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Eidesstattliche Erklärung

Hiermit versichere ich, dass die vorliegende Arbeit von mir selbstständig verfasst wurde und ich keine außer den angegebenen Hilfsmitteln und Quellen verwendet habe. Alle Gedanken in schriftlicher wie in bildlicher Form, welche aus fremden Quellen übernommen wurden, sind als solche gekennzeichnet. Die Arbeit wurde bisher keinem Prüfungsamt in gleicher oder ähnlicher Form vorgelegt.

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List of Symbols and Abbreviations

α	Relief correction factor
θ	Available water capacity of the soil
τ	Water use efficiency
AA	Aust approach (referring to Aust 2012)
AGEB	Arbeitsgemeinschaft Energiebilanzen e.V. [Working group energy balances]
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe [Federal Institute for Geosciences and Natural Resources]
BKG	Bundesamt für Kartographie und Geodäsie [Federal Agency for Cartography and Geodesy]
BMELV	Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz [Federal Ministry of Food, Agriculture and Consumer Protection]
BMU	Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit [Federal Ministry for the Environment, Nature Conservation and Nuclear Safty]
BÜK	Bodenübersichtskarte [Soil survey map]
BUND	Bund für Umwelt und Naturschutz Deutschland [Association for Environmental and Nature Conservation Germany]
c_r	Content of roots in plant biomass
c_l	Content of leaves in plant biomass
CHP	Combined heat and power production
CPU	Central Processing Unit
CWB	Climatic water balance
DGM	Digital elevation model
DLM	Digital land cover model
DWD	Deutscher Wetter Dienst [German Weather Service]
EEA	European Environmental Agency
EQ	Equation
ET	Evapotranspiration
FAO	Food and Agricultural Organization of the United Nations
FNR	Fachagentur Nachwachsende Rohstoffe e. V. [Specialist agency of renewable resources]
frPHU	Fraction of potential heat units
GIS	Geographical Information System
GW	Ground water | in context with energy production GW stands for the unit gigawatt

HPC	High performance computer/computing
HRU	Hydrologic response unite
I	Interception
LAI	Leaf area index
MA	Murach approach (referring to Murach et al. 2009)
MoA	Modified approach (referring to develop in this study)
NSE	Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970)
P	Precipitation
PAW	Plant available water | describes the amount of water which can be utilized by plants from the water balance
PBIAS	Percentage bias
odt	Oven dry tones of biomass
RSR	Standard deviation ratio of the root mean square error
SRC	Short Rotation Coppices
SUFI-2	Sequential Uncertainty Fitting, Version 2
SWAT	Soil Water Assessment Tool
SWAT-CUP	Soil Water Assessment Tool - Calibration and Uncertainty Programs
UBA	Umweltbundesamt [German Environment Agency]
Ws	Harvestable yield of a plant

Abstract

According to the 2015 climate negotiations in Paris, it is evident that climate change can only be reduced by international efforts to decrease greenhouse gas emissions. To achieve the “2°C-target”, or rather the optional “1.5°C-target”, international agreements have to be implemented into national strategies. In previous years, similar efforts have brought about an increase in the development of renewable energies. This advance was guided by the intention to minimize CO_2-emissions. The future intended objectives, such as the decarbonization of the world economy by 2100, will promote the development of renewable energies. At the present time, biomass as a renewable energy carrier covers the lion’s share of Germany’s sustainable energy production. This infers that the biomass share will increase due to the increased focus on climate objectives. In this context, woody biomass has a key role, since 87% of renewable heat production in 2014 is related to this energy carrier. To ensure and enhance the supply with this resource, for some time past, short rotation coppices were applied to field sites in Germany. In this practice, fast-growing tree species such as willow or poplar are cultivated in a harvesting cycle of three to five years. After the indicated growing period, the harvest occurs in winter, to allow for tree regrowth to begin in the following spring.

However, the use of short rotation coppices is controversial as it’s debatable if this cultivation practice meets sustainability criteria. This discussion mainly focuses on the possible negative impacts to the water balance. But, concrete numbers regarding the regional or supra-regional influences are missing as well as universal results on a local level. This dissertation investigates partial aspects regarding sustainability and influences on the water cycle with this type of cultivation, in order to generate representative statements. These statements are directly related to the following issues: sustainable treatment of land and water resources, identification of suitable und unsuitable regions for cultivation, as well as the analysis and quantification of influences, particularly the sensitive components of the water balance.

Literature survey research shows that the establishment of short rotation coppices could derive positive effects. Such effects could be an enhancement of habitat variety in agricultural marked regions, an increase of the nutrient retention potential, as well as optimized management operation on drained field sites. This behavior implies that multiple win-win situations could arise through sustainable use.

However, not every region in Germany is equally suitable for this cultivation. Based on the plant available water, a Germany-wide suitability assessment was established on a regional scale. In the process it was shown that the approaches of Murach et al. (2009) and Aust (2012) could be significantly enhanced by their combination and an adjustment of the evapotranspiration calculation. With this enhancement, it could be proven that the Northern German Plain provides a particularly high suitability for woody biomass production in short rotation coppice. This is especially true in areas of high groundwater levels, which enhance the plant available water.

Further, this marks the area as a priority to future intensified cultivation, which implies an increased influence on the water balance in this region. To quantify the effects, four focus areas were defined as hydrological basins, which characterizing the Northern German Plain. Such focus areas are the basins of Ems, Treene, Aland as well as the river system of Uecker, Randow and Welse. After a successful calibration and by using plant parameters, estimated by the Eberswalde University for Sustainable Development in the research project AGENT, different scenarios of willow and poplar cultivation in short rotation coppices (SRC) were applied and calculated in the hydrological model SWAT. The results show that the influence on the regional water cycle is insignificant if up to 10% of the suitable agricultural area is converted. If applied in the specified scale, the establishment of SRC is irrelevant regarding the influences on regional scale. However, influences on the local level due to cultivation are much more considerable. If willow or poplar SRCs are cultivated, the results confirm, that the actual evapotranspiration is exceeding compared to conventional crops. Further, the results for this scale also show a decrees of groundwater recharge, surface runoff and base flow. These are consequences out of the behavior of water consumption and other framework conditions. The change of these conditions due to climate change, should be focused in further research to determine the future effects of this cultivation.

Zusammenfassung

Auch nach den jüngsten „Klimaverhandlungen“ in Paris 2015 zeigt sich, dass der Klimawandel nur mit einer einzelnen internationalen Strategie zur Reduzierung der Treibhausgasemissionen gebremst werden kann. Um das avisierte „2°C-Ziel“ oder gar das optionale „1,5°C-Ziel“ zu erreichen, müssen die internationalen Übereinkünfte in nationale Strategien umgesetzt werden. Schon in den vergangenen Jahren und Jahrzenten haben ähnliche Bemühungen zu einem verstärken Ausbau der erneuerbaren Energien beigetragen, mit der Absicht den CO_2-Ausstoß zu vermindern. Die zukünftig angestrebten Ziele, wie das der „Dekarbonisierung“ der Weltwirtschaft bis 2100, werden den Ausbau regenerativer Energien weiter vorantreiben. Schon heute stellt Biomasse als regenerativer Energieträger den größten Beitrag für die nachhaltige Energiegewinnung in Deutschland und so ist anzunehmen, dass dieser Anteil, bei Verfolgung der „Klimaziele“, in den kommenden Jahren weiter ausgebaut wird. Gerade holzartige Biomasse spielt in diesem Kontext eine entscheidende Rolle, da durch sie schon im Jahr 2014 87% der gewonnen regenerativen Wärmeenergie bereitgestellt wurde. Um die Versorgung mit diesem Rohstoff zu sichern und weiter auszubauen, werden seit einiger Zeit in Deutschland sogenannte Kurzumtriebsplantagen auf Ackerstandorten realisiert. In dieser Anbauform werden schnell wachsende Gehölze wie Weiden oder Pappeln in einem drei- bis fünfjährigen Erntezyklus angebaut. D.h. nach einer Aufwuchsphase in der angegebenen Größenordnung werden die Bäume meist im Winter geerntet und treiben im kommenden Frühjahr wieder aus.

Inwiefern diese Anbauweise jedoch verschiedenen Nachhaltigkeitskriterien entspricht, wird in der Fachwelt sehr kontrovers diskutiert. Diese Diskussion wird vor allem durch mögliche negative Auswirkungen auf den Wasserhaushalt angefacht. Jedoch fehlen bislang konkrete Zahlen zur regionalen bzw. überregionalen Einflussnahme sowie allgemeingültige Ergebnisse für die lokale Ebene. Um im Kontext dieses Themengebietes weiterführende Aussagen zur Nachhaltigkeit und zur Beeinflussung von Wasserhaushaltskomponenten durch diese Kulturen zu generieren, werden im Rahmen dieser Dissertation verschiedene Teilaspekte untersucht. Diese beziehen sich auf die Einflussnahme dieser Kulturen auf den nachhaltigen Umgang mit den Ressourcen Anbaufläche und Wasser, die Identifizierung von Gunst- und Ungunst-Regionen für die Etablierung dieses Anbaus, sowie die Analyse und Quantifizierung des Einflusses auf verschiedene besonders sensitive Wasserhaushaltskomponenten.

Die durch eine Literaturstudie gewonnenen Informationen zeigen, dass sich aus der Etablierung von Kurzumtriebsplantagen unterschiedliche positive Effekte auf den Naturraum ableiten lassen. So zeigen sich u.a. Verbesserungen der Habitatvielfalt in durch Landwirtschaft geprägten Regionen, positive

Effekte auf die Retention von Nährstoffen sowie große Chancen in der Managementoptimierung von stark gedränten Ackerstandorten. Dies impliziert, dass aus einer nachhaltigen Nutzung eine Vielzahl von win-win-Situationen erwachsen kann.

Jedoch ist nicht jede Region in Deutschland gleichermaßen für den Anbau geeignet. Basierend auf dem Transpirationswasserdargebot wurde die Anbaueignung deutschlandweit im regionalen Maßstab ausgewiesen. Hierbei zeigte sich, dass die Ansätze von Murach et al. (2009) und Aust (2012) durch Kombination und Anpassung der Evapotranspirationsberechnung deutlich verbessert werden konnten. Mit Hilfe dieser verbesserten Methodik konnte nachgewiesen werden, dass das Norddeutsche Tiefland eine besonders hohe Eignung für den Anbau holzartiger Biomasse im Kurzumtrieb bietet. Dies hängt insbesondere mit den hier häufig hohen Grundwasserständen zusammen, welche das Transpirationswasserdargebot für die Pflanzen deutlich erhöhen.

Somit ist das Norddeutsche Tiefland als Schwerpunkt für einen zukünftig intensivierten Anbau auszumachen, welches auch einen steigenden Einfluss auf den Wasserhaushalt dieser Region mit sich bringt. Um diese Auswirkungen zu quantifizieren wurden vier Schwerpunktregionen anhand von hydrologischen Einzugsgebieten ausgewiesen, welche das Norddeutsche Tiefland charakterisieren. Bei diesen Regionen handelt es sich um die Einzugsgebiete von Ems, Treene, Aland sowie des Flusssystems von Uecker, Randow und Welse. Nach erfolgreicher Kalibrierung und mit Hilfe von Pflanzenparametern, welche im Rahmen des Forschungsprojektes AGENT durch die Hochschule für Nachhaltige Entwicklung Eberswalde bestimmt wurden, konnten verschieden Szenarien für einen Anbau von Weiden und Pappeln mit dem hydrologischen Modell SWAT gerechnet werden. Es zeigte sich, dass der Einfluss auf den regionalen Wasserhaushalt bei einer Nutzung von bis zu 10% der geeigneten Anbaufläche keine signifikanten Veränderungen aufweist. Was den Anbau der genannten Kulturen im Kurzumtrieb und für die angegebenen Größenordnungen im regionalen Kontext des Wasserhaushaltes als unerheblich beschreibt. Jedoch ist die Einflussnahme auf den lokalen Wasserhaushalt weitaus deutlicher. Werden Weiden- oder Pappel-Kurzumtriebsplantagen etabliert, so bestätigen die Ergebnisse eine Zunahme der aktuellen Evapotranspiration im Vergleich zu konventionellen Anbaukulturen. Darüber hinaus zeigen die Ergebnisse auch eine Abnahme der Grundwasserneubildung, des Oberflächenabflusses sowie des Basisabflusses. Dies sind Auswirkungen, die auf den Wasserverbrauch und andere Rahmenbedingungen zurückzuführen sind. Bedingt durch den Klimawandel werden sich diese Rahmenbedingung ändern, was zum Gegenstand zukünftiger Forschung werden sollte, um die zukünftigen Auswirkungen des Anbaus besser abschätzen zu können.

1 Introduction

Human-induced climate change is a major challenge of the international community. To counteract this and decrease CO_2-emissions, different strategies have been applied to change the way energy is produced — namely, a withdrawal from fossil energy carriers and a focus on renewable solutions. Such intentions are confirmed by international efforts such as the “2°C target”, the long-term decarbonization objective decided by the G7-nations, as well as specific CO_2-reduction aims on a national and international scale. These efforts have to be integrated into concrete concepts and adapted to the sustainability of different environmental conditions and requirements all over the world.

1.1 Motivation

Germany’s contributions to the international CO_2-emission goals were based on broad political and social discourses. As a result, comprehensive reduction aims were established in 2011 to decrease emissions by 40% in 2020, 55% in 2030, and 80 to 95% in 2050, as compared to 1990 levels (BMU 2011). To achieve these aims, renewable energy carriers are focused on meeting the needs in heat and power production as well as increasing efficient use. However, the Fukushima disaster was a turnaround in Germany’s nuclear energy concept, initiating a phasing out of nuclear energy, which should be achieved by 2022. This intensifies the efforts in the energy system transformation. The current decline in nuclear energy is covered by renewable energy carriers. But it is questionable if the reduction goal for 2020 can still be achieved, due to a fuel change from gas to coal by power plant operators (Agora-Energiewende 2014).

To establish a broad basis for renewable energy, different energy carriers need to be focused. These focused energy carriers are mainly water power, photovoltaics, biogenous waste, wind energy, and biomass. Since biomass covered 6.7% of the total primary energy consumption in 2014, it is the lion’s share of all renewable energy carriers. But biomass is far more visible when considering that in the heat production of renewable energy carriers, it took 87% of the share in 2014 (AGEB 2015). The aims set in the context of CO_2-emissions reduction show that the need for biomass will increase in the near future.

