2006). These studies are based on the assumption that the outflow of resources from a region (especially the outflow of capital) is reduced when flows and cycles of energy and substances are completed within the region. Accordingly, the implementation of technical innovations for recycling P may lead to the emergence of innovative value chains that foster a more efficient management of P.

The value chain perspective in this paper is driven by a functional business view, evaluating costs, benefits and ultimately the added-value as a basis for competitive comparisons. Researchers and practitioners have used this approach to improve the efficiency and effectiveness of value chains by analyzing the added-value at the steps of a value chain and redesigning the internal and external processes (Brown, 2009). The added-value indicates the increase of value created by economic activities at every step of the value chain. It is the difference between the market value of a good or service and the value of the inputs required for producing and delivering that particular good or service (Haller, 1997).

The value chain analysis approach is further used to understand the distribution of costs, benefits and revenues in the value chain. The distribution of the added-value among the participants can be quantified and critical stages and transactions in the value chain can be identified (Kaplinsky and Morris, 2001). According to Kaplinsky and Morris (2001: 42) "the distributional outcome (...) is to be seen in the incomes arising to capital (for its entrepreneurship, risk-taking and ownership of technology), labour (for its effort), and to the owners of natural resources (for their command over inputs which arise as gifts of nature) in each of the links in the value chain." The distribution of the added-value along the value chains and the return on the individual production factors can be performed methodologically by means of decomposition (Kimmich and Grundmann, 2008). Further, conclusions can be drawn about the effect of governance structures and the determinants on distribution. This aids in making policies that foster economic activity at certain steps of the value chain, e.g., with participants in deprived areas.

Costs, benefits and technical challenges influence the efficient usage of nutrients in innovative value chains. In addition, institutional arrangements affect resource management (Hagedorn, 2008; Ostrom, 2005). Whenever goods or services are transacted, frictions, e.g., transaction costs, play a major role. To reduce frictions, specific governance structures and rules are needed to manage the resource transactions and interactions of the actors (Williamson, 1996). We state that not only does a linkage in several value chains contributes to managing resources more cost–efficiently, but also that the cooperation of actors minimizes transaction costs and the costs needed to run the system. Although the transaction costs theory forms the background of this study, the focus of this paper is on the added-value approach.

2.3 Material and Methods

2.3.1 Boundaries of the investigation

The production of struvite and its utilization as P-fertilizer is an innovation that links the value chains of wastewater treatment and crop production. Figure 2-1 shows how the value chains of wastewater treatment and crop production are linked through the production and utilization of struvite in the specific case of this study (Waßmannsdorf Treatment Plant). The figure indicates that several outputs result from the treatment of wastewater, including treated wastewater, sewage sludge and the precipitated struvite. The treated wastewater is discharged into the receiving water. Built-up sewage sludge is stabilized anaerobically and the obtained sewage gas is used in cogeneration units to produce electricity and heat. Struvite is precipitated from the digested water–sludge mixture. After the precipitation and separation of struvite, the digested sludge is dehydrated and incinerated in power plants for energy production. The grey boxes in Figure 2-1 show the focus of this study. They include the steps in the value chain that are altered by the introduction of struvite, and depict the boundaries of the value chain analysis.

The value chain step of the production of energy from sewage gas is not altered, since the precipitation of struvite takes place after the sewage sludge has been digested. The subsequent added-value steps of dewatering and sludge disposal are affected, since the precipitation of struvite leads to an improvement of the dehydration characteristics of the sewage sludge. The percentage of water in the water–sludge mixture is reduced and higher dry substance values can be achieved. Furthermore, struvite is extracted from the sewage sludge. These effects result in a reduction of the quantities of sewage sludge that have to be transported and disposed. The subsequent steps in the value chain of sludge disposal (i.e., the incineration of digested sludge, the generation of energy and the disposal of ashes) are not influenced by the precipitation of struvite. The same applies to the downstream steps of the food and energy value chains, since the replacement of conventional mineral P-fertilizer with struvite has no further implications for the succeeding links in the value chains. Therefore, the boundaries of the value chain analysis do not include these sections of the value chains, but focus on the added-value from struvite precipitation, and the added-value from struvite fertilization in agriculture.

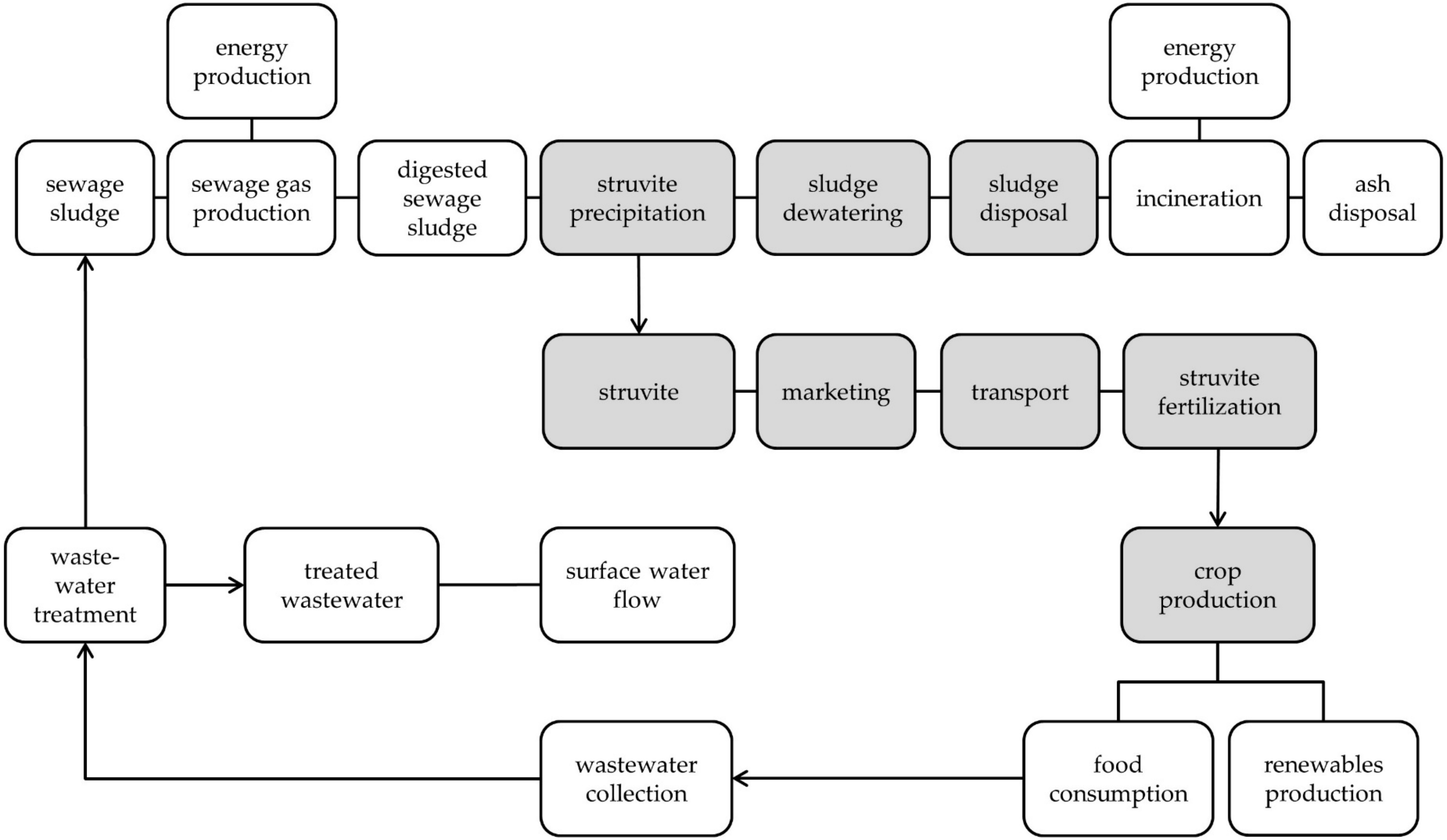

Figure 2-1: Map of value chains and boundaries of the investigation (grey boxes) in the specific case of the Waßmannsdorf Treatment Plant.

2.3.2 Case study

The value chain analysis is based on a case study of struvite production at the Waßmannsdorf Treatment Plant, located in the Federal State of Brandenburg, Germany. This treatment plant is operated by the Berlin Water Works (Berliner Wasserbetriebe) and has a treatment capacity of 230,000 m^3 d^{-1} with a population equivalent (p.e.) of 1,200,000. In 2011, an average of 197,000 m^3 d^{-1} of wastewater was treated in this plant. Struvite precipitation can be applied in the treatment process because the wastewater is purified through an enhanced biological phosphorus removal system which leads to dissolution processes during the anaerobic treatment of sludge.

In the past, the spontaneous formation of struvite caused substantial incrustations and blockage in the sludge treatment equipment. In order to ensure for stable operations, and to reduce the operating costs, a controlled precipitation of struvite was introduced by a set of modifications in the process and technology (Heinzmann and Engel, 2006). In 2010 an innovative struvite precipitation process (AirPrex®) was implemented to optimize the recovery and separation of P and other nutrients from the digested sewage sludge. The AirPrex® technique is innovative since it precipitates struvite from the digested water–sludge mixture in an upstream process of dewatering. This way, possible operational problems can be avoided such as an uncontrolled formation of struvite during the mechanical sludge-dewatering. This process differs from other full scale precipitation processes such as OSTARA PEARL™ or PHOSNIX®, in which struvite is precipitated from liquors derived from the dewatering of digested sewage sludge. The precipitation reaction at the Waßmannsdorf Treatment Plant is induced in a large-scale prototype of a struvite reaction vessel by aerating the digested sludge and adding magnesium chloride (Stumpf et al., 2009). Furthermore, a washer was installed for purifying the struvite from organic matter. The investment costs of this technology were 2.3 Mio Euros. Under the stable-system operating conditions, an annual production of up to 900 t of struvite can be realized.

Table 2-2 presents the pure nutrient and heavy metal contents of the struvite produced at the Waßmannsdorf Treatment Plant. The main nutrients are magnesium and phosphorus. Furthermore, the struvite contains amounts of nitrogen and calcium, as well as small amounts of sulfur and potassium. The struvite from the Waßmansdorf Treatment Plant has an N:P:K-ratio of approximately 4:9:0.

Table 2-2: Nutrient and heavy metal contents of struvite, superphosphate (SUP) and other P fertilizers.

Component	Unit	Struvite [a)]	Superphosphate [b)]	other P-fertilizer [b)]
Nutrients				
Phosphorus (P)	g kg^{-1}	91.0	84.0	
Nitrogen (N)	g kg^{-1}	42.7	3.0	
Kali (K)	g kg^{-1}	0.5	7.0	
Sulfur (S)	g kg^{-1}	1.2	116.0	
Magnesium (Mg)	g kg^{-1}	70.0	3.6	
Calcium (Ca)	g kg^{-1}	8.4	212.0	
Heavy metals				
Cadmium (Cd)	mg kg^{-1}	0.3	15.5	9.0 - 100.0
Chromium (Cr)	mg kg^{-1}	11.0	65.9	90.0 - 1500.0
Copper (Cu)	mg kg^{-1}	39.0	51.3	10.0 - 60.0
Nickel (Ni)	mg kg^{-1}	2.0	36.0	5.0 - 70.0
Arsenic (As)	mg kg^{-1}	-	2.4	
Lead (Pb)	mg kg^{-1}	5.0	4.0	0.5 - 40.0
Zinc (Zn)	mg kg^{-1}	100.0	312.0	50.0 - 600.0
Manganese (Mn)	mg kg^{-1}	210.0	21.0	

[a)] (Theobald et al., 2012).
[b)] (Adler, 2001).

The heavy metal content of struvite varies, since it greatly depends on the ambient abundance pattern of these elements. In addition, the amount of enclosed heavy metals may vary, depending on the precipitation technique used. The concentrations of heavy metals in mineral P-fertilizers vary considerably (Adler, 2001; Camelo et al., 1997). Compared to conventional mineral P-fertilizer, some studies revealed that contaminants (e.g., heavy metals) pass into the struvite in only small portions (Kern et al., 2008; Ronteltap et al., 2007; Ueno and Fujii, 2001). A comparison of the content of heavy metals in mineral P-fertilizer, or superphosphate (SUP), sold in Brandenburg reveals that struvite produced at the Waßmannsdorf Treatment Plant has comparatively lower heavy metal contents (Table 2-2). Only the loading rates of lead (Pb) and manganese (Mn) in the struvite are higher than those in SUP (Theobald et al., 2012).

The struvite from Waßmannsdorf fully complies with the requirements of the German Fertilizer Ordinance (DüMV) and can therefore be distributed as fertilizer for agriculture. Its highly plant-available P content has been confirmed by pot experiments done by Kern et al.

(2008), Römer (2006), and Johnston and Richards (2003). Since struvite guarantees a slow but steady nutrient supply, it is considered to be a valuable slow-release fertilizer (Gaterell et al., 2000; Rahman et al., 2011; Yetilmezsoy and Sapci-Zengin, 2009).

The struvite produced at the plant in Waßmannsdorf has been sold since 2008 in the region of Berlin-Brandenburg under the brand name "Berliner Pflanze". Various strategies and concepts have been considered for marketing the struvite. Currently, small quantities of struvite are sold at local retail markets. This market segment was chosen in order to advertise "Berliner Pflanze". An expansion of this marketing channel is not planned by the Berlin Water Works, due to high distribution costs. Most of the struvite is sold directly from the treatment plant to farmers and fertilizer traders who offer bids on large quantities. The struvite is transported by the traders themselves, or by the Berlin Water Works in the case of direct sales to farmers.

The market price of struvite is derived from the price for the product, transportation costs, as well as the packaging logistics. In 2011, on average, struvite was sold at a pure nutrient price of 0.83 € kg^{-1} P to 1.00 € kg^{-1} P.[5] Depending on the selling arrangements, the price paid by the end customers (i.e., mostly farmers) can differ from the selling price of the Berlin Water Works. In the case of distribution via traders, farmers have to pay a higher price for struvite than those who purchase it directly from the plant in Waßmannsdorf. In order to establish struvite as a regional sustainable fertilizer, the Berlin Water Works aims to sell the struvite directly to farmers through permanent contracts with local farmers. Farmers in the area may intend to use struvite as a slow-release fertilizer, since agricultural soils in Brandenburg are characteristically sandy and poor in nutrients, with a limited P storage capacity. These soil properties require a frequent and regular P-fertilization.

2.3.3 Data collection and data analysis

The economic assessment of establishing nutrient cycles via struvite was based on the determination of the costs, benefits and added-value along the value chains of wastewater treatment, struvite and crop production. The analysis of the added-value gained from the precipitation of struvite included the estimation of the costs and the benefits resulting from the revenues of struvite sales and the reduction of the operating costs. The added-value from using struvite was found by calculating the fertilizer costs when struvite is substituted for conventional mineral fertilizer. In addition, the analysis provided information on farmers willingness' to substitute struvite for conventional mineral P-fertilizer.

Three open interviews were conducted with employees of the Berlin Water Works to obtain information on the value chain of wastewater treatment, the introduction of struvite precipitation into the wastewater treatment process and the marketing strategy. These interviews were complemented by standardized questionnaires in order to determine the costs and benefits of struvite production. An open interview with a farmer was conducted to obtain purchase information on struvite by farmers and its application as fertilizer. The added-value of the struvite production was calculated by conducting a cost/benefit analysis.

[5] Here and in the following the term P refers always to pure P.

The analysis followed the method for calculating the added-value described by Haller (1997). According to this method, we calculated the net added-value by subtracting the total costs for purchased inputs and depreciations from the total benefits of struvite production. The total benefits include revenues from struvite sales and possible cost reductions in the wastewater treatment process. The added-value can also be interpreted as the sum of profits, tax payments and remuneration for capital (i.e., interest payments) and labour (i.e., wage payments) (Haller, 1997). Accordingly, the interest and wage payments are not regarded as inputs, but as revenues for the capital providers and employees and thus, as part of the added-value of struvite production. The annuity of the interest payments was calculated by assuming a funding of the applied precipitation technology by a municipal loan.

The market potential for struvite was assessed using the results from a written survey of 146 farmers in Brandenburg. The survey was conducted in 2012 and collected data on the structure of the crops cultivated in 2011 and the willingness of the farmers to substitute struvite for conventional mineral P-fertilizer. The information on the cultivated crops was used to ascertain the share of cropland allocated to single crops in Brandenburg. Determining the P-fertilizer needs of this crop distribution helped to identify the agricultural area in Brandenburg that could be supplied with struvite produced in Waßmannsdorf.

The contribution to the added-value, by substituting struvite for mineral P-fertilizer in crop production, was determined by calculating the expenditures per hectare (ha) for conventional mineral fertilizer and struvite. This was done for the 26 main crops cultivated in Brandenburg. The fertilizer needs of each crop were taken from LELF (2010), which gives an overview of agriculture production methods and costs in Brandenburg (Table 2-3).

Table 2-3: Fertilizer needs of different crops and soil-quality categories in Brandenburg (with a soil-quality index scale from 7 (lowest) to 100 (highest)) (LELF, 2010).

Crop	Soil-quality category (SQC) and fertilizer needs of N, P, K and Ca in kg ha^{-1}																			
	SQC I				SQC II				SQC III				SQC IV				SQC V			
	N	P	K	Ca	N	P	K	Ca	N	P	K	Ca	N	P	K	Ca	N	P	K	Ca
Winter rye	125	30	101	320	112	27	90	280	90	21	73	220	69	16	55	160	45	11	36	100
Spring wheat	166	34	107	320	139	29	90	280	111	23	71	220	84	17	54	160	-	-	-	-
Winter barley	140	31	104	320	120	26	89	280	96	21	71	220	72	16	54	160	-	-	-	-
Summer feed barley	109	24	86	320	92	20	73	280	70	15	55	220	57	13	46	160	-	-	-	-
Oats	114	27	113	320	92	22	92	280	70	17	70	220	52	12	51	160	-	-	-	-
Winter triticale	139	31	117	320	126	28	106	280	97	21	81	220	76	17	64	160	-	-	-	-
Grain maize	193	35	166	320	169	31	146	280	145	26	125	220	-	-	-	-	-	-	-	-
Winter rape	191	45	183	320	163	38	157	280	136	32	131	220	100	24	96	160	-	-	-	-
Summer rape	99	24	96	320	76	18	74	280	63	15	61	220	49	12	48	160	-	-	-	-
Sunflowers	137	41	288	320	118	36	247	280	88	27	185	220	74	22	154	160	-	-	-	-
Linseed	-	-	-	-	60	9	36	280	43	7	26	220	30	5	18	160	-	-	-	-
Ware potatoes	-	-	-	-	131	21	188	280	117	19	168	220	107	18	154	160	-	-	-	-
Starch potatoes	-	-	-	-	148	24	213	280	137	22	196	220	125	20	179	160	-	-	-	-
Sugar beets	253	41	308	320	230	38	280	280	207	34	252	220	-	-	-	-	-	-	-	-
Grain peas	-	21	116	320	-	18	100	280	-	15	83	220	-	12	66	160	-	-	-	-
Grain lupines	-	-	-	-	-	15	83	280	-	13	70	220	-	11	60	160	-	9	50	100
Buckwheat	-	-	-	-	-	-	-	-	-	-	-	-	40	13	60	160	40	13	60	100
Silage maize	162	30	158	320	149	28	145	280	128	24	125	220	101	19	99	160	176	33	172	100
Whole crop silage	160	50	150	320	144	45	135	280	115	36	108	220	123	39	116	160	112	35	105	100
Corn-cop-mix	156	27	143	320	143	25	131	280	123	21	113	220	97	17	89	160	168	29	155	100
Liesch-cop-silage	162	30	158	320	149	28	145	280	128	24	125	220	101	19	99	160	176	33	172	100
Forage crops	120	29	238	320	80	23	188	280	80	12	69	220	-	7	55	160	40	-	-	100
Lucerne dry green	15	29	257	320	15	27	243	280	15	24	216	220	15	21	189	160	-	-	-	100
Lucerne silage	15	29	257	320	15	27	243	280	15	24	216	220	15	21	189	160	-	-	-	100
Extensive grassland	-	8	42	-	-	8	39	-	-	6	32	-	-	5	23	-	-	4	18	-
Poplar	-	14	42	-	-	14	42	-	-	10	28	-	-	6	18	-	-	6	18	-

In practice, farmers may apply lower quantities of fertilizers if they consider that the P residuals from crop production and the fertilizer reserves in the soil are sufficient (LELF, 2010). Additional nutrient supplies through organic fertilizers were not taken into account. Furthermore, we assumed that conventional mineral fertilizers and struvite have the same effect on crop growth. The calculation of the fertilizer costs was performed on the basis of the nutrient prices paid for commercial fertilizers commonly used in Brandenburg in 2010 (Table 2-4).

Table 2-4: Nutrient contents and prices of conventional mineral fertilizer in 2010 (LELF, 2010).

Fertilizer	Nutrient	Nutrient content %	Fertilizer price in Euro per 100 kg	Pure nutrient price in Euro kg^{-1}
Triple superphosphate	P	20	22.00	1.10
Calcium ammonium nitrate	N	27	18.00	0.67
Kali 60	K	50	30.00	0.60
Calcium	Ca	32	3.30	0.10

The reduction of the fertilizer costs was determined by comparing the costs of applying conventional mineral fertilizers and the costs of applying struvite in combination with mineral N-, K- and Ca-fertilizer. This was done for each crop and for all existing categories of soil quality in Brandenburg in order to determine the minimal and maximal value derived through reduced costs from the application of struvite-fertilizer. In a first step, the costs of applying conventional mineral P-, N-, K- and Ca-fertilizer were calculated. Then, the conventional mineral P-fertilizer was replaced by struvite and the corresponding fertilizer costs were calculated analogously. Since struvite contains amounts of nitrogen (N) and calcium (Ca), the respective amounts of nutrients were deducted from the required quantities of mineral N- and Ca-fertilizers. Due to the low potassium (K) content of struvite, the replacement effect of struvite on the requirements of the mineral K-fertilizer was not taken into account.

In a second step, the results were used for determining the reduction of the direct costs of crop production and for calculating the range of possible cost reductions for each of the surveyed farms. The direct costs of each crop were taken from (LELF, 2010) and included the costs for fertilizer, seeds, pesticides and the capital costs for the means of production. Furthermore, the range of possible cost reductions (i.e., struvite's contribution to added-value in crop production) was calculated based on the agricultural area that can be supplied with struvite from the Waßmannsdorf Treatment Plant. Since the plant availability of the nutrient N contained in the struvite is uncertain, a sensitivity analysis was conducted assuming that only 50% of the N is plant available.

We calculated the additional costs for labour and machines when spreading struvite in a separate workstep, since in some cases struvite may not be spread in the same workstep as mineral fertilizer for technical reasons. In the case of applying mineral fertilizer, we calculated the costs for a single spreading of the N- and Ca-fertilizer and a joint spreading of the P- and K-fertilizer. In the case of struvite fertilization, we calculated the costs for two separate worksteps for spreading the struvite and the mineral K-fertilizer. Changes in the quantities of the applied fertilizers were considered in the costs for labour and machines. The fertilization of struvite reduces the required quantities of mineral N- and Ca-fertilizer. Furthermore, higher quantities of struvite need to be spread, since the P-content in struvite is lower than the P-content in the mineral P-fertilizer. These effects were taken into account when calculating the cost for spreading struvite.

2.4 Results

2.4.1 Substitution potential of struvite for mineral P-fertilizer in Brandenburg

The statistical analysis of the survey revealed the basic willingness of farmers to substitute struvite for mineral P-fertilizer, if the price of struvite does not exceed the price for conventional mineral P-fertilizer. About 66% of the farmers questioned show a willingness to apply struvite. Of that number, 71% would apply struvite without any concern for food crop cultivation, and 70% would use struvite for energy crop cultivation (Daedlow, Maaß and Theobald, unpublished survey results). Based on this information, we deduce that substituting struvite for conventional mineral P-fertilizer would be an option in Brandenburg.

In 2011/2012, 3,760 t per year of pure P were sold as mineral fertilizer in Brandenburg (Federal Statistical Office Germany, 2012). The maximum amount of P that can be recovered via struvite precipitation at the Waßmannsdorf Treatment Plant is 81 t per year of pure P. This implies that P recovered at the Waßmannsdorf Treatment Plant can replace about 2.2% of the mineral P-fertilizer sold to the agricultural sector in Brandenburg.

2.4.2 Effect of struvite production on the added-value in the wastewater value chain

The implementation of struvite precipitation in the wastewater treatment process generated an added-value of about 416,000 € per year. This added-value was mainly generated through the reduction of the operating costs. The reduction of the operating costs was principally due to a decrease of flocculating agents required in the process. This improvement contributed to 51% of the cost reduction. Another large reduction of operating costs resulted from the improvement of the dehydration characteristics of sewage sludge. This improvement reduced the costs of sludge transportation and disposal by higher dry substance values of the sewage sludge. It contributed to 39% of the total cost reductions. Further cost reductions were gained through the reduction of maintenance work on the centrifuges (4%), the reduction of cleaning costs (3%), and the prevention of incrustations in the sludge treatment equipment (2%). Due to a reduced mass flow of sewage sludge, resulting from struvite extraction, there was also a marginal reduction of energy consumption by the centrifuges, which accounted for 1% of the total cost reductions. Although struvite extraction from the sewage sludge reduced the cost of transportation, the effect of struvite extraction on the transportation costs was excluded here because it is only marginal and the extracted struvite had to be transported as well. Figure 2-2 gives an overview of the annual operating costs and benefits of the struvite production in the Waßmannsdorf Treatment Plant in 2011.

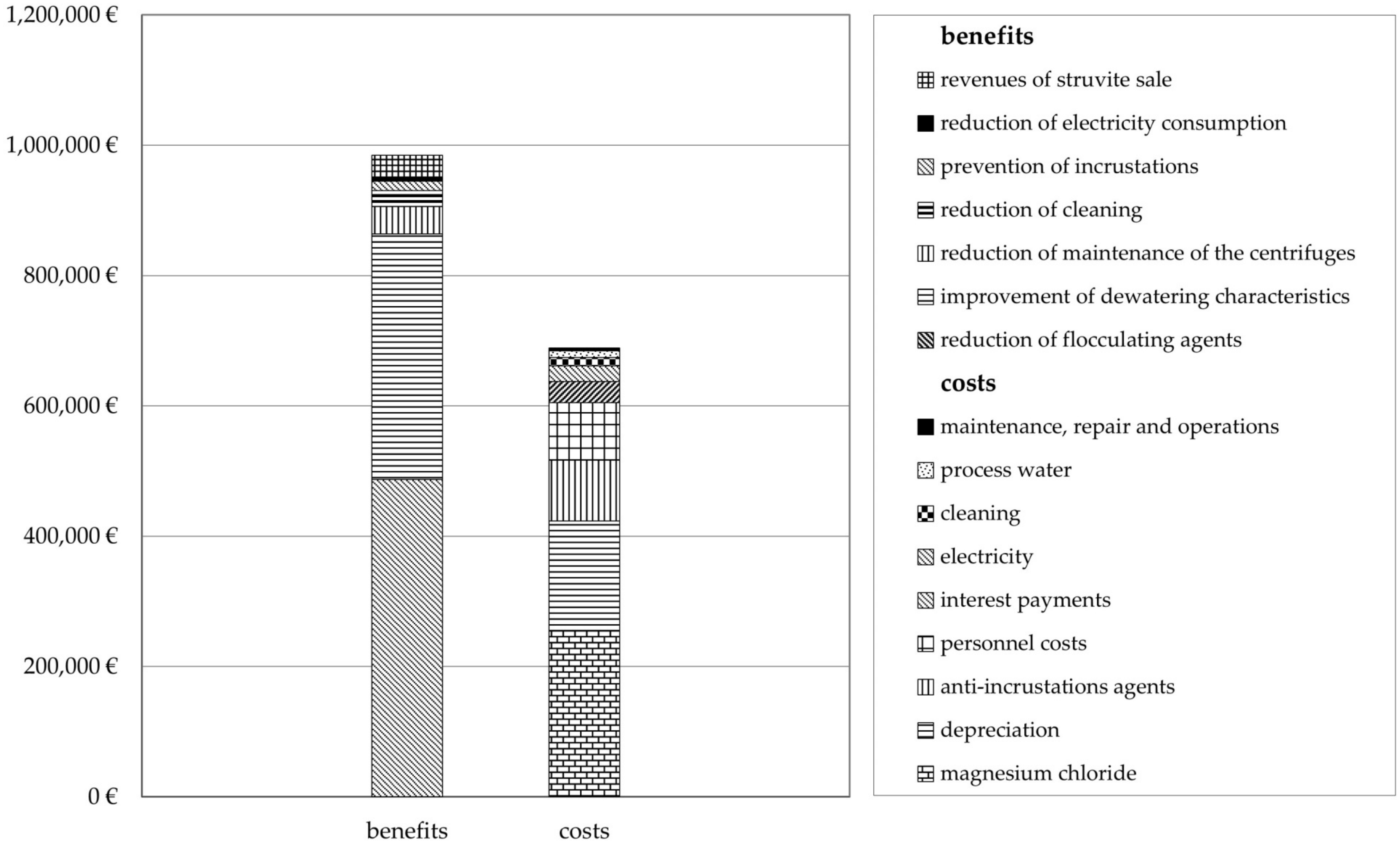

Figure 2-2: Costs and benefits of the struvite production in the Waßmannsdorf Treatment Plant in 2011.