Sustainability of biomass production has to consider a framework of conditions that have to be met on both environmental and socio-economic aspects. As a result of a rising requirement for heat production, the conventional woody biomass forest output is not a sustainable option (Aust 2012). In consequence, fast growing tree species like willow or poplar are cultivated on arable land as short rotation coppice (SRC) to close the gap on supply and demand (Figure 1-1 and Figure 1-2). The cultivation system of SRCs includes a growing period, or rather harvesting cycle, of three to five years. After a harvest, the plants regrow from their stump. Such a plantation remains in use for almost 20 years, and then they are transferred back to an annual cultivation.

Figure 1-1: Harvest of a willow short rotation coppice in February 2014; Blumberg, Brandenburg, Germany (picture by Rainer Schlepphorst 2014)

Figure 1-2: Four year old poplar short rotation coppice in May 2015; Dörntal, Saxony, Germany (picture by Daniel Rasche 2015)

Positive as well as negative effects of SRCs on land and water resources have been the subject of numerous approaches (Elowson 1999, Hall 2003, Börjesson & Berndes 2006, Dimitriou et al. 2009a, Köhn 2009, Baum et al. 2009, Schmidt & Glaser 2009, Nisbet et al. 2011). On one hand these approaches indicate a general enhancement of water quality and habitat functions, while on the other hand show a negative impact on water quantity as well as a reduction of farmland used for food production, triggering the "food vs. fuel dilemma". Considering these effects, the woody biomass production in SRCs is described in terms of sustainability by a framework of different aspects. To assess the components of this framework, it is necessary to describe and quantify their impact. This could provide proper environmental management concepts resulting in win-win situations.

The current area of arable land used for SRCs of approximately 10,000 ha is applied in this case (BMELV 2012, Internationales Institut für Wald und Holz NRW 2014). However, to cover the projected woody biomass need in 2020, the Internationales Institut für Wald und Holz NRW (2014) predicts the need of an agricultural area between 0.6 and 1.3 million ha. As shown by former approaches, the landscape conditions for SRCs are not always suitable (Andersen et al. 2005, Murach et al. 2009, Aust 2012). These and further approaches (Lindroth & Båth 1999, Boelcke 2006, Stork et al. 2014) also point out that a key factor for an appropriate assessment is water availability to the plants. Irrigation is seen as uneconomic and fertilization viewed as unnecessary, due to a low nutrient uptake of the typical plants in SRCs. Finally, the water availability triggers the spatial distribution and quality level of suitable sites.

If such plantations are established primarily on sites with a high proportion of water available for the plants, this could affect water balance components. This behavior is also assumed by different approaches (Petzold et al. 2009, Webb et al. 2009, Wahren et al. 2014, 2015), which also indicate concrete effects on water balance components, such as groundwater recharge, base flow, surface runoff as well as actual evapotranspiration. However, most of these effects were only assumed and not qualified. Measurements often indicated the effects were related to a specific site's particular environmental conditions (Guidi et al. 2008, Mirck & Volk 2009, Persson 1995, Persson & Lindroth 1994, Pistocchi et al. 2009, Stephens et al. 2001). The main concern is heterogeneous landscape conditions have to be taken into account for regional scalability, which could increase or decrease the assumed effects on the water balance. This also counts for general comparison of SRCs with conventional annual crops to quantify their impact on local conditions.

1.2 Research questions and aims

This dissertation project is associated with the science project AGENT[1], which will determine the potentials of woody biomass in the Northern German plain by considering water availability and its competition with other regular crops. With this background and the perceived problem, this doctoral thesis focuses on a Germany-wide assessment of the regional suitability of SRCs, as well as their impact on sustainability of land and water resources. This implies the following research questions:

1. How is the sustainable use of SRCs in terms of land and water availability characterized?
2. In which conditions could SRCs achieve win-win situations?
3. How can the methodological concept of Aust (2012) and Murach et al. (2009) be improved in order to better comply with environmental conditions and enhance the determination of suitable sites?
4. Which agricultural regions in Germany are suitable for SRC cultivation as well as associated with a certain bioenergy potential?
5. Considering the impact on regional and local water balance, which quantities and effects could result in suitable regions?

To answer these questions, different approaches have to be combined to satisfy all requirements. The concept of this doctoral thesis covers an overview of SRCs in relation to the sustainability of land and water resources. In the next step, landscape aspects were analyzed to determine suitable sites in Germany and to determine the impact on regional and local water balance if these sites were used for an SRC cultivation practice.

For sustainability efforts, a literature survey provided clarification on framework conditions and win-win situations — which would serve both environmental conditions in a cultural landscape as well as societal need for a renewable energy carrier. While several previous approaches focused on different aspects of the impact of SRCs on land and water resources (Hall 2003, Nisbet 2005, Dimitriou et al. 2009a) they showed only limited results by combining these aspects or not mentioning such conclusions.

[1] AGENT: Potentiale agrarer Dendromasseproduktion im Norddeutschen Tiefland unter Berücksichtigung der Wasserversorgung und Konkurrenzfähigkeit von Kurzumtriebsplantagen [Potentials of agricultural fuelwood production on the northern German plain, in consideration of water supply and competitiveness of short rotation coppice]

To estimate suitable sites in Germany, some studies were applied to a regional scale. The sites Brandenburg and Saxony federal states were set as a limitation (Murach et al. 2009, Ali 2009). In contrast, the approach of Aust (2012) focused on the entire national territory of Germany. However, the latest approaches of Murach et al. (2009) and Aust (2012), mainly use the plant available water (PAW) as factors to determine suitability. As such, the estimation methods were adapted and improved to accommodate an evapotranspiration calculation. This optimization leads to results of higher significance, which more accurately reflect the plant and landscape conditions.

Several approaches monitored side specific conditions and the effects of SRC cultivation on the water balance (Ettala 1988, Hall & Allen 1997, Allen et al. 1998, Dimitriou et al. 2009b, Nisbet et al. 2011). But, fewer studies have focused on regional aspects (Hall 2003, Wahren et al. 2014, 2015). This follows from lack of plant parameters, which were used in hydrological models to determine such impacts. The lack has been decreased, due to the measurements on willow and poplar SRCs by the Faculty of Forest and Environment at Eberswalde University for Sustainable Development in the research project AGENT. Using data in the Soil Water Assessment Tool (SWAT), it was possible to determine the effects on the water balance in quantity and quality by hydrological modelling. Several approaches suggest the suitability of SWAT to characterize hydrological effects related to land use changes (Arnold et al. 1998, Srinivasan et al. 1998, Gassman et al. 2007, Wahren et al. 2014, 2015).

The aims of this research are to inform the SRC conditions needed for a sustainable framework that shows win-win situations. Further, this research will help locate suitable sites for SRC establishment and determine spatial aspects, such as their quantity and quality. In relation to the sites with a high suitability level, the impact on the regional and local water balance will be observed by hydrological modelling. In consequence, these aims help find a sustainable way to implement SRCs as a renewable energy carrier.

1.3 Structure of this dissertation

In Chapters 2 through 5, the objectives of this study are described in detail by several publications and manuscripts (Table 1-1). All contributions listed are majorly carried out by me in conception, implementation and writing, which is also indicated by my first and correspondent authorship. However, my co-authors are all participators of the research project AGENT and contributed by setting up framework conditions for the research, carefully revising the manuscript and inducing new perspectives for the articles. In particular, the approach presented in Chapter 5 is based, inter alia, on plant parameters observed by Dr. Markus Schmidt and determined during the research project AGENT.

All journals use a peer-review process and are ranked internationally. All articles were also originally published and submitted in English, except for the article in the journal "Hydrologie und Wasserbewirtschaftung", which was translated for this dissertation. The presented order of these articles refers to the scientific preparation of the work and is not oriented on the publication date. As a consequence, some articles introduced by self-citations will partly appear subsequently in this doctoral thesis.

Table 1-1: Chapters in this dissertation and related publications as well as manuscripts submitted

Chapter	Publication	Status
2	Hartwich J, Bölscher J, Schulte A (2014) The impact of short rotation coppice on land and water resources. *Water International* 39 (6): 813-825. DOI: 10.1080/02508060.2014.959870 as well as Hartwich J, Bölscher J, Schulte A (2014) The impact of short rotation coppice on land and water resources. In: Thomas Hartmann & Tejo Spit (Hrsg.): Frontiers of Land and Water Governance in Urban Regions - Routledge Special Issues on Water Policy and Governance. Taylor & Francis Ltd. 813-825. ISBN: 978-1-138-91115-4	First published in: October, 2014 Water International
3	Hartwich J, Bölscher J, Schulte A (in review): Identification of suitable areas for willow short rotation coppices in Germany from a hydrological perspective and evaluation of the yield potential. *Biomass & Bioenergy*.	Submitted in: March 2016 Biomass & Bioenergy
4	Hartwich J, Bölscher J, Schulte A, Schmidt M, Pflugmacher C, Murach D (2015) Das Transpirationswasserdargebot als steuernder Faktor für die Produktion von Energie aus Weiden in Kurzumtriebsplantagen – Abschätzung des Bioenergiepotentials für Deutschland [The plant available water as a controlling factor for the energy production from willow SRC – Estimation of bioenergy potentials in Germany]. *Hydrologie und Wasserbewirtschaftung* 59 (5): 217-226. DOI: 10.5675/HyWa_2015,5_2	Published in: October 2015 Hydrologie und Wasserbewirtschaftung
5	Hartwich J, Schmidt M, Bölscher J, Reinhardt-Imjela C, Murach D, Schulte A (2016): Hydrological modelling of changes in the water balance due to the impact of woody biomass production in the North German Plain. *Environmental Earth Sciences* 75 (14). DOI: 10.1007/s12665-016-5870-4	Published online in: July 2016 Environmental Earth Sciences

2 The impact of short rotation coppice on land and water resources

Abstract

The European Union is focusing on increasing renewable energy sources. One of these sources, known as short rotation coppice (SRC), involves planting wood, as an energy carrier, on agricultural sites. By presenting a literature research, this paper studies the advantages and disadvantages of SRC in relation to its effects on water and land resources. In terms of renewable energy sources, considering these effects in the current process of social reconstruction is essential for sustainable development. With regard to this, SRC is a key element in the environmental management of land and water.

2.1 Introduction

In 2007 the European Council mandated that the proportion of renewable energy in electricity production should increase to 20% in the European Union by 2020 to reduce CO_2-emissions and lessen the effects of climate change. In Germany, after an intense public debate, the targeted percentage has been established at a minimum of 35%, out of which 8% should be met by bioenergy (and 27% from other renewable energy sources) (BMELV & BMU 2010, BMU 2012). Already, 92% of the heat production in Germany that is generated from renewable energy is gained from biomass, most of which is wood (BMU 2012).

Thus, there is a great potential and also a great need for woody biomass production. The conventional output of forests cannot provide sufficient wood production amounts because of regulatory restrictions and, to an even greater extent, because sustainable usage of forestland is not realistic (Aust 2012). As a result, cultivation methods such as short rotation coppice (SRC) have become increasingly important in closing this gap. With this method, willows or poplars are planted on agricultural sites like 'normal' annual cultures. But instead of being harvested after one season, they are allowed to grow for a period of three to five years. In total, such plantings remain in use for almost 20 years. Furthermore, different studies have shown that, on the national scale for Germany, SRC has a high potential for being a renewable and decentralized energy carrier (Murach et al. 2009, Aust 2012, Hartwich et al. 2014a). Such potential ought to be considered on the European scale.

However, this type of cultivation also has its drawbacks. SRC often requires the reassignment of land and water resources away from their current usage. For example, farmland used for food production may be reassigned to biomass creation for bioenergy. Moreover, SRC has positive and negative effects on land and water issues, especially water quality and quantity. In terms of renewable energy sources, considering these effects in the current process of social reconstruction is essential for reaching the goal of overall sustainable development. This creates a dilemma for the sustainable use of water in the field of renewable energy creation. On the other hand, win-win situations could arise within a proper environmental management concept.

In order to optimize yield and environmental conditions, decision makers such as land-use planners and private stakeholders (i.e. landowners and farmers) must be provided with information regarding the positive and negative aspects of SRC that affect environmental conditions. This need is further amplified by the variety of perspectives generated by this optimization process in decision-making.

This process gives rise to the following questions. Which positive or negative effects are important and need to be taken into account in the land-use planning and later the cultivation process? Moreover, which challenges arise and have to be considered in the establishment process? These questions relate directly to the aim of this approach: to provide decision makers and stakeholders with the relevant information about the land and water aspects of SCR. To fulfil this aim, this approach offers a framework of conditions to prevent a dilemma in sustainable water use and to initiate a win-win situation through the establishment of SRC.

To answer these central questions and achieve this aim, this study first introduces the hydrological aspects of SRC cultivation. Next, the focus of this approach shifts to the main aspects of environmental management and considers the effectiveness of SRC in terms of land and water management. As a general rule, the usage of water and land in cultivation practises must be efficient to guarantee sustainability. To address this, the efficiency of SRC will be studied in this approach. Moreover, to realize successful cultivation in relation to water management and ecologic benefit, this study suggests a way to gain establishment and identifies the profiteers of such an establishment. By way of literature research, this approach reflects different environmental management aspects of SRC cultivation and their relevancy to decision makers and stakeholders.

Conceptually, this study is oriented towards this special issue, in which the editors are seeking to establish a new vision of environmental frontiers. This framework allows one to concentrate the discussion on the physical boundaries between land and water. Consequently, this work considers the vertical frontier and focuses on the influences of SRC establishment on the water cycle (Hartmann & Spit 2014).

2.2 Hydrological aspects of SRC cultivation

This section provides information about the impacts of SRC on the water balance, especially concerning groundwater recharge. The recharge of groundwater is, in general, controlled by aspects of the landscape, such as climate, geology, topography, soil, vegetation and land use (Healy 2010). The last two mentioned characteristics, vegetation and land use, influence evapotranspiration and interception, which are the dominant aspects that affect groundwater recharge. Evapotranspiration is defined as the total of components that evaporate from plants and soil, and transpiration is defined as the water used by plants to develop biomass. Interception describes the water content that is stored on the outer vegetation layer (Dimitriou et al. 2009a). All these landscape characteristics are strongly influenced by a change of cultivation from annual crops to SRC (Webb et al. 2009, Petzold 2009). Such a dramatic change may result in a decrease of percolation to the aquifer and could trigger a lowering of the groundwater level (BUND 2010).

Due to canopy development and a large leaf surface area, plants like willow or poplar are able to intercept much more precipitation than shorter types of foliage plants during the vegetation period (Nisbet 2005, Dimitriou et al. 2009a). Similar to other woody plants, and in comparison with annual crops, there is a higher loss to interception, which also persists at a lower amount during the dormant period in winter. Values of intercepted precipitation during the vegetation period have been reported: Ettala (1988) recorded 31% interception for willow SRC in Finland; Hall & Allen (1997) reported 21% interception for poplar in the UK. Due to variations in stand ages, canopy heights or diverse local conditions, these values tended to cover a large range. But in contrast to conventional field crops, with an interception of about 15%, the reported amounts for SRC are significantly higher (Hall 2003, Dimitriou et al. 2009a). These higher levels of interception lead to a decrease in the water amounts that are reaching the ground, or, in other terms, it lowers the amount of effective rainfall.