The costs of the struvite production included mainly the costs for the applied magnesium chloride (37%), the depreciations of the reaction vessel and the magnesium chloride container (24%), the costs for the anti-incrustation agents (13%) and the personnel costs for operating the precipitation vessel (13%). Further costs included interest payments (capital costs) (5%), electricity (4%), cleaning (2%), process water (1%), maintenance, repair and operations (1%).

The revenues from struvite sales were relatively low compared to the cost reductions attained in the wastewater treatment process. The revenues accounted for only about 4% of the total benefits. With these revenues, only about 5% of the direct struvite production costs could be covered. Therefore, the added-value from the production of struvite was mainly realized through the reduction of the operating costs of wastewater treatment.

2.4.3 Impact of struvite fertilization on the added-value from crop production

The market prices for conventional mineral P-fertilizer were higher than those for struvite in the studied case (Table 2-5). Hence, substituting struvite for conventional mineral P-fertilizer reduced the costs of fertilization and increased the added-value in crop production.

Table 2-5: Commodity prices of different P-fertilizer in 2011 (World Bank, 2013; LELF, 2010).

P-fertilizer	Fertilizer price in Euro t^{-1}	P nutrient content in %	Pure P nutrient price in Euro kg^{-1}
DAP (world market)	452.00	20	2.26
TSP (world market)	393.00	20	1.96
TSP in Brandenburg	220.00	20	1.10
Struvite in Brandenburg	-	9	0.83 - 1.00

Depending on the crop, the soil quality and the amount of fertilizer applied, the potential savings on fertilizer costs were between 1.00 € $ha^{-1}$and 21.00 € ha^{-1}, at a struvite selling price of 1.00 € kg^{-1} P (Figure 2-3).[6] The corresponding cost reductions are between 0.4 and 5.9% of the total direct cost of crop production.

[6] Unless otherwise stated, the results refer to the case in which the application of struvite was completed in the same workstep as the application of mineral fertilizer.

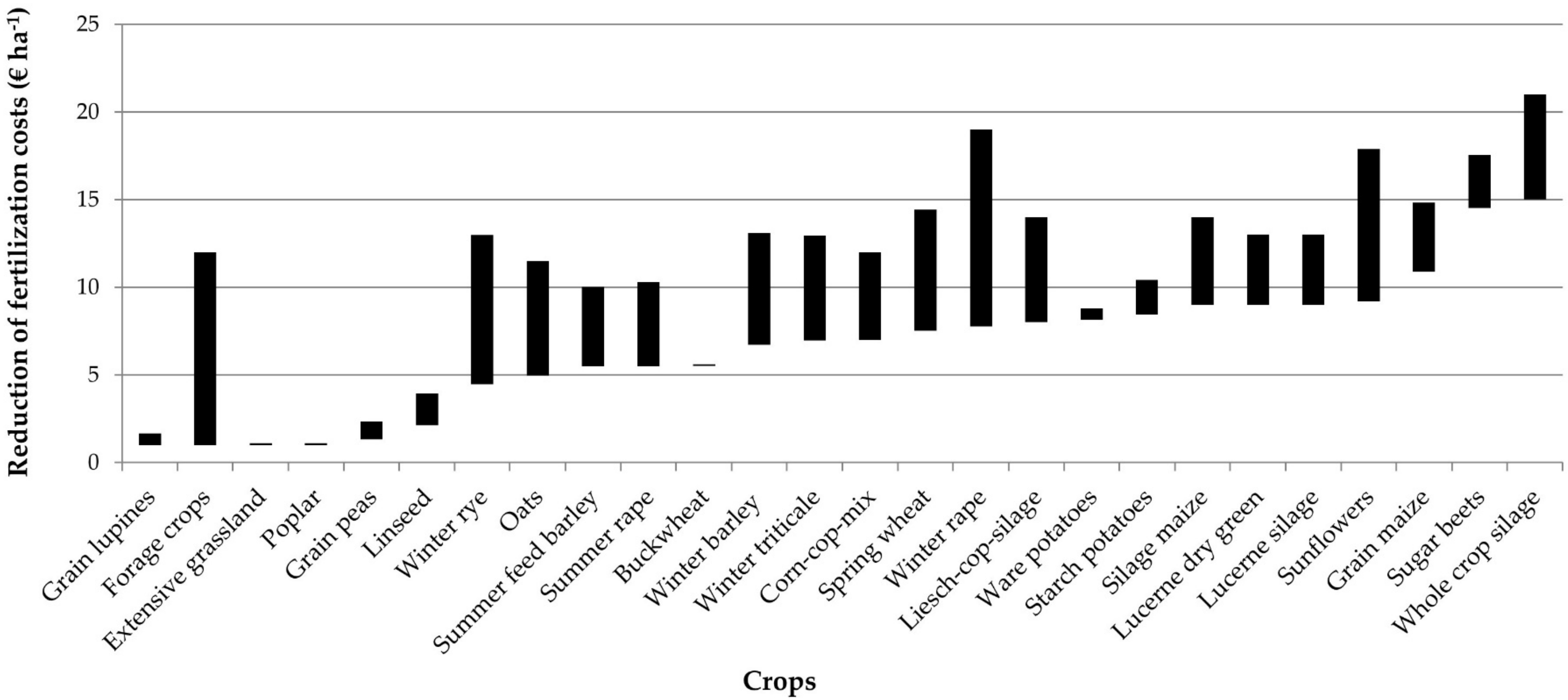

Figure 2-3: Reduction of the fertilizer costs from the use of struvite sold at the average maximum selling price (based on different soil-quality categories, with a soil-quality index scale from 7 (lowest) to 100 (highest)).

The savings on fertilizer costs through struvite application resulted from directly substituting struvite at a lower price than the conventional mineral P-fertilizer. Additional savings resulted from the reduced quantities of the required N- and Ca-fertilizer. The analysis showed that struvite fertilization could reduce the costs for P-fertilization by 9%. Depending on the crop and soil quality, the quantities and costs of mineral N- and Ca-fertilizer were reduced by 7–16% and 1–2%, respectively.

Concerning the distribution of the overall cost reductions from using struvite, the analysis further revealed that the major cost savings (69–76%) resulted from reducing the required amounts of the mineral N-fertilizer. The reduction of the costs due to the substitution of P in the struvite for P in the mineral fertilizer accounted for about 22–25% for most of the crops. The reduction of the required amounts of the mineral Ca-fertilizer accounted for 2–3% of the total cost reductions.

The additional costs for a separate spreading of struvite were between 3.00 € ha^{-1} and 5.00 € ha^{-1}. The analysis revealed that for crops which have relatively low P-needs, and do not need N-fertilization (grain peas, grain lupines, grassland, poplar), the cost of an extra spreading of struvite would exceed the benefits resulting from purchasing struvite at a lower price than conventional mineral P-fertilizer.

2.4.4 Total effect on the added-value of struvite introduction in value chains in Brandenburg

The substitution of struvite for conventional mineral fertilizer resulted in a reduction of the fertilization costs from 2,500 € to 6,000 € per farm and year. This result applied to the specific cropping patterns and outputs of the farms surveyed in Brandenburg. According to the information obtained from the survey, the share of cultivated land allocated to the single crops in Brandenburg is 58% for grain (i.e., winter rye and spring wheat), 19% for winter rape, 8% for grain maize, 6% for maize silage and 9% for others. Assuming this cropping pattern, the production of 900 t $year^{-1}$ of struvite would be sufficient to meet the P-fertilizer needs of 2,300 ha to 5,000 ha $year^{-1}$. The associated increase of the added-value in the value chain of crop production would be approximately 33,000 € to 35,000 € $year^{-1}$. The total added-value of struvite in the value chains of wastewater treatment in Waßmannsdorf and crop production in Brandenburg would be 451,000 € $year^{-1}$.

2.4.5 Distribution of added-value from struvite production and application

The added-value from struvite production and application occurs in the value-added steps of wastewater treatment, struvite marketing and crop production. The value-added step of wastewater treatment accounted for the greatest part of the added-value. The distribution of the added-value generated in the downstream steps of the value chain, including marketing and crop production, depends on the marketing modalities and the price of struvite and conventional mineral P-fertilizer. In general, a higher share of the added-value from struvite production and use will remain in the local economy if the struvite is distributed via direct sales to local farmers. Direct sales allow farmers to purchase the struvite at a price below that of conventional mineral fertilizer. However, presently, struvite is hardly sold directly to farmers. Low direct sales may indicate that transaction costs play a major role in the distribution of struvite and the distribution of the added-value from struvite.

The added-value from struvite use in crop production increases with (a) lower prices for struvite and (b) higher amounts of struvite applied as a substitute for conventional mineral fertilizers. The added-value at the farmers' level is less if the struvite is distributed via fertilizer traders, because the traders sell the struvite at almost the same price as conventional mineral P-fertilizer.

Further effects on distribution are caused by the sales price of struvite. Table 2-6 illustrates the effects of a 20% price increase of struvite on the added-value in the steps of the value chain, assuming direct sales to farmers. This variation corresponds to the price range for struvite sold on site by the wastewater treatment plant in Waßmannsdorf.

Table 2-6: Distribution of added-value along the struvite value chain at different prices of struvite.

Value-added step	Added-value $year^{-1}$ at pure nutrient price of 830 € t^{-1} P	Added-value $year^{-1}$ at pure nutrient price of 1,000 € t^{-1} P	Change of added-value	
Wastewater treatment	410,000 €	416,000 €	6,000 €	+2%
Crop production	49,000 €	35,000 €	-14,000 €	-29%
Total added-value	459,000 €	451,000 €	-8,000 €	-2%

Table 2-6 shows that the added-value generated in the value chain of struvite is reduced if the sales price for struvite is increased from 830 € t^{-1} P to 1,000 € t^{-1} P. The loss of added-value in the added-value step of crop production exceeds the gain of added-value in the wastewater treatment step by 8,000 €.

2.5 Discussion

2.5.1 Changes in the value chains of wastewater treatment and crop production

Implementing struvite precipitation and its application in agriculture lead to changes in the value chains of wastewater treatment and crop production. In the value chain of wastewater treatment, the treatment process is influenced and extended by the production of struvite as an additional output. Some portion of the phosphate (i.e., only the dissolved phosphate) contained in the sewage sludge can be used for producing a tradable product (struvite) which can generate additional revenues for plant operators. The value chain of crop production is altered by the opportunity of substituting struvite for conventional mineral fertilizer. This linkage of the value chains of wastewater treatment and crop production via struvite leads to the emergence of an innovative value chain for nutrient recycling, including struvite producers, traders and farmers.

The precipitation of struvite and its use as fertilizer can also significantly change the present flow of nutrients in wastewater treatment and crop production. Meinel (2011) indicates that 10–15% of the phosphorus (P) contained in the influent of the treatment plant can be precipitated in the form of struvite. Our findings showed that the actual productivity of struvite precipitation is insufficient to reinsert larger quantities of P into the nutrient cycle. Large amounts of the P contained in the treated wastewater and sewage sludge still get discharged into the receiving waters (4%) or remain in the dewatered sewage sludge (81%) (Meinel, 2011). However, struvite precipitation may become particularly attractive for treatment plants with biological P removal and operational problems which are caused by uncontrolled struvite formations. Other techniques with higher P-recovery rates (e.g., P-recovery from sludge ashes) may be combined with struvite precipitation in future. This way, operational problems due to uncontrolled struvite formations can be prevented and higher yields of P can be obtained.

Struvite precipitation is applicable only in treatment plants which use biological P removal. Currently, struvite is produced in Brandenburg only in the wastewater treatment plant in Waßmannsdorf. Hence, the struvite production is small compared to the large demand for P-fertilizer in Brandenburg. According to MIL (2012), the application of mineral P-fertilizer has stagnated at a low level in Brandenburg in the last few years. In 2010, only 2 kg P ha^{-1} were applied, on the average. In addition, 7 kg P ha^{-1} was spread by manure (MIL, 2010). If this is taken into account, there is a higher probability that struvite could contribute to meeting the P-needs of the agricultural sector in Brandenburg. Since struvite also contains nutrients such as N, K and Ca, precipitating struvite may contribute to the recycling of these nutrients as well.

Struvite fertilization needs to be supplemented with other N-, K- and Ca-fertilizers, since the nutrient contents of struvite are too low to fully cover the plant nutrient requirements. The sensitivity analysis revealed that the accessibility of the nutrient N contained in the struvite for the plant has a significant impact on the cost reductions and added-value from using struvite in crop production. The total added-value gained in crop production by substituting struvite for mineral fertilizer would be 13,000 € year^{-1} less (i.e., 20,000–22,000 € year^{-1} instead of 33,000–35,000 €) if the N nutrient uptake of the plants is only 50% of the previously assumed 100% uptake. The potential savings on fertilizer costs would be in the range of 1.00 € ha^{-1}and 13.00 € ha^{-1}, and the corresponding cost reductions would be only between 0.4 and 4.1% of the total direct costs of crop production. In the case of a plant uptake of 50% only, the sensitivity analysis revealed that the quantities and costs of mineral N-fertilizer could be reduced by only 3–8% through struvite fertilization. The cost reduction share from the single nutrients, when using struvite instead of mineral fertilizers, showed the same pattern as before, but with a higher share for P (37–51%) and Ca (3–5%) and a lower share for N (56–61%). This result points out the need for further research to secure the accessibility of N in struvite for the plants.

The technology for spreading the fertilizer has a significant impact on the benefit reaped from struvite use in crop production. A separate fertilizer application is needed if struvite cannot be spread in the same workstep (for technical reasons) as conventional mineral fertilizer. In this case, the added-value from struvite use in crop production would be approximately 20,000 € year^{-1} lower (i.e., 13,000–24,000 € year^{-1} instead of 33,000–35,000 € year^{-1}). This result indicates the relevance of providing technologies that enable spreading struvite and mineral fertilizer jointly in one workstep.

2.5.2 Cost, benefits and profitability

The precipitation vessel of the studied treatment plant in Waßmannsdorf was not in continuous operation during the reference year 2011, due to building operations at the treatment plant, which means that the capacity of struvite production was not fully reached in this production year. We did not extrapolate the results for a full-capacity production scenario, since this would have jeopardized the quality of our results, due to arbitrary assumptions. However, the operators of the treatment plant stated that the operation of the prototype precipitation vessel is still in the beginning phase and that they are continuously gaining experience with it. Also, they see a considerable potential for optimizing the production of struvite.

The economic viability of P-recovery via struvite precipitation and its reuse as fertilizer depends on the profitability of the precipitation process and the market price of the struvite fertilizer. The case analysis of Waßmannsdorf revealed that the revenues from struvite sales cover only about 5% of the production costs. However, struvite precipitation significantly reduced the operation costs of wastewater treatment. These results are consistent with those of Shu et al. (2006), who described struvite precipitation as economically beneficial when savings for reduced sludge handling and disposal are taken into account. Our findings demonstrate that the costs of struvite precipitation need to be assessed in relation to the cost savings achieved in the overall wastewater treatment process. In our study the economic viability of struvite production is secured, due to the reduced operation costs for wastewater treatment. The revenues from struvite sales are an additional incentive that may become more relevant with rising prices for P in the future.

The farmers' benefit from using struvite will greatly depend on the development of the price of P from mineral sources compared to P from struvite. Between 2002 and 2012, the price of P in the form of triple superphosphate (TSP) fluctuated between 0.5 and 3.21 € kg^{-1} P (World Bank, 2013). The price of phosphate and associated fertilizer is expected to increase over the long-term (Cordell et al., 2009; Von Horn and Sartorius, 2009). Thus, the economic value of struvite may increase by reaping higher revenues from struvite sales. Currently, in mid-2013, the price of the nutrient P contained in TSP is about 1.21 € kg^{-1} P (World Bank, 2013). A price for struvite, which is significantly below the price of mineral P-fertilizer, is needed to compensate farmers for the uncertainty of availability as well as the additional handling and spreading of struvite. Our results show that the difference in the price between struvite and mineral P-fertilizer in 2011 was large enough to compensate for the costs of extra handling and spreading and to reduce the fertilization costs for most crops.

2.5.3 Distribution of the added-value

Concerning the distribution of the added-value, we found that it is not equal in each of the steps in the struvite value chain. The largest share of the added-value was found in the production phase of struvite (416,000 €, 92%), while a comparatively small share of the added-value (35,000 €, 8%) was reaped by the farmers substituting struvite for conventional mineral fertilizer.

The results highlight that the share of the total added-value afforded to the farmers is related to the sales strategy for struvite. Empirical evidence suggests that direct sales to farmers are seldom. The Berlin Water Works also sold struvite to specialist fertilizer traders. It is assumed that traders mixed the struvite with other mineral P-fertilizers and sold it to farmers at around the same price as conventional mineral P-fertilizer. Another marketing strategy pursued by traders is to sell struvite as premium fertilizer at a much higher price than that for conventional mineral P-fertilizers. In both cases, the traders would seek to siphon off the price-margin between conventional mineral P-fertilizers and struvite, and retain some of the added-value that accrues from the substitution of struvite for conventional mineral P-fertilizer in agriculture. The analysis indicated that the added-value generated in crop production was more elastic towards price changes in struvite than the added-value value in the struvite production. The market players seem to know that an increase in the sales price of struvite will result in added-value losses for the farmers and a decreased willingness to substitute struvite for conventional mineral fertilizer.

The results of the survey reveal a basic willingness of farmers to substitute struvite for conventional mineral P-fertilizer. However, struvite has not yet been widely demanded as a fertilizer by farmers. One reason for the sluggish development of the struvite fertilizer market in Brandenburg may be the currently small quantities of struvite produced and marketed (400 t in 2011). Added to that is a dearth of knowledge about its availability, applicability and benefits. Lowering the sales price of struvite could prove to be a powerful strategy for penetrating the fertilizer market, since the farmers interviewed said that the price is the decisive factor, provided that struvite fulfilled the same requirements as the conventional mineral P-fertilizer. For struvite producers, this could be a worthwhile strategy, since they would mainly benefit from lower operation costs, while the revenues from struvite sales contribute only little to their added-value gains.

2.6 Conclusion

The return of P nutrient from wastewater to crop production contributes to an economical stewardship of the scarce P reserves. Technical innovations and innovative value chains for the instauration of nutrient cycles may generate a higher added-value for local economies. In the value chain of wastewater treatment, the precipitation of struvite can reduce the loss of nutrients within the wastewater treatment process. In the value chain of crop production, it supplies a substitute for conventional mineral P-fertilizer as well as for conventional mineral N- and Ca-fertilizer. At the same time, struvite precipitation reduces costs of wastewater treatment, provides a tradable product which is capable of generating revenue, and decreases the costs of fertilization. We conclude that the value chains of wastewater treatment and crop production can return a higher added-value by reinserting P and other nutrients into the nutrient cycle.

Establishing nutrient cycles requires the implementation of technical as well as institutional innovations. Our analysis suggests that direct interaction and cooperation between actors in the value chains of nutrient-recovery and re-use pose a challenge to establishing local nutrient cycles. The establishment of the P nutrient cycle via struvite precipitation is subject to the acceptance of the innovation by all actors involved in the value chains. We argue that institutional arrangements for marketing can have a considerable impact on the distribution of added-value from establishing nutrient cycles. In the case studied here, P-use within nutrient cycles led to a higher added-value in crop production if struvite was sold directly to farmers. However, direct sales to farmers are still seldom. A readjustment of the rules in use and governance structures is essential to promoting personal interaction and cooperation between the involved actors in order to keep transaction costs low.

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3 Added-value from linking the value chains of wastewater treatment, crop production and bioenergy production: A case study on reusing wastewater and sludge in crop production in Braunschweig (Germany)

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Abstract

The limited availability of natural water resources and dependency on mineral fertilizer challenge agricultural value chains in arid and nutrient-poor areas. Reusing wastewater in agriculture may help and could reduce costs and lead to increased added-value. The objective of this analysis is to assess the economic impact of linking the value chains of wastewater treatment, crop production and the generation of bioenergy by reusing treated municipal wastewater and sludge. The assessment was based on the cost/benefits and the added-value from the reused wastewater by the Braunschweig Wastewater Association (Germany). Benefits were assessed by comparing the costs of wastewater irrigation and sludge application with conventional disposal options, as well as comparing the costs of irrigation and fertilization with treated wastewater to groundwater irrigation and mineral fertilization. The added-value was calculated by ascertaining the remunerations received by the stakeholders in the various value chains. The results indicate that the reuse of wastewater and sludge results in: (a) the development of linked regional value chains; (b) lower costs of wastewater treatment and sludge disposal; (c) higher profitability and added-value in crop production; and (d) a high share (77%) of regional added-value. However, the results also show that the reuse of wastewater and sludge within linked value-chains can restrict actors and lead to crowding out effects on the added-value. Agricultural reuse schemes should provide additional opportunities that enable farmers to increase their scope of possibilities and compensate for missed economic potential.

Keywords: Wastewater reuse; Irrigation; Regional added-value; Economic benefits; Circular economy; Nexus

3.1 Introduction

The primary task of conventional wastewater treatment is the purification and disposal of wastewater, and the elimination of nutrients and hazardous substances, in order to minimize hazards to humans and the environment. Doubtlessly, conventional systems of wastewater treatment have enhanced the living conditions in urban areas and relieved environmental burdens (Dockhorn, 2006). However, due to the possibility of recycling wastewater and the nutrients contained in it, additional goals of improving sustainable resource management in wastewater treatment have gained importance (Gude, 2015).

Indications of this paradigm shift are an increase in research on nutrient recovery in wastewater treatment (Cordell et al., 2011; Mehta et al., 2015; Satorius et al., 2011) or the European Union's Urban Wastewater Treatment Directive which says that "treated wastewater should be reused whenever appropriate" (EU, 1991:4). At the same time, dependency on limited natural fresh water resources and mineral fertilizer pose a challenge for the future of agricultural value chains in arid and nutrient-poor areas. Currently, about 70% of global water withdrawals are used for agricultural irrigation (World Bank, 2015; WWAP, 2014). Estimates indicated that with current efficiencies, agricultural water consumption will increase by about 20% globally by 2050 (WWAP, 2012). These concerns have created a growing interest in seeking for alternative water resources and treatment options that can recirculate nutrients. One solution for addressing both concerns is the reuse of treated wastewater via irrigation.

The FAO (2010) promotes the recycling of urban wastewater as an essential component of integrated water resource management, which can simultaneously benefit farmers, cities and nature. It can contribute to meeting increasing water demands, saving potable water and reducing the disposal of wastewater to surface water bodies (Aiello et al., 2007). Furthermore, it can reduce purification levels and treatment costs, as soils and crops act as bio-filters (Haruvy, 1997; Rosenqvist and Dawson, 2005). Wastewater can also supply macronutrients and, therefore, contribute to securing and/or increasing the yields of crop production (Aiello et al., 2007; Bedbabis et al., 2015; Dimitriou and Rosenqvist, 2011; Singh et al., 2012; Zema et al., 2012), and saving finite mineral fertilizers (Paranychianakis et al., 2006).

Reusing wastewater in agriculture is not new; it has been a common practice in many developing countries (Norton-Brandão et al., 2013) and is now increasingly being explored in regions with water scarcity, growing urban populations and areas that demand irrigation water (FAO, 2010). Some of the concerns regarding the reuse of wastewater in agriculture include potential health hazards for farm workers and food consumers (Pedrero et al., 2010), soil salinization (Muyen et al., 2011) and the buildup of heavy metals and anthropogenic trace contaminants in soils and food crops (Fatta-Kassinos et al., 2011; Khan et al., 2008; Mapanda et al., 2005; Pedersen et al., 2005; Toze, 2006). When reusing wastewater for irrigation in agriculture, precise management strategies, including the application of proper purification levels, periodic monitoring of soil and plant properties, as well as suitable irrigation, cultivation and harvesting practices, are imperative to minimize hazards to humans and the environment (Aiello et al., 2007; Muyen et al.,2011; Qadir et al., 2010; Rusan et al., 2007).

The reuse of wastewater and sludge in agriculture causes linkages between the water and agriculture sectors, due to shared resources (e.g., land), input-output relations (e.g., nutrients), and interdependence of actions (e.g., interdependence of crop cultivation practices and wastewater treatment practices). The linkages may extend further to the energy domain through the irrigation of dedicated crops for bioenergy production. These linkages do not only connect the use of resources across sectors, but may also lead to the development of linked regional value chains comprising various economic activities, as well as actors and organizations (Maaß et al., 2014). Taking advantage of the synergies within such linked value chains may contribute to meeting increasing demands for water, food, biomass and energy as well as to convert from linear to circular production and consumption patterns. Several authors mention the benefits of integrating value chains, due to synergy effects resulting from collaboration and joint resource use, optimization of production processes and higher cost efficiency (Bausch and Glaum, 2003; Cao and Zhang, 2011; Möller, 2006; Van der Vaart and van Donk, 2008). This is supported by empirical studies showing that value chains integrated within local economic cycles can contribute to an increase of added-value for local economies (Bentzen et al., 1997; Hoffmann, 2009; Kimmich and Grundmann, 2008; Kosfeld and Gückelhorn, 2012; Marcouiller et al., 1996). However, the existing studies say little about the economic effects of specific linkages of value chains from different sectors, including those affecting the distribution of the generated added-value.

Present studies on the reuse of wastewater in agriculture have mainly focused on the suitability of wastewater for irrigation, evaluating its impact on soil and crop properties as well as the ability of particular techniques to meet specific parameters of the irrigation water quality (Norton-Brandão et al., 2013). Assessment studies have so far evaluated monetary and environmental costs and benefits from exemplary schemes only for farmers and operators of wastewater treatment facilities (Garcia and Pargament,2015; Haruvy, 1997; Molinos-Senante et al., 2011; Rosenqvist and Dawson, 2005). The research has thus far neglected the added-value resulting for utilities and stakeholders as well as the impact of wastewater reuse on the local economic development. As operators of wastewater treatment facilities realize that the support and acceptance from the local communities and public bodies is indispensable for the future development of wastewater reuse schemes, there is high interest in assessing the impacts at the local level (BIO by Deloitte, 2015; TYPSA, 2012).

This paper will undertake an economic assessment of interconnected natural-resources-based value chains for providing water, crops and bioenergy. It will investigate the theoretical assumption that the reuse of treated municipal wastewater and sludge in agriculture is conducive to the development of linked regional value chains which bring about cost reductions and higher added-value generation. In this context, we will present a methodological approach for comparing alternative systems of wastewater treatment and crop production with conventional ones from a regional economic perspective. In particular, the study will address the following specific research questions:

[1] What monetary costs and benefits are associated with reusing wastewater and sludge in agriculture?

[2] What additional added-value can be generated from the agricultural reuse of wastewater and sludge in the value chains of crop production?

[3] What is the added-value from the linkage of the value chains of treated water provisioning, food and energy crop production and bioenergy generation?

[4] How is the added-value from the nexus of natural resources distributed among linked value chains and stakeholders?

[5] What impact does the linkage of natural-resource-based value chains have on the added-value of local economies?

3.2 Conceptual foundations

This research is mainly guided by the concept of the circular economy, an adaptation of the "Water–Food–Energy Nexus" and the added-value concept. "A circular economy is an industrial system that is restorative or regenerative by intention and design" (EMF, 2012: 7). As a theoretical concept it is primarily concerned with the transition of the linear production and consumption model of 'take-make-dispose' towards restoration and reusing, repairing, refurbishing and recycling existing materials and products (EU, 2014). Based on the core principles of "reducing, reusing and recycling" (Su et al., 2013), the concept of circular economy aims to achieve "optimum production by minimizing natural resource utilization and pollution emission simultaneously, and minimum wastage by reusing the wastes from production and minimum pollution by recycling and restoring the technically useless wastes" (Wu et al., 2014: 164). Several authors have shown that the transition to a circular economy can be important for mitigating environmental impacts and reducing waste and resource consumption (Geng et al., 2009; Hu et al., 2011; Li et al., 2010; Ma et al., 2014). Furthermore, it can contribute to keeping the added-value in products for as long as possible (Smol et al., 2015) and to ensuring higher regional and domestic competitiveness by increasing the effectiveness of resource allocation, resource utilization and productivity (Su et al., 2013).

Circular economies involving natural-resources-based sectors and activities, like agriculture, are characterized by the interdependencies of water, biomass and energy. These resources are either used as inputs or produced as outputs of the sectors' activities. It is important to better understand these interdependencies because natural-resources-based sectors are experiencing more and severe shortages of supply, due to misalignments in the use of interdependent natural resources (Beisheim, 2013).

In this context, the FAO (2014a: 3) promotes the "Water–Food–Energy Nexus" as a conceptual and analytical approach to "better understand and systematically analyze the interactions between the natural environment and human activities, and to work towards a more coordinated management and use of natural resources across sectors and scales." This general idea of the "Water–Food–Energy Nexus" has been adapted and framed in several ways which vary in their consideration of different resources, dimensions and scales. The different framings have a common main scope in addressing the segmentation, fragmentation and lack of coordination in sectorial decision-making and actions, which are postulated to be the key challenges for natural resources management (Hoff, 2011). An inherent assumption derived from the "Water–Food–Energy Nexus" approach is that a coordinated integration across natural-resources-related sectors is frequently expedient for solving water, energy and food supply security. The core argument of the nexus approach is that the multiplicity of feedbacks and interdependencies resulting from linkages among subsystems, such as water, food and energy, jointly affect the sustainability of the broader social–ecological system (Ganter, 2011; Hellegers et al., 2008; Hussey and Pittock, 2012;

Villamayor-Tomas et al., 2015; Waughray, 2011). These effects are generally overlooked when independently analyzing sub-systems.

The present study adopts the approach of the "Water–Food–Energy Nexus" for setting the focus on the linkages between natural resources sectors when analyzing the economic effects of the integration of natural-resources-based value chains for enhancing water, food and energy security on a local scale. In this way, we extend the "Water–Food–Energy-Nexus" approach from the FAO (2014a,b), as we take into account not only the linkages between single resources, but also the connections between whole value chains which use these resources. Furthermore, we explore the economic impact of reducing natural resource utilization and turning waste products at one point in a value chain into inputs at another, which complies with the core principles of a circular economy (Mathews and Tan, 2011; Sterr 2003; Wu et al., 2014). Value chains are defined as "[...] the full range of activities which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use." (Kaplinsky and Morris, 2001: 4). Researchers and practitioners have studied value chains to obtain a functional view of business processes, as well as evaluating costs, margins and the added value at the different stages of a value chain, in order to make competitive comparisons and redesigning of the internal and external processes (Brown, 2009; Maaß et al., 2014). This perspective on value chains is appropriate for our study, since we assess the economic value created in the different phases of connected value chains for water, energy and food provisioning. In contrast to the conventional perspective of sequential and linear activities comprising a value chain, we look at the value chains with their manifold connections in which value is co-created by a combination of players (Peppard and Rylander, 2006). This perspective comports with the concept of value networks as structures of "[...] value proposing social and economic actors interacting through institutions and technology, to: (1) co-produce service offerings, (2) exchange service offerings, and (3) co-create value." (Lusch et al., 2010: 20). The economic value created in value chains is commonly measured with the added-value as a success indicator that describes the performance of a company, industry or economy in its entirety. The added-value is defined as the increase in value resulting from production, processing, marketing and other economic activities (Haller, 1997). Accordingly, added-value can be understood as the difference between the value of a good or service delivered from one business to another, and the value of all inputs received by this business from other businesses for producing the particular good or service (Busse von Colbe et al., 2011). Simultaneously, the added-value represents the disposable income for remunerating all those stakeholders which have contributed to the created value. Thus, the added-value can be interpreted from two different perspectives: first, the added-value represents in real economic terms the value that is added, for example, by a company to the goods and services purchased from other companies; second, the added-value describes in nominal economic terms the sum of incomes generated in this company in a particular period (Haller, 1997). The added-value perspective adopted in this study refers to the latter view according to which the added-value is the sum of the remunerations received by the stakeholders participating in the treatment and reuse of wastewater and sludge, crop production and bioenergy generation. The added-value also reveals some social and distributional implications of the studied value chains. The parameter differs from the conventional profit calculation because the remunerations paid to the employees, the creditors, and the state are considered as part of the added-value and not as value-reducing components (Möller, 2006). The added-value is used in this research to broadly capture economic performances. Other success indicators such as EAT (earning after taxes) are considered to be less adequate for this research, since they merely reflect cash flows and earnings of business owners.

3.3 Material and methods

In order to answer our research questions we combine cost/benefit and value chain analysis within a case study research. The case study approach is proposed, due to its suitability for in-depth studying of socio-economic phenomena with rather small numbers of observations (Blatter and Haverland, 2012; Yin, 2009). Cost/benefit analysis was chosen to assess in detail the allocation of the costs and benefits from the reuse of wastewater and sludge and the associated linkage of value chains. Value chain analysis was selected to get an overview and a better understanding of the value creation within linked value chains and the exchange of resources and services between the actors involved.

3.3.1 Study area

The results are based on the analysis of the agricultural reuse scheme of treated municipal wastewater and sludge from the city of Braunschweig, located in the Federal State of Lower Saxony, Germany. The wastewater reuse scheme has been managed by the Wastewater Association Braunschweig since 1954. The members of the association are the city of Braunschweig, the water association of the neighbouring city Gifhorn and 430 owners of land that is cultivated and/or leased to farmers. The physical and natural conditions in Braunschweig are rather favourable to the reuse of wastewater for agricultural production, since agricultural soils in the region are sandy and poor in nutrients, having a limited water and nutrient retention capacity (Ternes et al., 2007). Furthermore, the area has a climatic water balance deficit from April to September (Ahlers and Eggers, 2004). A continuous additional supply of water and nutrients is therefore essential for crop production here.

Figure 3-1 shows how the value chains of wastewater treatment, crop production and bioenergy production are organized and linked in the case of the Braunschweig Wastewater Association. The figure shows the outputs resulting from the primary and secondary treatment of wastewater, including secondary treated effluent and sewage sludge. These outputs are further processed in the value chains of wastewater treatment and reused as inputs for crop production in the value chains of food and energy. The energy crops are inputs for the anaerobic digestion step in the bioenergy value chain. In this way, the material flows of value chains are linked, including wastewater treatment, crop production and bioenergy production, based on the agricultural reuse of treated wastewater and sludge. Figure 3-1 displays the linkages between the value chains, indicated by the dotted lines, as well as the involved actors, indicated by the abbreviations above the single added-value steps and products.

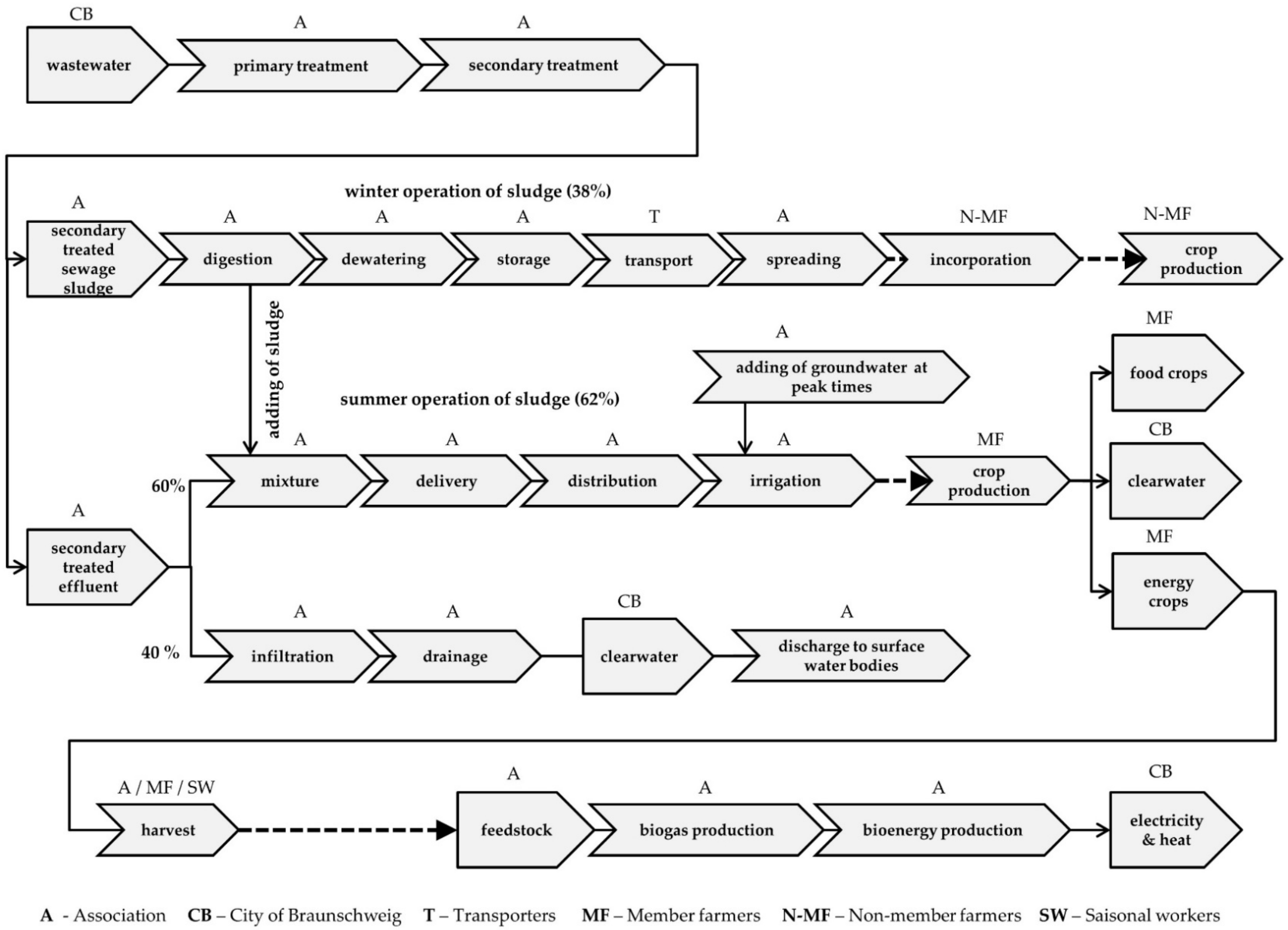

Figure 3-1: Linkages between the value chains of the wastewater reuse scheme in Braunschweig.

The wastewater of Braunschweig and surrounding communities is delivered for primary purification to the wastewater treatment plant with a capacity of 60,000 m^3 d^{-1} and a population equivalent of 350,000. The current treatment process includes mechanical treatment, biological phosphate removal, in combination with nitrification and denitrification, and anaerobic stabilization of sludge (Ternes et al., 2007). In addition, a downstream system of irrigation and infiltration fields is used for the final treatment of the secondary effluent. The largest part of the effluent (60%) is used directly for irrigation on croplands of the member farmers (about 2,700 ha). The remaining part (40%) is discharged to infiltration fields (about 220 ha) near the treatment plant. These infiltration areas serve as a natural treatment step by using a meandering system and the soil passage before the drained water is discharged to the surface water bodies.

The sewage sludge produced is stabilized via anaerobic digestion and utilized in two different value chains. In the winter period, the sewage sludge is dewatered and stored on-site before it is transported by transporters in the summer time to croplands (700 ha) of farmers who are not members of the association in the greater Braunschweig area. Subsequently, the sludge is spread by the associations' staff and the farmers incorporate the sludge into the croplands.

During the vegetation period, the sewage sludge is added to the effluent prior to irrigation. The mixed effluent–sewage sludge is discharged to a gravity sewer system which brings the mixture to the irrigation fields. The mixture is there spread by the associations' staff on the croplands of the member farmers. In 2012, approximately 12,000,000 m^3 of the secondary effluent were irrigated on the irrigation fields and approximately 8,000,000 m^3 were discharged to the infiltration fields. In addition, about 604,000 m^3 a^{-1} of groundwater were used to meet the irrigation requirements at peak times. The total quantity of sludge produced in 2012 was 4,482 t dry matters (DM). Approximately 2,770 t DM of sludge were irrigated together with the effluent inside the association territory and 1,712 t DM were dewatered and applied as fertilizer outside the association territory.

High safety standards and a sophisticated monitoring system are applied to minimize hazards to the environment, inhabitants and food consumers (Remy, 2012). The loading rates of heavy metals contained in the effluent–sludge mixture fall below the tolerable limits of the German Sewage Sludge Ordinance (LWK H, 2000). However, due to precautionary hygienic restrictions, farmers are not allowed to produce fruit or vegetables in the association territory for direct consumption (Bezirksregierung Braunschweig, 2001). Therefore, the main crops cultivated in the irrigation area are maize, grain and sugar beets (Table 3-1).

Table 3-1: Acreage, productivity and sales prices of crops cultivated in the Braunschweig wastewater reuse scheme in 2012 (Ripke, 2014[7]).

Cultivated crops	Acreage		Yields	Sales price
	ha	%	100 kg ha^{-1}	€ 100 kg^{-1} (without value-added tax)
Silage maize (cultivated for the association)	597	22	530	2.21
Silage maize (cultivated for private purposes)	413	15	530	2.35
Winter wheat	464	17	72	23.77
Sugar beets	459	17	730	4.60
Winter rye	221	8	70	22.04
Summer barley	156	6	60	23.45
Winter barley	114	4	72	22.04
Starch potatoes	111	4	450	7.23
Winter rape	64	2	40	47.86
Others	72	3	-	-
In total	2,671	100		

The wastewater reuse scheme was enhanced in 2007 by a biogas plant operated by the association, using energy maize and rye as feedstock. The association maintains quantity-based contracts with 45 member farmers for the delivery of maize in order to ensure a steady feedstock supply for the biogas plant. The machines for harvesting maize are provided by the association, whereas the operations are mainly executed by the farmers themselves, as well as by seasonal workers. In return, the association purchases the maize at preferential price.

3.3.2 Data collection and data analysis

The analysis is based on primary data and information collected between 2013 and 2014 and refers to the reference year 2012. Three semi-structured interviews were used to obtain information about the value chains of wastewater treatment, crop production and bioenergy production from five employees of the Braunschweig Wastewater Association. The interviewees were selected according to their roles in the management of the wastewater reuse scheme, including farmers, managers and employees. The interviews asked about the operations and links between the value chains, the actors and their respective positions and

[7] Personal communication.

responsibilities, and questions on the organizational and institutional setting. The face-to-face interviews were complemented by standardized questionnaires and several telephone interviews in order to collect techno-economical data needed for the cost/benefit and added-value analysis. In addition, data from the financial accountings of the association in 2012 (ABWV BS, 2012) and secondary data on agricultural production methods and costs in the study area were collected (LWK H, 2000; LWK NS, 2011). Preliminary results of the analysis were validated in a focus group discussion. The focus group was comprised of the previously interviewed managers and employees of the association as well as three member farmers of the association.

3.3.3 Cost/benefit analysis

The evaluation of the monetary benefits was based on a comparative cost–analysis of two scenarios for disposing wastewater and sludge, and cultivating crops:

The scenario "with groundwater use" represents the basis scenario without the linking of value chains. In this scenario the secondary effluent is discharged directly to surface water bodies and built-up sludge is incinerated. Crop production relies exclusively on private irrigation schemes using groundwater tapped by farmers individually. Since the nutrients from wastewater and sludge are not available in this scenario, the farmers have to exclusively use mineral fertilizers instead. In sum, the farmers have to bear all costs related to the irrigation, fertilization and harvest themselves.

The scenario "with wastewater reuse" represents the current state of the investigated scheme. The wastewater association carries out the irrigation operations and bears the full costs of the investments and operations. The member farmers pay an annual membership fee to the association of about 81 € ha^{-1} as a contribution towards the irrigation costs. The application of mineral fertilizer is reduced in this scenario due to the nutrients supplied by the effluent–sludge mixture from the wastewater treatment plant.

3.3.3.1 Wastewater treatment and reuse

The determination of the costs of treating and reusing wastewater and sludge was based on data obtained from the questionnaires and the financial accountings of the association (ABWV BS, 2012).

The economic benefits resulting from the reuse of wastewater in agriculture instead of discharging wastewater to surface water bodies were found by comparing the amount of the wastewater fees paid in both scenarios. The wastewater fee is a classical emission fee paid when exceeding the permitted marginal pollution limits by discharging effluents directly to surface water bodies (Möller-Gulland et al., 2011). While the discharge of residual pollutants from the drainage of infiltration fields is subjected to the wastewater fee, the irrigation of treated wastewater on agricultural fields during the vegetation period is considered as an agricultural soil treatment measure which is exempted from the wastewater fee. The reduced costs from this practice were estimated by calculating the hypothetical wastewater fees operators of the wastewater treatment plant would have paid if the irrigated effluent–sludge mixture were discharged directly to the surface water bodies.

Further benefits were found by comparing the costs of the agricultural utilization of sludge with the cost of the thermal disposal of the total sludge volumes produced. The costs of the thermal disposal of sludge were calculated according to the standard values of the German Association for Water, Wastewater and Waste (DWA, 2010) for incinerating dewatered sludge in coal-fired plants and mono- or waste-burning plants.

3.3.3.2 Crop production and bioenergy generation

The benefits from reusing wastewater for member farmers were determined by comparing the costs of cultivating the main crops (Table 3-1) "with groundwater use" and "with the reuse of treated wastewater and sludge". The investment for irrigating groundwater were stipulated according to Fricke (2014)[8] for the development and operation of an irrigation area of 30 ha with one shallow well with a diesel pump drive and one irrigation machine (Table 3-2). The volume of irrigated groundwater was equated to the additional water demand required for optimal plant growth in the location (i.e., 100 mm ha^{-1} a). Further data required for calculating the costs of crop production were taken from LWK NS (2011), which gives an overview of agriculture production methods and costs in Lower Saxony.

[8] Personal communication.

Table 3-2: Costs for groundwater irrigation using diesel pumps (based on Fricke (2014) and own calculations).

Investments	Investment costs* (€)	Useful life* (a)	Imputed depreciation (€ mm^{-1})	Imputed interest (€ mm^{-1})	Energy* (€ mm^{-1})	Repair* (€ mm^{-1})	Labour* (€ mm^{-1})	Fee for groundwater extraction (€ mm^{-1})
Shallow well	5,000	25	0.07	0.03				
Pump aggregate (diesel) 50 $m^3 h^{-1}$	15,000	15	0.33	0.10				
Earth tube (600 m)	12,000	30	0.13	0.08				
Hydrants, elbows, outlets	3,000	20	0.05	0.02				
Irrigation machine	25,000	15	0.56	0.17				
Total costs	60,000		1.14	0.40	1.44	0.10	0.50	0.05

* Based on Fricke (2014).

In the scenario "with wastewater reuse" we considered the supply of additional nutrients contained in the irrigated effluent–sludge mixture (Table 3-3) when calculating the variable costs for purchasing and spreading mineral fertilizer. The calculated effective substitution potentials were 60 kg N ha^{-1} for maize, sugar beets and potatoes and 40 kg N ha^{-1} for grain and rape, since the timing of nitrogen supply via effluent–sludge mixture irrigation does not always match the optimal fertilization time required by these crops.

Table 3-3: Effectively usable nutrient quantities in the irrigated effluent-sludge mixture.

Nutrient		Effectively plant available nutrient quantities (kg ha^{-1})
Nitrogen	N	40-60[a]
Phosphorus	P_2O_5	61[b]
Kali	K_2O	76[b]
Magnesium	MgO	42[b]
Calcium	CaO	200[a]

[a] Ripke (2014).
[b] LWK H (2000).

The benefits for non-member farmers from applying dewatered sludge as fertilizer on croplands in the greater Braunschweig area were calculated by comparing the costs for incorporating sludge into the soil and the respective financial compensation received by farmers. The value of the effective fertilization from the applied sludge was estimated on the basis of the total effectively usable annual nutrient quantities spread with the sludge (Table 3-4) and the nutrient prices paid for commercial fertilizers commonly used in Lower Saxony in 2012 (LWK NS, 2011).

Table 3-4: Effectively used nutrient quantities in the Braunschweig reuse scheme in 2012 (Ripke, 2014).

Nutrient		Nutrient quantities	
		Effluent-sludge mixture (t a^{-1})	Dewatered sludge (t a^{-1})
Nitrogen	N	250	48
Phosphorus	P_2O_5	332	263
Kali	K_2O	195	8
Magnesium	MgO	105	47
Calcium	CaO	1,218	320

The benefits for bioenergy producers were calculated by comparing the price of maize paid by the association to member farmers (2.21 € 100 kg^{-1}) and the price usually paid in the region in 2012 (2.35 € 100 kg^{-1}). Table 3-5 summarizes the economic activities and the monetary costs and benefits considered in the analysis of the reuse scheme. Non-pecuniary effects such as environmental benefits or other externalities were neglected since the analysis was focused solely on the monetary impacts of wastewater reuse.

Table 3-5: Cost and benefits considered in the analysis of the reuse scheme.

Actors perspectives	Actors activities considered in the analysis	Costs included in the analysis	Benefits included in the analysis
Operators of the treatment plant	Wastewater treatment	- For discharging treated wastewater to surface water bodies - For reusing treated wastewater in agriculture	- Savings in wastewater fees
	Sludge treatment	- For thermal sludge treatment - For reusing sludge in agriculture	- Savings in costs for dewatering sludge - Savings in costs for incinerating sludge
Member-farmers	Irrigation	- For groundwater irrigation - For wastewater irrigation	- Savings in costs for irrigation
	Fertilization	- For applying mineral fertilizer - For fertilization with irrigation and mineral fertilizer	- Savings in costs for purchasing and spreading mineral fertilizer
	Harvesting energy maize	- For harvest services provided by contractors - For harvest services provided by the association	- Savings in costs for hired labour
Non-member-farmers	Sludge spreading	- For incorporating dewatered sludge into the soil	- Fertilization value of dewatered sludge - Advantage from the financial compensations
Bioenergy producers	Feedstock supply	- For purchasing energy maize at the regional market - For purchasing energy maize from member farmers	-Savings in purchasing maize

3.3.4 Added-value analysis

The methodology for the analysis of the direct added-value effects of linking the value chains of wastewater treatment, crop production and bioenergy production was comprised of three steps, including (1) the calculation of the added-value, (2) the assessment of the impact on the local economy and (3) the determination of potential crowding out effects on the added-value from crop production.

The calculation of the added-value generated in the value chains was based on the decomposition of the added-value into the remunerations received by participating enterprises, salaried labourers, creditors and the state. Accordingly, the added-value was calculated by determining and adding together the following components:

$$NAV_t = PAT_t + NWP_t + IP_t + PT_t \quad (1)$$

where NAV is the net added-value; PAT are the after-tax profits of equity providers; NWP are the net wage payments to employees; IP are the interest payments to creditors; PT are the payments of taxes, fees and social contributions to the state; and *t* is the period of time (i.e., the reference year 2012). This was done for each branch of the association linked to the treatment and reuse of wastewater and the production of bioenergy. Analogously, the added-value from crop production was calculated for the main crops (Table 3-1) cultivated by the member farmers of the association.

3.3.4.1 Profits after taxes

First, the pre-tax profits of the participating enterprises were calculated. This was done by deducting the total costs from the total revenues of production. By deducting the payments of the business and income tax from the pre-tax profits, the after-tax profits of the equity providers were determined. Since the total costs included the depreciations of the investments, the calculated added-value represents the net added-value.

3.3.4.2 Net wage payments

The net wages received by employees were estimated by deducting the employees' share of social contributions from their gross wage. For the employees involved in the treatment and reuse of wastewater and the production of bioenergy production, this information was taken from the financial accountings of the association (ABWV BS, 2012). The share of net wages and social contributions in crop production were estimated according to the labour cost structure presented by Brandner (2013) for the agriculture sector in Germany. Taxes and fees on the wage income of employees were neglected because they largely depend on the individual social–economic situation of each employee.

3.3.4.3 Interest payments

The interest payments received by creditors involved in the treatment and reuse of wastewater and the production of bioenergy were taken from the financial accountings of the association (ABWV BS, 2012). The interest payments of farmers to creditors were assumed to be equivalent to the imputed interest on bonded capital, since the ratio of external financing of crop production in the study area could not be defined precisely.

3.3.4.4 Payments of Taxes

Stakeholders are taxed on the specific fiscal regulations of wastewater treatment, crop production and bioenergy generation. Therefore, the taxes considered in the analysis differ between the different value chains. Basically, all costs and revenues were calculated at net prices without value-added tax (VAT). Whereas the VAT was taken into account when calculating the added-value of the different branches of wastewater treatment and reuse, we did not consider VAT in crop production and bioenergy production. This procedure was chosen because the farmers in Germany are allowed to deduct from their VAT account the amount of the input tax which they have paid to other taxable persons. This means the majority of farmers do not pay VAT (Altehoefer et al., 2010). Similarly, the operators of commercial biogas plants are entitled to reclaim input tax and pass the payments of the VAT to the end consumer. By contrast, the operators of wastewater treatment facilities are not entitled to reclaim input tax and have to bear the full VAT.

The treatment and disposal of wastewater by the association are performed in its capacity as public authority without commercial interests. In this function the association is by law not allowed to generate profits and has no tax liability on profits and incomes. By contrast, the biogas plant is operated as business enterprise, and therefore, it is subjected to taxation on profit and income. The tax payments on the pre-tax profits of farmers were calculated on the assumption of an average income tax burden of 13%. This value was roughly estimated from the average annual profits gained by farmers and foresters, but not from their total income, but only from that deriving from agricultural and forestry activities (i.e., of 43,381 € $year^{-1}$) and the associated average annual income tax payment of farmers and foresters (i.e., 5,461 € $year^{-1}$) in Lower Saxony in 2010 (Federal Statistical Office Germany, 2015). Table 3-6 gives an overview of the remunerations of stakeholders considered in the calculation of the added-value for the different branches of the reuse scheme.

Table 3-6: Remunerations of stakeholders considered in the analysis of the added-value.

Components of added-value	Considered branches and remunerations of stakeholders		
	Wastewater treatment and reuse	Crop production	Bioenergy generation
Remunerations of equity providers		After-tax profits	After-tax profits
+ Remunerations of employees	Net wages	Net wages	Net wages
+ Remunerations of creditors	Interest payments	Interest payments	Interest payments
+ Remunerations of the state	Social contributions	Social contributions	Social contributions
	Groundwater extraction fees	Groundwater extraction fees	
	Wastewater fees		
	Vehicle tax		Vehicle tax
	Value-added tax		
		Income tax	Income tax
			Business tax
= Net added-value			

3.3.4.5 Regional added-value

The impact of linked value chains on the local economy was assessed by ascertaining the regional added-value, i.e., the share of the added-value that remains in the municipalities that host the association and the enterprises of the members. We assumed that the equity providers and employees live in the subject municipalities. Accordingly, it was assumed that the after-tax profits of equity providers and the net wages of employees remained at 100%. The regional share of the interest payments of farmers to creditors was assumed, according to Kosfeld and Gückelhorn (2012), to be equivalent to the proportion of savings banks, credit cooperatives and regional banks in the local credit business. In 2012, the proportion of these financial institutions was 86% of the overall credit business in the agriculture, forestry and fisheries sector in Lower Saxony (Deutsche Bundesbank, 2015). The regional share of interest payments of the operators of the different branches of the wastewater treatment and reuse as well as the biogas plant was set at 80%, according to information from the management board of the wastewater association. The share of the payments of taxes, fees and social contributions remaining in the communities was ascertained on the basis of the proportional claim of local authorities on the tax and fee revenues of the state.

3.3.4.6 Crowding out effects

The substitution of treated wastewater and sludge for groundwater and mineral fertilizer may result in changes in the use of the production factors of capital and labour, and this in turn may decrease the remunerations of some stakeholders in the value chains of crop production. The potential crowding out effects on the added-value from crop production were calculated by comparing the remunerations received by the stakeholders in both scenarios of crop production.