Poplar and willow are efficient plants in terms of biomass production, which is linked to a high water use. This results from their natural environment on floodplains or wetland areas, where water availability is high. Moreover, a rapid growth dynamic is essential in these habitats, where physical events like flooding or sediment transport present much stronger limitations to growth. However, their water use increases even more in warm climates (Dimitriou et al. 2009a). Dimitriou et al. (2009a) and Busch (2009) compared the results of nine different studies that estimated the evapotranspiration amounts for poplar and willow SRC in Sweden, Great Britain and Germany. On average, the test sites reached precipitation amounts of 700 mm during one year. Two thirds of this amount were lost to evapotranspiration. In comparison with Penman open water evaporation, SRC shows higher values. A similar effect is reported for a crop coefficient, which reflects the evapotranspiration in comparison with a grass-covered site. When compared with grassland, SRC areas reached 20% higher rates of evapotranspiration (Allen et al. 1998, Dimitriou et al. 2009a, Nisbet et al. 2011, Hartwich et al. 2014a).

A high water abstraction from the ground, due to a well-developed root system, results in soil with lower moisture content compared with regular field sites (Lamersdorf et al. 2010). This requires a rain event with a longer time span and a higher water content to fill up the porous space in the soil. Following this saturation phase, a percolation to the aquifer takes place, which recharges the groundwater. On the other hand, tillage needs to be done only once before the establishment of an SRC. Consequently, a consistent pore system exists, which supports the percolation process. The above-mentioned aspects make it difficult to determine the influences on leaching when compared with other arable crops (Dimitriou et al. 2009a). However, poplar and willow are able to reach groundwater with roots growing to depths up to 2 m (Volk et al. 2001). If the groundwater table is accessible to the plants, they could expand their water use. Nisbet et al. (2011) report a doubling of water use compared with locations without access to groundwater. Furthermore, it is mentioned that the volume of groundwater recharge can be reduced by 50% in comparison with sites where grassland is established.

Nevertheless, due to their impact on the water balance, and because of the general management practices of SRC, the cultivation of these products has a positive impact on water quality (EEA 2008). With regard to ex-agricultural land with a high nutrient content resulting from previous fertilization, the establishment of SRC is able to lower the fertilization leakage to ground or surface water bodies (Nisbet et al. 2011, Dimitriou et al. 2009a). Such an effect is also possible in the case of heavy metals, but Dimitriou et al. (2009a) have acknowledged a lack of research in that field. However, in comparison with other arable crops, the need for physical and chemical treatment is reduced to a minimum in SRC areas. Tillage and pest and weed control are only applied during the plant establishment, which results in an extremely low impact on water quality. This becomes even clearer when it is taken into account that the lifespan of this crop varies between 10 and 20 years (Dimitriou et al. 2009a).

2.3 Different perspectives regarding the establishment of SRC

To provide decision makers and stakeholders with relevant information about SRC and its influences on the landscape it is necessary to focus on the different aspects of environmental management. These different aspects rise from the variety of spheres existing in the environmental management decision-making process. Furthermore, the consequences of cultivation, an aspect of land and water management, are also influencing these spheres. These influences and their consequences are studied in this approach by means of a literature review.

The literature reviewed and presented herein was identified as suitable for describing the influences of SRC and their relevance in the decision-making process. This paper is structured around perspectives of decision-making, derived from Hartmann & Needham (2012) and Hartmann & Spit (2014), which emphasize inter alia the role of effectiveness and efficiency in decisions on scarce natural resources. This structure highlights the main subjects of this paper, which relate to the reassignment of land and water by SRC and the effectiveness of that process. Furthermore, the efficiency of that cultivation is presented, reflecting the situation from a land- and water-use perspective. The mode of establishment is considered, as it is a key factor in implementing SRC and increasing its positive benefits while limiting its negative consequences on water management and the ecology. In addition, an important element in the decision-making process is the framework in which the profiteers of that concept are arranged.

These main subjects foster both a scientific and a management perspective and aim at analyzing, reflecting upon and evaluating the advantages and disadvantages of SRC and its influence on land and water issues. By providing pertinent information for decision-makers and stakeholders, this study can facilitate the future reassignment of land and water resources for generating renewable energy through biomass. This study also aims to counteract the dilemma between sustainable water use and renewable energy production by identifying win-win situations.

2.3.1 Effectiveness of SRC

Effectiveness is the ratio between the forecasted and actual achievement of objectives. When applied to the reassignment of land and water resources, effectiveness involves a scale for measuring cultivation and water. However, in this study it is necessary to distinguish between primary and secondary objectives. The primary aim of SRC is to establish a renewable energy source triggered by an economic model. Of equal importance, the secondary aim of SRC is to provide ecological benefits. Such results can be achieved by controlling the effects of water abstraction by the plants. Further results may include enhancing bird habitats or minimizing land consumption, thus counteracting the 'food versus fuel dilemma'.

For the primary objective, the first link in the system is the farmer. According to Murach et al. (2009), a farmer would produce willow SRC if the harvestable amounts were over 8 odt ha^{-1} a^{-1} (odt = oven dry tons of biomass). At that amount, the production would be economical and could compete with other agricultural products. Additionally, the primary objective is to find a renewable energy source that reduces CO_2-emissions. Therefore, it becomes obvious that woody biomass is a promising renewable energy carrier. In contrast to a fossil energy source, SRC biomass does not emit any 'new' CO_2 into the atmosphere. However, it should be taken into account that farming and transporting the product produces emissions that cannot be compensated by the biomass production of these plants (Heller et al. 2004, Cocco 2007, Styles & Jones 2007, Dimitriou et al. 2009a).

Unlike the primary objective, the secondary objectives for the establishment of SRC are more closely to the management of land and water resources. Thus, they influence both ecological and social issues. This link becomes even clearer when considering the growing conflict between biofuel and food production, a conflict in which SRC is taking a special position. In recent years, critics have argued that, in general, biomass production as an energy carrier reduces arable land, lowers harvestable amounts of food, and finally, creates a nutrition deficit, predominantly in developing countries. The last argument relates to higher costs of food due to a reduced supply (Mitchell 2008, FAO 2009, Zichy et al. 2011). On the other hand, a World Bank report by Baffes & Haniotis (2010) explained that the extreme rise of food prices from 2007 to 2008 mainly resulted from 'speculation' on commodities and, only to a lesser extent, the development of the biofuel market. However, due to its low nutrition needs, SRC does not require special treatments like fertilizer, unlike maize or other crops. For this same reason, it can be planted in fields with a very low agricultural potential. If these low potential areas were primarily used, SRC would avoid conflicts with food production (Gerold et al. 2009). Furthermore, according to the findings of Biswas (2009), the lack of food production is more a water and food management problem than a problem caused by the availability of land resources.

Regarding the secondary objectives of SRC, or the ecological standpoint, the dominant subjects are water management, land consumption and the variety of habitat structures in a cultivated landscape. In this context, if SRC is not cultivated in monoculture, it is capable of providing the maximum amount of habitat structures by offering the key elements in a biotope network (Köhn 2009, Baum et al. 2009, Schmidt & Glaser 2009). If these cultivation structures were established as buffer zones next to aquatic environments, they would also have positive effects on water quality. This would be achieved by both a reduction of water percolation through the soil, which reduces leakage of nutrients, heavy metals or other chemicals, and a minimum of fertilization and chemical applications on the plants (Elowson 1999, Börjesson & Berndes 2006, Dimitriou et al. 2009a, Nisbet et al. 2011). Beyond water quality, the water quantity would be influenced by the high water consumption of the plants. This basic issue of water abstraction leads to diverse effects, especially in cases where the groundwater recharge is affected. Problems occur when the groundwater level decreases and the base flow of creeks declines. In such cases, ecosystems would be harmed, especially during dry summer periods when rivers generate discharge through groundwater components (Hall 2003, Dimitriou et al. 2009a, Nisbet et al. 2011). To avoid these consequences, it is recommended that SRC should not be applied in landscapes with a negative climatic water balance (Nisbet et al. 2011). On the other hand, lowering the groundwater table can benefit regions with a high level of water saturation. The application of SRC in these areas also provides an approach for lowering general maintenance costs. This refers in particular to technical infrastructures that utilize pumping or drainage practices to adjust the groundwater level according to certain standards. Because of their potential for reducing secondary CO_2-emissions and costs produced by the above-mentioned infrastructures, the secondary or ecological objectives of SRC should be brought into greater focus in further research.

In relation to the primary objectives for establishing a renewable energy source, SRC has the ability to reduce CO_2-emissions and compete with other bioenergy solutions like wind or photovoltaics (Heller et al. 2004). If the secondary objectives are also taken into account, which are mainly related to water issues and other ecological impacts, the complexity of SRC advantages and disadvantages becomes visible, especially in the ‘food versus fuel dilemma’. However, the facts suggest that SRC will most likely have a positive impact on the environment. Accounting for both the primary and secondary aims of SRC, this bioenergy model rests on a broad basis in terms of effectiveness.

2.3.2 Efficiency from a land- and water-use perspective

Land and water are rare goods, and the efficiency of their usage depends on the comparison of their ‘consumption’ against the produced benefits. These produced benefits are not determined exclusively by economic factors, but rather they are tied closely to ecological or more water-related issues. Therefore, the functional capability of an environment becomes an integral part of human well-being (Gleick 2000, Biswas 2009). Land and water management ensure that sustainable utilization concepts are implemented to guarantee the present and future use of these resources (Roger & Hall 2003). Thus, the efficiency of land and water use is less dependent on economic issues and is more a matter of ecological and sustainable utilization.

The establishment of SRC serves multiple needs, which increases its level of efficiency. With regards to its primary objective, to produce a renewable energy source, SRC is a very sustainable solution, especially in contrast to the use of fossil energy carriers or wood from forests (Heller et al. 2004, Cocco 2007, Styles & Jones 2007). This point rests on two principal arguments: (1) The majority of forest timber products have a high quality. Their use for energy production presents an uneconomic scenario in which high-quality raw material is used for energy production without former usage. Moreover, the amount of preferred tree species in conventional forests is too low to serve the needed energy demand (Marland & Schlamadinger 1997). (2) If a forest is managed properly, it serves a need for high-quality wood. More importantly, a forest is a sustainable and ecological system, which needs time as a central criterion to achieve these objectives. These aspects show that conventional forestry meets both an economic need for high-quality wood products and mitigates long-term environmental issues. Also, considering the terms of a cultivated landscape, it is essential that landscape functions are being preserved for bioenergy production. This approach is conducive to the establishment of a sustainable land management, particularly in a landscape with clustered environmental functions.

The same applies to the water use perspective. The relevance of efficiency, or rather sustainability, is connected to multiple issues (Söderbaum & Tortajada 2011). These water-related issues are defined by Gleick et al. (2011) as water quality, productivity, reliability and energy demands. As shown previously, the influences of SRC on water quality are primarily positive compared with the influences of other agricultural crops. Furthermore, research indicates that, when planted as buffer strips along fields in the vicinity of aquatic ecosystems, SRC enhances water quality (Elowson 1999, Börjesson & Berndes 2006, Dimitriou et al. 2009a, Nisbet et al. 2011). The productivity yield of SRC is often estimated by using the water-use efficiency of the tree species planted. Additionally, an estimation of the plant-available water in the environment must be calculated. Different assessment strategies have been developed for this purpose, but in general a close proximity to groundwater is essential for an optimal yield because of the high water consumption of SRC. If SRCs are able to reach the groundwater level with their root system, this establishes optimal conditions for water availability. SRC productivity also refers to the fact that this type of cultivation does not generally require fertilization operations, due to economic conditions and the physiological structure of the plants. The nutrition needs and limited yield prices of the plants are too low to justify fertilization (Murach et al. 2009, Aust 2012, Hartwich et al. 2014a). In the case of reliability, if the water amounts are restricted in the landscape because of a negative water balance or other issue, it is possible that there will be adverse effects on the biomass production and on the environment. In this context, reliability is defined by Hashimoto et al. (1982) as the extent to which a system is in a suitable state. When this idea is transferred to an environmental management concept, it implies the need for a sustainable selection of locations where the water requirements will be met. If such regulations are not introduced, the system would lose balance and, with it, sustainability. However, if the required energy demands of SRC are met, it seems that a positive energy balance in the cultivation process will be the result. These findings are confirmed by several studies in the field (Heller et al. 2004, Cocco 2007, Styles & Jones 2007). However, these studies also suggest that frameworks of components like transportation, cultivation and harvesting are able to lower the general energy output. In order to achieve optimal efficiency and sustainability in land and water usage, it is necessary that these components of energy efficiency be addressed economically.

A sustainable treatment could be achieved if recommendations or regulations were used to set a framework to minimize negative impacts on the environment and optimize sustainable development in ecological terms. This approach would especially support the development and expansion of ecosystem functions in a cultivated landscape.

2.4 A way to gain an establishment for SRC

To enable the establishment of SRC, it is necessary to generate and use a win-win situation to trigger positive development in water and ecological issues as well as socio-economic benefits. Pain et al. (1996) published a solution for avoiding conflicts between water resource management, food and energy crops that focused on cultivation of SRC on (1) land with a highly erosive quality, (2) agricultural land with a high water content and (3) land that is not fertile enough for effective food production. This approach stands with other studies that not only count the direct monetary profit of SRC but also consider the environmental benefits (Hanegraaf et al. 1998, Duer & Christensen 2010, Uchida & Hayashi 2012). These studies highlight the benefits of bioenergy by focusing on environmental objectives like the improvement of water quality, the increase of habitat variety and the reduction of greenhouse gas emissions. Since these often water-related benefits are linked to the well-being of society, it is logical that SRC should gain the support of subventions. Currently, direct monetary subventions are not established, however, indirect support systems can be found. In this context, it is possible to adapt SRC to so-called ‘greening activities’. These activities are part of the ‘common agricultural policy’ (CAP). As such, they use monetary benefits to encourage farmers to establish agricultural sites with high ecosystem functions or qualities to counteract climate change (Busch 2012, Schmidt et al. 2014). The system of emission trading generates a further indirect subvention for SRC by improving the energy production from renewable sources (Köhn 2009).