3.4 Results

3.4.1 Costs and benefits in the wastewater reuse scheme

3.4.1.1 Wastewater treatment and reuse

3.4.1.1.1 Costs

The costs analyzed as part of the treatment and reuse of wastewater included the costs for (1) primary and secondary wastewater treatment, (2) irrigating wastewater and non-dewatered sludge, (3) spreading wastewater on infiltration fields, and (4) for spreading dewatered sludge on croplands in the greater Braunschweig area (Table 3-7).

The total costs for the treatment and reuse of wastewater and sludge were 14,918,000 €. The largest share was for the operation and maintenance of the treatment plant (58%), followed by the irrigation of the wastewater (33%), the infiltration processes (7%) and the spreading of dewatered sludge on croplands in the greater Braunschweig (2%).

In reference to the total volumes of wastewater irrigated in 2012, the specific costs of irrigating wastewater and sewage sludge were 0.41 € m^{-3}. The specific costs of sludge disposal via irrigation were 19.40 € t^{-1} DM, and the specific costs for spreading dewatered sludge as fertilizer were 189.10 € t^{-1} DM in terms of the total sludge quantities used, respectively.

Table 3-7: Individual cost items for treatment and reuse of wastewater and sludge (based on ABWV BS (2012) and own calculations).

	Branches of wastewater treatment and reuse			
Cost items	Treatment plant	Irrigation	Infiltration	Sludge spreading
	(€ a^{-1})	(€ a^{-1})	(€ a^{-1})	(€ a^{-1})
Raw materials and operating supplies	539,283	8,908	10,725	-
Purchased services	964,972	657,304	58,947	47,327
Hired labour	1,933,487	64,394	416,676	71,684
Personnel	8,850	1,949,982	14,685	28,643
Depreciations	2,551,035	762,363	170,074	8,491
Maintenance and repair	595,933	131,836	-	-
Sludge and soil analysis	5,056	2,887	-	20,018
Administration	592,915	556,566	77,343	27,590
Wastewater fees	-	42,375	188,050	-
Groundwater extraction fees	-	3,088	-	-
Transportation of dewatered sludge	-	-	-	15,668
Payments for incorporating dewatered sludge	-	-	-	68,532
Other operating expenses	288,703	322,391	73,068	32,709
Interest payments	1,132,063	348,579	99,415	2,335
Vehicle tax	3,687	17,488	1,360	746
Total costs	8,615,985	4,868,162	1,110,343	323,741
Value-added tax	255,726	196,910	9,070	3,474
Net added-value[1)]	1,400,326	2,558,422	312,580	35,197

1) Net added-value = Personnel costs + Interest payments + Wastewater fees + Groundwater extraction fees + Vehicle tax + Value-added tax.

3.4.1.1.2 Benefits

The savings in the wastewater fees from avoiding discharges of residual pollutants to the surface water bodies were 392,000 € (Table 3-8). This corresponds to the amount of the wastewater fees that would have to be paid if the fee-relevant residual pollutants were not irrigated on croplands, but rather discharged directly to the surface water bodies.

Table 3-8: Damage units of pollutants in the irrigated wastewater and saved amount of wastewater fees in 2012 ((Ripke (2014) and own calculations).

Pollutants		Damage units (DU)*	Fee per damage unit (€ DU^{-1})	Saved amount of wastewater fee ** (€ a^{-1})
Chemical Oxygen Demand	(CSB)	12,065	17,90	215,903
Phosphorus	(P)	4,022	17,90	71,974
Inorganic nitrogen	($N_{inorg.}$)	5,791	17,90	103,630
Total		21,878		391,507

* Calculated as equivalents of pollutants (Ripke, 2014).

** Referred to wastewater quantities of 12,000,000 m^3 a^{-1}.

The total cost of the thermal disposal of the sludge were estimated to be between 538,000 € and 1,434,000 €, when incinerating the sludge in coal-fired plants, or between 896,000 € and 1,793,000 € when incinerating the sludge in mono- or waste-burning plants (Table 3-9). By contrast, the total costs of the agricultural utilization of sludge were only 377,000 €, or only 70% of the minimum costs for incinerating sludge. Accordingly, the annual cost savings with the existing disposal strategies are between 160,000 € and 1,057,000 € in the case of sludge incineration in coal-fired plants, and between 519,000 € and 1,415,000 € in the case of sludge incineration in mono- or waste-burning plants. In addition, the operators saved the costs for dewatering the sludge quantities, which were co-irrigated together with the effluent on the irrigation fields. These savings were about 416,000 €.

Table 3-9: Costs of sludge disposal via agricultural and thermal utilization (based on DWA (2010) and own calculations).

Cost items	Quantities produced in 2012 t (DM) a^{-1}	Costs of agricultural sludge utilization in 2012			Costs of thermal sludge utilization				
		Cost for irrigating non-dewatered sludge	Costs for dewatering sludge	Costs for spreading dewatered sludge	Costs for dewatering sludge	Costs for incinerating dewatered sludge in coal-fired plants (incl. transportation)[c]		Costs for incinerating dewatered sludge in mono- or waste-burning plants (incl. transportation)[c]	
						Min.	Max.	Min.	Max.
Specific costs		19 € t^{-1} (DM)	410 € t^{-1} (DM)	189 € t^{-1} (DM)	410 € t^{-1} (DM)	120 € t^{-1} (DM)	320 € t^{-1} (DM)	200 € t^{-1} (DM)	400 € t^{-1} (DM)
Annual costs		€ a^{-1}	€ a^{-1}	€ a^{-1}	€ a^{-1}	€ a^{-1}	€ a^{-1}	€ a^{-1}	€ a^{-1}
Non-dewatered sludge	2,770	53,738	-	-	415,500 [a]	332,400	886,400	554,000	1,108,000
Dewatered sludge	1,712	-	701,920	323,741	701,920 [b]	205,440	547,840	342,400	684,800
Total	4,482	53,738	701,920	323,741	1,117,420	537,840	1,434,240	896,400	1,792,800

[a] hypothetical costs.

[b] real costs in 2012.

[c] based on DWA (2010).

3.4.1.2 Crop production

3.4.1.2.1 Costs

Table 3-10 presents the revenues, costs and the added-value of the main crops cultivated by member farmers in 2012 for the scenarios with groundwater use (scenario A) and with wastewater reuse (scenario B).

Based on the additional water demand for optimal crop growth (i.e., 100 mm ha^{-1}) and depending on the crop specific bonding time of capital, the costs for farmers for irrigating groundwater were 367 € ha^{-1}. By contrast, the costs for the association for irrigating wastewater were 406 € ha^{-1}.

The total costs of crop production were between 1,202 € ha^{-1} and 3,314 € ha^{-1} when crops were irrigated with groundwater by farmers (scenario A) and between 745 € ha^{-1} and 2,831 € ha^{-1} when crops were irrigated with wastewater and sludge by the association (scenario B).

Concerning the pre-tax profitability of crop production, profitability was lower with groundwater irrigation than with wastewater irrigation. Depending on the crop, the pre-tax profits for farmers were between −66 € ha^{-1} and 2,083 € ha^{-1} with groundwater irrigation compared to between 414 € ha^{-1} and 2,568 € ha^{-1} with wastewater irrigation. The profitability of maize production was not secured in the case of groundwater irrigation, since the total costs exceeded the revenues of production. By contrast, the profitability of maize production was secured and substantially increased with the irrigation of treated wastewater and sludge and the harvesting by the association.

The sum of the total costs of producing the principal crops cultivated by member farmers were 4,279,000 € in the scenario with groundwater use and 2,915,000 € in the scenario with wastewater reuse. Accordingly, the linkage of wastewater treatment and crop production via the irrigation of wastewater and sludge in agriculture resulted in a decrease of the total costs of crop production by 32% in the studied area.

Table 3-10: Revenues, costs and added-value of crop cultivation in the study area in 2012 (based on LWK NS (2011) and own calculations).

	Units	Cultivated crops																	
		Silage maize[a]		Silage maize[b]		Winter wheat		Sugar beets		Winter rye		Summer barley		Winter barley		Starch potatoes		Winter rape	
		Scenario		Scenario		Scenario		Scenario		Scenario		Scenario		Scenario		Scenario		Scenario	
		A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Revenues																			
Sales revenues	€ ha^{-1}	1,245	1,173	1,245	1,245	1,711	1.711	3,357	3,357	1,543	1,543	1,407	1,407	1,613	1,613	3,252	3,252	1,914	1,914
Transfer payments	€ ha^{-1}	313	313	313	313	313	313	313	313	313	313	313	313	313	313	313	313	313	313
Additional remunerations	€ ha^{-1}	-	-	-	-	-	-	376	376	-	-	-	-	-	-	-	-	-	-
Total revenues	€ ha^{-1}	1,558	1,486	1,558	1,558	2,025	2,025	4,046	4,046	1,856	1,856	1,721	1,721	1,926	1,926	3,566	3,566	2,228	2,228
Variable costs																			
Seeds	€ ha^{-1}	190	190	190	190	87	87	194	194	114	114	89	89	96	96	828	828	75	75
Fertilizer	€ ha^{-1}	410	220	410	220	343	172	568	376	326	154	259	91	304	133	384	192	359	187
Pesticides	€ ha^{-1}	46	46	46	46	91	91	189	189	114	114	96	96	110	110	212	212	117	117
Insurance	€ ha^{-1}	16	16	16	16	20	20	40	40	19	19	17	17	19	19	36	36	45	45
Soil analysis	€ ha^{-1}	-	-	-	-	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Machine costs	€ ha^{-1}	226	70	226	70	315	158	272	116	320	163	289	133	307	151	645	488	319	162
Hired labour	€ ha^{-1}	218	0	218	218	-	-	238	238	-	-	-	-	-	-	-	-	-	-
Imputed interest	€ ha^{-1}	13	7	13	9	17	11	24	18	18	12	9	6	17	10	26	22	21	14
Personnel costs	€ ha^{-1}	139	87	139	87	166	114	112	60	170	118	143	91	154	102	481	429	172	120
Groundwater extraction fee	€ ha^{-1}	5	-	5	-	5	-	5	-	5	-	5	-	5	-	5	-	5	-
Total variable costs	€ ha^{-1}	1,263	635	1,263	856	1,051	660	1,650	1,238	1,092	701	914	530	1,019	628	2,623	2,214	1,118	726
Fixed costs																			
Machine costs	€ ha^{-1}	73	73	73	73	29	29	39	39	30	30	25	25	27	27	65	65	32	32
Depreciations	€ ha^{-1}	248	134	248	134	239	125	233	119	241	127	222	108	230	116	585	471	236	122
Imputed interest	€ ha^{-1}	40	0	40	0	40	0	40	0	40	0	40	0	40	0	40	0	40	0
Membership fee	€ ha^{-1}	-	81	-	81	-	81	-	81	-	81	-	81	-	81	-	81	-	81
Total fixed costs	€ ha^{-1}	361	288	361	288	309	236	313	240	311	238	288	215	298	225	691	618	308	236
Total costs	€ ha^{-1}	1,624	924	1,624	1,144	1,360	896	1,963	1,478	1,403	939	1,202	745	1,317	853	3,314	2,831	1,426	962
Pre-tax profits	€ ha^{-1}	-66	563	-66	414	665	1,129	2,083	2,568	453	917	519	976	610	1,074	251	734	801	1,266
Income tax	€ ha^{-1}	0	71	0	52	84	142	262	323	57	115	65	123	77	135	32	92	101	159
After-tax profits	€ ha^{-1}	-66	492	-66	362	581	987	1,821	2,244	396	802	453	853	533	939	220	642	700	1,107
Net added-value[c]	€ ha^{-1}	131	656	131	509	893	1,254	2,264	2,646	686	1,047	716	1,073	825	1,186	803	1,185	1,039	1,400
Total acreage in study area	ha	597	597	413	413	464	464	459	459	221	221	156	156	114	114	111	111	64	64
Total net added-value	€	78,063	391,681	54,003	210,386	414,188	581,752	1,039,230	1,214,532	151,633	231,443	111,710	167,325	94,057	135,225	89,175	131,568	66,472	89,584
Delta of total costs	€ ha^{-1}		-700		-479		-464		-485		-464		-457		-464		-483		-465
Delta of pre-tax profits	€ ha^{-1}		628		479		464		485		464		457		464		483		465
Delta of after-tax profits	€ ha^{-1}		557		427		406		424		406		399		406		422		406
Delta of net added-value	€ ha^{-1}		525		379		361		382		361		357		361		382		361

(A): Scenario with groundwater use (B): Scenario with wastewater reuse

[a] Harvest of maize by the association.

[b] Harvest of maize by farmers.

[c] Net added-value = Imputed interest + Personnel costs + Groundwater extraction fee + Income tax + After-tax profits

3.4.1.2.2 Benefits

Table 3-11 presents the benefits gained by member farmers of the association from the reuse of wastewater and sludge and outsourcing the harvesting of maize to the association.

The benefits for member farmers resulted mainly from savings in the costs of irrigation, due to the supply and outsourcing of the irrigation operations to the wastewater association. Member farmers saved up to 367 € ha^{-1} in depreciations, personnel, variable machine costs, groundwater extraction and imputed interests required for irrigating groundwater.

A further benefit was reduced fertilization costs, since the nutrients in the irrigated wastewater and sludge decreased the quantities of mineral fertilizers applied. Depending on the crop, farmers reduced the application of mineral fertilizer by 40% to 66%. This saved between 167 € ha^{-1} and 193 € ha^{-1} when purchasing mineral fertilizers. The reduction of the variable costs for spreading mineral fertilizer, including the costs for machines, personnel and capital, was between 5.27 € ha^{-1} and 6.81 € ha^{-1}.

Another benefit for member farmers who provided energy maize to the association's biogas plant resulted from outsourcing the harvest of maize to the association. This service decreased the costs of hired labour on the farm level by 221 € ha^{-1}.

As a result of the supply and operation of the irrigation of wastewater and sludge by the association, the farmers could save between 538 € ha^{-1} and 566 € ha^{-1} compared to the scenario with groundwater use. Cost savings for producers of maize were up to 781 € ha^{-1} when the harvest of maize was also conducted by the association. Over against these savings are the annual membership fees (81 € ha^{-1}) which amounted to 211,000 € for the acreage of the investigated crops.

Benefits for non-member farmers from applying dewatered sludge in the greater Braunschweig area resulted from the fertilization value of the sludge, which was 308,000 € (or 439 € ha^{-1}), and the financial compensation received by farmers for incorporating the sludge in the soil. In 2012, about 68,500 € (or 98 € ha^{-1}) were paid as financial compensation to non-member farmers for incorporating sludge. According to the association, the costs for farmers for incorporating sludge were approximately 17,500 € (or 25 € ha^{-1}). This yielded 51,000 € (or 73 € ha^{-1}) for the farmers.

Table 3-11: Benefits for member farmers of the Braunschweig Wastewater Association in 2012.

Benefits (savings)	Units	Cultivated crops																		total cost savings in study area
		Silage maize[a]		Silage maize[b]		Winter wheat		Sugar beets		Winter rye		Summer barley		Winter barley		Starch potatoes		Winter rape		
			(X)		(X)		(X)		(X)		(X)		(X)		(X)		(X)		(X)	€ a^{-1}
Irrigation																				
Depreciations (fixed)	€ ha^{-1}	113.89	*-7.0%*	113.89	*-7.0%*	113.89	*-8.4%*	113.89	*-5.8%*	113.89	*-8.1%*	113.89	*-9.5%*	113.89	*-8.6%*	113.89	*-3.4%*	113.89	*-8.0%*	295,997
Imputed interest (fixed)	€ ha^{-1}	40.00	*-2.5%*	40.00	*-2.5%*	40.00	*-2.9%*	40.00	*-2.0%*	40.00	*-2.9%*	40.00	*-3.3%*	40.00	*-3.0%*	40.00	*-1.2%*	40.00	*-2.8%*	103,960
Machine costs (variable)	€ ha^{-1}	154.48	*-9.5%*	154.48	*-9.5%*	154.48	*-11.4%*	154.48	*-7.9%*	154.48	*-11.0%*	154.48	*-12.9%*	154.48	*-11.7%*	154.48	*-4.7%*	154.48	*-10.8%*	401,506
Personnel costs (variable)	€ ha^{-1}	50.00	*-3.1%*	50.00	*-3.1%*	50.00	*-3.7%*	50.00	*-2.5%*	50.00	*-3.6%*	50.00	*-4.2%*	50.00	*-3.8%*	50.00	*-1.5%*	50.00	*-3.5%*	129,950
Imputed interest (variable)	€ ha^{-1}	2.04	*-0.1%*	2.04	*-0.1%*	3.37	*-0.2%*	3.07	*-0.2%*	3.37	*-0.2%*	2.04	*-0.2%*	3.37	*-0.3%*	2.04	*-0.1%*	3.78	*-0.3%*	6,957
Fees for groundwater extraction (variable)	€ ha^{-1}	5.11	*-0.3%*	5.11	*-0.3%*	5.11	*-0.4%*	5.11	*-0.3%*	5.11	*-0.4%*	5.11	*-0.4%*	5.11	*-0.4%*	5.11	*-0.2%*	5.11	*-0.4%*	13,281
In total	€ ha^{-1}	365.53	*-22.5%*	365.53	*-22.5%*	366.86	*-27.0%*	366.55	*-18.7%*	366.86	*-26.1%*	365.53	*-30.4%*	366.86	*-27.9%*	365.53	*-11.0%*	367.27	*-25.7%*	951,651
Fertilizer spreading																				
Fertilizer purchase (variable)	€ ha^{-1}	189.36	*-11.7%*	189.36	*-11.7%*	171.84	*-12.6%*	192.63	*-9.8%*	171.84	*-12.2%*	167.22	*-13.9%*	171.84	*-13.0%*	192.63	*-5.8%*	171.84	*-12.0%*	475,439
Machine costs (variable)	€ ha^{-1}	1.92	*-0.1%*	1.92	*-0.1%*	1.92	*-0.1%*	1.92	*-0.1%*	1.92	*-0.1%*	1.92	*-0.2%*	1.92	*-0.1%*	1.92	*-0.1%*	1.92	*-0.1%*	4,980
Personnel costs (variable)	€ ha^{-1}	1.65	*-0.1%*	1.65	*-0.1%*	1.65	*-0.1%*	1.65	*-0.1%*	1.65	*-0.1%*	1.65	*-0.1%*	1.65	*-0.1%*	1.65	*0.0%*	1.65	*-0.1%*	4,288
Imputed interest (variable)	€ ha^{-1}	1.93	*-0.1%*	1.93	*-0.1%*	2.89	*-0.2%*	2.94	*-0.1%*	2.89	*-0.2%*	1.71	*-0.1%*	2.89	*-0.2%*	1.96	*-0.1%*	3.25	*-0.2%*	6,304
In total	€ ha^{-1}	194.86	*-12.0%*	194.86	*-12.0%*	178.30	*-13.1%*	199.14	*-10.1%*	178.30	*-12.7%*	172.49	*-14.4%*	178.30	*-13.5%*	198.16	*-6.0%*	178.65	*-12.5%*	491,010
Harvest of maize																				
Hired labour (variable)	€ ha^{-1}	218.49	*-13.5%*	-		-		-		-		-		-		-		-		130,437
Imputed interest for hired labour (variable)	€ ha^{-1}	2.18	*-0.1%*	-		-		-		-		-		-		-		-		1,304
Total cost savings	€ ha^{-1}	781.06	*-48.1%*	560.38	*-34.5%*	545.16	*-40.1%*	565.69	*-28.8%*	545.16	*-38.8%*	538.02	*-44.8%*	545.16	*-41.4%*	563.69	*-17.0%*	545.92	*-38.3%*	
Total acreage in study area	€ ha^{-1}	597		413		464		459		221		156		114		111		64		
Total cost savings in study area	€	466,291		231,439		252,953		259,653		120,480		83,931		62,148		62,570		34,939		1,574,403

[a] Harvest of maize by the association.

[b] Harvest of maize by farmers.

(X): Contribution to the reduction of the total costs of production.

3.4.1.3 Bioenergy production

The total costs for producing bioenergy in the association's biogas plant were 3,065,000 €, including the cost for the substrates and depreciations as the major cost components (Table 3-12). Although the biogas plant generated significant profits in 2012, no taxes on profit and income had to be paid. This was due to the losses carried forward from previous periods which were offset against the profits generated in 2012. The benefits for the operators of the biogas plant from purchasing energy maize at a lower price from the member farmers were 43,000 €.

Table 3-12: Revenues, costs and added-value of bioenergy production in 2012 (based on ABWV BS (2012) and own calculations).

Biogas plant of the association	€ a^{-1}
Revenues	
Feed-in tariffs and gas sales	3,299,327
Costs	
Raw materials and operating supplies	132,936
Substrates	1,246,830
Purchased services	286,609
Hired labour	64,850
Personnel	261,463
Depreciations	544,125
Maintenance and repair	200,192
Administration	30,000
Other operations costs	100,170
Interest payments	195,173
Vehicle taxes	2,190
Total costs	3,064,539
Profits	234,788
Added-value[1)]	693,614

[1)] Added-value = Personnel costs + Interest payments + Vehicle tax + Profits.

3.4.1.4 Total benefits

The estimated savings from linking the value chains of wastewater treatment, crop production and bioenergy generation via the reuse of treated wastewater and sludge were 3,302,000 € (Figure 3-2). The member farmers' savings accounted for the greatest part of the benefits (48%). The savings of the operators of the wastewater treatment plant accounted for 40%, if it is assumed that the operators save the minimum cost for incinerating sludge in mono-burning plants.[9] The share of the savings of non-member farmers from spreading dewatered sludge in the greater Braunschweig area was 11%, while the proportion of the bioenergy producers in the total savings was only 1%.

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[9] This assumption was made, due to the recommendation of the German Federal Environmental Agency for incinerating sludge in mono-burning plants in case there is a legal withdrawal from the agricultural sludge utilization in Germany in the future (UBA, 2012).

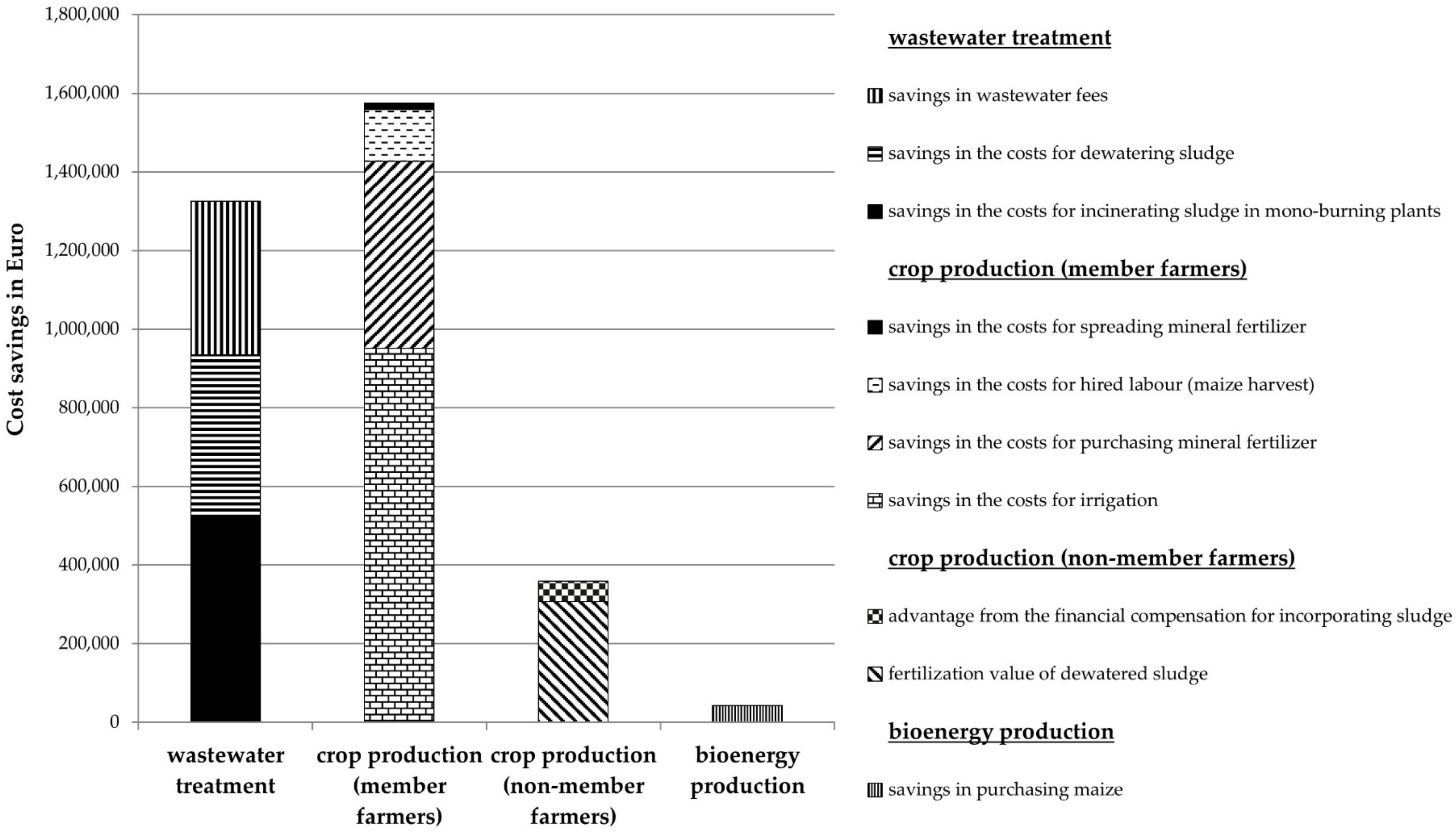

Figure 3-2: Cost savings in the Braunschweig wastewater reuse scheme in 2012.

3.4.2 Added-value generated in the wastewater reuse scheme

The total added-value generated only in the value chains of wastewater treatment and reuse was 4,307,000 € (Table 3-7). The comparison of the added-value generated in both scenarios of crop production revealed that linking the value chains of wastewater treatment and crop production results in a higher added-value in crop production. Depending on the crop, the substitution of wastewater and sludge for groundwater and mineral fertilizer increased the after-tax profits of the equity providers (i.e., the farmers) by between 399 € ha^{-1} and 427 € ha^{-1}. In contrast, the total added-value gains of all stakeholders participating in the value chain of crop production (i.e., the sum of the added-value gains of the equity providers, creditors, employees and the state) were only between 357 € ha^{-1} and 382 € ha^{-1} (Table 3-10). This was due to crowding out effects reflected in a partial decrease of the remunerations received by creditors, employees and the state, as described in Section 3.4.2.2. Total added-value gains in the value-chain of energy maize production rose to 525 € ha^{-1} if the irrigation of wastewater and the harvest of maize was conducted by the association.

The total added-value generated in the value-chains of crop production in the study area was 2,099,000 € in the scenario with groundwater use and 3,153,000 € in the scenario with wastewater reuse. Accordingly, the linkage of wastewater treatment and crop production resulted in an increase of 50% of the total added-value from crop production in the study area. The added-value generated from bioenergy produced by the associations was 694,000 €.

3.4.2.1 Distribution of the added-value

The added-value from the linked value-chains of wastewater treatment, crop production and bioenergy generation was 8,154,000 €. The value chains of wastewater treatment and reuse accounted for the greatest part of the added-value (53%). Food crop production in the association territory accounted for 28%, energy crop production (maize and rye) for 10% and for bioenergy production 9% of the total added-value (Figure 3-3).

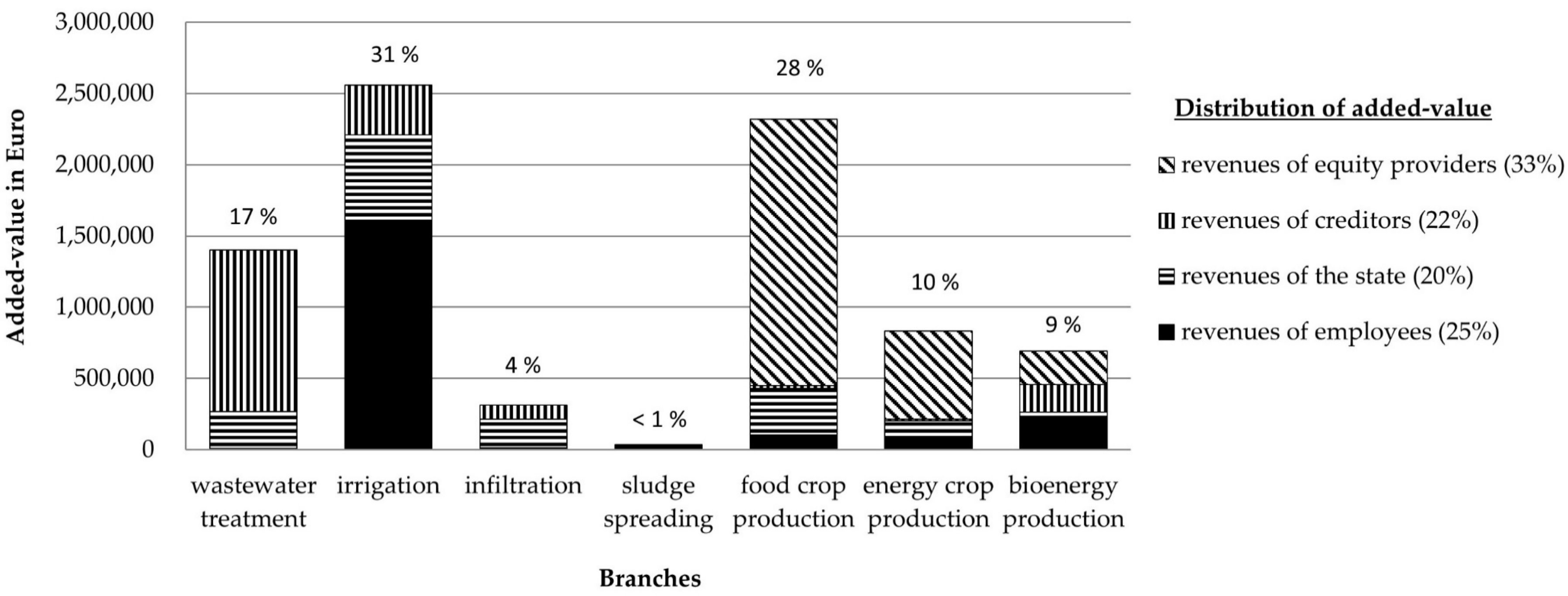

Figure 3-3: Added-value and its distribution among stakeholders in the Braunschweig wastewater reuse scheme in 2012.

Among stakeholders, the largest part of the added-value was captured by equity providers, including the operators of the biogas plant and the farmers, who received 2,725,000 € (33%) of the total added-value as after-tax profits. Employees obtained 2,042,000 € (25%) as net wages. Creditors received 1,807,000 € (22%) in interest payments and the state received 1,580,000 € (20%) in taxes, fees, and social contributions of employers and employees.

The added-value for the local economy was 6,277,000 € (77%). This amount of the added-value remained in the communities in which the Braunschweig Wastewater Association is active (Table 3-13).

The most important contribution to the added-value for the local economy was the after-tax profits of equity providers (43%), followed by the net wages of employees (33%) and the interest payments to creditors (23%). About 95% of these remunerations remained in the local economy. By contrast, about 96% of the remunerations received by the state did not remain in the local economy. Local authorities were granted 15% of the income tax revenues and 2% of the VAT revenues. Only these shares flowed back to the communities that host the association and contributed to the added-value for the local economy. The payments for social security, vehicle tax, wastewater and groundwater extraction fees went completely to the national insurance, the federal and the state governments. These payments were transferred completely out of the locality and did not contribute added-value to the local economy. In total, the outflow of added-value from the locality was 1,876,000 €, or 23% of the total added-value.

Table 3-13: Added-value of the Braunschweig wastewater scheme remaining in the local economy in 2012.

Stakeholders	Remunerations received by the stakeholders	Added- value	Share remaining in the local economy	
		€ a^{-1}	%	€ a^{-1}
Equity providers	After-tax profits	2,725,249	100	2,725,249
Employees	Net wages	2,041,905	100	2,041,905
Creditors	Interest payments (wastewater treatment and reuse)	1,582,392	80	1,265,913
	Interest payments (crop production)	29,069	86	25,000
	Interest payments (bioenergy production)	195,173	80	156,138
State	Social contributions	497,024	0	0
	Income tax	358,661	15	53,799
	Business tax	-	-	-
	Value-added tax	465,180	2	9,304
	Vehicle tax	25,471	0	0
	Wastewater fee	230,425	0	0
	Groundwater extraction fee	3,088	0	0
	In total	8,153,636	77	6,277,308

3.4.2.2 *Crowding out effects*

The crowding out effects on the added-value from crop production were about 306,000 €. These effects were mainly due to smaller farmer labour inputs in the irrigation and fertilization, which in turn decreased the wage payments to employees in agriculture by 87,000 € and the social contributions to the state by 47,000 € . Similarly, the reduction of capital use by farmers led to a decrease of the interest payments received by creditors by 119,000 €. The revenues of equity providers of feedstock for biogas production (i.e., maize farmers) were reduced by 43,000 €, due to the difference in the price paid by the association and the price on the region's market. Finally, the use of wastewater instead of ground-water decreased the payments from farmers for the groundwater extraction fee by 13,000 € a^{-1}. However, if the payments of the association for using groundwater for irrigation at peak times are considered, the effective reduction of the groundwater extraction fees is only 10,000 € a^{-1}.

Table 3-14 shows the impact of the crowding out effects on the distribution of the added-value from crop production among the stakeholders. Compared to the scenario with groundwater use, the remunerations of the creditors were 80% and the remunerations of the employees were 33% lower than in the scenario with wastewater reuse. In contrast, the remunerations of the equity providers (i.e., farmers) were 88% higher. This was caused by the overall savings in food and energy crop production which offset the effect of the partial decrease in the revenues of maize producers. The total remunerations of the state were 27% higher, due to higher income tax payments of farmers resulting from the increase of the profitability of crop production. This effect exceeded the decrease in social contributions of employers and employees and the reduction of the payments of the groundwater extraction fee.

Table 3-14: Distribution and change of added-value from crop production among stakeholders for different scenarios of crop production.

Stakeholders	Scenario with groundwater use		Scenario with wastewater reuse		Delta	
	(€)	(%)	(€)	(%)	(€)	(%)
Remunerations of equity providers	1,327,415	63%	2,490,461	79%	1,163,046	+88%
Remunerations of employees	266,940	13%	179,444	6%	-87,496	-33%
Remunerations of creditors	147,595	7%	29,069	1%	-118,525	-80%
Social contributions	*142,604*	*7%*	*95,862*	*3%*	*-46,742*	*-33%*
Groundwater extraction fees	*13,281*	*1%*	*-**	*0%*	*-13,281*	*-77%*
Income taxes	*200,697*	*10%*	*358,661*	*11%*	*157,964*	*+79%*
Remunerations of the state	356,582	17%	454,523	14%	97,941	+27%
Total added-value	2,098,532	100%	3,153,497	100%	1,054,965	+50%

* The payments of the association for the groundwater extraction fee (i.e., 3,088 €) are not included here as they were assigned to the added-value from wastewater treatment.

3.5 Discussion

The study's central questions are relevant for practitioners involved in agricultural wastewater reuse schemes, as well as for stakeholders at the national and international level concerned with future wastewater management practices. Although the scope of our quantitative analysis is limited in the sense that we do not consider transaction costs, non-pecuniary externalities and further parameters for measuring economic success, we can still affirm that the presented results contribute to the discussion on the potential benefits and outcomes of linking value chains of wastewater treatment, agriculture and bioenergy. In particular, the results may contribute to a solid basis of information and knowledge about the economic impacts of agricultural wastewater reuse schemes for local economic development.

The nexus and value chain frameworks used here proved to be helpful for structuring and guiding the research, as they created a common ground to combine the theoretical concepts of circular economy and added-value. The combination of the methodological approaches of cost/benefit analysis and value-chain analysis enabled us not only to quantify the cost and benefits to the equity providers, but also the cost and benefits to employees, creditors and the state as well as the regional economic effects. The proposed approach may provide a tool for practitioners and decision makers to better evaluate and communicate the value of wastewater reuse schemes for local economies and making more sustainable decisions.

An empirical observation made in this study is that the agricultural reuse of wastewater and sludge led to the development of linked regional value chains which did not only link the use of resources across sectors, but also produced a variety of interconnected relationships and interdependencies between actors. The wastewater association benefits from the farmer as customers of the wastewater and sludge and from the local supply of energy crops. Conversely, the farmers benefit from the supply of inputs and services, such as the irrigation infrastructure and machines, as well as the nutrient-rich irrigation water and sludge. The energy crop producers benefit by having a local buyer for their produce as well as from the outsourcing of the maize harvest to the association. The city of Braunschweig and surroundings communities benefit from the provision of clear water as well as electricity and heat from bioenergy production. Despite the many synergies arising from these interrelations, networks of interconnected relationships do not only provide opportunities, but also constraints on the action of actors (Brass et al., 2004). These constraints may discourage actors from entering into alternative opportunities of cooperation (log-out effects) or make them persist in less productive business relationships (log-in effects) (Möller, 2006). Member farmers of the association are restricted in their choice of crops for cultivation, excluding particularly crops for direct consumption. Hence, they may forgo the opportunity to obtain higher profits and added-value from producing fruits or vegetables. Single producers of sugar beets and potatoes have to occasionally deal with problems of marketing their products, as not all purchasers are willing to accept products irrigated with treated wastewater and sludge. Single landowners as members of the association are not allowed to freely resign from the association but have to be discharged from it. Similarly, the landowners are restricted in selling their land for purposes other than for agricultural production (e.g., construction purposes). Furthermore, the association is allowed to prescribe the structure of the cultivated crops if the cultivation plans of the member farmers do not guarantee an all-season acceptance of the effluent and utilization of the nutrients contained in it. However, the cultivation of energy crops provides an opportunity for farmers to increase their scope of action, to diversify their cropping pattern, and may even compensate for the missed potential of added-value from producing fruits and vegetables and strengthening the acceptance of the reuse scheme.

In the study area the main part of the generated added-value remained in the communities that host the wastewater association. Our findings on the share of the local economy in the added-value coincide with the conclusions from other authors who state that local production, consumption and disposal of goods and services are conducive to increasing the regional share of added-value (Bentzen et al., 1997; Hoffmann, 2009; Kimmich and Grundmann, 2008; Kosfeld and Gückelhorn, 2012; Marcouiller et al., 1996). In particular, the studied case shows how the conversion of waste products from wastewater treatment into usable inputs for agriculture can generate additional added-value and establish regional value and substances cycles. Furthermore, the study shows how the agricultural reuse of wastewater and sludge can replace ground-water and imported mineral fertilizer and therefore reduce the consumption of natural resources as well as the outflow of capital from the region.

We observed that the operators of the wastewater treatment plant and the farmers entertain a variety of long-term commercial relationships with local suppliers, service providers and traders. The activities of the association may also lead to an expansion of the production of the upstream suppliers and, therefore, may further increase the added-value in the study area. The spending of the additional income that remains in the locality will stimulate additional demand which in turn stimulate further production. These so-called induced or multiplier effects can continue and, therefore, further increase the added-value for local economies (Kosfeld and Gückelhorn, 2012). The quantification of the indirect and induced effects was beyond the scope of our analysis, yet have to be taken into account for a more comprehensive assessment of the impact of linked value chains on local economies.

The findings for the studied case indicate crowding out effects and changes in the distribution of the added-value among stake-holders. In the value chains of crop production, we found that the added-value gains from the reuse of wastewater and sludge are distributed unevenly among stakeholders and some stakeholders even experience losses of added-value (see Table 3-14). However, crowding out effects were lower than the overall added-value gains in crop production, i.e., the net impact on the added-value were positive. Furthermore, the irrigation operations and the conduction of the maize harvest by the association also generate additional payments of interests and wages in the value chains of wastewater treatment. These effects may outbalance the crowding out effects in crop production by increasing the share of employees and creditors in the added-value generated in the value chains of wastewater treatment. In fact, the strength of the studied wastewater reuse scheme is that all involved actors have a monetary benefit from their engagement in the scheme. We found that the total share of the single stakeholders in the total added-value from the reuse scheme is distributed evenly (see Figure 3-3). We believe that this has contributed to enhancing the acceptance of the reuse scheme in Braunschweig.

The validity of the presented results is subject to the assumption that crop yields do not differ significantly when using ground-water instead of wastewater. The possibly different impacts of groundwater and wastewater irrigation on crop yields could not be tested in our study, due to a lack of data on crop yields for the two scenarios. Moreover, we did not consider the impact of external costs and benefits when assessing the wastewater reuse scheme. Recent studies have shown that externalities can significantly influence the economic feasibility of wastewater reuse projects (Garcia and Pargament, 2015; Molinos-Senante et al., 2011). The studied reuse scheme may not only be justified by monetary reasons but also by non-monetary environmental benefits or the increase in the availability of a scarce resource. Further research is needed to determine the impact of wastewater irrigation on the crops' yields, the associated costs as well as the effects of externalities.

The agricultural reuse of wastewater and sludge in the study area requires high safety standards and a regular monitoring in order to minimize hazards to humans and the environment (Remy, 2012). Currently, issues of the presence of trace contaminants such as pathogens, pharmaceuticals and endocrine disruptors are being critically questioned (Pedersen et al., 2005; Toze, 2006). As these negative externalities may significantly influence the benefits of the reuse scheme, we also recommend further research to analyse the impact of potential risks and the associated costs on the benefits of the studied wastewater reuse scheme.

3.6 Conclusion

This study indicates that the reuse of treated wastewater and sludge in agriculture may be conducive to the development of linked regional value chains for providing water, crops and bioenergy. In the studied area the linkages between the value chains bring about cost savings, a higher added-value from crop production, and a high share of added-value for the local economy. In the value chain of wastewater treatment, the reuse of wastewater and sludge serves as a final treatment step and reduces the costs of wastewater treatment and sludge disposal. In the value chain of crop production, it reduces the costs of irrigation and fertilization. Since it provides water from an alternative resource and a substitute for mineral fertilizers, it may also lessen the dependency of crop production on natural fresh water resources and mineral fertilizer in arid and nutrient-poor areas.

We conclude that the linking of the value chains of wastewater treatment, crop production and bioenergy production via the agricultural reuse of wastewater and sludge can contribute to developing regional economic and substance cycles, thus enhancing the competiveness of regions and meeting the demands for a more sustainable use of resources in wastewater treatment and crop production. However, for the study area, we also found that the agricultural reuse of wastewater and sludge within interconnected value-chains can restrict actors and lead to crowding out effects and changes in the distribution of the added-value along the value chains.

In order to compensate actors for the restrictions and strengthen acceptance, agricultural wastewater reuse schemes should provide additional opportunities that enable the actors to increase their scope of possibilities and make up for missed economic potential. In case of legal restrictions for food crop production, these opportunities can be provided by combining wastewater reuse schemes with bioenergy production and be enhanced with the provision of additional agricultural services for cultivating and harvesting energy crops. Besides the economic benefits for cities, operators of wastewater treatment facilities and farmers, acceptance of the buyers and consumers of agricultural products irrigated with wastewater is of equal importance. As buyers and consumers might reject purchasing crops irrigated with wastewater, assuring them that high quality standards have been met, e.g., through certification proofs, is needed. Furthermore, agricultural reuse schemes should involve as much as possible regional-located employees, creditors and suppliers in order to keep a high share of added-value for the local economy. In this context the communication of the regional economic impact of wastewater reuse schemes can be essential to overcoming rejection by affected residents, authorities and communities.

3.7 Outlook

The persistence of the studied reuse scheme in its present form will very much depend on possible changes in the institutional regulation of the agricultural sludge utilization. In case of future legal restrictions on the agricultural sludge use, the operators will have to seek for thermal options for the disposal of sludge, which will require additional investments and increase the operating costs of wastewater treatment. At the same time, farmers will need to substitute the nutrients supplied by the sludge by imported mineral fertilizer. This may significantly reduce the benefits of the reuse scheme, since the operators of the wastewater treatment plant and the farmers mainly take advantage of the cost savings from sludge disposal and fertilization. In addition, higher application rates of commercial mineral fertilizer will increase the outflow of capital from the locality and decrease the share of the added-value for the local economy.

The analysis of the impact of institutions on the performance of linked value chains is an interesting subject for future research, since we observed that the transactions between the value chains of wastewater treatment, crop production and bioenergy generation require proper institutions and governance structures to safeguard the functioning and sustainability of the linkage and the benefits obtained from it. As the understanding of the mutual influence of transactions and institutions and governance structures might be of great importance for the future development of wastewater reuse in agriculture, we suggest further research to analyse the interplay of transactions according to their properties and the institutional coordination of the transactions associated with the linking of wastewater treatment, crop production and bioenergy generation.

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4 Governing Transactions and Interdependences between Linked Value Chains in a Circular Economy: The Case of Wastewater Reuse in Braunschweig (Germany)

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Abstract

Reusing wastewater in agriculture has attracted increasing attention as a strategy to support the transition towards the circular economy in the water and agriculture sector. As a consequence, there is great interest in solutions for governing the transactions and interdependences between the associated value chains. This paper explores the institutions and governance structures for coordinating transactions and interdependences between actors in linked value chains of wastewater treatment and crop production. It aims to analyze how transactions and interdependences shape the governance structures for reusing wastewater at the local level. A transaction costs analysis based on data from semi-structured interviews and a questionnaire is applied to the agricultural wastewater reuse scheme of the Wastewater Association Braunschweig (Germany). The results show that different governance structures are needed to match with the different properties and requirements of the transactions and activities between linked value chains of wastewater treatment and crop production. Interdependences resulting from transactions between wastewater providers and farmers increase the need for hybrid and hierarchical elements in the governance structures for wastewater reuse. The authors conclude that aligning governance structures with transactions and interdependences is key to efficiently governing transactions and interdependences between linked value chains in a circular economy.

Keywords: agriculture; wastewater reuse; irrigation; value chains; linkage; interdependence; institutions; governance structures; transaction costs, circular economy

4.1 Introduction

Increasing waste production and the scarcity of natural resources are expected to aggravate with growing populations and consumption. For this reason, solutions for reducing waste and recycling and reusing materials are gaining importance. In this context, the concept of the circular economy has attracted increasing attention from policy, science, business, and civil society. The circular economy is often characterized as an "industrial economy that is restorative or regenerative by intention and design" [1] (p. 7). In contrast to the largely linear "take-make-use-dispose" economic model, the circular economy aims to minimize waste and to keep the value of products, materials, and resources in the economy for as long as possible [2].

Moving towards a more circular economy could provide many opportunities, including reduced pressures on the environment, enhanced security of supply of raw materials, increased competitiveness, innovation, growth, and jobs [2,3]. However, the transition towards a circular economy is challenging, since it requires, among other things, finance, economic enablers, and technical skills, as well as fundamental changes in consumer behavior, business models, and last but not least, institutions and governance at all levels [3]. The European Commission has addressed these issues by presenting an action plan including legislative proposals on EU waste policy, areas for actions, and specific measures to promote the implementation of the circular economy [2]. One of the areas for action proposed in the plan is the promotion of reusing treated wastewater in agriculture.

In safe conditions, the reuse of wastewater presents an opportunity to reduce the demands on natural water resources and the discharge of pollutants to surface water bodies [4]. Furthermore, it can increase crop yields [5–7] and reduce purification levels and wastewater treatment costs [8–10]. Since wastewater supplies nutrients, it can also reduce the application of mineral fertilizer and decrease fertilization costs [9,11]. Concerns about the reuse of wastewater in agriculture include potential health risks for farm workers and food consumers [12,13], soil salinization [14], and the accumulation of hazardous substances in soil and crops [13,15–19]. When reusing wastewater for irrigation, adequate risk management strategies, including the application of proper purification levels, periodic monitoring of soil and crop properties, as well as suitable irrigation, cultivation, and harvesting practices, are indispensable to minimize hazards to humans and the environment [4,14,20,21].

Reusing wastewater in agriculture is characterized by transactions between the value chains of wastewater treatment and crop production, like the irrigation of wastewater for cultivating crops. The transactions create linkages and interdependences between the value chains due to shared resources (e.g., land), input–output relations (e.g., water and nutrients), and interdependences of activities and actors (e.g., interdependence of irrigation and crop cultivation practices and the respective providers and users of water) [9]. As a result of such linkages and interdependences, linked regional value chains and value cycles may develop [9]. Empirical studies show that value chains integrated within local economic cycles can reduce costs [22] and contribute to an increment of added-value for regional economies [23–26]. Findings from an added-value analysis provide evidence that linking the value chains of wastewater treatment and crop production by reusing wastewater can conserve natural resources and lead to significant cost savings, added-value gains, and a high share of local added-value [9].

However, despite the benefits associated with wastewater reuse, there is still no widespread implementation of wastewater reuse applications in the European Union [27]. Studies on the reuse of wastewater show that the challenges for implementing more reuse applications lie, among others, in the design of institutions and governance structures for reusing wastewater [27–32]. At the EU level, no common standards or quality guidelines for wastewater reuse have been implemented yet [28,33]. Instead, member states are expected to adopt the requirements of various EU directives correlated with water reuse applications due to health and environmental concerns [28,33]. The principal directives with implications for wastewater reuse are the Water Framework Directive and the Urban Waste Water Treatment Directive. The Water Framework Directive establishes "a framework for action in the field of water policy and indirectly recognizes reuse as a strategy for increasing water availability, which thereby contributes to the good quality status of water bodies" [33] (p. 560). The Urban Waste Water Treatment Directive concerns the quality of wastewater discharged to receiving waters and states that "treated wastewater shall be reused whenever appropriate" [34] (p. 4). This implies that "wastewater reuse is acceptable in as much as it does not breach other EU legislation or national laws" [33] (p. 560). Other directives containing provisions that are relevant to water reuse include the Groundwater Directive, the Drinking Water Directive, the Sewage Sludge Directive, the Nitrates Directive, the Thematic Strategy for Soil Protection, the Bathing Water Directive, the Freshwaters Fish Directive, the Habitats Directive, and the Industrial Emissions Directive [28]. Remarkably, none of the directives "is directed at regulating or supporting water reuse as such" [33] (p. 561). Moreover, the non-existence of common criteria at the EU level for managing health and environmental risks related to water reuse is a cause of mistrust in the safety of water reuse practices and thus, one of the main obstacles for water reuse in Europe [33,35]. The EU Commission aims to overcome this barrier by proposing EU minimum quality requirements for water reuse in agricultural irrigation and aquifer recharge [35]. However, the proposed requirements are still being discussed [36] and have not yet become legally binding.

With the growing need for a transition towards a circular economy and the potential of wastewater reuse in terms of economic and environmental benefits, there is an increasing interest not only in developing common wastewater reuse criteria at the EU level, but also in appropriate governance solutions for wastewater reuse and interdependent value chains at the local scale [9]. This requires more research on the governance structures for reusing wastewater including analysis of the specific transactions and interdependences between the value chains of wastewater treatment and crop production and analysis of the alignment of governance structures with transactions and interdependences. The alignment of governance structures with transactions is essential since misalignments can result in lower profitability and higher failure rates [37–40].

Existing studies on the governance of wastewater reuse have analyzed different applications for wastewater, including agricultural uses as well as urban, industrial, and potable uses. The studies have focused either on collaboration and risk management [41], or referred predominantly to the institutional challenges for the wastewater reuse sector at higher levels of governance, including regulatory and legislative issues at the national and international level [28,29,33,42–45]. Only a few researchers have analyzed the institutional arrangements for reusing wastewater for agricultural purposes at the local level [30–32]. Consequently, the empirical basis for deriving conclusions and recommendations for the governance of wastewater reuse at the local level is scant. Saldías et al. [31] analyzed the indirect and unplanned agricultural wastewater reuse in Hyderabad (India) and found that the ambiguous objectives of institutions, fragmentation among or within institutions, and a lack of regulatory enforcement are major constraints for developing formalized practices. A study by Al-Khatib et al. [30] investigated governance-related factors that influence the reuse of treated wastewater for irrigation in Jericho (Palestine) and identified overlapping and unclear responsibilities among actors, the absence of laws, as well as overlapping and conflicting provisions as obstacles for the reuse of wastewater. Saldías et al. [32] explored the institutional arrangements for a self-managed agricultural wastewater reuse scheme in Western Cape (South Africa) and identified the presence of an effective policy and regulatory framework as a key requirement for the successful implementation of the scheme.

However, from an institutional economic perspective, there is a clear gap in the current research on the design of governance structures for reusing wastewater at the local level. The body of literature is lacking in the characterization of the specific transactions between the value chains of wastewater treatment and crop production according to their properties, the analysis of the governance structures regarding their features and the consideration of the interdependences between the actors involved. Furthermore, the research on wastewater reuse has not yet addressed the alignment of governance structures with transactions and interdependences between actors. As a result, the understanding of the governance structures for coordinating the specific transactions that create linkages and interdependences between the value chains of wastewater treatment and crop production is insufficient. In particular, to the best of our knowledge, no previous studies have analyzed how transactions and interdependences between wastewater providers and crop producers shape the governance structures for wastewater reuse and how the alignment between governance structures with the transactions and interdependences facilitates reusing wastewater at the local level.

The present paper seeks to address this gap by looking at the specific transactions and activities in the agricultural wastewater reuse scheme of the Wastewater Association Braunschweig (Germany) which uses treated municipal wastewater to irrigate food and energy crops. We aim to analyze empirically the interplay of the transactions and interdependences between the actors with the institutions and governance structures of the reuse scheme. In particular, the study will answer the following research questions:

(1) How do the properties of the transactions and the interdependences of actors shape the governance structures for reusing wastewater?

(2) How does the alignment of the governance structures with the transactions and interdependences contribute to the smooth operation of agricultural wastewater reuse schemes?

We assume that by better understanding how governance structures are shaped by transactions and interdependences between actors we can contribute to developing appropriate governance structures for wastewater reuse in a circular economy at the local scale. Moreover, understanding the alignment of governance structures with transactions and interdependences of actors may help to improve the performance of wastewater reuse schemes in a circular economy. With this paper, we seek to introduce a novel perspective in the discussion on governance structures for linked value chains—i.e., the perspective of transaction cost economics—which offers new possibilities for analyzing and interpreting circular economies.

The rest of the paper is structured as follows: Section 2 describes the conceptual and theoretical framing of the research with emphasis on the transaction cost theory. Section 3 introduces the case study and explains the methods employed for the collection and analysis of data. Section 4 presents the empirical findings from analyzing the case study, including a detailed description of the core characteristics of the actors, transactions, and institutional arrangements of the wastewater reuse scheme in Braunschweig. In Section 5, we discuss the results according to the research questions and the lessons learned for governing transactions and interdependences between linked value chains in a circular economy. In this section, we also discuss the research design and suggest future research directions.

4.2 Conceptual and Theoretical Framing

The conceptual and theoretical framing of this research draws on several concepts and theories described in the following sections, including the concept of linked and interdependent value chains in a circular economy, the related concepts of transactions, institutions, and governance structures in action arenas and action situations, as well as the theory of transaction cost economics.

The concept of the circular economy is a very young research field that "still requires development to consolidate its definition, boundaries, principles and associated practices" [46] (p. 703). A multitude of different circular economy definitions, varying with the actors and point of view, has been developed [1,2,46–51] but no commonly accepted definition has become established yet [46,52]. Several authors stress that the lack of a commonly accepted and shared definition could lead the circular economy discussion to a conceptual deadlock [46,49]. Bearing this in mind, Kirchherr et al. [49] encourage scholars to deliberate on the circular economy concept through the explicit adoption of a circular economy definition to facilitate cumulative knowledge development on the topic. In the study at hand, we refer to the definition of Kirchherr et al. [49] (pp. 224–225), who describe a circular economy as "an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations." The circular economy "is enabled by novel business models and responsible consumers" [49] (p. 229). We adopt this definition for our research as a working definition, since it provides a brief but comprehensive depiction of the core characteristics of the circular economy concept, including its principles, operating levels, aims, and associated implications and enablers. It is important to understand that moving towards the circular economy implies "a fully systemic change, affecting all stakeholders in the value chain" [53] (p. 12). We note that "a circular economy goes beyond the pursuit of waste prevention and waste reduction to inspire technological, organizational and social innovation across and within value chains" [53] (p. iv).

Applying the thinking of the circular economy to water means to transform the conventional linear water use model—which is based on extracting, treating, distributing, consuming, collecting, treating, and disposing water—into a circular water use model [54]. In such a model, "wastewater is not considered as waste but rather as a valuable non-conventional resource" [55] (p. 229) that can generate additional added-value [9,22], and that should be circulated to preserve natural resources of water and nutrients [55]. In contrast to the linear model where water becomes successively polluted [56], the circular water use model aims at reducing pollution [57]. Further aims of the circular water economy are the reduction of freshwater demand, the reuse of wastewater [57–59], and increased retention of water [57]. We refer to this model but focus only on the reuse of wastewater in agriculture.