However, the community has to set up stimuli to trigger the developments of SRC so that it can serve society in the broadest sense. As with all economic concepts, monetary incentives generate a strong vehicle for the dispersion of innovation. This applies very well to the innovation of SRC. But a pure monetary incentive would result in an uncontrolled spread of SRC without regard to the social and environmental risks or benefits of its cultivation. Subventions can lower these risks if they are channelling SRC efforts to useful sites. On the other hand, an approach that is not economically based could also provide a good solution to this problem. Such an idea could be based on the above-mentioned ‘greening activities’ and emission trading, which are also related to ecological treatment of a landscape. In this case, SRC would receive a ‘formal’ or an economic weight that indicates an intangible value linked to the positive environmental effects of SRC.

2.5 Profiteers of cultivation

One of the central questions of this discussion is who benefits from SRC and to what extent do they profit. To answer this question, the actors and their roles must first be identified. The owner of an SRC takes the position of the primary economic beneficiary who profits directly from the harvest. Due to the owner’s position in the establishment of SRC, his profit has a strong connection to the market price of wood chips and the costs of cultivation. In this way, and due to his ability to plant, harvest and earn money from planting, the farmer is the main stakeholder in this sector (Pretzsch & Skodawessely 2010).

The benefit a society receives is based on the level of sustainability that is created by a well-established SRC. In this case, ‘well established’ refers to the positive aspects described in the former subsections. If these aspects are taken into account, a maximum sustainability is achieved by way of cultivation, which refers to the most positive characteristics. Such an approach also takes the environment into account or, in a broader context, nature. The environment stays preserved due to a sustainable treatment. This benefit counts even more in a cultivated landscape, which is hardly clustered into ecosystem functions. SRC provides the opportunity to reestablish these functions in relation to the discussed water issues. This wide range of ecological profit is expressed by several discussions and studies (Schmidt & Glaser 2009, Schägner 2009, Dimitriou et al. 2009b, Schmidt & Gerold 2010).

If society and nature can be described as stakeholders in this context, then profits can be attributed to them. Schägner (2009) formulated a list of profits and indirect benefits of SRC cultivation which included: (1) a contribution to climate protection due to carbon storage and the lessening of greenhouse gas emissions, (2) positive regulatory effects on the environmental water balance, (3) flood control by water retention, (4) improvement of microclimate and air quality, due to the evapotranspiration characteristics of SRC, (5) enhancement of soil and water quality by limiting erosion and fertilizer application and (6) improvement of habitat variety and ecosystem functions.

2.6 Discussion

The establishment of SRC can be seen as a consequence of the new European energy policy. Due to the high volume of timber needed for a future of renewable electricity rather than heat production, the conventional forestry model cannot provide the needed amounts of wood while also remaining sustainable (Aust 2012). As an alternative, SRC is a type of cultivation associated with the reassignment of land and water resources away from their current usage. Furthermore, SRC may have positive and negative effects on the environment, which should be considered in the planning and cultivation process, and which may counteract a possible dilemma between sustainable water use and renewable energy. From an environmental management standpoint, the effectiveness and efficiency of SRC mainly affects water-related issues.

With regard to the primary objective to establish a renewable energy source, SRC is able to compete with other bioenergy solutions, like solar power or wind. Furthermore, SRC has the ability to reduce CO_2-emissions, if framework parameters like cultivation and transportation of the product are set up properly (Heller et al. 2004).

As another benefit, in a cultivated landscape, SRC is capable of adopting ecosystem functions and enhancing the habitat variety. Moreover, it is reported that a cultivation has positive effects on water quality, especially when these plantings are established in the vicinity of drainage systems or between rivers and agricultural areas (Elowson 1999, Börjesson & Berndes 2006, Dimitriou et al. 2009a, Nisbet et al. 2011).

As to its impact on the ecosystem, SRC is able to reduce groundwater recharge up to 50%, due to its high water abstraction (Nisbet et al. 2011). This ability could have negative effects (e.g., for the base flow of creeks during summer months, or in generally dry periods, this behaviour would stress the ecosystem). Due to this effect, a cultivation of SRC should not be applied in areas with a negative climatic water balance (Hall 2003, Dimitriou et al. 2009a, Nisbet et al. 2011). Alternatively, SRC could be used in agricultural areas where the soil has a very high water content and/or groundwater level. This would avoid the necessity of maintaining cost- and labour-intensive drainage and channel systems, such as those used in the cultivated peat and wetlands in Northern Germany and the Netherlands. Furthermore, the ability of SRC to flourish in high water areas could be used to manage high groundwater levels in the vicinity of urban areas as well as to reduce costs for technical groundwater management. Perry et al. (2001) described a further positive effect of SRC: the reduction of peak water levels in a medium flood event. The water retention capacity of SRC could be used in decentralized flood protection concepts. Bölscher et al. (2010) have shown that in riparian areas of the Upper Rhine, a retention effect not only occurs in the landscape, but also is generated by young, flexible willows on the floodplain.

If SRC was cultivated in the above mentioned situations and implemented in environmental management strategies, it could serve effectively in multiple water-related needs. SRC could also improve the efficiency of water use, which is closely associated with sustainability, which in turn is related to the issues of quality, productivity, reliability and energy (Gleick et al. 2011). Taking all these issues and aspects into account, SRC is presented as an efficient cultivation practice, as long as it is implemented in a sustainable management concept.

2.7 Conclusion

A sustainable management concept, must take the positive and negative effects of SRC into account, thus considering the challenges arises of its establishment. In order to realize such a sustainable cultivation, the potential areas for cultivation should be identified to provide an optimal spatial basis for decision-making in terms of environmental benefit. The productivity of SRC is related to water potentials in the landscape and the water-use efficiency of the plants. This connection necessitates the process of approximating yield amounts in the landscape. If the environment is not suitable, due to insufficient water potentials, the expected yield will be low (Murach et al. 2009, Aust 2012, Hartwich et al. 2014a). This also shows a link to reliability, which is defined as the extent to which a system acts sustainable (Hashimoto et al. 1982). With this in mind, the question arise of how investigations could provide information about sustainable locations where the water requirements for SRC will be met.

In addition to considering the above-mentioned landscape potentials, it is essential to set up stimuli to trigger the development of SRC. A combination of both aspects would help to reduce an uncontrolled spread of SRC. Such a spread could result from a purely economic model of establishment, which does not consider the risks and rewards for society. A strategy using subventions could lower these risks by focusing the SRC efforts on useful sites. ‘Greening activities’, as a part of the European ‘common agricultural policy’, could also facilitate the spread of SRC by encouraging farmers to establish SRC to enhance ecosystem functions or rather the shown water related issues, as well as to counteract climate change (Busch 2012, Schmidt et al. 2014). This establishment concept would also serve the profiteers, with the farmer acting as the main stakeholder through monetary benefit, followed by society and nature, who benefit on the level of sustainable land and water usage (Schägner 2009, Pretzsch & Skodawessely 2010).

The challenges of establishing SRC are most highly related to water issues in sustainable cultivation. These water issues can only be taken into account by establishing win-win situations that serve both the monetary and the environmental aspects. Current research uses Germany to show the spatial distribution of high potential areas for SRC and locates priority areas on the northern German plain (Murach et al. 2009, Aust 2012, Hartwich et al. 2014a, Hartwich et al. 2014b). These water-based yield approaches show the strong linkage between water management and yield optimization, which encourages new perspectives in the field of water energy. In addition, these spatial approaches offer information to counteract the possible dilemma of sustainable water use and energy production.

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3 Identification of suitable areas in Germany for willow short rotation coppices from a hydrological perspective and evaluation of the yield potential

Abstract

With the change in Germany's energy strategy, woody biomass as an essential part of bio-heat production has become much more important in the past few years. One option to cover the proposed energy demand is the introduction and extension of short rotation coppices (SRCs), which are established on arable land. The aim of this research is to identify suitable areas for SRCs and to estimate the potential yield, as well as energy potentials, for willow SRCs in Germany, in order to provide a database for policymakers and stakeholders. The identification of suitable areas is based on two GIS-based approaches (i.e. the methods of Murach et al. (2009) as well as Aust (2012). In addition, a new approach is introduced by Hartwich et al. (2015a) using a combination of previous approaches with an improved evaporation correction. The paper compares the different approaches, discusses their advantages and disadvantages, and presents the potentials for SRCs as determined by the modified method. In Germany, a total of 12.8 million hectares is used for intensive agricultural production. If 5% (600,000 ha) of the agricultural area in Germany is cultivated with willow SRCs, 1 GW of electricity could be produced, which is sufficient to supply 2.4 million households with electric power. A combined heat and power plant with better efficiency could expand the performance to 1.4 GW. SRCs in this dimension would reduce CO_2-emissions by 10 Mt yr^{-1} compared to fossil fuels.

3.1 Introduction

Rapid global climate change, as reported by the Intergovernmental Panel on Climate Change (IPCC), (Solomon et al. 2007) is widely accepted. With this change, aspect greenhouse gases, such as CO_2, play a major role in the energy budget of the atmosphere. As such, any anthropogenic emissions, including carbon dioxide from fossil fuel consumption, result in an increased energy adsorption in the atmosphere and an increase of atmospheric temperatures. Considerating the global climate change, as well as the resulting demand for sustainable development, in 2009, the European Council decided with Directive 2009/28/EC that the use of renewable energy sources had to increase 20% by 2020 to reduce carbon dioxide emissions (Solomon et al. 2007).

One important source of renewable energy is woody biomass, which is used for the production of heat as well as electricity. In Germany, 92% of the national bio-heat in 2013 was already generated by biomass (BMWE 2014). Germany's energy wood demand is mostly met by forestry, but this type of production is limited and will not be able to supply an increasing amount of timber for energy production in the future. To increase timber output for bio-energy and keep forestry sustainable, it is necessary to expand shares of arable land to wood production in the form of short rotation coppices (SRCs) (Aust 2012).

Walsh (2000) previously showed how important it is for politicians to know the high potentials of bio-energy crops. This knowledge informs discussions of agricultural contributions to bio-energy production worldwide. Many studies with various scales and methods focus on SRCs and their cultivation potential. As a result, some socioeconomic approaches have already been made (Graham et al. 2000, Krotscheck et al. 2000, Mitchell 2000, Roos & Rakos 2000, Ugarte & Ray 2000, Walsh 2000). However, these approaches did not take into account the various physical restrictions or drivers, such as environmental conditions, which limit or increase the yield. Graham (1994) was one of the first to consider physical parameters by using the Land Resource Regions created by the U.S. Department of Agriculture to analyze the potential of SRCs in the USA. Later, Lindroth & Båth (1999) calculated the impact of water availability on willow yield SRCs in southern Sweden. Computer performance development and software Geographic Information Systems (GIS) have become increasingly important as they allow the processing and combining of spatial data. In addition to estimating yield amounts for a specific location, the GIS allows the mapping of a yield potential for large regions, as shown by Andersen et al. (2005), Beccali et al. (2009), Fiorese & Guariso (2010), Viana et al. (2010), Dengiz et al. (2010), Palmas et al. (2012) and Tenerelli & Carver (2012).

Murach et al. (2009), Reeg (2009), and Bemmann & Knust (2010) applied previous methodological knowledge (especially that of Lindroth & Båth (1999)), to develop a GIS-based method to identify agricultural areas suitable for SRCs and to evaluate crop yields in central eastern Germany (Brandenburg). A similar approach is used by Aust (2012) and Roesch et al. (2011) who evaluated yields in south-western Germany (Baden-Württemberg) as well as Germany as a whole.

Both approaches of Murach et al. (2009) and Aust (2012) use physical parameters to predict the potential for SRCs and can be transferred to similar regions in the world. This method is not only applicable for SRCs, but can also be adapted to other crop type locations limited by the availability of water as well as in regions where irrigation is not a cultivation option. However, for Germany as a spatial unit, the results of both methods differ strongly. Both studies consider the plant available water (PAW) as a limiting factor for plant growth and assume that nutrients in the soil are available in optimal amounts or are supplied by fertilizer. The term PAW describes the amount of water which can be utilized by plants, including available precipitation as well as soil and groundwater. One reason for the difference in previous biomass potential results are the differing methods for calculating evaporation, which, in the approach of Murach et al. (2009), causes an overestimation and in Aust (2012), an underestimation of predicted biomass potentials. A second major factor for area suitability is the crop yield. SRCs are economically efficient if the yield exceeds 8 odt ha^{-1} yr^{-1} (odt: oven dry tons) (Andersen et al. 2005, Murach et al. 2009).

The aim of this study is to compare the approaches and biomass potential results in Germany of Murach et al. (2009) and Aust (2012) to a new approach developed by Hartwich et al. (2015a). The Hartwich et al. (2015a) approach combines the advantages of Murach et al. (2009) and Aust (2012). It then uses a better calculation method for evapotranspiration by using the FAO Penman-Monteith equation and crop coefficient of 1.2 for willow SRCs.

3.2 Methods

For the study presented here, the model of Aust (2012) for the total area of Germany is reproduced using GIS techniques. In a second step, the model of Murach et al. (2009), which was previously used for smaller areas only, is applied to the total area of Germany to compare both approaches. Finally, the previous methods are merged and refined to solve the existing methodological problems, to reduce uncertainties, and to improve the identification of suitable areas and the estimation of crop yields (Hartwich et al. 2015a).

3.2.1 Data

The investigations used 1 km gridded data of mean monthly air temperature, annual precipitation, total evaporation, and the climatic water balance provided by the German Weather Service (DWD). To correct the evaporation calculation, the digital elevation model ATKIS DGM25 of the Federal Agency for Cartography and Geodesy (BKG), with a resolution of 25 m, was used and implemented into a terrain correction factor defined by Haufe et al. (1998), Bechler & Toth (2010), Aust (2012) and Hartwich et al. (2015a). Information on the groundwater table and the available water capacity were extracted via GIS from the digital version of the Soil Map of the Federal Republic of Germany 1:1,000,000, published by the Federal Institute for Geosciences and Natural Resources (BGR). Because of the arable land restriction of SRC cultivation, areas with other land use types (settlements, forests, pastures, etc.) were excluded using the digital land cover model DLM-DE2009 provided by the Federal Agency for Cartography and Geodesy.

3.2.2 GIS modeling

3.2.2.1 Plant available water

The identification of potential areas for SRCs in Germany is based on the calculation of the plant available water (PAW), as described by Murach et al. (2009) and Aust (2012). PAW is generally defined as water usable for a plant, which is supplied by precipitation, and soil and groundwater. However, Murach et al. (2009) and Aust (2012) used different approaches to calculate the PAW. Table 3-1 gives an overview of the different approaches and their required input data.

Table 3-1: Data requirements for the different methods for identifying potential areas for short rotation coppices.