Figure 4-1 shows the flow of water in the linear water use model, in contrast to the wastewater reuse model with crop production. The figure indicates that human water consumption is based on the treatment and distribution of water resources extracted from the natural system. After consumption, wastewater is ideally collected for treatment. Subsequently, the treated water is used in two different ways depending on the economic water use model. In the linear model the treated water leaves the economy via disposal without further use. In this case, crop production depends exclusively on extracting water from the natural system. By contrast, in the wastewater reuse model the treated wastewater circulates in the economy through various options for reuse [59], including crop production.

In this case, the figure shows that the reuse of treated wastewater is an option for turning wastewater into a resource and reducing the demand for natural fresh water resources in crop production.

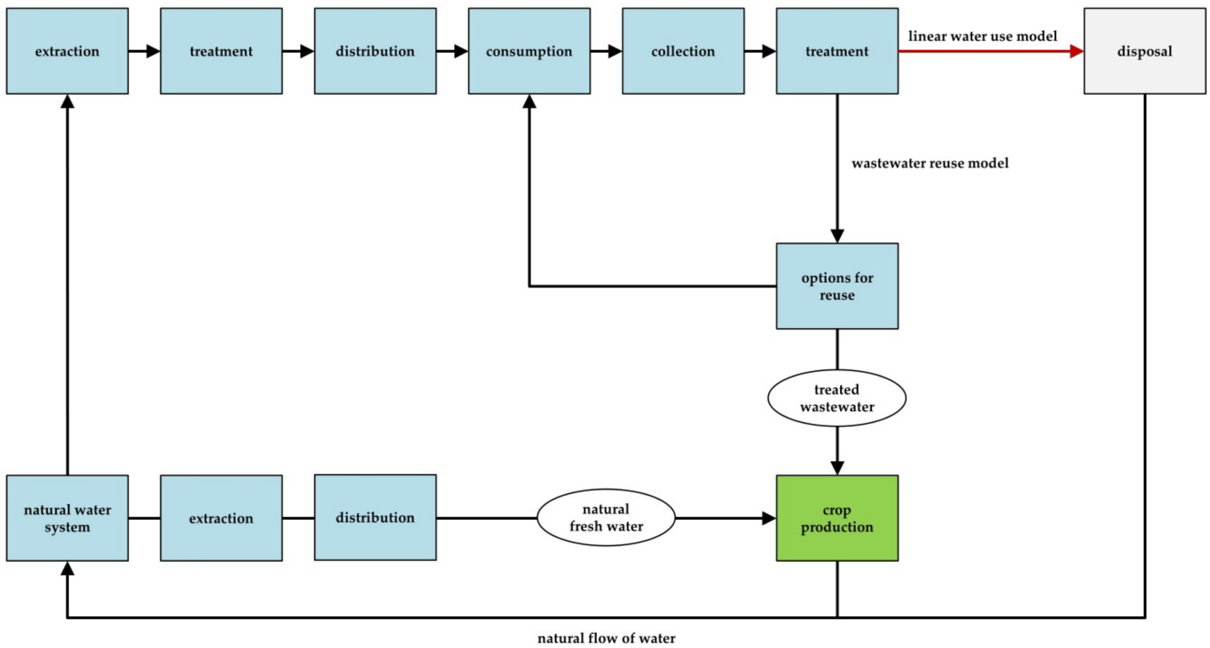

Figure 4-1: Flow of water in the linear water use model and in the wastewater reuse model with crop production.

Our approach for analyzing the reuse of wastewater in the circular economy is based on the concept of value chains, and focuses on the linkages and interdependences between the value chains of wastewater treatment and crop production at the local level. Value chains include "the full range of activities which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use" [60] (p. 4). In the case of wastewater reuse in agriculture, several goods and services are produced, including treated water and crops. Commonly, these goods pertain to distinct value chains. In the scrutinized case of wastewater reuse in agriculture, however, the production of treated water and crops goes together. This leads us to assume linkages and interdependences between the value chains of wastewater treatment and crop production in the scrutinized case. These interdependences may be due to the joint use of resources (e.g., land), the sharing of substances through input–output relations (e.g., water and nutrients), as well as immaterial interactions and interdependence of activities and actors (e.g., interdependence of irrigation and crop cultivation practices' respective providers and users of water) [9].

The linkages and interdependences between the value chains are believed to result from different physical and social processes taking place in distinct action situations located in various action arenas (The terms "action arena" and "action situation" originate from the Institutional Analysis and Development framework (IAD) developed by Ostrom [61]. We adopt the terms and related definitions for this research but do not further refer to the IAD framework.). An action arena is defined as the "conceptual space in which actors […] make decisions, take action, and experience the consequences of these actions" [62] (p. 20). The action arena includes one or multiple action situations and the actors who interact in the action situation regarding activities and/or transactions [62]. The action situation refers to the "social space where participants [...] interact, exchange goods and services, solve problems, dominate one another, or fight (among the many things that individuals do in action arenas)" [61] (p. 14).

In the present study, we conceptualize the agricultural reuse of wastewater as an action arena which is composed of three sub-arenas: (1) the provision of wastewater through the value chain of wastewater treatment; (2) the use of the wastewater as input in the value chain of crop production; and (3) the transference of wastewater between both value chains (Figure 4-2). The actors in all three sub-arenas participate in various action situations. Action situations associated with reusing wastewater in agriculture include, for instance, provision situations in which actors provide resources and services (e.g., land, water or irrigation service), distribution situations where actors define the allocation of resources (e.g., distribution of wastewater between farmers and plots) and appropriation situations in which actors make use of resources (e.g., use of wastewater and land for cultivating crops).

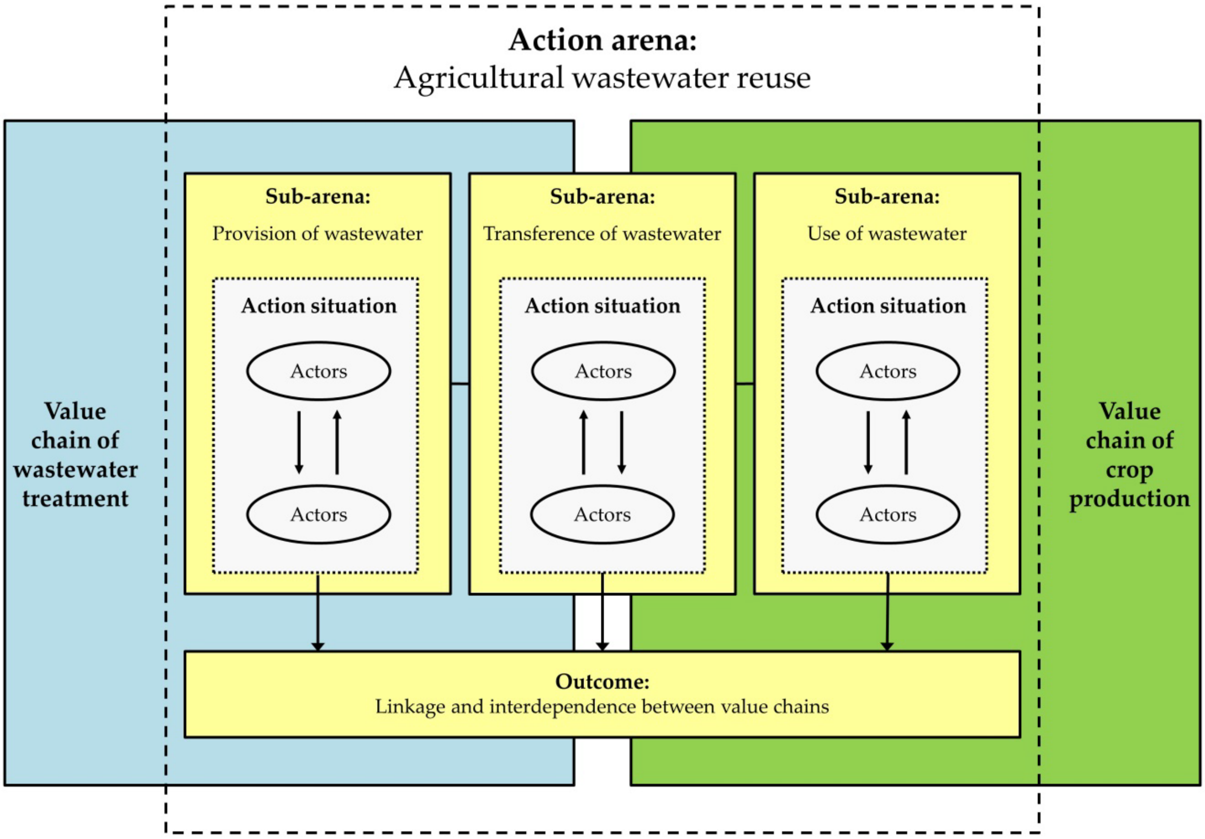

Figure 4-2: Conceptual framework for analyzing the agricultural reuse of wastewater.

The theory of transaction cost economics was chosen as the theoretical framework for understanding the alignment of transactions and governance structures in linked value chains. Researchers have used this framework to analyze various problems related to the economics of organization and contractual relationships [38,63]. Transaction cost theory has also been used in many empirical studies for explaining phenomena of agricultural supply chains [64–71]. The main goal of analyses based on the transaction cost theory is to assess the relative efficiency of organizing transactions while assuming that actors are rationally bound and tend to behave opportunistically. In our present research, we use the insights from the transaction cost theory to analyze the transactions and governance structures linking value chains in a circular economy for reusing wastewater and sewage sludge in agriculture. The basic unit of analysis is the transaction defined as "an exchange which occurs between two stages of the production/distribution chain as the product changes in form and/or in ownership rights" [72] (p. 17). The transaction cost theory emphasizes that transactions are associated with transaction costs because they require information, negotiation and conclusion of agreements, monitoring and enforcing compliance with those agreements, as well as adaptation of agreements [73,74].

Transactions differ mainly with respect to the three properties of asset specificity, uncertainty, and frequency, from which "the condition of asset specificity is the most important" [75] (p. 366). Asset specificity matters when actors invest in specific assets and refers to "the degree to which an asset can be redeployed to alternative uses and by alternative users without sacrifice of productive value" [76] (p. 59). The fundamental consequence of investing in specific assets is the creation of a condition of bilateral dependency which may allow actors to opportunistically siphon off the quasi-rents of the actors who made transaction-specific investments [77]. The property of uncertainty in transactions refers to the difficulties of anticipating exogenous disturbances and to predict whether the exchange partners may behave opportunistically [78]. Frequency indicates how often a certain transaction is repeated.

Transactions may cause interdependences between value chains, when actors or actions are affected by or depend on each other's actions [79,80]. Interdependences between value chains or actors may result "in either conflicts to be solved or opportunities for cooperation" [81] (p. 363). In order to mitigate conflicts and to realize gain from cooperation, actions and transactions leading to interdependences need to be regularized by institutions and governance structures [81]. "Institutions are the rules of the game of a society or, more formally, are the humanly devised constraints that shape human interaction" [82] (p. 3). Institutions can be either formal (e.g., laws, ordinances, etc.) or informal (e.g., norms, values, and conventions). In order to implement and enforce institutions, adequate governance structures are necessary. Governance structures are conceptualized as "organizational solutions for making institutions effective, i.e., they are necessary for guaranteeing rights and duties and their use in coordinating transactions" [81] (p. 360). The structures present distinct features such as incentive intensity, administrative control, capacity for autonomous and coordinated adaptations and contract law [77].

The feature incentive intensity of a governance structure characterizes the magnitude of the motivation of the transactional partners to be efficient and adapt to changing conditions [83]. Strong incentives are those provided by transactions in which gains from efficiency improvements flow directly to the individuals who contributed to the improvement. They stimulate individuals to innovate and increase efficiency. Weak incentives, by contrast, are those associated with transactions in which individuals can not personally lay claim to the gains from efficiency improvements [84,85]. The degree of administrative control in a governance structure describes to what extent hierarchical instructions and monitoring of activities are used for directing the actor's activities and efforts, in particular, for adapting to changes and for preventing actors from behaving opportunistically [83]. The autonomous adaptability characterizes how easy the transactional partners can adapt to changes independently from each other within a given governance structure. By contrast, coordinated adaptability describes the supportiveness of a given governance structure towards coordinated adaptations between transacting individuals [83].

Scholars categorize governance structures according to these features along a spectrum ranging from the pure, anonymous spot market to the completely integrated firm (hierarchy) [71,77,86]. Between these two pure forms of governance structures there is a continuum of hybrid (or intermediate) types of governance structures including various forms of long-term contracting, clusters, networks, symbiotic arrangements, supply chain systems, franchise arrangements, partnerships, cooperatives and alliances among firms [70].

Market governance structures are characterized by strong incentives and weak administrative control. The structures strongly support autonomous adaptations based on a strong legalistic contract law regime. In contrast, hierarchical governance structures are characterized by weak incentives and strong administrative control. They are strongly supportive to coordinated adaptations, and they are further characterized by a weak contract law regime [77]. Hybrid governance structures show "intermediate values in all features" [76] (p. 104) that describe markets and hierarchies. They are characterized by "semi-strong incentives, an intermediate degree of administrative apparatus, display semi-strong adaptations of both kinds, and work out of a semi-legalistic contract law regime" [76] (p. 281). Table 4-1 summarizes the distinguishing features of market, hybrid, and hierarchical governance. It shows that an increase (decrease) in intensity in one feature is accompanied by a decrease (increase) of intensity in another feature.

Table 4-1: Distinguishing features of market, hybrid, and hierarchical governance [77].

Features	**Governance structure**		
	Market	**Hybrid**	**Hierarchy**
Incentive intensity	++	+	0
Administrative control	0	+	++
Autonomous adaptation	++	+	0
Coordinated adaptation	0	+	++
Contract law	++	+	0

++ = strong + = semi-strong 0 = weak

Ménard [70] identified three empirical regularities within the great heterogeneity of hybrid governance structures: First, resource users in hybrid arrangements pool some of their resources but keep the associated ownership and decision rights distinct. Second, the coordination of the resource users in hybrids relies usually on contracts providing only a general framework which remains highly incomplete. Third, resource users in hybrids compete with each other as well as with other hybrid arrangements and other types of organization.

Transaction cost economists evaluate the relative cost-efficiency of coordinating transactions by assessing the fit between the properties of the transaction and the associated governance structure. They refer to the discriminating alignment hypothesis which predicts that "transactions, which differ in their attributes, are aligned with governance structures, which differ in their costs and competencies, in a discriminating (mainly transaction-cost-economizing) way" [77] (p. 277). In other words: actors will ideally assign transactions to the governance structure that minimizes transaction costs. Yet which governance structure fits with which kind of transaction? The transaction cost theory predicts that the market is the most efficient governance structure for non-specific transactions. By contrast, if the degree of asset specificity and uncertainty increases, it will be more efficient to organize the transaction in a hybrid or even in a hierarchical governance structure. Hybrids are efficient in coordinating transactions when relation-specific investments are strong enough to "generate substantial contractual hazards without justifying integration and its burdens, and when uncertainties are consequential enough to require tighter coordination than what markets can provide" [87] (p. 31). For transactions that are characterized by high degrees of asset specificity, transaction cost theory recommends organizing transactions in a hierarchy in order to minimize transaction costs [77].

4.3 Materials and Methods

We have chosen a qualitative research approach based on case study methods [88–91] for analyzing the governance structures for transactions and interdependences between actors in linked value chains of wastewater treatment and crop production. Qualitative research on case studies is commonly proposed by researchers for studying socioeconomic phenomena with a rather small number of observations [92], such as the combination of wastewater treatment and agricultural value chains. It allows researchers to study the complex nature of linked value chains in depth, as it facilitates describing transactions and governance structures regarding their characteristics and identifying different perceptions, attitudes and motivations that underlie and influence the behavior of the actors involved [93].

4.3.1 Case Study

The case study chosen for the analysis is the agricultural wastewater reuse scheme of the city of Braunschweig in Germany. This reuse scheme has gone through several developmental phases resulting in the combination of agricultural reuse of wastewater and sludge, crop production, and bioenergy production. The reuse scheme is managed by the Wastewater Association Braunschweig which was founded in 1954 with the aim of implementing a large-scale agricultural wastewater irrigation system in the region of Braunschweig. Since then, the reuse scheme has developed into a complex net of linked activities at regional level with various environmental and economic benefits [9]. The members of the association are the city of Braunschweig, the water board of the neighboring city Gifhorn, and 90 farmers with agricultural land in the association territory.

The scheme treats the municipal wastewater of the cities of Braunschweig and some neighboring communities. A full biological treatment process produces purified wastewater which is delivered for reuse from the treatment plant to a selected territory covering a coherent area of 2700 ha of cropland with infrastructure facilities for irrigation (e.g., roads, canals, pumping stations, pressure tubes, hydrants). The infrastructure—which is designed for a technical capacity to irrigate two-thirds of the irrigation area simultaneously—is operated by the association´s staff, who makes daily decisions about the distribution of the treated water on the farmer's cropland. Continuous water supply via irrigation is indispensable for cultivating crops in the region, since the sandy soils suffer from a climatic water balance deficit [94] and have a low water retention capacity [95]. The main crops cultivated by the farmers in the irrigation area are maize, wheat, sugar beets, and rye.

Nutrient-rich sewage sludge is another output of the treatment process which is added to the irrigated wastewater during the vegetation period. The sewage sludge accrued during the winter season is dewatered, stored, and spread as fertilizer in summer on croplands in the greater Braunschweig area. The reuse scheme includes a biogas plant which is operated by the association and which uses energy crops produced with wastewater and dewatered sludge as feedstock for its operations.

Figure 4-3 shows the simplified value chains of the reuse scheme and how they are linked by the physical transactions and activities associated with the agricultural wastewater and sludge use. The figure shows the outputs from the treatment of wastewater, including treated wastewater and sewage sludge. These outputs are further processed in the value chain of wastewater and sludge treatment before they are reused as inputs in the value chain of crop production for producing food and energy crops. The energy crops produced with wastewater and sludge are inputs for producing electricity and heat in the value chain of bioenergy production. In this way, the material flows of value chains are linked based on the reuse of treated wastewater and sludge. Figure 4-3 displays the actors involved, indicated by the abbreviations above the single process steps and products, as well as the focus of the analysis, indicated by the dashed line box.

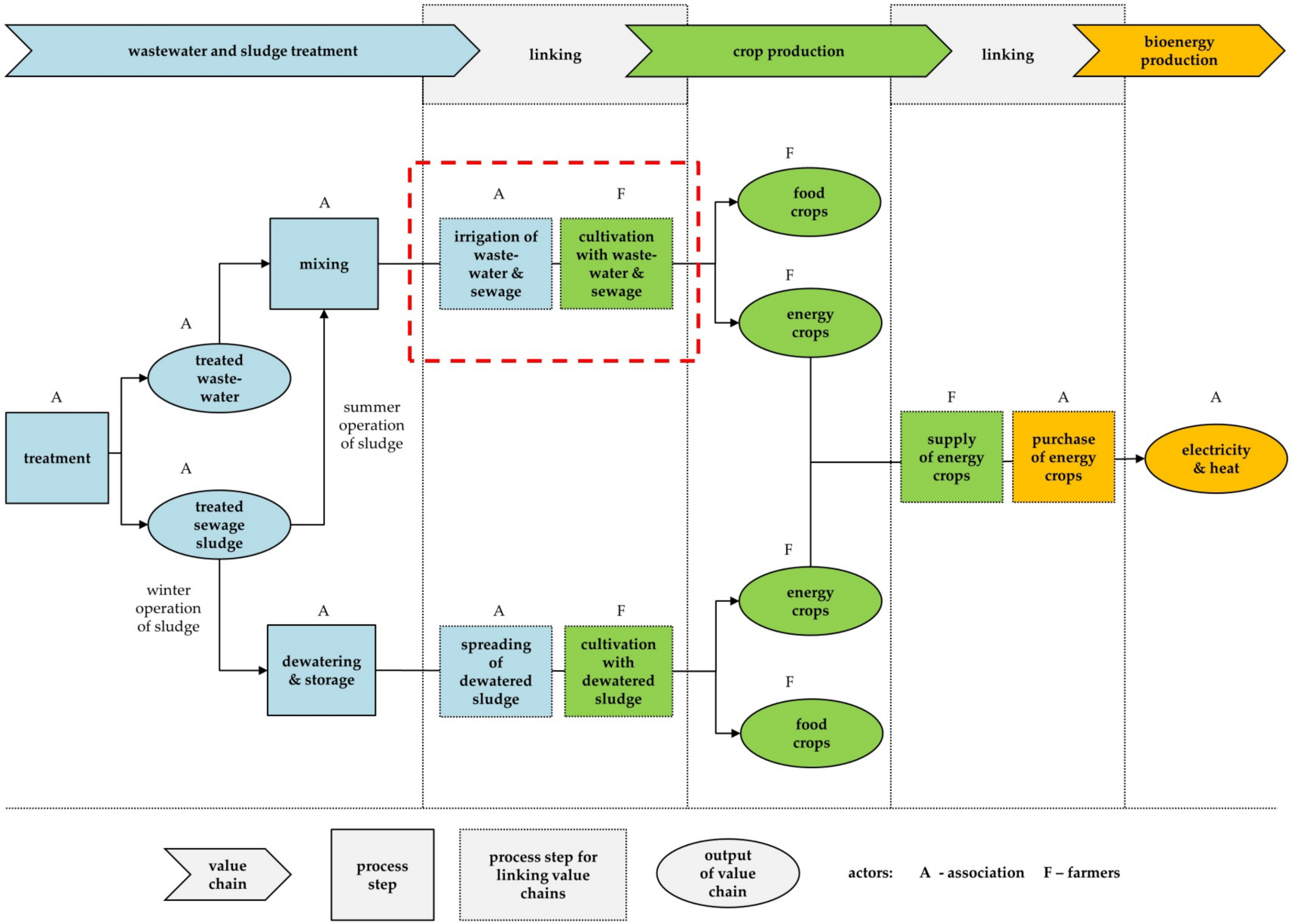

Figure 4-3: Linked value chains in the wastewater reuse scheme in Braunschweig.

4.3.2 Data Collection

The analysis draws on primary data collected between 2013 and 2016. We conducted six semi-structured in-depth interviews with eight key actors involved in the operation and management of the reuse scheme to obtain detailed information on the agricultural wastewater reuse in Braunschweig. The interviewees were carefully selected according to their roles in the reuse scheme, including farmers, managers, and employees, to learn about the topics addressed in the interviews from different perspectives. The interviews lasted between two and four hours, and took place in the administrative buildings of the Wastewater Association Braunschweig.

The interviews revolved around the operation and organization of the reuse scheme, the specific transactions and activities between the value chains of wastewater treatment and crop production, and the interests and motivations of the actors involved. In particular, the interviews focused on the properties of the transactions and activities, the interactions and interdependences between the actors, the institutional setting, and the features of the governance structures. The format of the interviews, in terms of duration and location, was chosen to give the interviewees enough time, space, and comfort to report comprehensively about the reuse scheme and respond in detail to the questions. This was done in order to facilitate a deeper understanding of the case study.

In addition to personal communication, we sent a questionnaire to the management of the association prior to the interviews for collecting data on the information exchange, communication, negotiation, contracting, monitoring, and adaptation between the actors involved in the reuse scheme. The questionnaire was to get a rough overview of the actor's interactions which we further elaborated upon in the interviews. We complemented the interviews and the questionnaire with five telephone interviews to clarify details and any open questions. The telephone interviews were conducted with some of the previously interviewed managers and employees and lasted between 30 and 90 min.

Furthermore, we conducted one face-to-face interview with three employees of the local water authority to gain information on the official permit and statutory regulations for reusing wastewater in the study area. The interview lasted 60 min, and the interviewees were selected according to their expertise in legal and practical matters of reusing wastewater. The information was supplemented by secondary data on the topic [96–98]. All face-to-face interviews were digitally recorded, and relevant parts were transcribed and summarized. During the telephone interviews, we took notes which were summarized. Table 4-2 provides details on all the interviews conducted within this study, including information about the date and duration of the interviews, the type of interviews (i.e., face-to-face or telephone interview) as well as anonymized information about the interviewees and their specific roles in the wastewater reuse scheme in Braunschweig.

Table 4-2: Description of interviews conducted with actors in the wastewater reuse scheme in Braunschweig.

Date	Duration	Type of interview	Interviewees	Roles of the interviewees
07.08.2013	115 min.	Face-to-face interview	Interviewee 1	Director of the association
			Interviewee 2	Head of the agricultural department of the association Deputy director of the association
			Interviewee 3	Chairman of the association
			Interviewee 4	Vice chairman of the association Farmer operating in the association territory
02.12.2013	150 min.	Face-to-face interview	Interviewee 1	Director of the association
			Interviewee 2	Head of the agricultural department of the association Deputy director of the association
			Interviewee 3	Vice chairman of the association Farmer operating in the association territory
02.12.2013	60 min.	Face-to-face interview	Interviewee 1, 2, 3	Employees of the local water authority
19.12.2013	360 min.	Face-to-face interview	Interviewee 1	Director of the association
			Interviewee 2	Head of the agricultural department of the association Deputy director of the association
			Interviewee 3	Chairman of the association
			Interviewee 4	Vice chairman of the association Farmer operating in the association territory
24.02.2014	80 min.	Telephone interview	Interviewee 1	Head of the agricultural department of the association Deputy director of the association
09.04.2014	65 min.	Telephone interview	Interviewee 1	Head of the agricultural department of the association Deputy director of the association
23.09.2014	30 min.	Telephone interview	Interviewee 1	Head of the administration department of the association
28.04.2015	180 min.	Face-to-face interview	Interviewee 1	Director of the association
			Interviewee 2	Head of the agricultural department of the association Deputy director of the association
			Interviewee 3	Chairman of the association
			Interviewee 4	Vice chairman of the association Farmer operating in the association territory
			Interviewee 5, 6, 7	Board member of the association Farmer operating in the association territory
27.06.2016	175 min.	Face-to-face interview	Interviewee 1	Head of the agricultural department of the association Deputy director of the association
06.07.2016	150 min.	Face-to-face interview	Interviewee 1	Head of the agricultural department of the association Deputy director of the association
20.09.2016	90 min.	Telephone interview	Interviewee 1	Head of the agricultural department of the association Deputy director of the association
19.12.2016	45 min.	Telephone interview	Interviewee 1	Head of the agricultural department of the association Deputy director of the association

4.3.3 Data Analysis

The present analysis focuses on the irrigation of treated wastewater where substance flows directly link the value chains of wastewater treatment and crop production (Figure 4-3). We began the analysis of the interview data by elaborating upon a system of thematic categories based on the elements of our conceptual and theoretical framework to systematically structure the data. The four main categories were (1) transactions and activities; (2) actors; (3) institutions; and (4) governance structures. These categories were subdivided into further categories also based on the elements of our conceptual and theoretical framework. The first category "transactions and activities" was split up into (i) asset specificity; (ii) uncertainty; and (iii) frequency. The second category "actors" was split into (i) tasks and responsibilities; (ii) interests; (iii) ownership and decision rights; (iv) interactions; and (v) interdependences. The third category "institutions" was split into (i) formal rules; and (ii) informal rules. The fourth category "governance structures" was divided into (i) contractual relations; (ii) incentives; (iii) command and control; and (iv) adaptions.

In the next step, we repeatedly went through the transcripts and notes and assigned all relevant text sequences to the matching categories. After this, we created additional thematic subcategories for each category according to the content of the material collected per category to further structure the data. Then, we scrutinized the transcripts and notes once again, and assigned all relevant text sequences to the matching subcategories. Finally, we identified the text sequences which were relevant for answering our research questions and summarized this material.

Building on this analysis, we continued by decomposing the sub-arenas of the agricultural reuse of wastewater and sewage sludge into different action situations. Decomposing the action arenas into different action situations allows for better understanding the multiple and complex linkages and interdependences between the value chains of wastewater treatment and crop production. After determining the case-specific action situations, we identified the specific elements of the action situations, including the focal transactions and activities, the participating actors, and their interactions. We then characterized the actors by describing their task and responsibilities, their interests, as well as their ownership and decision rights, before advancing with the four-step analysis of the discriminating alignment of transactions and governance structures as suggested by Williamson [99]:

First, we described the transactions and activities according to their properties including asset specificity, uncertainty, and frequency for better differentiation and uncovering the needs for regulation and coordination. In addition, we described the interdependences between the actors resulting from the transactions and activities; Second, we characterized the actor's contractual relations and scrutinized the governance structures in terms of the provision of incentives, the use of administrative control, and the capacity for autonomous and coordinated adaptations; Third, we worked out the efficiency of alignment between the governance structures and the properties of the transactions and activities according to the transaction cost theory. In other words: We assessed which governance structure would match the case-specific properties of the transactions and activities best. We focused on the condition of asset specificity, since it is the most important property for determining what governance structure minimizes transaction costs [75]. Fourth, we ascertained whether the expected alignments of the governance structures with the properties of the transactions and activities as derived from the theoretical framing are corroborated by our findings. Next, we analyzed how the properties of the transactions and activities including the interdependences between the actors shape the governance structures. Finally, we evaluated how the alignment of the governance structures with the relevant properties of the transactions and activities, including the interdependences, contributes to the smooth operation of the wastewater reuse in the studied case.