Data	**Murach et al. (2009)**	**Aust (2012)**	**Hartwich et al. (2015a)**	**Source**
Monthly mean temperature	-	+	+	German Weather Service (DWD) (resolution 1 km)
Monthly mean precipitation	+	-	+	German Weather Service (DWD) (resolution 1 km)
Monthly mean total evaporation	-	-	+	German Weather Service (DWD) (resolution 1 km)
Climatic Water balance	-	+	-	German Weather Service (DWD) (resolution 1 km)
Digital elevation model	-	+	+	Federal Agency for Cartography and Geodesy (resolution 25 m)
Soil Map and data of the Federal Republic of Germany 1:1,000,000	+	+	+	Federal Institute for Geosciences and Natural Resources
Digital land cover model	+	+	+	Federal Agency for Cartography and Geodesy

In the approach of Murach et al. (2009), the PAW is defined by the flooring terms: the available water capacity in the uppermost 50 cm of the soil structure (θ_{50}), the amount of precipitation during the vegetation period May to October (P_{veg}), and the total intercepted water (I_{veg}) (Eq. 1):

$$PAW = \theta_{50} + \left(P_{veg} - I_{veg}\right) + GW \qquad (1)$$

The total intercepted water (I_{veg}), is estimated according to Lindroth & Båth (1999) with 35% of precipitation during the vegetation period (P_{veg}). Furthermore, the groundwater (GW) is considered to have an influence on the PAW, if the rooting zone of plants reaches the groundwater table. Based on a literature survey, Volk et al. (2001) estimated a zone thickness of approximately 2 m. This infers plants will be able to use the groundwater if it is available in the upper 2 m of this zone.

Aust (2012) also uses the water capacity in the topsoil (θ_a), but with a flexible limitation according to the effective rooting depth of the specific soil type, as defined by Ad-Hoc-Arbeitsgruppe Boden (2005) (Eq. 2):

$$PAW = \theta_a + CWB + \alpha + GW \qquad (2)$$

Here, the climatic water balance (CWB) for the growing season, as well as the factor for relief correction (α), are implemented. Relief correction factor (α) values were published by Aust (2012), Haufe et al. (1998) and Bechler & Toth (2010) (Table 3-2). Groundwater (GW) influences were also considered as in Eq. 1.

Table 3-2: Values of terrain correction factor α based on Aust (2012), Bechler & Toth (2010), Haufe et al. (1998) and standardized to the growing season from May to October

Terrain correction factor α in mm				
Slope in % / **Exposition**	**9-18**	**18-27**	**27-58**	**>58**
N, NE, NW	+50	+100	+100	+100
S, SE, SW	-50	-50	-100	-150
E, W				-50
Relief position				
Ridge, Upper Slope	-50			
Valley, Lower Slope	+50			

Based on these approaches, the new concept of Hartwich et al. (2015a) was developed to reduce the weaknesses in the evaporation estimations and to explain differences in the calculated results. The modification is demonstrated in Eq. 3.

$$PAW = \theta_{50} + (P_{veg} - 0.35 * ET_{veg}^{SRC}) + \alpha + GW \quad (3)$$

To estimate the PAW, the terms known as available water capacity (θ_{50}), relief correction (α), groundwater (GW) and precipitation during the vegetation period P_{veg} were defined as in the other approaches. However, a correction of the evaporation calculation was carried out using an approach of Persson & Lindroth (1994), which constitutes that the total evaporation of a willow stand is characterized by 25% soil evaporation, 10% interception evaporation and 65% transpiration of the plants. Consequently, 35% of the total evaporation of a willow stand was used to calculate the effective rainfall consumable by the plants during the vegetation period (ET_{veg}^{SRC}). The total evaporation of a willow stand during the vegetation period (ET_{veg}^{SRC}) was calculated with the FAO Penman-Monteith equation (Allen et al. 1998). A willow crop coefficient of 1.2 was estimated taking various references into account (Guidi et al. 2008, Mirck & Volk 2009, Persson 1995, Persson & Lindroth 1994, Pistocchi et al. 2009, Stephens et al. 2001).

ESRI's ArcGIS 10.1 Model Builder was used for data processing. Figure 3-1 illustrates schematically how the data was processed. The arrangement of the input data was subdivided into three main steps. The first step is the calculation of climatic water input due to precipitation, evaporation and DEM data. Then available water capacity (θ) and groundwater (GW) input were extracted from the soil data. Afterward, PAW was calculated and then combined with the limiting factors for plantation establishment. Areas with annual mean temperature below 6.5°C were excluded as they are not suitable, according to Aust (2012). Suitability maps were created for every methodology in the process.

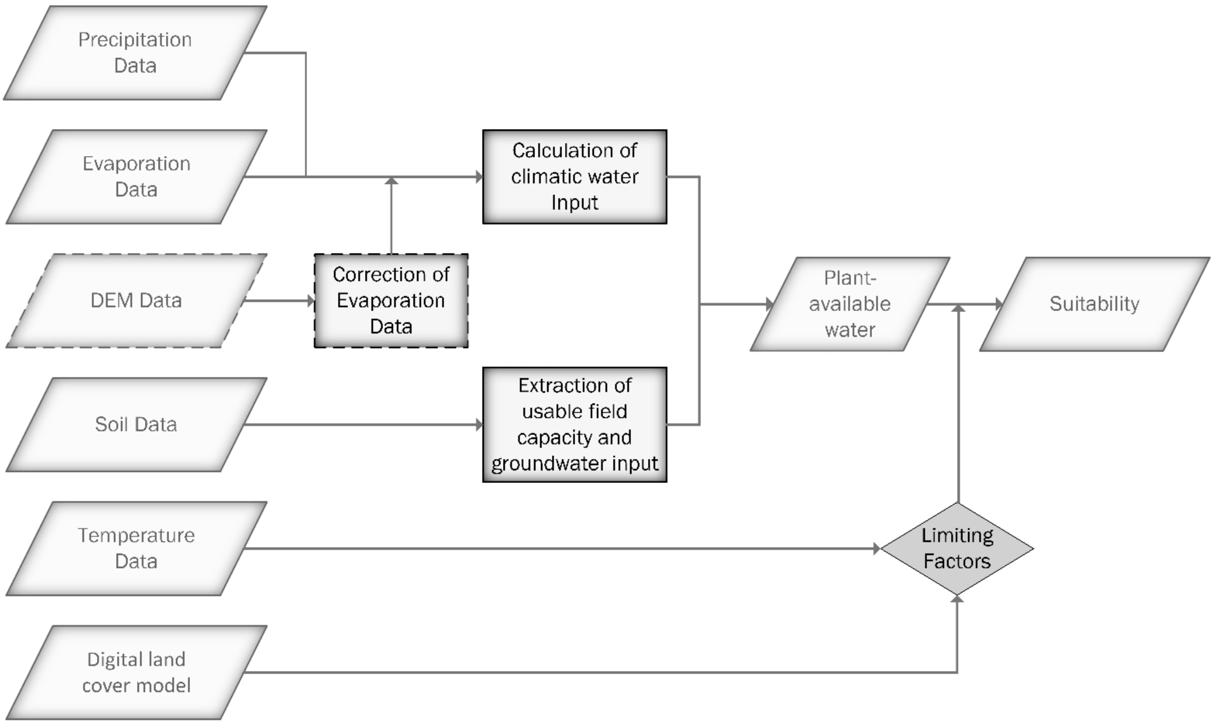

Figure 3-1: Schematic representation of the general steps in the GIS-analysis; referring to input data, processing and results

3.2.2.2 Crop yield estimation

For the yield estimation, the methodology of Lindroth & Båth (1999) was used. Their research presents a simple model based on water-use efficiency, which provides yield data for a water-limited production, adapted to the relationship between transpiration and carbon dioxide uptake. The equation they presented is adapted to the aims of this study (Eq. 4):

$$W_s = \tau(1 - c_l - c_r) * PAW \quad (4)$$

To estimate the harvestable yield of a plant (W_s), it is necessary to extract the woody parts of the above-ground production from the total biomass production by subtracting the root system and the leaves. Lindroth & Cienciala (1996) and Lindroth & Båth (1999) specify these parts from the total biomass production as follows: the root system (c_r) 0.25 and the leaves (c_l) 0.20. Furthermore, Lindroth & Cienciala (1996) and Lindroth et al. (1994) show a water use efficiency (τ) of 6.3 g kg^{-1}, which is also used by Lindroth & Båth (1999) to estimate the yield of Salix viminalis in Sweden. In a later study published by Linderson et al. (2007), it was shown that this water use efficiency (τ) was overestimated. They presented an average water use efficiency (τ) of 5.3 g kg^{-1} for six willow clones: L 78189, Rapp, Jorunn, Jorr, Tora and Loden. Due to the latest findings, and to prevent an overestimation in the yield amounts, the water use efficiency (τ) of 5.3 g kg-1 was used. PAW is estimated by the explained methodology, but to provide a realistic calculation of the yield, it was necessary to restrict plant growth by limiting the available amount of water.

Monteith (1978) has shown from a plant physiological perspective that C_3 plants have a maximum growth rate range of 34-39 g m^{-2} d^{-1}. With the parameter used in this study, this would indicate a PAW range of 1,150-1,300 mm. This values characterizes the maximum grow rate of C_3 plants in general. But to minimize the risk of overestimations, the harvestable yield (W_s) was calculated with a PAW limited to 550 mm, as suggested by Lindroth & Cienciala (1996) and Murach et al. (2009) for willows in SRCs. However, a suitable production of SRCs is defined by Murach et al. (2009) and Andersen et al. (2005) as a potential yield of more than 8 odt ha^{-1} yr^{-1}. Thus, this approach defines suitable areas with a potential yield over 8 odt ha^{-1} yr^{-1}. This process suggests that all areas below this potential (< 8 odt ha^{-1} yr^{-1}) are characterized as unsuitable.

3.2.2.3 Energy potentials and CO_2-reduction

To calculate predicted biomass energy potentials and the influence on CO_2-emissions, a method based on Venturi & Venturi (2003) and Andersen et al. (2005) was chosen. This determined electricity potentials as well as a combined heat and power production (CHP). To facilitate these potentials, the following power stations were selected as examples:

For the production of electricity, a power station was chosen with a capacity of 20 MW. This station was built in 2003 in Berlin, Germany by MVV Energie GmbH, with a biomass consumption of 120,000 t yr^{-1}. Also chosen was a CHP of Ilmenauer Wärmeversorger GmbH, which was built in 2005 in Ilmenau (Germany) with a requirement of 43,000 t yr^{-1} and a combined output of 9.7 MW (electricity 3.7 MW and heat 6.0 MW). To estimate the CO_2-reduction, the calculation was based on equations and constants presented in Venturi & Venturi (2003) and Andersen et al. (2005).

Two scenarios were applied: A 100%-scenario, which takes into account the whole suitable area for willow SRCs, as well as a 5%-scenario, which refers to a 5% share of the suitable area. The first scenario with 100% is theoretical, since such an area will not be totally converted to willow SRCs. But it shows the upper extreme boundary, which enhances the comparability of the approaches. The second scenario, with 5% of the suitable area, is based on the predictions by the Internationales Institut für Wald und Holz NRW (2014), that assumes a minimum conversion of 600,000 ha in SRCs (5% of the agricultural area in Germany) to cover the woody biomass need in 2020.

3.3 Results

3.3.1 Approach by Murach et al. (2009)

The spatial distribution of suitable agricultural sites estimated with the approach of Murach et al. (2009) is illustrated by Figure 3-2. Only a minority—about 1%--of the agricultural area was classified as unsuitable or, in other terms, only has a potential yield of < 8 odt ha^{-1} yr^{-1}. A share of 76.2% is suitable and 22.8% is highly suitable. Because of high groundwater levels, the latter are located mainly in the Northern German Lowlands or along the cultivated riparian area of the major rivers in southern Germany. In summary, 99% of the agricultural areas in Germany are classified as suitable for SRC establishment. Table 3-3 summarizes the potential by quantifying yield amounts and the percentage of unsuitable, suitable and highly suitable areas. In the theoretical case of using the total suitable agricultural area, the yield of willow SRCs is estimated as 146.14 million odt yr^{-1}.

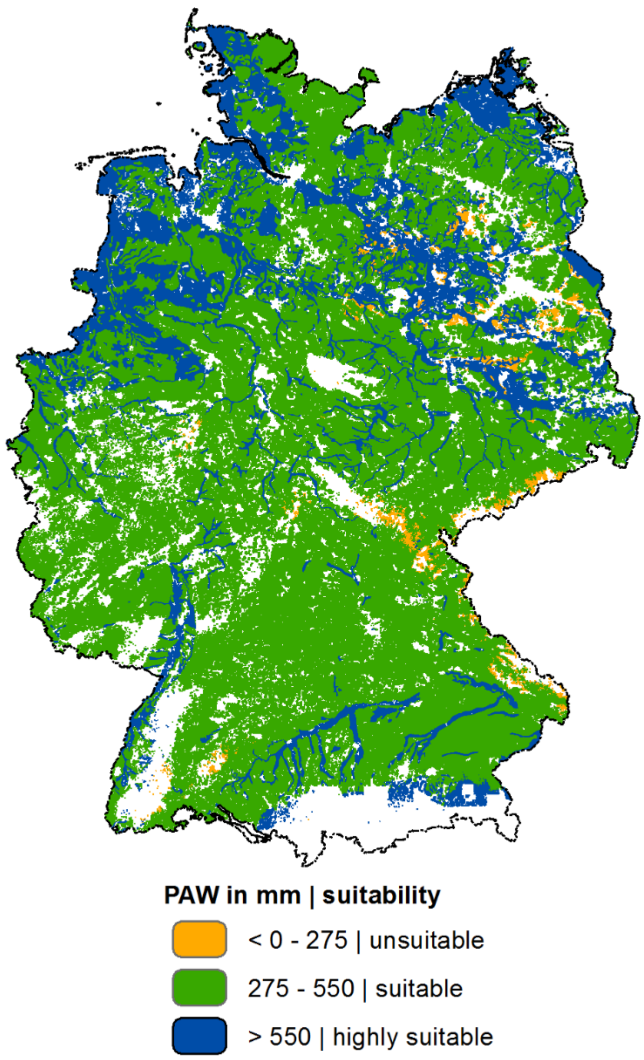

Figure 3-2: Spatial distribution of unsuitable (PAW 0 – 275 mm), suitable (PAW 275 – 550 mm) and highly suitable (PAW > 550 mm) sites on cultivated land in Germany determined with the approach of Murach et al. (2009). Suitable areas have a potential biomass production > 8 odt ha^{-1} yr^{-1}.

Table 3-3: Percentage of different suitability levels, according to the approach of Murach et al. (2009)

Suitability	Area in million ha	Percentage of the total arable land in Germany	Harvestable amounts in million odt/yr
Unsuitable	0.13	1.04%	0.53
Suitable	9.80	76.17%	101.25
Highly suitable	2.93	22.79%	44.89
Suitable in total	12.73	98.96%	146.14
Total	12.86	100%	146.67

3.3.2 Approach by Aust (2012)

In contrast to the previous results in the approach of Aust (2012), the majority of agricultural areas (73.7%) are classified as unsuitable for willow SRCs, due to a deficit of PAW. Suitable sites are located in the foothills of the Alps in southern Germany. The highly suitable sites (22.5%), are similarly distributed as in the approach of Murach et al. (2009) and show a concentration in the Northern German Lowlands and in the vicinity of the river systems in the south (Figure 3-3 and Table 3-4). For the total suitable and highly suitable area of 3.38 million ha, a potential yield of 48.82 million odt yr^{-1} can be calculated.

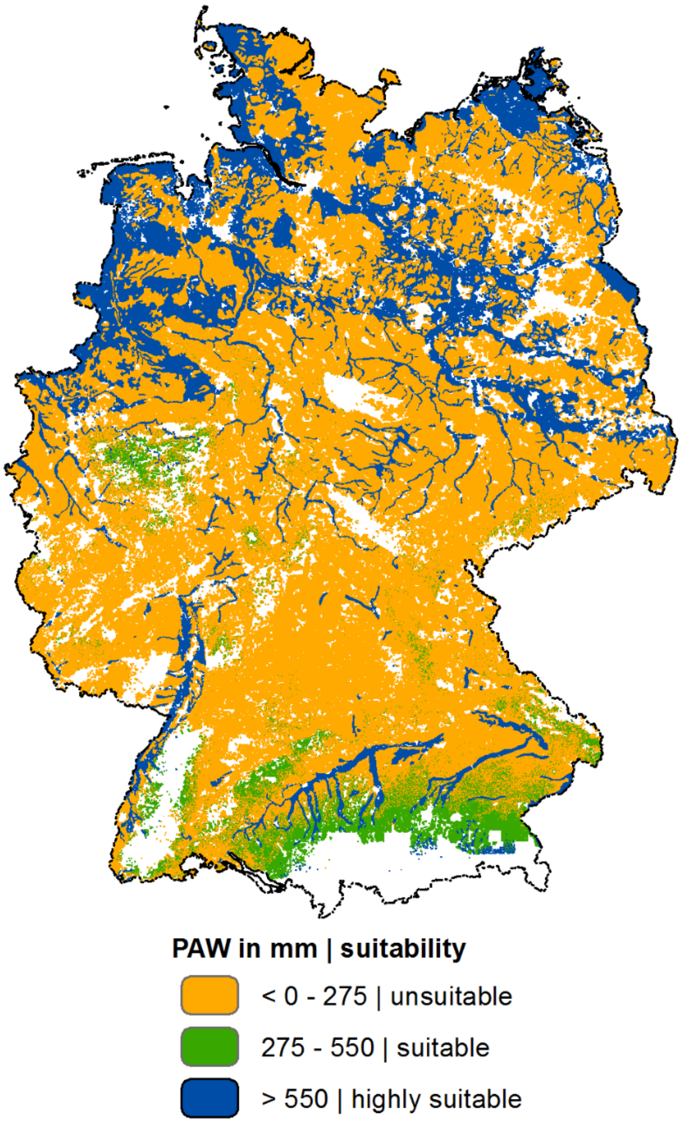

Figure 3-3: Spatial distribution of unsuitable, suitable, and highly suitable areas in Germany, determined with the approach of Aust (2012). Suitable areas have a potential biomass production > 8 odt ha^{-1} yr^{-1}.

Table 3-4: Percentage of different suitability levels in the approach of Aust (2012)

Suitability	**Area in million ha**	**Percentage of the total arable land in Germany**	**Harvestable amounts in million odt/yr**
Unsuitable	9.48	73.71%	17.59
Suitable	0.48	3.76%	4.48
Highly suitable	2.90	22.54%	4.43
Suitable in total	3.38	26.29%	48.82
Total	12.86	100%	66.40

3.3.3 Approach of Hartwich et al. (2015a)

The approach of Hartwich et al. (2015a) results in a very heterogeneous spatial distribution of the suitability classes (Figure 3-4). 21.3% percent of the agricultural areas in Germany are classified as unsuitable, 54.7% are classified as suitable and 24.0% are highly suitable, due to their content of PAW (Table 3-5). The majority of unsuitable areas is located in the northeastern parts of Germany, where the climate is more continental and rainfall is considerably lower than in the west. Suitable areas are concentrated in the southern and western parts of the country. Similar to Murach et al. (2009) and Aust (2012), most of the sites that are classified as highly suitable can be found in the Northern German Lowlands in regions with high groundwater levels. Taking the estimated yields into account (Table 3-5), the total suitable and highly suitable areas provide a potential of 117.39 million odt yr^{-1}.

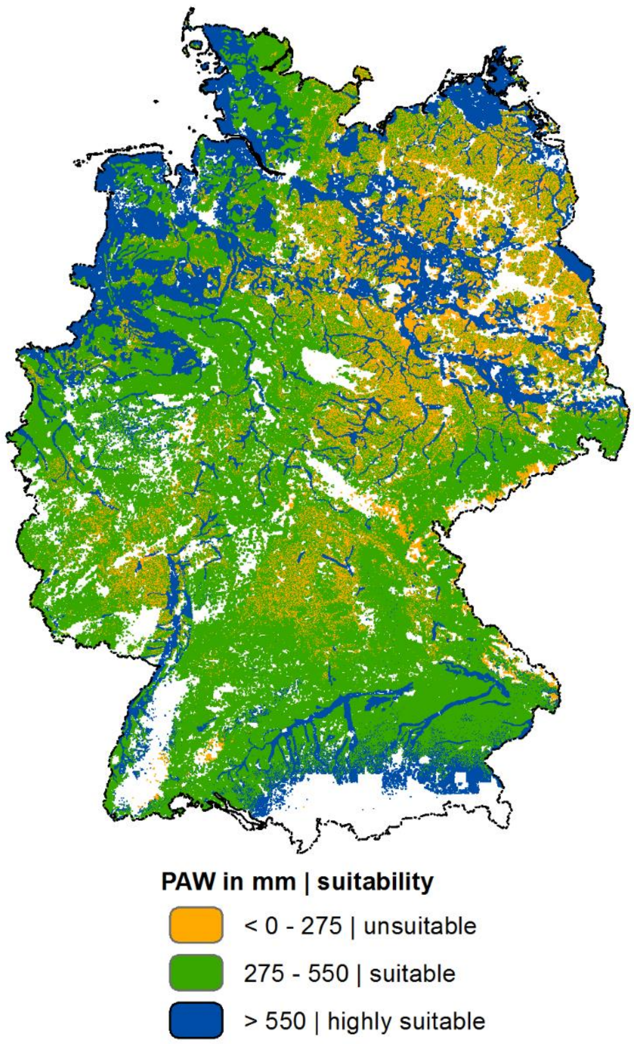

Figure 3-4: Spatial distribution of unsuitable, suitable, and highly suitable areas determined with the approach of Hartwich et al. (2015a). Suitable areas have a potential biomass production > 8 odt ha^{-1} yr^{-1}.

Table 3-5: Percentage of different suitability levels in the approach of Hartwich et al. (2015a)

Suitability	Area in million ha	Percentage of the total arable land in Germany	Harvestable amounts in million odt/yr
Unsuitable	2.74	21.34%	15.90
Suitable	7.03	54.69%	70.21
Highly suitable	3.08	23.98%	47.18
Suitable in total	10.11	78.66%	117.39
Total	12.86	100%	133.29

3.3.4 Comparison of the approaches

3.3.4.1 Yield potentials

To illustrate the differences between the three approaches in detail, the distribution of the calculated PAW within the total agricultural areas is shown in Figure 3-5, in combination with the estimated yield potential. The largest deviation can be observed between the approaches of Murach et al. (2009) and Aust (2012). In the latter, a large percentage of the areas is classified as unsuitable (PAW < 275 mm, potential yield < 8 odt ha^{-1} yr^{-1}), which is a result of an underestimation of the PAW. The distribution has a positive skewness where the percentage of areas clearly decreases with increasing PAW (Figure 3-5). In contrast, the approach of Murach et al. (2009) results in a more symmetric distribution of areas around the maximum of 325 mm (equal to 9.5 odt ha^{-1} yr^{-1}). In addition, only a small percentage of the agricultural areas have a PAW lower than 275 mm, which are classified as unsuitable areas. By using the approach of Hartwich et al. (2015a), the distribution of the PAW is symmetric too, but compared to Murach et al. (2009), the maximum is much lower and occurs at a PAW of 275 mm. Finally, for all three approaches, a similar area with a PAW of ≥ 550 mm was calculated, reflecting areas with groundwater influence and hence a very high water availability.

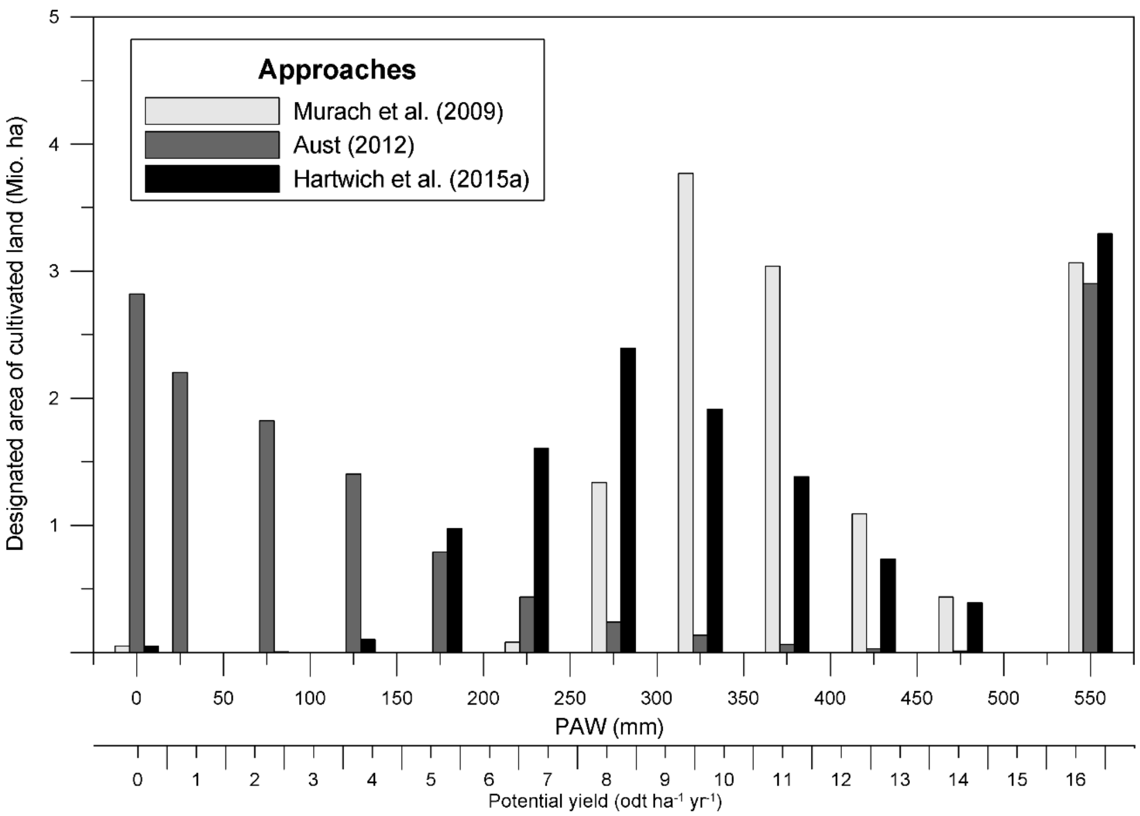

Figure 3-5: Variations of the designated area of cultivated land (area in Mio. ha) with PAW (mm) and potential yield (odt ha^{-1} yr^{-1}). The high values of the designated area at a PAW of 550 mm are highly correlated to locations with groundwater levels, which is equal in all approaches.

3.3.4.2 Energy potentials

Referring to the ranges in yield potential, Table 3-6 shows the variations in energy potentials calculated by the different approaches for the total suitable area (100%-scenario). The potential for electricity from suitable sites is estimated between 8.1 +/-0.4 GW (based on Aust (2012)) and 24.4 +/-1.5 GW (based on Murach et al. (2009)). In the power station, which uses a combined heat and power production (CHP) and has higher efficiency, the production of energy would increase to values ranging from 11.0 +/-0.6 GW (based on Aust (2012)) to 32.9 +/-2 GW (based on Murach et al. (2009)). In both, the approach of Hartwich et al. (2015a) defines a potential for electricity of 19.7 GW and for CHP of 24.4 GW.

Table 3-6: Values for potential yield, electricity and heat production for the different approaches and the 100%-scenario

Approach	Total potential yield [million odt/yr]	Total production of potential electricity [GW]	Total production for CHP [GW]	Potential yield from suitable sites [million odt/yr]	Production of potential electricity from suitable sites [GW]	Production from suitable sites for CHP [GW]
Murach et al. (2009)	146.67	24.4	33.0	146.14	24.4	32.9
Aust (2012)	66.40	11.1	15.0	48.82	8.1	11.0
Hartwich et al. (2015a)	133.29	22.2	30.0	117.39	19.7	26.4

However, the 100%-scenario in which all suitable (including highly suitable areas) areas are used for energy production is not realistic in practice. To consider more realistic conditions, 5% of the suitable areas in the approach of Hartwich et al. (2015a) with a mean potential yield were assumed to be used for SRCs in a second scenario (5%-scenario). This would include an area of cultivated land of approximately 600,000 ha (including suitable and highly suitable areas). Table 3-7 gives an overview over the results. In this area, a harvestable amount of 5.9 106 odt yr^{-1} is predicted. The 1.32 GW of electricity and heat produced would be sufficient to provide the annual requirement for around 714,000 households. 2.4 million households could be supplied by 0.98 GW electricity out of this area. This assumption is based on a number of 40.4 million households in Germany (2011) with an average annual requirement for electricity of 3,490 kWh yr^{-1} and for heat of 12,760 kWh yr^{-1} (heating 10,890 kWh a^{-1} and domestic hot water 1,870 kWh yr^{-1}) (Statistisches Bundesamt 2013a, b). Concerning the reduction of CO_2-emissions, it is possible to substitute 3.68 Mt oe (oe = oil equivalent) for electricity or 4.98 Mt oe for CHP. Thereby CO_2-emissions to the atmosphere could be reduced by 4.73 Mt, which is 0.5% of the total CO_2-emission in Germany in 2010 (952.7 Mt).