4.4 Results

The results section is structured according to the analyzed action situations identified on the basis of our conceptual framework and the information obtained from the interviews. First, we describe the actors participating in the different action situations with their interests, interactions, and their ownership and decision rights. Then, we characterize the focal activities and transactions by their properties, and determine the governance structures that would minimize transaction costs according to the discriminating alignment hypothesis. We then describe the existing institutions and characterize the governance structures by their features.

Drawing on our conceptual framework and the information obtained from the interviews, the analysis revealed the following three focal action situations that take place in the action arenas of the agricultural reuse of wastewater in Braunschweig (Figure 4-4).

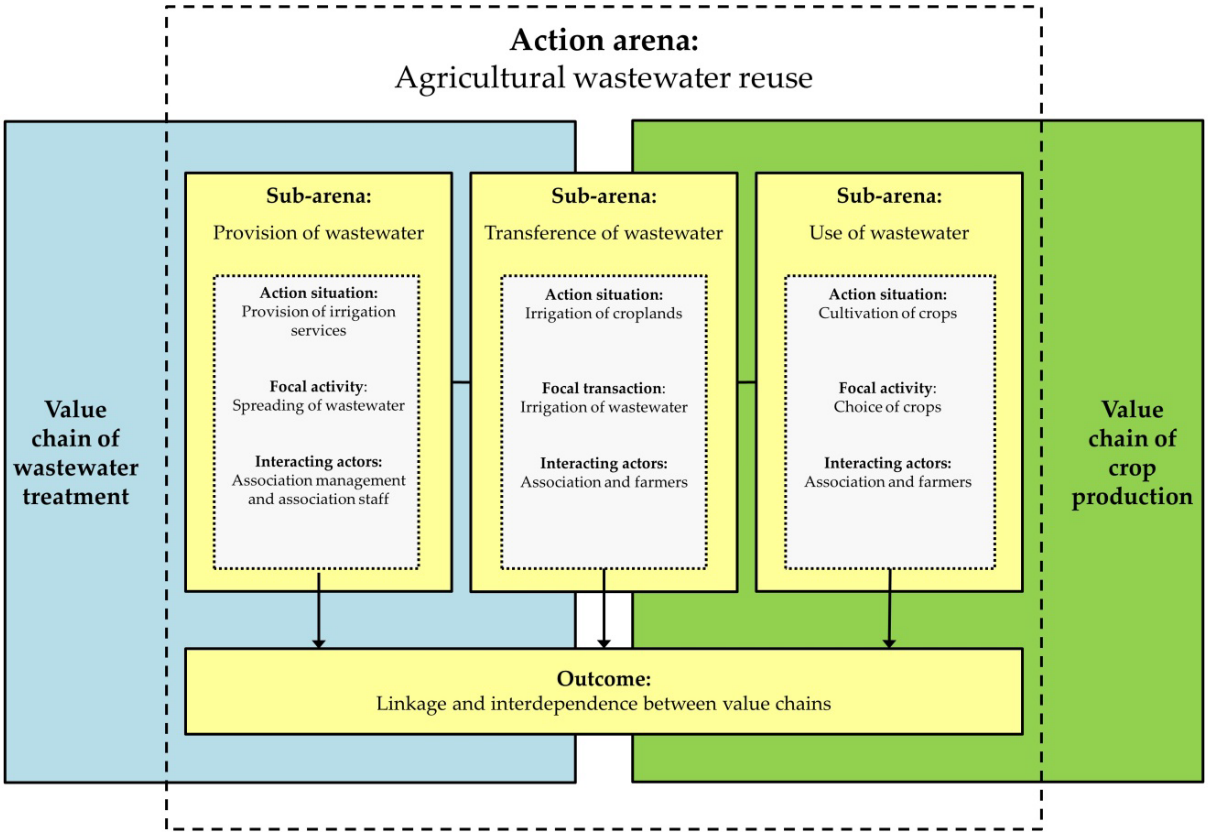

Figure 4-4: Action arenas and action situations of the agricultural wastewater reuse in Braunschweig.

The focal situation in the arena of wastewater provision is the provisioning of irrigation services for crop cultivation including the spreading of wastewater as the focal activity of the association staff. In this situation, the association management interacts with the association staff regarding the practical implementation of the spreading operations.

The focal situation related to the transference of wastewater between wastewater treatment and crop production is the irrigation of croplands with the irrigation of wastewater as the focal transaction between the association and the farmers. In this situation, the association interacts with the farmers regarding the provision of land and irrigation services as well as the distribution of the water and other practical matters of irrigation (e.g., schedule).

The focal situation in the arena of wastewater use is crop cultivation with wastewater, including the choice of crops a principal activity for farmers. This activity is influenced by the interaction between the association and farmers regarding the crops and cropping patterns on the irrigation fields. The joint outcome of the physical and social processes in the three arenas and situations is the linkage and interdependence of the value chains of wastewater treatment and crop production.

4.4.1 Provision of Irrigation Services

4.4.1.1 Actors and Actors' Rights

The actors involved in the provision of irrigation services include one manager of the association, six *rainmasters*, and twelve workers. The manager determines the dates for starting and ending the irrigation of certain crops (e.g., maize and sugar beets), as well as adding sewage to the irrigated wastewater. The *rainmasters* are in charge of implementing the decisions of the manager and coordinating the irrigation operations on site. They set up the schedules for the workers and decide about the distribution of the water, based on parameters such as the soil conditions and the development of the crops. The workers, whose task is to operate the irrigation machines, perform the operations only according to instructions from actors in the upper levels of the associations' hierarchy i.e., the *rainmasters* and the manager. All assets used by the association staff for providing irrigation-related services belong to the association. Neither the manager nor the *rainmasters* or the workers hold rights of ownership of the assets used for the operations. The interactions between the manager, the *rainmasters*, and the workers are driven by the interest of the association to spread the wastewater for reuse in a proper way without causing damage to the farmers, the residents, and the environment.

4.4.1.2 Focal Activity

The activity of spreading wastewater is characterized by a relatively high frequency of about seven to eight times throughout the vegetation period. The physical infrastructure (e.g., canals, pumps, pressure tubes, hydrants, irrigation machines) for spreading wastewater is highly specific in its use and site, as it cannot be easily moved nor used for other purposes.

The spreading of wastewater causes interdependences between the association and the farmers, since the crop yields of the farmer's depend, among other factors, on the ability of the association staff to spread the wastewater and sewage in a safe way without damaging crops and soils. The association has built up a good reputation for the safety and quality of the spreading operations. This reputation is indispensable to maintaining the trust of the farmers in the association and wastewater cultivation. The skills and experiences of the personnel operating the irrigation system are not specific to the spreading of wastewater as they may be easily utilized for similar activities in the agricultural sector.

4.4.1.3 Institutional Arrangements

Institutions and governance structures regulating the spreading of wastewater need to secure the safety and high quality of the related operations. The high specificity of the physical infrastructure and the special reputation of the association regarding the safety and quality of the spreading, raise the expectation that hierarchical governance could be an efficient solution to coordinating the interactions between the association management and the association staff regarding the operation of the spreading. In the following, we will characterize the institutions and governance structures in terms of the contractual arrangements, incentives, command and control, and adaptability.

The contractual arrangements between the association management and the association staff performing the spreading is based on long-term employment contracts, which are typically incomplete, as they only stipulate the basic conditions of the employment, including the general working tasks and remuneration. Potential conflicts between the association management and the staff regarding the spreading (e.g., improper operations) are settled internally within the association without involving courts or arbitrators.

The incentive intensity for the manager, the *rainmasters*, and the workers was found to be weak because the actors cannot personally lay claim to the benefits from cost savings or efficiency improvements in the spreading. Administrative command and control is the predominant steering mechanism as the association manager and the *rainmasters* direct the operations related to the spreading of wastewater and instruct the workers by means of commands transmitted in the form of oral and written instructions.

Administrative control, including monitoring activities and outcomes, is strong in order to ensure that operations are carried out in accordance with the legal regulations, and that the workers maximize their efforts in the interests of the association.

In terms of the adaptability, we observed that the manager arranges the adaptation of the spreading operations to any changes in the legal framework or technical matters. On the fields, the *rainmasters* are in charge of coordinating the adaptations of the operations (e.g., the adaptation of the schedules for the irrigation) to the weather and soil conditions, to the development of the crops and to ongoing cropping activities of farmers like pest management and fertilization. The capacity for coordinated adaptations is strong, due to the formal authority of the association manager and the *rainmasters* to direct the workers' spreading activities.

4.4.2 Irrigation of Croplands

4.4.2.1 Actors and Actors' Rights

The actors involved in the action situation of cropland irrigation are the association and the farmers. The relationship between the association and the farmers is characterized by separated ownership and decision rights. The association owns the wastewater and the infrastructure of the irrigation, while the farmers own or lease the land of the irrigation fields. The manager responsible for irrigation has the authority to decide about the dates for starting and ending the irrigation of certain crops (e.g., maize) without consulting the farmers, but generally asks board members of the association with agricultural background for advice. The *rainmasters* who implement the decisions of the manager decide about the sequence of the fields to be irrigated. They make the decisions about the sequence independently from the farmers, but coordinate individual irrigation schedules with the farmers. The interactions between the association and the farmers are driven by the complementary interests of the association to release the wastewater and sewage for its reuse into the farmer's fields and the interests of the farmers to obtain irrigation services and nutrient-rich water from the association for cultivating crops.

4.4.2.2 Focal Transaction

The irrigation of wastewater as a transaction between the association and the farmers is characterized by the high frequency of the operations and the high specificity of the physical infrastructure as described in Section 4.4.1.2. Another characteristic of the irrigation transaction is the site specificity of the irrigated fields because of their immovability and proximity to the wastewater treatment plant. Natural rainfall, evapotranspiration rates, crop growth, and soil conditions are nature-related sources of uncertainty that determine the optimal quantity and timing of wastewater applications. In dry periods, the crops may experience water stress if rainfall and wastewater are less than required. In wet periods, the water supply from rainfall and irrigation may exceed the maximum water absorption capacity of the crops and soil. An oversupply of wastewater increases the risk of crop damages and excessive inputs of nutrient and pollutants into soils, groundwater, and adjacent water bodies. The capability of the association to suspend irrigation is limited since wastewater is produced continuously.

The irrigation transaction establishes a relationship of interdependence between the association and the farmers based on the complementarity of the resources of water and land, the specificity of the irrigation infrastructure, as well as the mutual influence between the activities of crop cultivation and wastewater irrigation. On one hand, the association depends on the cooperation with the farmers, since the access to their fields is indispensable to releasing the wastewater for its reuse. Furthermore, the production value of the irrigation infrastructure would decrease if the farmers were to take land away from the irrigation area or refuse to irrigate their fields. On the other hand, the farmers depend on the cooperation with the association, since the provision of water and irrigation services by the association are essential for securing the profitability of cultivation under unfavorable natural conditions. Other matters that produce interdependences between the association and the farmers are related to the technical capacity of the irrigation equipment and the practice of adding sewage to the wastewater. The limited capacity of the irrigation equipment affects cultivation as it requires cropping patterns that include a variety of crops with different temporal demand for water. The practice of adding sewage to the wastewater affects cultivation, since the nutrient loads contained in the sewage are an important determinant for the farmer's individual fertilization management.

4.4.2.3 Institutional Arrangements

Institutions and governance structures regulating the irrigation of wastewater need to know the irrigation area in its size and coherent structure, and secure access for the association to carry out irrigation-related operations on the farmer's land. Furthermore, institutions and governance structures need to regulate the financial contribution of the association members to cover operating costs, as well as the distribution of available wastewater among the farmers, especially in cases of mismatches between the demand and supply of water.

The properties of the focal transaction suggest that a hybrid governance structure or hierarchical forms of governance are more efficient than the spot market for coordinating collaborative interactions between the association and the farmers regarding the provision of land, water, and irrigation services. Next, we will characterize the actual institutions and governance structures with respect to the contractual arrangements, incentives, command and control, and adaptability.

The preservation of the irrigation area in its size and coherent structure is secured by the permanent affiliation of the irrigated fields to the association. Farmers who want to withdraw land from the irrigation scheme have to ask the association for permission, and they are generally required to provide compensatory areas and to compensate the association for investments, as well as to finance new investments for wastewater reuse on the compensatory areas.

The interactions between the association and the farmers regarding the provision of land and irrigation services are regulated by the *Statute of the Association*. The *Statute of the Association* defines the specific tasks of the association, clarifies the affiliation of the irrigated fields to the association, and regulates how tasks and responsibilities are shared between the association bodies. Furthermore, the statute clarifies the right of the association to use the land of the farmers for irrigating wastewater and determines the share of the farmers, the City of Braunschweig, and the Water Board Gifhorn for covering the costs of the irrigation operations. The financial contribution of the association members to covering the costs of the irrigation is regulated in such a way that each farmer pays a fixed fee (81 ha^{-1}) per hectare of irrigated cropland. The remaining costs for the irrigation are assumed by the City of Braunschweig and the Water Board Gifhorn according to the quantities of wastewater produced in both cities.

The *Statute of the Association* is complemented by the *Irrigation Ordinance* of the association, which regulates the responsibility of the association for the operation of the irrigation and the liability for damages due to improper operations. The *Irrigation Ordinance* further stipulates the rights and duties of the farmers to accept wastewater and sewage, and specifies the conditions laid down for the expiry of the right to receive irrigation services.

The distribution of wastewater between the farmers competing for this resource is regulated in such a way that each farmer has a proportional claim to the total available wastewater according to the total size of croplands cultivated. In cases of water scarcity, the farmers generally accept the prioritizing of fields with particularly sandy soils. These soils have a lower water retention capacity, and hence, crops on these fields tend to suffer more and earlier from water scarcity. In periods of water surplus, the farmers accept the even irrigation of wastewater on their fields. In the event of a water surplus, the association tends to dispose higher charges of wastewater on fields with sandy soils and low clay content, since the percolation rate is higher in these fields and the risk of waterlogging and damaging crops is lower.

With regard to the substance flows, the reuse of wastewater on the croplands is subject to the official permission of the Upper Water Authority, which establishes specific rules and instructions about the quantity and quality of the wastewater, the sampling of water for analysis, and the practice of adding sewage to the wastewater [97]. The reuse of the sewage is further regulated by the legal provisions defined in the *German Sewage Sludge Ordinance* and the *German Fertilizer Ordinance*. The provisions establish value limits for hazardous substances in the sewage, stipulate the conditions permitting applications of sewage, define bans and restrictions for the application, limit application quantities and prescribe the obligation to precisely control and document the reuse of sewage.

The contractual arrangements in the action situation of cropland irrigation are shaped by the collective decision made by the City of Braunschweig and the farmers during the foundation of the association in the year 1954, to reuse wastewater in the public interest and for the benefit of all members. No formal contracts exist between the association as a legal entity and the individual farmers because the association is obliged to reuse wastewater as a public service. Instead, transactions and interactions are regularized based on the institutions as defined in the *Associations' Statute* and the *Irrigation Ordinance*. The rules of the *Statute* and the *Irrigation Ordinance* are legitimated by the official bodies of the association, which are composed of representatives of the City of Braunschweig, the Water Board Gifhorn, and the farmers. The collective agreement between the association members including the farmers regarding the reuse of wastewater has an indefinite duration, and can only be terminated if the members do not benefit from the reuse scheme anymore, or if the association is not able to fulfill its statutory tasks. The agreements regarding the irrigation of wastewater are incomplete, since it is not possible to regulate, ex ante, all possible contingencies due to the uncertainties and complex nature of the interplay between natural conditions (e.g., weather conditions, soil characteristics, and vegetation), the technological opportunities (e.g., capacity of the irrigation equipment), and the behavior of the actors (e.g., cultivation activities of farmers). The provisions of the *Statute* and the *Irrigation Ordinance* provide that the association and the farmers resolve conflicts regarding irrigation (e.g., damages due to improper operations) through mutual consent or by arbitration, in case internal settlement fails.

The association is not allowed to generate profits from the reuse of wastewater and sewage. For this reason, the association has no claim to keeping profits from efficiency gains, but has to pass on profits to the members by reducing their financial contributions towards covering the costs. The incentives for operating efficiently result from the cost competition between the current wastewater reuse and conventional treatment procedures without wastewater reuse, as well as from the competition between the association and other wastewater associations in the region. The incentive intensity of the governance structure is therefore semi-strong.

The farmers have no possibility to direct the operations of the irrigation besides the informal agreements with the *rainmasters* about their individual schedule for the irrigation. Every irrigation operation is precisely documented, and information on the exact distribution of the wastewater and nutrients is passed on to all farmers and the supervisory authorities via internet, telephone, or in written form. Operations are also monitored by the regional chamber of agriculture, including soil and crop sampling, to assess risks to humans and the natural environment. The association and the farmers perceive the efforts for sharing information and controlling the activities of the irrigation as semi-strong.

The association and the farmers may adapt independently to changing conditions based on the existing ownership and decision rights for the land and the irrigation infrastructure. The association, for instance, does not consult individual farmers when adapting the operations of the irrigation to new technologies or regulations. However, the associations' capacity for autonomous adaptation is limited, because the farmers have the option to block any fundamental changes which affect the agricultural use of the land in the decision-making bodies of the association. The farmers are limited in their capacity for autonomous adaptations because they cannot withdraw their fields from the reuse scheme, or change the type of land use without consulting the association.

Coordinated adaptation between the association and the farmers is enabled under the current governance structure through association bodies in which the association and the farmers can discuss and agree upon joint adaptations in formal procedures. More frequent interactions between the farmers and the association workers also facilitate coordinated adaptations. The *rainmasters* and the farmers continuously consult each other when adapting the individual irrigation schedules to the weather and soil conditions, the crop growth, or the ongoing cropping activities of the farmers. Other means supporting coordinated adaptations include the information letters of the association and the annual meetings of the members of the association. The information letters explain, for instance, changes in the legal framework and their implications for irrigation. In the annual meetings, problems such as the correlation between irrigation capacity and the cropping patterns of the farmers are explained. The influence of these information channels is limited, since they can only stimulate but not enforce adaptations. To summarize, the capacity of the governance structure to support autonomous and coordinated adaptations is semi-strong, since both types of adaptation are possible, but subjected to substantial limitations.

4.4.3 Cultivation of Crops

4.4.3.1 Actors and Actors' Rights

The farmers who receive wastewater from the association own or lease the land and the other assets (e.g., machinery) needed for cultivating crops. They are autonomous entrepreneurs who decide independently about the crops and the production methods. The farmers make these decisions based on market prices, yield expectations, and their individual business strategies. However, the farmer's freedom of choice is restricted by some of the institutions regulating the crops and cropping patterns on the irrigation fields. The interactions between the association and the farmers regarding crop cultivation on the irrigation fields are driven by the different interests of the farmers and the association. The farmers have an interest in receiving sufficient wastewater for their crops and cultivating those crops from which they expect to maximize their profits. The association wants the farmers to cultivate a wide range of different crops as this facilitates the sufficient supply of wastewater to the farmers. The association is interested in supplying sufficient wastewater to the farmers, since crop yield stability and the profitability of cultivation with wastewater are necessary requirements for the continuation of the reuse scheme from the farmers' point-of-view.

4.4.3.2 Focal Activity

The specificity of the farmers' machines, equipment, and know-how for cultivating crops with wastewater is relatively low, since it does not differ significantly from conventional crop production. Uncertainty exists about the farmers' individual selection of crops. The choice of crops as the farmers' focal activity is made before the beginning of the cultivation period. Individual farmers may decide to cultivate crops which are highly profitable, but are not allowed for wastewater irrigation. Farmers may further decide to produce less varieties of crops (e.g., only sugar beets and maize) to benefit from a greater share of more profitable crops in their cropping pattern. This behavior increases the risk of an excessive demand for water in certain periods of time caused by the uniform water requirement of one or more crops. Since only two thirds of the irrigation fields can be irrigated simultaneously with wastewater, the association can only supply sufficient water according to the crop needs if the farmers cultivate a variety of crops with different demands for water over time.

The cultivation with a choice of crops is characterized by interdependences between the association and the farmers. On one hand, the irrigation of nutrient-rich wastewater increases crop yields and enables the farmers to cultivate a wide variety of different crops that otherwise would be unsuited to sandy soils. On the other, it limits the farmer's options as it imposes bans on cultivating high-profit crops, such as fruits and vegetables. The farmer's choice of crops for cultivation influences the operations of the irrigation as it affects the association's capacity to meet the demand for water and to operate the reuse scheme efficiently. Pest control and fertilization also influence the operation of the irrigation, since they require the suspension of irrigation at certain times.

4.4.3.3 Institutional Arrangements

Institutions and governance structures coordinating cultivation with wastewater need to regulate crops and cropping patterns on irrigated fields, as well as the information exchange between the association and the farmers regarding the farmer's crop decisions. Taking into account the characteristics of the focal activity, choice of crops, like the low involvement of specific investments, one can expect that a governance structure which is close to market governance is efficient to coordinate cultivation with wastewater.

The principle mechanism that coordinates the farmer's crop decisions is the price mechanism which indicates the current market demand for certain crops. The price mechanism is complemented by the institutions regulating cultivation in irrigated fields (e.g., cultivation bans). In fact, the farmers are not allowed to cultivate fruits and vegetables on irrigated fields, due to the sewage component in wastewater. Furthermore, farmers are required to inform the association about their individual choice of crops, and to agree with the association on their individual cultivation plan. The cultivation agreement is an informal agreement which is valid for one cultivation period only, and which clarifies what crops are cultivated by the farmers. The rules of the *Irrigation Ordinance* stipulate the right of the association to decide upon the cultivation plan if the cropping patterns proposed by the farmers cannot be aligned with the scheme's operational requirements (i.e., cropping patterns that include a variety of crops), and no agreement is reached. The association and the farmers normally resolve conflicts regarding the cultivation plan bilaterally, and with the help of the regional chamber of agriculture as an independent external arbitrator. In cases of violations of cultivation bans, the association may also use the option of resolving conflicts through the courts.

The farmers are subject to competition with other agricultural market players. The better their crops fulfill market needs and the more efficiently they produce, the higher the chance of increasing their individual profit. The incentives for the farmers to adapt to changing market demands and to increase the efficiency of their cultivation activities are therefore strong.

The options for the association to direct the farmer's cultivation activities are limited, as the association may only object to the cultivation plans proposed by the farmers, and eventually prescribe a different cropping plan on the irrigation fields, if the farmer's cultivation plans hamper the efficient operation of the irrigation scheme. Administrative control is perceived as semi-strong, and refers to the control activities of the manager and the *rainmasters* who check if the farmers adhere to the cultivation bans and the cultivation agreements. The association refuses to irrigate the fields of individual farmers as a sanction if these farmers violate the cultivation bans, or if they do not stick to the agreed cultivation plan.

The strong incentives motivate the farmers to constantly adapt the cultivation to changes in technology and the demand for certain crops. The capacity of the farmers to adapt their businesses independently from the association is high, due to the autonomy resulting from separated ownership and decision rights. Nevertheless, the capacity for autonomous adaptations is restricted, since the farmers need to consult the association about any changes in the cultivation plans as it affects the operation of the irrigation scheme. The adaptation of the farmer's cultivation plans in a coordinated way is supported by the frequent and direct contact between association staff and the farmers. This frequent and direct contact also facilitates short-term adaptations of the irrigation schedules to the farmers' current cropping activities. The capacity of the governance structure to coordinate adaptations, other than those of the farmer's cultivation plans and the adaptation of the irrigation schedules, is weak.

4.5 Discussion

The theoretical assumption in transaction cost economics is that governance structures are chosen to fit the specific properties of transactions and to minimize transaction costs [38,77,81]. Interdependences between actors—like in the case of the association and the farmers engaging in wastewater reuse—are believed to shape the nature and features of governance structures [81]. Understanding how governance structures are shaped by the properties of the transactions and the interdependences of actors is of utmost interest when aiming at a circular economy characterized by value chains linked through transactions.

In the following section, we verify whether the governance structures observed in the case of the wastewater reuse in Braunschweig are consistent with the governance structures expected according to the transaction cost economic theory. We start with discussing how the governance structures are shaped by the relevant properties of the transactions and activities, including the interdependences between the association and the farmers. We then determine the governance structures (i.e., market, hybrid or hierarchy) according to their features. We then discuss how the alignment of the governance structures with the properties of the transactions and activities contributes to the smooth operation of the wastewater reuse scheme. After this, we will reflect upon the lessons learned for governing transactions and interdependences between linked value chains in a circular economy. Finally, we will discuss the research design regarding its strengths and weaknesses and suggest potential directions for future research.

4.5.1 Alignment of Transactions, Interdependences and Governance Structures

Based on our findings, we argue that different governance structures coordinate the transactions and activities in the action situations of the wastewater reuse scheme in Braunschweig. The provision of irrigation services with the spreading of wastewater is coordinated in a hierarchical way, and crop cultivation with the choice of crops is close to market governance. The irrigation of croplands with the irrigation of wastewater links the value chains of wastewater treatment and crop production, and displays features of a hybrid governance structure. Table 4-3 summarizes the main features of the governance structures observed in the focal transactions and activities of the different action situations of wastewater reuse in Braunschweig.

Table 4-3: Features of the governance structures for focal transactions and activities in the action situations of wastewater reuse in Braunschweig.

Features	Action situations with focal transactions and activities		
	Provision of irrigation services with spreading of wastewater	**Irrigation of croplands with irrigation of wastewater**	**Cultivation of crops with choice of crops**
Incentive intensity	weak	semi-strong	strong
Administrative control	strong	semi-strong	semi-strong
Autonomous adaptation	weak	semi-strong	generally strong, but restricted
Coordinated adaptation	strong	semi-strong	generally weak but possible for certain adaptations

4.5.1.1 *Provision of Irrigation Services*

The governance structure used for coordinating the spreading of wastewater is shaped by the properties of the activity, including the specificity of the irrigation infrastructure, the good reputation of the association regarding the quality of the spreading, and the interdependence between the association and the farmers. These characteristics constitute the need for discouraging opportunism to ensure a continued provision of high quality spreading. The governance structure chosen to fit with the properties of the spreading is characterized by weak incentives, strong use of administrative command and control, as well as a strong capacity to coordinate adaptations. These features clearly indicate that the spreading is coordinated by a hierarchical governance structure. The observation of a hierarchical governance structure corresponds with the expectations based on transaction cost theory, which leads us to assume that the governance structure for the spreading was chosen in a transaction cost minimizing way, following discriminating alignment [76,77]. In particular, it becomes evident that the hierarchical governance structure responds to the high asset specificity of the activity.

The alignment of the governance structure with the properties of the spreading contributes to the smooth operation of the reuse scheme. The hierarchical coordination with weak incentives and strong administrative control prevents the association staff from behaving opportunistically. The strong administrative control compensates the weak incentives for the association staff and stimulates good operating performance, which is indispensable to spreading wastewater without causing damage to the farmer's crops and soils. Another benefit of the alignment is that hierarchical coordination between the association staff enables the association to adapt the operations of the spreading quickly to the farmer's ongoing cropping activities, and any changes of the weather, soil, and crop conditions. Hierarchical governance structures, like the governance structure for the spreading of wastewater, are characterized by high bureaucratic costs [77]. In the studied case, it can be expected that the high frequency of the spreading helps the association to make the hierarchical governance structure more cost-effective. Furthermore, the interviewees reported that the frequency of the spreading have contributed to developing trust and well-established routines between the manager, the *rainmasters*, and the workers. This may also help to keep the transaction costs for the spreading low, since empirical studies show that trust among actors can reduce transaction costs and improve the performance of collaborative actions between actors [100,101].