Table 3-7: Values for mass, energy, power production and CO_2-reduction for the 100% and 5% scenario using the biomass potential estimated by the approach of Hartwich et al. (2015a) (CHP = combined heat and power production)

Bioenergy for suitable sites	**Oven dry biomass [odt/yr]**	**Energy equivalent [TJ]**	**Oil equivalent [Mt oe]**	**Electrical power [GWh]**	**Electrical power [GW]**	**Oil C saved [Mt]**	**Saved CO_2 [Mt]**	**% of 2010 CO_2-emissions saved**
100% SRC for electricity	117,386,880	616,936	147.32	171,384.85	19.56	51.65	189.38	19.88
5% SRC for electricity	5,869,344	30,846	7.36	8,569.2	0.98	2.58	9.46	1.0
100% SRC for CHP	117,386,880	833,571	199.06	231,566.1	26.43	51.65	189.38	19.9
5% SRC for CHP	5,869,344	41,678	9.96	11,578.3	1.32	2.58	9.46	1.0

3.4 Discussion and conclusions

The aim of the study is to develop an optimized approach for the designation of willow SRCs and to estimate potential yield as well as energy potentials in relation to former studies. The approach of Hartwich et al. (2015a) is based on a combination of previously published approaches by Murach et al. (2009) and Aust (2012), with an enhancement of the evapotranspiration calculation by using the FAO Penman-Monteith equation with a crop coefficient of 1.2. The comparison of the approach of Hartwich et al. (2015a) with the former studies reveals significant differences. Aust (2012) provides the smallest suitable area and yield potentials. This underestimation is caused by using the climatic water balance as an input, resulting in an underestimation of the PAW. The original assessment of Aust (2012) predicted a total potential yield of 85 million odt yr^{-1}. With the reconstruction of this calculation and new data with better spatial resolution, this approach estimates a potential yield of 66 million odt yr^{-1}. Assuming an underestimation in the study of Aust (2012), the Hartwich et al. (current approach) approach is the first study, to our knowledge, which focuses on willow SRCs for the whole area of Germany and compares three different methods to define the yield potential for willow SRCs via PAW.

In contrast, the approach of Murach et al. (2009) leads to an overestimation in yield potentials. This is related to the static percentage of 35% interception, which ignores the influence of natural variability of vegetation and environmental conditions on interception storage. Furthermore, relief conditions are not covered by the approach of Murach et al. (2009) as they are implemented by Aust (2012). This terrain correction used by Aust (2012), as well as the available water capacity in the uppermost 50 cm of the soil structure, were implemented in the new approach by Hartwich et al. (2015a) as the central positive aspects of the former approaches. To solve the 35% constant interception problem, the loss of the interception was linked to evapotranspiration based on the studies of Persson & Lindroth (1994) as well as Lindroth & Båth (1999). Furthermore, the FAO Penman-Monteith evapotranspiration was used and adjusted by a crop coefficient characteristic for willow stands. With these improvements in the direct evapotranspiration estimation and the terrain correction, the PAW estimation in the approach of Hartwich et al. (2015a) is an advancement compared to the former methods.

The harvestable amounts predicted by the approach of Hartwich et al. (2015a) for the suitable areas have an electricity potential of 19.7 +/-1.2 GW and for CHP of 24.4 +/-1.2 GW. However, from an economic point of view, the implementation of SRCs in all identified areas does not seem to be realistic. In 2012, Strohm et al. (2012) reported an area of 4,000 ha of SRCs in Germany in. Since then, the area increased to 10,000 ha (Internationales Institut für Wald und Holz NRW 2014). Considering this information, even the assumed percentage of 5% of the agricultural area (600,000 ha) in Germany will not be established in the near future. Nevertheless, the calculation is useful to demonstrate the potential of SRCs, which provide 2.4 Mio. households with electricity or 714,000 households with electricity and heat. A similar percentage is used by Andersen et al. (2005) for Scotland, which assumes an implementation of SRCs on 5% of the suitable sites identified in the study, to show the implications for energy economics.

In general, the applicability of the method developed by Hartwich et al. (2015a) is limited by the availability of digital spatial data as well plant growing and water demand data. In this context, the data quality is the main source of uncertainty. Because the method was developed for application at the regional scale, a direct transfer of the results to smaller scales such as the plot or field scale is not recommended. This also excludes a direct validation with yield data from field sites. In addition, the upper limit for the PAW was set to 550 mm, resulting in a possible limitation of the yield potential. Detailed investigation on this physical parameter is still missing in the literature so an underestimation of the real yield is likely, especially for areas with groundwater level within the root zone and theoretical unlimited water availability. Further investigations on the water consumption of the willow hybrid species used for SRCs are required.

An economic and environmental benefit out of such scenarios can only be achieved if specific framework conditions of the whole production chain are established (Hartwich et al. 2014c). The framework conditions, such as the environmental characteristics, management and logistic concepts, a balance in the food vs. fuel discussions for the given region, as well as monoculture problems are essential to establish win-win situations. For the environmental conditions, that means that the climatic water balance should not be extremely negative. But estimations on regional level shows that willow as well as poplar SRCs do not have a negative impact on the water balance (Hartwich et al. 2016). Furthermore, logistic concepts must provide energy efficient solutions for the cultivation and wood processing (e.g. short transit from production to consumption of fuel wood) in order to maximize the economic output and the final energy yield and not least, to save CO_2.

3.5 Outlook

Heller et al. (2004) research shows that woody biomass produced in SRCs can compete with other renewable energy sources like solar energy. The "food vs. fuel-discussion" (i.e. the assumption that the cultivation of bioenergy plants on agricultural sites would trigger rising food prices) was analyzed by Mitchell (2008), FAO (2009), Baffes & Haniotis (2010) as well as Zichy et al. (2011). They conclude that the increase of prices for food observed in recent years is related more to commodity market speculations than the local establishment of SRCs or other bioenergy crops. This development was caused by speculations on commodities. If planted in large scale, monoculture SRCs are vulnerable to pest infestations and plant diseases, so the combination of wood production and conventional agriculture, which has little influence on food production, is reasonable. With such combined plantations, a maximization of habitat structures can be achieved, which would introduce a possible win-win situation (Baum et al. 2009, Köhn 2009, Schmidt & Gerold 2009). In addition, the cultivation of SRCs could be implemented to environmental management concepts by focusing further win-win situations such as:

- reduction of medium flood events (Perry et al. 2001),
- flood retention effects on the riparian zone of large river systems (Bölscher et al. 2010),
- enhancement of ground and surface water, due to lowering fertilizer leakage (Dimitriou et al. 2009a, b, Nisbet et al. 2011),
- utilization adapted to local conditions to avoid drainage systems or compensation payment in the case of flood events (Hartwich et al. 2014c).

Due to such management concepts, a sustainable use of SRCs could be implemented in agriculture, with a maximum benefit to the ecosystem.

Acknowledgements

This work was supported by the Federal Ministry of Food and Agriculture Germany [Bundesministerium für Ernährung und Landwirtschaft] and Specialist agency of renewable resources [Fachagentur Nachwachsende Rohstoffe e. V.] under Grant 2012410. In addition, our thanks goes to the Federal Agency for Cartographie and Geodesy [Bundesamt für Kartographie und Geodäsie], the Federal Institute for Geosciences and Natural Resources [Bundesanstalt für Geowissenschaften und Rohstoffe] and the German National Meteorological Service [Deutschen Wetterdienst] for the provision of data.

4 The plant available water as a controlling factor for the energy production from willow short-rotation coppices – Estimation of bioenergy potentials in Germany

Abstract

The European Union and national policy goal intends to increase the share of renewable energy to 20% of the total energy mix by 2020. This has created, and will continue to create, a growing demand for woody biomass. Already today woody biomass provided 92% of the renewable thermal energy in Germany. Short rotation coppices (SRCs) of fast-growing tree species, such as willows and poplars, are already being established on arable land in Germany to secure the sustainable supply of biomass. This has led to a growing interest in the biomass production potential of this method of cultivation. To evaluate production in Germany, Murach et al. (2009) and Aust (2012) developed GIS-based models that calculate biomass potential from water-management parameters, but the studies produced show differing results.

The current study combines the methods of these previous studies but improves the calculation of evaporation, using the FAO-Penman-Monteith evapotranspiration and a crop coefficient of 1.2. Our modeling efforts suggest harvestable amounts of 117 million t/y of woody biomass from SRCs on the maximum acreage of suitable sites in Germany. However, a more realistic, but still challenging, scenario of 300,000 ha of SRC—assuming an average biomass yield—results in the capacity to supply 357,000 households with electricity and thermal energy, or to provide 1.2 million households exclusively with electricity. The findings also indicate that suitable sites are heterogeneously distributed throughout Germany, due to groundwater availability. The Northern German Plain was identified as a prime area for short rotation coppice systems. However, in regions with a negative climatic water balance, the establishment of SRC systems should be reconsidered or at least kept to a minimum, due to the high rate of water extraction of the plants, which could have negative effects on environmentally valuable wetlands and streams.

4.1 Introduction

To achieve a sustainable energy sector in the European Union, the directive 2009/28/EC established a legal base. This stated that renewable energy should rise to 20% of the total energy mix by 2020 (European Parliament & Council 2009). In that context, in addition to wind and solar energy the available water could also be considered as a natural energy source. This energy resource, if managed in a sustainable way, would also serve the previously mentioned objectives of European Union. While hydropower has traditionally been part of water management, its share of the German energy mix in 2013 accounted for a marginal 0.8% of the total supply (Fachagentur für Nachwachsende Rohstoffe [FNR] 2014). Energy production from biomass is also closely linked to the water balance of the landscape, accounting for 7.6% of the supply in 2013 (FNR 2014). That means, this energy carrier has a significantly higher proportional impact on the energy supply in Germany than "conventional" water power. The water available to plants for transpiration controls biomass yields and significantly impacts the amount of energy produced. However, for economic reasons, SRCs are generally not irrigated, so the naturally renewable water resource of high standing ground water or rain water is the main controlling or limiting factor. In terms of nutrients, numerous studies in potential estimation suggest that SRCs are optimally supplied (Lindroth & Båth 1999, Boelcke 2006, Murach et al. 2009, Aust 2012, Stork et al. 2014).

This infers there should be a strong societal interest in the effective and sustainable use of resources. A spatial and quantitative assessment of the SRC potential is a basis for a sustainable production of renewable energy from biomass. The outstanding position of woody-biomass is reflected in its share of 92% of the renewable thermal energy produced in Germany in 2011 (BMU 2013). A restructure of the energy market will increase the demand for woody-biomass, which will increase the importance of short rotational coppices on field sites. This cultivation practice uses rapid growth trees such as willows, poplars and robinia, which are grown on arable land and harvested after a period of three to six years. After drying, the wood is mostly used in energy generation. National and international studies estimate the potential of these energy sources through different approaches. Studies on socio-economic bases are presented by different authors (Graham et al. 2000, Krotscheck et al. 2000, Mitchell 2000). The physical factors of landscape space were evaluated by Graham (1994) in the United States, as well as Lindroth & Båth (1999) in southern Sweden to distinguish suitable and unsuitable sides. These approaches were the basis for a natural-founded evaluation of the bioenergy potential. The subsequent investigations included methodological advancements, used geographic information systems, and intersected different parameters to evaluate especially large areas (in scale of state territories) (Andersen et al. 2005, Beccali et al. 2009, Fiorese & Guariso 2010). Based on the approaches of Lindroth & Båth (1999), Murach et al. (2009) and Aust (2012) used GIS-based approaches in an assessment for Germany. These approaches used multi-criteria analyses to estimate the plant available water (PAW) of a specific region. In this context, the PAW describes the amount of water in the landscape, which the plants consume for transpiration and growth (Lindroth & Båth 1999, Murach et al. 2009, Aust 2012). In the present study, conducted by the free University of Berlin in cooperation with the University for Sustainable Development of Eberswalde, the approaches of Murach et al. (2009) and Aust (2012) are expanded, combined, and improved in calculating evapotranspiration.

Using this new approach, it is possible to make more detailed statements regarding the yield potential for Germany, as well as to represent the spatial distribution. The potential contribution of SRCs to the energy mix and derivable CO_2 savings are also investigated. However, the culture-specific data used in spatial determination and the estimated potential are questioned critically.

4.2 Materials and Methods

To make a yield assessment for the entire federal territory, data was provided by the German weather service (DWD), the Federal Agency for cartography and Geodesy (BKG) and the Federal Institute for Geosciences and natural resources (BGR). This is shown in the records in Table 4-1, which serve as input for the multi-criteria GIS analysis.

Table 4-1: GIS-implemented data used in the multi-criteria analysis

Dataset	Resolution	Source
Corrected mean monthly precipitation (1971-2000) (Correction method Richter 1995)	1 x 1 km	DWD
Mean monthly potential evapotranspiration, Penman-Monteith FAO (1971-2000)	1 x 1 km	DWD
Monthly average of air temperature (1971-2000)	1 x 1 km	DWD
Digital elevation mode, Germany	25 x 25 m	BKG
Digital land cover model, Germany	true to area	BKG
Soil survey map and soil database, Germany (BÜK 1000)	1:1,000,000	BGR

The studies of Lindroth & Båth (1999), which are based on lysimeter experiments with willows in southern Sweden (see also Persson & Lindroth (1994)), were integrated by Murach et al. (2009) and Aust (2012) in their yield potential assessment. The resulting approaches to estimate the PAW by Murach et al. (2009) and Aust (2012) are combined in this study and enhanced in the calculation of evapotranspiration (EQ. 1).

$$PAW = \theta_{50} + \left(P_{veg} - 0{,}35 * ET_{veg}^{SRC}\right) + \alpha + GW \qquad \text{(EQ. 1)}$$

θ_{50}	Available water capacity in the topsoil [mm] soil depth up to 50 cm (primary root zone defined by Murach et al. 2009)
P_{veg}	Long-term mean precipitation during the growing season from May to October [mm]
$35\% \; ET_{veg}^{SRC}$	Share of soil and interception evaporation of the potential evapotranspiration on SRC over the growing season from May to October [mm]
α	Topographic correction factor [mm] (siehe Tab. 2)
GW	Influence of ground water in the upper 2 m of the soil column [in case of GW connection GW = 550 mm]

By using the parameters in EQ. 1, the major water balance components for an SRC can combine additively. The first parameter is the water capacity in the topsoil (upper 50 cm, θ_{50}), which describes the primary root space of willow (Volk et al. 2001, Murach et al. 2009, Pacaldo et al. 2013, Stork et al. 2014) and the water available for transpiration. According to Murach et al. (2009) this parameter is especially sensitive to plant growth. Further, it is assumed that while this water content is fully available for the plants after the dormant period, it is only available once during the growing season (May to October). In the present study, this value is determined by Germany's Soil survey map 1: 1,000,000 and the linked soil database. For the soil horizon, the specific value θ_{50} of the root zone (50 cm) is used for the calculation. The values and their methodological processing are described by AD-Hoc Arbeitsgruppe Boden (1994, 2005). The second term of EQ. 1 $\left(P_{veg} - 0{,}35 * ET_{veg}^{SRC}\right)$ describes the calculation for the plants' available precipitation. This calculation uses different requirements from the approach of Aust (2012) and Murach et al. (2009)—an essential difference to the approach in the studies mentioned. Aust (2012) defined this share using the climatic water balance (P - ET_{pot}). If rainfall value is reduced by the potential evapotranspiration and not the actual evapotranspiration, the amount of water available to the plants is significantly underestimated. This underestimation results from plant transpiration in the evapotranspiration. But this transpired water is generally still available as a water resource for the plants. Further, this approach refers to the grass reference evapotranspiration rate by Penman-Monteith and has not been corrected in terms of vegetation cover. In addition, the PAW is made without considering the growing season, and instead uses annual values of rainfall and the potential evapotranspiration.