4.5.1.2 *Irrigation of Croplands*

The governance structure used for coordinating irrigation is shaped by the properties of the transaction, including the specificity of the assets and the interdependence between the association and the farmers. The site specificity of the irrigation fields and the physical specificity of the irrigation infrastructure, along with the complementarity of the resources of water and land, increase the interest of the association and the farmers, to give continuity to the transaction and drive them to engage in long-term cooperation. The association thus commits to providing irrigation services, and the farmers commit to providing cropland for wastewater irrigation. On the operational level, the interdependence leads to an increased need for administrative control, including the necessity for monitoring operations and sharing information on the activities of irrigation and cultivation. In particular, the actors need to share information on the distribution of wastewater and nutrients, as well as the individual schedules for the activities of irrigation and cultivation. The interdependence further results in restrictions for autonomous adaptations, and the necessity to coordinate certain adaptations, such as suspending irrigation when farmers carry out pest management or fertilization measures. Last but not least, interdependence leads to the association and farmers resolving conflicts bilaterally or through arbitration, since conflict settlement via courts is not conducive to preserving mutual trust and the continuity of the spirit of cooperation.

The governance structure chosen to match with the properties of the irrigation is characterized by pooling resources with separated ownership and decision rights (e.g., land and irrigation infrastructure), incomplete contracts (e.g., absence of formal contracts) and competition between resource users (e.g., farmers regarding the available wastewater) and between other forms of organization (e.g., competition of the association with other wastewater associations). From these empirical observations, we conclude that the governance structure for irrigation corresponds to a hybrid governance structure. This finding is underpinned by the observation of semi-strong incentive intensity, semi-strong use of administrative control, and semi-strong capacity for autonomous and coordinated adaptations. The observation of a hybrid governance structure is consistent with the governance structure expected according to the transaction cost theory, which leads us to assume that the governance structure for irrigation is able to sufficiently economize transaction costs.

The alignment of the governance structure with the specificity of the irrigation and the interdependence between the association and the farmers facilitates the smooth operation of the reuse scheme. The long-term cooperation between the association and the farmers based on the permanent affiliation of the irrigated fields to the association helps to protect the investments of the association against the potential opportunistic behavior of farmers. The monitoring of operations and the information sharing, regarding the substance flows and the activities of the irrigation and cultivation, facilitates the integration of wastewater reuse into cultivation, by making actions and activities more transparent and predictable. The restriction of autonomous adaptations prevents possible independent actions of the association and the farmers from negatively influencing the cultivation and operation of the reuse scheme. The support of coordinated adaptations helps to achieve mutual consent among the association and the farmers about any adaptation of the irrigation operations to changes in the natural conditions, the cultivation plans, or the cropping activities. Last but not least, the use of arbitration, in cases where bilateral conflict resolution has failed, has proven to be efficient in solving conflicts and enhancing the legitimacy of actions.

4.5.1.3 *Cultivation of Crops*

The governance structure used for coordinating the choice of crops is marked by the uncertainty regarding the activity and the interdependence between the association and the farmers. This results in the farmers sharing information on their choice of crops and formulating agreements with the association on cultivation plans. The need for administrative control, including the need to monitor cropping patterns and to sanction violations of cultivation bans, is a further result of the uncertainty and the interdependence between the association and the farmers. Other implications of the interdependence for the governance structure include the need to restrict autonomous adaptations of the farmer's cultivation plans and to coordinate the respective adaptations.

The governance structure used for coordinating the cultivation with wastewater shows features that are typical for market governance, like separated ownership rights, strong incentives, and the support of autonomous adaptations. Other features, such as the semi-strong use of administrative control, the restrictions for autonomous adaptations, the possibility of coordinating certain adaptations, as well as the right of the association to prescribe the cultivation plans of the farmers, are not typical for pure market governance structures, and display features of hybrid or even hierarchical governance structures. In general, market governance corresponds to prior expectations on the basis of the low asset specificity in the activity. In addition, the governance structure matches with the uncertainty and the interdependence by adopting hybrid and hierarchical features into the governance structure. This leads us to assume that the governance structure is in line with the properties of the activity, and is able to keep transaction costs low.

The alignment of the governance structure with the uncertainty and the interdependence between the association and the farmers results in various benefits which contribute to the smooth operation of the reuse scheme. The sharing of information and the agreements on the cultivation plans reduce the uncertainty regarding the farmer's choice of crops, and allow for better planning of the operations of irrigation. This helps the association to organize the operations efficiently, and to supply sufficient water to all farmers. The monitoring of the cropping patterns and the practice of sanctioning violations of cultivation bans discourages farmer opportunism. The consultations between the farmers and the association regarding the adaptations of the cultivation plans hinder autonomous actions of farmers, that may reduce the efficiency of the reuse scheme due to misalignments between the adapted cultivation plans and the scheme's operational requirements. Furthermore, the consultations regarding the adaptations of the irrigation schedules to the farmers' cropping activities prevents the operations of irrigation and cultivation from interfering with one other.

4.5.2 Lessons Learned and Contribution to the Literature

Several lessons for governing transactions and interdependences between linked value chains in circular economies can be derived from the study of the wastewater reuse scheme in Braunschweig. The study shows that reusing wastewater in agriculture involves various transactions and activities which are characterized by specific properties. The transaction of wastewater irrigation creates interdependences between the association and farmers, which significantly shape the design of the governance structures in the reuse scheme. In particular, the findings show that interdependences can result in an increased need for administrative control, including the monitoring of activities and mutual information sharing between interdependent actors. Furthermore, the study shows that dealing with interdependences requires governance structures that can restrict autonomous adaptations and support coordinated adaptations, and bilateral conflict resolution between interdependent actors. In theory, these requirements can be best fulfilled by features typical for hybrid and hierarchical governance structures. In practice, we found that the governance structures correspond with the expectations based on theoretical thinking. In particular, the governance structure for the choice of crops exhibits features of hybrid and hierarchical governance structures, even though market governance is still the predominant governance structure for the activity, due to the low asset specificity. This may indicate that the condition of asset specificity remains the most important characteristic for determining the choice of governance [75]. However, it may also indicate that linking value chains for reusing wastewater drives market governance structures to adopt features of hybrid and hierarchical governance structures to better cope with interdependences resulting from transactions.

Referring to the case of reusing wastewater in agriculture, we conclude that different governance structures are needed to match the different properties and requirements of the transactions and activities between linked value chains. Another conclusion we draw from the case study is that interdependences resulting from transactions increase the need for coordination between actors. Interdependences between actors should be identified and taken into account when developing appropriate governance structures for transactions between linked value chains. Last but not least, we conclude that aligning governance structures with the properties of transactions and activities potentially contributes to efficiently governing transactions and interdependences between linked value chains. A better understanding of the governance structures for coordinating transactions and interdependences between linked value chains is important for developing circular economies [9,22]. Therefore, we believe that the lessons learned from the wastewater reuse scheme in Braunschweig can also enhance solution findings related to the governance of circular economies characterized by linkages and interdependences between value chains.

Our research contributes to the literature in several aspects: First, it provides a detailed characterization of the specific transactions and governance structures for reusing wastewater at the local level. Second, our study helps to understand how transactions and interdependences between actors shape the governance structures for wastewater reuse at the local level. Third, our study provides valuable insights in how the alignment of the governance structures with the transactions and interdependences of actors contributes to the smooth operation of agricultural wastewater reuse schemes. In this way, the study facilitates the understanding of governance structures for coordinating the specific transactions and activities that create linkages and interdependences between the value chains of wastewater treatment and crop production.

The findings of the study could be of use to practitioners involved in wastewater reuse schemes and for stakeholders concerned with future wastewater management practices, and the transition towards the circular economy. We believe that the findings can assist in developing appropriate governance structures for transactions between interdependent value chains, which, in turn, can help practitioners, like wastewater providers and farmers, take advantage of the economic and environmental benefits of reusing wastewater and the circular economy.

4.5.3 Research Design and Future Research Directions

The results of our analysis refer specifically to the case of reusing wastewater in agriculture, and may not be simply generalized or transferred without critical reflection upon other cases of linking value chains in the circular economy. However, the conceptual, theoretical, and analytical framing used in this study may potentially also be applied for studying transactions and interdependences between value chains from other sectors.

The conceptual and analytical approach of decomposing the agricultural reuse of wastewater into different action arenas and action situations proved to be a suitable guideline assistance for investigating the transactions and interdependences between the value chains of wastewater treatment and crop production. In particular, this approach helped us to better structure the analysis and to break down the complexity of reusing wastewater into manageable sets of practical activities.

The theory of transaction cost economics proved to be expedient for explaining the choice of the governance structures for the focal transactions and activities within the action situations of our conceptual framework. However, the theory is static in nature, and thus might be less useful when it comes to explaining the impact of dynamics between actors and transactions on the governance structures. The theoretical explanation of the impact of dynamic issues would facilitate future studies on linked value chains in a circular economy, since the transition from the linear economic model towards the circular economy is a dynamic process, and the characteristics of actors and transactions may change and require different governance structures over time.

Regarding the analysis of the properties of the transactions, we focused on the conditions of asset specificity, which is considered by Riordan and Williamson [75] as the most important transaction property. Furthermore, we analyzed the conditions of uncertainty and frequency. Other authors suggest taking into account further transaction properties in order to increase the analytic content of transaction cost analysis in socioecological systems like agriculture [102,103]. Hagedorn et al. [102], for instance, proposes the inclusion of, among others, the excludability of actors, the rivalry among resource users, the degree of complexity, separability or jointness, as well as the measurability of the cost and benefits when analyzing nature-related transactions. These properties may also be relevant for the studied case, and can add explanatory power to the observed choices of governance structures.

The methods applied in this study are subject to the general limitations of qualitative research, including the more complex collection and interpretation of data, the lower robustness of the data, as well as the limited generalizability of the results [90,91,104]. However, we argue that using a case study and semi-structured face-to-face interviews to study the transactions and interdependences between linked value chains, in depth, was appropriate for answering the research questions. We acknowledge that more empirical work on the governance of wastewater reuse schemes is needed to prove whether the findings remain valid in other cases of combining wastewater treatment and crop production.

Future research may address the challenge of measuring the cost and benefits from aligning the governance structures with the transactions and interdependences. We did not measure the costs and benefits in nominal terms, since the data required for conducting a quantitative transaction cost analysis could not be provided by the actors of the reuse scheme. Our approach is in line with many other empirical studies which confine transaction cost analysis to an application of the discriminating alignment hypothesis [71,93,103,105]. Another suggestion for future studies is to focus on the dynamics in linked value chains, and to take into account the development of the characteristics of the actors, the transactions, and the governance structures over time. In addition, future work may elaborate on the specific characteristics of the interdependences between actors in linked value chains. This could include a more detailed analysis of how the degree and the type of interdependence (e.g., resource-based, technical, operational, economic) influence the choice of the governance structures.

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5 General Discussion

5.1 Empirical findings

5.1.1 Changes in and between the value chains of wastewater treatment and crop production

The results presented in Paper I and Paper II show that implementing innovative transactions for reusing wastewater and nutrients such as phosphorus (P) can lead to significant socio-technical changes in and between the value chains of wastewater treatment and crop production. In the studied case of struvite precipitation, the value chain of wastewater treatment is altered by changes in the treatment process and the production of struvite as an additional output. The value chain of crop production is changed by the opportunity of substituting struvite for mineral fertilizer. In the studied case of wastewater reuse, the value chain of wastewater treatment is altered by changes in the treatment of water and sludge. The changes in the value chain of crop production include the opportunity of replacing wastewater for groundwater and mineral fertilizer. Another finding which confirms the theoretical assumptions made in this study is that transactions for reusing nutrients and wastewater establish linkages between the value chains of wastewater treatment and crop production. The linkages develop due to shared resources (e.g., land for releasing wastewater and cultivating crops), input-output relations (e.g., water and nutrients), and interdependences between activities and actors (e.g., interdependences between wastewater treatment and cultivation practices and the respective providers and users of resources). In the Waßmannsdorf case, the linkage of wastewater treatment and crop production leads to the emergence of an innovative value chain including struvite producers, traders and farmers. In the Braunschweig case, the linkage leads to the development of linked regional value chains for providing water, crops and bioenergy.

The study further shows that transactions for reusing nutrients and wastewater are conducive to the development of local value and substance cycles which contribute to preserving natural resources of phosphate and water. The findings lend support to several scholars proposing the development of local substance cycles as a strategy for using natural resources such as phosphorus and water more efficiently (Abu-Ghunmi et al., 2016; Dockhorn, 2006; Kern et al., 2008; Kern, 2014; Nölting et al., 2015; Pinnekamp et al., 2007). However, this study also points towards some challenges to establishing local value and substance cycles including the technical limitations of struvite precipitation, the low demand for struvite as fertilizer, the acceptance of wastewater reuse by affected landowners and farmers, the acceptance of crops irrigated with wastewater by buyers and consumers as well as direct interaction and cooperation between actors in the value chains of wastewater treatment and reuse. In particular, the latter seems to be important for developing local value and substance cycles. The Waßmannsdorf case demonstrates that the development of a struvite value chain proceeds sluggishly if local struvite producers and farmers rarely interact or cooperate. By contrast, the Braunschweig case illustrates that developing and sustaining local value and substance cycles via wastewater reuse requires direct interaction and long-term cooperation between cities, operators of wastewater treatment facilities and farmers.

5.1.2 Costs and Benefits

The results of the case studies provide evidence that the changes resulting from transactions for reusing nutrients and wastewater can lead to significant cost savings in the value chains of wastewater treatment and crop production. Paper I shows that struvite precipitation benefits operators of wastewater treatment facilities by reducing the costs of wastewater treatment and generating additional revenues through struvite sales. In addition, it shows that the substitution of struvite for mineral fertilizer benefits farmers by reducing the cost of fertilization. In the studied case the revenues from struvite sales are not sufficient to cover the cost of production. The profitability of the precipitation process is mainly secured by the reduction of the operational costs of wastewater treatment. This indicates that the costs of producing struvite need to be assessed in relation to the cost savings in the overall wastewater treatment process. The findings are in line with those of Shu et al. (2006) who showed that struvite precipitation is economically beneficial when savings in the handling and disposal of sludge are taken into consideration. Regarding the application of struvite in crop production, the study shows that the benefits of struvite fertilization in the study area depend on several factors including the plant availability of the nutrient N contained in the struvite, the technology for spreading struvite and the development of the price of P from mineral sources compared to P from struvite. The findings highlight that the difference between the price of P from mineral sources and the price of P from struvite needs to be large enough to reduce the cost of fertilization and to compensate farmers for the costs of potential extra handling and spreading of struvite.

Paper II shows that reusing wastewater and sludge can provide significant benefits for operators of wastewater treatment facilities and farmers. The operators of the wastewater treatment plant in Braunschweig benefit from savings in wastewater fees and the reduced costs for dewatering and incinerating sludge. The farmers participating in the reuse scheme mainly benefit from savings in the costs for irrigating and fertilizing crops. The results are consistent with the findings of other studies which showed that reusing wastewater in agriculture reduces treatment costs and the cost of fertilization (Haruvy, 1997; Rosenqvist and Dawson, 2005).

However, transactions for reusing nutrients and wastewater may not only provide costs and benefits for operators of wastewater treatment plants and farmers but also create a number of positive and negative externalities (Anderson, 2003; Daniels et al., 2012; Kolawole and Kan, 2016). Recent studies have shown that externalities can significantly influence the economic viability of P recovery and wastewater reuse projects (Garcia and Pargament, 2015; Molinos-Senante et al., 2011a; Molinos-Senante et al., 2011b). For example, Molinos-Senante et al. (2011a) studied different wastewater treatment plants and found that P recovery is economically feasible as long as environmental benefits are taken into account. Similarly, Garcia and Pargament (2015) showed that the economic feasibility of wastewater reuse projects is higher when social and environmental benefits are included in the analysis. These findings suggest that the reuse of P and wastewater within linked value chains may not only be justified by the monetary benefits for farmers and operators of treatment plants. Environmental and social benefits like the preservation of the quality of water bodies due to the avoidance of wastewater discharges or the increase in the availability of non-renewable resources may also provide a vindication for supporting value chains which enable the circulation of nutrients and water. On the other hand, the potential risks of P recovery and wastewater reuse (Christou et al., 2017; Khan et al., 2008; Mapanda et al., 2005; Pedersen et al., 2005; Toze, 2006) may negatively influence the economic viability of such value chains. This view is supported by Haruvy (1997) who showed that damage to the environment and human health caused by pollutants in the wastewater can significantly increase the costs of wastewater reuse. The analysis of the external costs and benefits of struvite precipitation and wastewater reuse was beyond the scope of this study. Further research is needed to analyze how potential externalities influence the economic viability of the studied value chains.

5.1.3 Distribution of Added-value

The findings presented in Paper I and Paper II show that transactions for reusing nutrients and wastewater can lead to significant added-value gains in the value chains of wastewater treatment and crop production. However, in the studied cases the added-value from struvite precipitation and wastewater reuse is distributed unevenly among the value chains of wastewater treatment and crop production. The added-value generated in the value chain of wastewater treatment was found to be higher than the added-value generated in the value chain of crop production. In addition, Paper I demonstrates that the marketing modalities and the price for struvite and mineral fertilizer can significantly influence the distribution of the added-value along the struvite value chain. The added-value for farmers is higher if struvite is marketed via direct sales. Moreover, the findings indicate that the added-value from struvite fertilization is more elastic towards changes in the price of struvite than the added-value from the production of struvite. Reducing the sale price of struvite could therefore be a strategy for increasing the demand for struvite in crop production, since struvite producers mainly benefit from cost savings in the wastewater treatment process, while the revenues from struvite sales only contribute marginally to their added-value gains.

Paper II highlights that transactions for reusing wastewater and sludge can generate a high share of added-value for the local economy. The results on the share of the local economy in the added-value corroborate the findings of empirical studies in the field of renewable energies which showed that local production, consumption and disposal of goods and services increases the share of the added-value for local economies (Heinbach et al., 2014; Hoffmann, 2009; Kosfeld and Gückelhorn, 2012; Marcouiller et al., 1996). A noteworthy observation made in the case analysis of the reuse scheme in Braunschweig is that the operators of the wastewater treatment plant and the farmers have developed many long-term business relations with local suppliers, service providers and traders. The transactions for reusing wastewater may also lead to a higher output of the upstream suppliers, and therefore may further increase the added-value in the study area. Moreover, the spending of the additional income that remains in the locality may stimulate additional demand and production. Empirical studies on regional economies have shown that indirect and induced effects of economic activities can significantly influence the added-value for local economies (Archer, 1982; Frechtling and Horváth, 1999; Kosfeld and Gückelhorn, 2012). For instance, Kosfeld and Gückelhorn (2012) analyzed different renewable energies at the local scale and found that the indirect and induced effects of the production activities contributed a significant share to the local added-value. These findings may indicate that indirect and induced effects of reusing wastewater can further increase the added-value for local economies. Analyzing the indirect and induced effects of economic transactions is a complex task (Heinbach et al., 2014) and requires extensive data (Frechtling and Horváth, 1999) that would have exceeded the scope and possibilities of this study by far.

In sum, Paper I and Paper II provide evidence that transactions for reusing nutrients and wastewater can benefit operators or wastewater treatment plants, farmers, communities and local economies. However, the results also highlight that transactions for reusing wastewater can put constraints on the actions of actors. For instance, farmers in the reuse scheme in Braunschweig are restricted in cultivating high-value crops such as fruits and vegetables due to wastewater reuse. As a consequence, the acceptance of wastewater reuse in crop production may decrease. This underlines the relevance of providing additional economic opportunities (e.g., bioenergy production) that enable farmers to diversify their cropping pattern and increase their scope of action in the event of restrictions due to wastewater reuse.

Paper II further shows that transaction for reusing wastewater can lead to crowding out effects and changes in the distribution of the added-value among stakeholders. The findings demonstrate that the added-value gains from reusing wastewater and sludge are distributed unevenly between the stakeholders in the value chain of crop production and some stakeholders, like employees and creditors, even sustain losses of added-value (see Table 3-14). However, in the studied case, the total added-value gains in crop production were higher than the crowding out effects, i.e., the net impact on the added-value was positive. These findings suggest that the decrease of added-value for some stakeholders needs to be considered in relation to the added-value gains of other stakeholders.

5.1.4 Impact of Transactions and Interdependences on the Governance Structures

Paper III provides a detailed characterization of the specific transactions and governance structures for reusing wastewater at the local level. The findings make an important contribution to the literature since they help to understand how transactions and interdependences between actors influence the choice of the governance structures for wastewater reuse at the local level. The observations made in the case of the wastewater reuse scheme in Braunschweig show that reusing wastewater in crop production involves various transactions and activities which are characterized by specific properties.

Furthermore, the study highlights that transactions for reusing wastewater can create interdependences between wastewater providers and farmers, which significantly shape the design of the governance structures for reusing wastewater. The findings suggest that interdependences increase the need for administrative control, including the monitoring of activities and mutual information sharing between interdependent actors. Furthermore, the findings point out that interdependences require governance structures that can restrict autonomous adaptations and support coordinated adaptations, and bilateral dispute resolution between interdependent actors. In general, the findings of this study regarding the choice of governance structures are consistent with the governance structures expected according to the transaction cost theory (Ménard, 2004; Williamson, 1991; Williamson, 1996). In particular, the findings give support to Riordan and Williamson (1985) who describe the condition of asset specificity as the most important characteristic for determining the choice of governance. However, this study also shows that linking value chains for reusing wastewater drives market governance structures to adopt features of hybrid and hierarchical governance structures to better cope with interdependences resulting from transactions.

The empirical findings presented in Paper III further illustrate that the alignment of governance structures with the transactions and interdependences results in various benefits which contribute to facilitating the integration of wastewater reuse into crop production. The findings highlight that long-term cooperation between wastewater providers and farmers based on permanent affiliation of croplands to wastewater reuse schemes is essential for protecting highly specific investments for wastewater reuse against potential opportunistic behavior. Furthermore, the findings show that the monitoring of activities and sanctioning violations of agreements reduce the risk of opportunistic behavior. Another observation made in this study is that mutual information sharing, consultations and agreements between interdependent actors reduce uncertainties by making actions and activities more predictable and transparent. Last but not least, the findings show that the restriction of autonomous adaptations helps to prevent independent actions of actors, whereas the support of coordinated adaptations and bilateral conflict resolutions helps to achieve mutual consent between interdependent actors.

5.1.5 Practical Conclusions

Several practical conclusions can be drawn from the cases studied in this research. The study suggests that transactions for reusing wastewater and nutrients such as P can be conducive to the development of linked regional value chains for providing water, nutrients, crops and bioenergy. These linked regional value chains are supportive to the transition towards the circular economy since they enable the reuse of nutrients and water within local value and substance cycles. Furthermore, they contribute to reducing the built-up of waste (e.g., sludge) and natural resource consumption (e.g., freshwater and nutrients), and mitigating possible environmental impacts, for instance from the incineration of sludge and the discharge of wastewater pollutants into natural water bodies. In the studied cases the transactions lead to significant changes in the value chains of wastewater treatment and crop production which bring about cost savings and added-value gains for wastewater treatment facilities, farmers and the local economy. However, it is important to consider that transactions for reusing wastewater can also restrict actors and lead to crowding out effects on the added-value. The provision of additional opportunities that enable the actors to increase their scope of possibilities is therefore indispensable for strengthening acceptance and compensating actors for restrictions and unfulfilled economic potential. Where legal restrictions for producing food crops apply such as in the Braunschweig case, these opportunities can consist of combining wastewater reuse with bioenergy production and providing additional agricultural services for cultivating and harvesting energy crops. The results further suggest that agricultural schemes for reusing nutrients and wastewater should involve a large number of local employees, creditors and suppliers to keep a high share of added-value for the local economy. In this context, the communication of the benefits of wastewater reuse schemes for the local economic development may contribute to enhancing acceptance and overcoming rejection by affected actors like farmers, residents, authorities and communities. Another conclusion drawn from the case analysis of the wastewater reuse scheme in Braunschweig is that different governance structures are necessary to match the different properties and requirements of the transactions between linked value chains. Interdependences resulting from transactions increase the need for coordination between actors in linked value chains. Interdependences should thus be identified and taken into consideration when developing appropriate governance structures for transactions between linked value chains. Lastly, the results show that aligning governance structures with the properties of the transactions contributes to the efficient governance of transactions between linked and interdependent value chains.

The findings of the study are useful for operators of wastewater treatment facilities, farmers and municipalities since they provide decision-relevant knowledge and information on the costs and benefits of reusing nutrients and treated wastewater at the local level. In addition, the findings provide important information on how to coordinate transactions between linked and interdependent value chains efficiently. This knowledge can be used to promote alternative value chains of wastewater treatment and crop production, and thus makes an important contribution to the development of circular economies.

5.2 Research design and Future Research Directions

The results of the study refer specifically to the case of reusing P and wastewater in crop production. Therefore, they may not be generalized or transferred without critical reflection upon other cases of transactions between linked and interdependent value chains. However, the conceptual, theoretical and analytical framing used in this study may also be applied for scrutinizing transactions between linked and interdependent value chains from other sectors.

The concept of linked and interdependent value chains in a circular economy formed an appropriate conceptual framework for better understanding the impact of transactions for reusing nutrients and wastewater on the value chains of wastewater treatment and crop production. However, the concept of the circular economy itself is an emerging research field which still lacks a commonly accepted and shared definition of its principles, operating levels, aims, and associated implications and enablers (Kirchherr et al., 2017; Merli et al., 2018; Yuan et al., 2006). Further theoretical development of the concept is required to consolidate its definition, boundaries, principles and related practices (Merli et al., 2018). This will contribute to better frame the research field and facilitate future work on transactions between linked and interdependent value chains in a circular economy.

The conceptual and analytical approach of decomposing the agricultural reuse of nutrients and wastewater into different action arenas and situations as well as the theory of transaction cost economics as part of the theoretical framing have been discussed in section 4.5.3. Therefore, the following section will mainly discuss the methods applied in the study. The methods are subjected to the general limitations of qualitative research, such as the more complex collection and interpretation of data, the decreased robustness of the data, and the limited generalizability of the results (Opdenakker, 2006; Queirós et al., 2017; Rahman, 2016). However, the strategy of using case studies, written questionnaires and in-depth interviews allowed for a detailed analysis of the impact of transactions for reusing nutrients and wastewater on the value chains of wastewater treatment and crop production. The combination of the methodological approaches of the cost-benefit and value chain analyses allowed for profound insights into the monetary costs and benefits of P recovery and wastewater reuse. However, the cost-benefit analysis did not take into account potential restrictions like cultivation bans for farmers resulting from wastewater reuse. Furthermore, the analysis neglected the impact of external costs and benefits when analyzing the transactions for reusing P and wastewater. The approach of the value chain analysis proved to be a well-suited complement to the cost-benefit analysis. In particular, it allowed in-depth analysis of the value creation in linked value chains and its distribution among the stakeholders (i.e., equity providers, creditors, employees, state) and the value chains of wastewater treatment and crop production. However, the value chain analysis neglected to consider indirect and induced effects of P recovery and wastewater reuse on the added-value for local economies. Future work may take into account the impact of restrictions, external costs and benefits as well as indirect and induced effects on the added-value when analyzing transactions between linked value chains.

The analyses of the struvite use in Berlin-Brandenburg and the wastewater reuse scheme in Braunschweig were static analyses which focused on the impact of transactions on the value chains of wastewater treatment and crop production at one specific point in time. An interesting observation made in the case analysis of the wastewater reuse scheme in Braunschweig is that some characteristics of the actors, transactions and governance structures involved in the scheme have significantly changed over time. Changes in the characteristics of actors, transactions and governance structures also characterize the transition from the traditional linear economic model towards the circular economy model. Therefore, I would recommend future studies to focus more on the interplay between the development of actors, transactions and governance structures over time. This could contribute to better understanding the dynamics in linked value chains and developing appropriate governance structures for the transition towards the circular economy.

Another suggestion for future research is to elaborate on the specific characteristics of interdependences between actors in linked value chains. The study shows that transactions for reusing wastewater can create different types of interdependences between the actors in the value chains of wastewater treatment and crop production. For instance, some of the interdependences observed in the study are based on specific investments of actors (e.g., irrigation infrastructure), whereas other interdependences result from the complementary use of resources (e.g., land and water) and related activities of actors (e.g., wastewater irrigation and cultivation practices). A deeper understanding of how the specific characteristics of the interdependences influence the choice of the governance structures could further contribute to enhancing solution findings regarding the governance of transactions in linked and interdependent value chains. Last but not least, future work could analyze what business models are supportive for transactions between linked and interdependent value chains in a circular economy.

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