In the study of Murach et al. (2009), the opposite effect is determined, which overestimates the PAW. The authors Lindroth & Båth (1999) determined the amount of intercepted water within the growing season as a constant share of 35% of the precipitation (P_{veg} -35% * P_{veg}). This means that, in principle, 65% of precipitation water is available as PAW. However, location and crop-specific factors that further reduce the remaining rainfall water through evapotranspiration processes are not entered into the calculation. This particularly impacts a missing terrain correction of the water budget as implemented by Aust (2012) as well as a missing adjustment of evaporation to environmental and climate specific factors. In the present study, the precipitation is reduced by 35% of potential evapotranspiration, as equivalent to interception and soil-evaporation (shares based on Persson & Lindroth (1994)). This proportion is a long-term average for the temperate zones. A lack of data in measurement approaches precludes a better regionalization of this share.

However, the reduced precipitation is counted as available for transpiration. To determine the PAW of a specific site of willow SRCs in the vegetation period, the potential evaporation data of the DWD are used. Letters values of potential evaporation were calculated by the Penman-Monteith-FAO approach. Further, these values were adjusted with a willow SRC specific crop coefficient of 1.2. This crop coefficient was determined by different studies and measured concepts for different regions of temperate zones (Persson & Lindroth 1994, Persson 1995, Stephens et al. 2001, Guidi et al. 2008, Mirck & Volk 2009 and Pistocchi et al. 2009). This defines the potential evapotranspiration of willow SRC (ET_{veg}^{SRC}) in EQ. 1 in the growing season. This value must be considered as dependent on environmental parameters, as implemented in their calculation by the DWD (Wendling 2001). The following site-specific parameters were used: global radiation, monthly mean temperature, coast factor (proximity to the sea), altitude, extraterrestrial solar radiation, as well as relative sunshine duration above a 15° solar altitude.

The correction parameter α, which reflects the influences of the topography (slope, exposure), is included by Aust (2012) in the calculation (Table 4-2). Due to the different radiation gain, on northern versus southern exposed slopes, water quantities were applied or reduced in calculation. Further, gradient and topographic positions enter into the calculation. For example, sinks and toe sections of slopes were subsidized with water, whereas hilltops and upper slope areas included a deduction.

Table 4-2: Values of terrain correction factor α based on Aust (2012), Bechler & Toth (2010), Haufe et al. (1998)

	Terrain correction factor α in mm standardized to the growing season from May to October			
Exposition	**Slope in %**			
	9-18	**18-27**	**27-58**	**>58**
N, NE, NW	+50	+100	+100	+100
S, SE, SW	-50	-50	-100	-150
E, W				-50
Topographic position				
Ridge, Upper Slope	-50			
Valley, Lower Slope	+50			

The influence of groundwater (GW), as in the case of θ_{50}, is provided by the database of the soil map. This approach only takes soiltypes into account that are characterized by a distance to groundwater-surface less than 2 m. At this depth, the plants are able to use the groundwater through the root system, thus building their biomass (Volk et al. 2001). However, the feasible quantity of water is not only limited by environmental parameters but also by plant ecophysiological characteristics. According to Monteith (1978), a maximum water consumption capacity is assumed for C_3 plants from 1,150 to 1,300 mm over the entire growing season. Lindroth & Cienciala (1996) as well as Murach et al. (2009) characterize the amount of water for willows as significantly lower. The value maximum was limited with 550 mm for this estimation, which excludes an overestimation in yield estimation. If GW is accessible by the plants, the PAW is set to 550 mm.

The harvestable yield (W_s) is determind by the approach of Lindroth & Båth (1999) and expressed mathematically in EQ. 2. W_s is specified as dry matter.

$$W_s = \tau(1 - c_l - c_r) * PAW \qquad (2)$$

W_s	Harvestable yield in g/(m²*a) or equal 1/100 t/(ha*a)
τ	Water use efficiency in g/kg or equal g/mm
c_l	Leaves as share of biomass
c_r	Root system as share of biomass
PAW	Plant avilable water in mm/a

In the calculation of biomass, water use efficiency (τ) is implemented to describe the ratio between water volume and biomass produced. On the basis of studies by Lindroth et al. (1994) and Lindroth & Cienciala (1996), Lindroth & Båth (1999) uses Salix viminalis a τ 6.3 g/kg. According to Linderson et al. (2007), this value is overrated; they give an average of 5.3 g/kg as a realistic size for willow clones (L 78189, Rapp, Jorunn, Jorr, Tora and Loden.)

The calculations carried out in this study use the latter value of 5.3 g/kg. As leaves and roots remain after the harvest on the fields, their share must be subtracted from the total biomass. This share of roots (c_r) and leaves (c_l) are determined by Lindroth & Cienciala (1996) as well as Lindroth & Båth (1999) with c_l= 0.2 and c_r= 0.25. However, a regression model for calculating the biomass, as it is used in this study, is often used to calculate the yield potential of SRC out of the PAW. At this point, all previous studies assume that the nutrient supply is not limiting plant growth. This refers to a low nutrient requirement of plants (Lindroth & Båth 1999, Murach et al. 2009, Aust 2012, Stork et al. 2014).

In addition to calculating the biomass potential of willow SRCs, it is possible to determine the spatial distribution of economically suitable sites. Therefore, the input data in Table 4-1 is processed on a grid size of 25 m using ESRI ArcGIS 10.1 and the integrated ModelBuilder. Further, an economic limit of cultivation was set, according to the approaches of Andersen et al. (2005) and Murach et al. (2009) which determine a minimum yield of 8 t/(ha*a) as an appropriate boundary. The present study focuses on this threshold, with the consequence that all sites which provide less biomass are assumed to be either unprofitable or unsuitable in cultivation of willow SRCs.

The calculated potentials of SRCs in Germany are examined in terms of energy efficiency and productivity. This examination is based on a model by Andersen et al. (2005), which describes a linear relation between biomass yield and performance of power plants. This demands a power plant with a capacity of 20 MW and an annual consumption of 120,000 t of wood biomass, which is what the company MVV Energie GmbH has operated in Berlin since 2003. Further, a power plant chosen supplies both electric and heat energy, which has a much higher energy efficiency. Such a power station is operated by the Ilmenau Wärmeversorger GmbH in Ilmenau and requires 43,000 t biomass per year at an output of 9.7 MW (3.7 MW electricity and heat 6.0 MW).

For a power plant with the same dimensions as MVV Energie GmbH, the FNR (2006) assumes an average efficiency of 30%. However, the power plant has an efficiency of approximately 36% and can serve more than the modern standard developed in the past. However, according to Ilmenauer Wärmeversorger GmbH, their power plant claims approximately 90% efficiency, representing a state-of-the-art model (UBA [German Environment Agency] 2013).

4.3 Results

The results provide both quantitative and spatial information about the bioenergy potential of willow SRCs on German agricultural sites. Figure 4-1 shows the PAW for all field locations in Germany and provides an overview of the spatial distribution of land suitability. The image is limited to three classes: the PAW in < 275 mm is unsuitable (yield < 8 t/(ha*a)), PAW in 275-550 mm is suitable, and PAW > 550 mm (yield > 16 t/(ha*a)) is a highly suitable location. This suggests 78% of the German field sides are suitable for willow SRCs, with 24% classified as highly suitable and 54% classified as suitable.

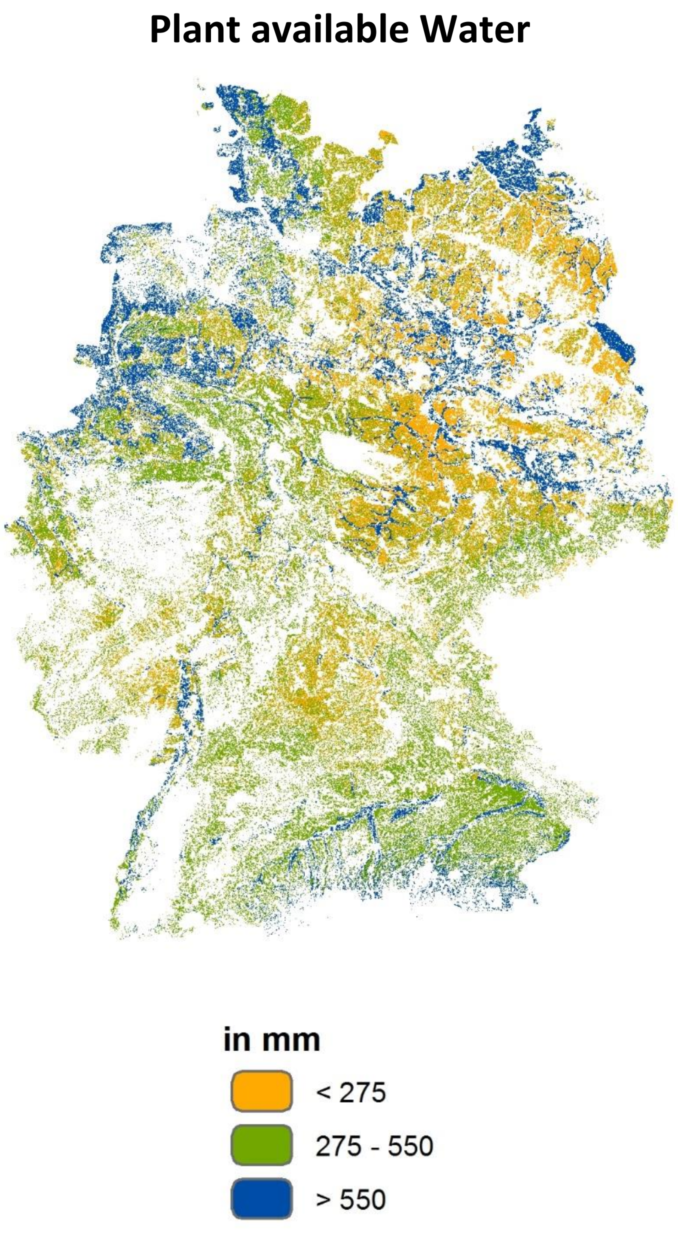

Figure 4-1: Spatial distribution of plant available water on German farmland sites

Large areas of the North German lowlands are well-situated for cultivation of SRCs. Special morphological units are highly suited with a PAW > 550 mm, such as glacial valleys, depressions, and wide river valleys. These have high groundwater levels, which have a favorable effect on plant growth. The effect of the increasing continental climate conditions in the East has to be considered as unfavorable. This climatic influence leads to a significant shift in PAW to the unsuitable level. However, central and southern Germany are characterized by a widespread favorable potential. This is restricted due to rain shadow effects of the low mountain range or increased in lowland areas such as the upper Rhine or Danube tributaries from the Alps.

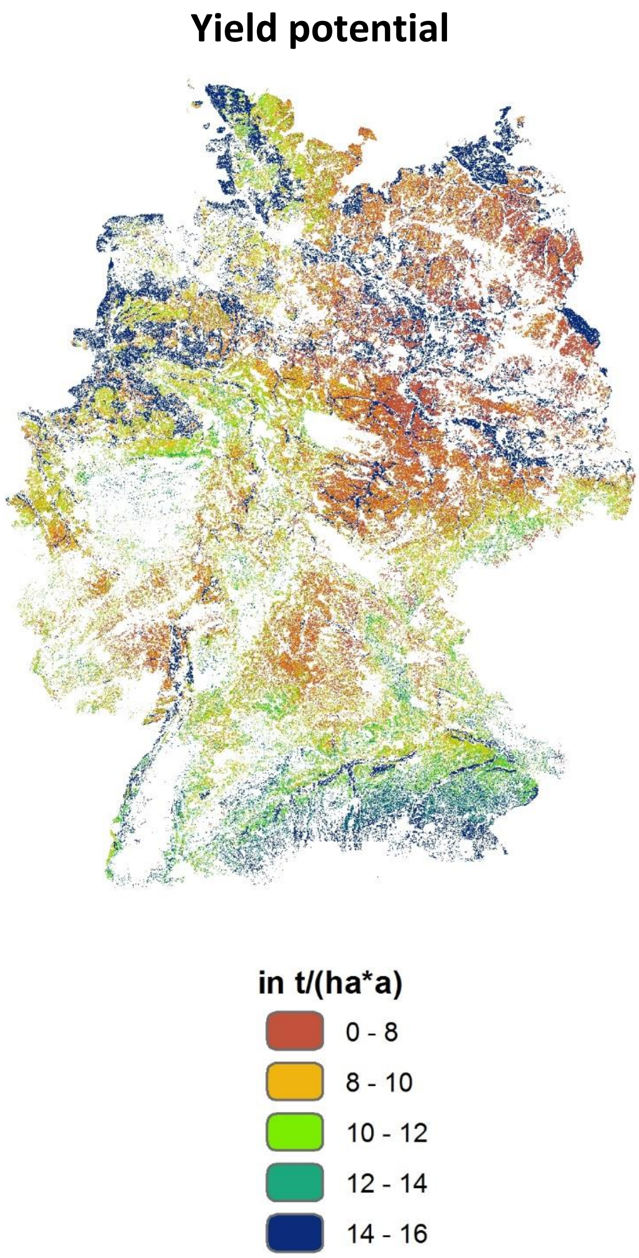

Figure 4-2: Spatial distribution of potential harvest amounts on German farmland sites

Using the data of PAW, the sites' yield potential is determined in t/(ha*a) (Figure 4-2). According to EQ. 2, the results shown in Figure 4-2 and Figure 4-3 are directly proportional to the PAW, thus resulting in non-spatial differences to Figure 4-1. This reveals the same unsuitable conditions, related to continental climate and rain shadow effects of the low mountain range, which results in yield potential of < 8 t/(ha*a). But, also suitable or highly suitable sites are covered. For example, the region of the Alpine foothills is characterized by high yield potential, that results from high precipitation.

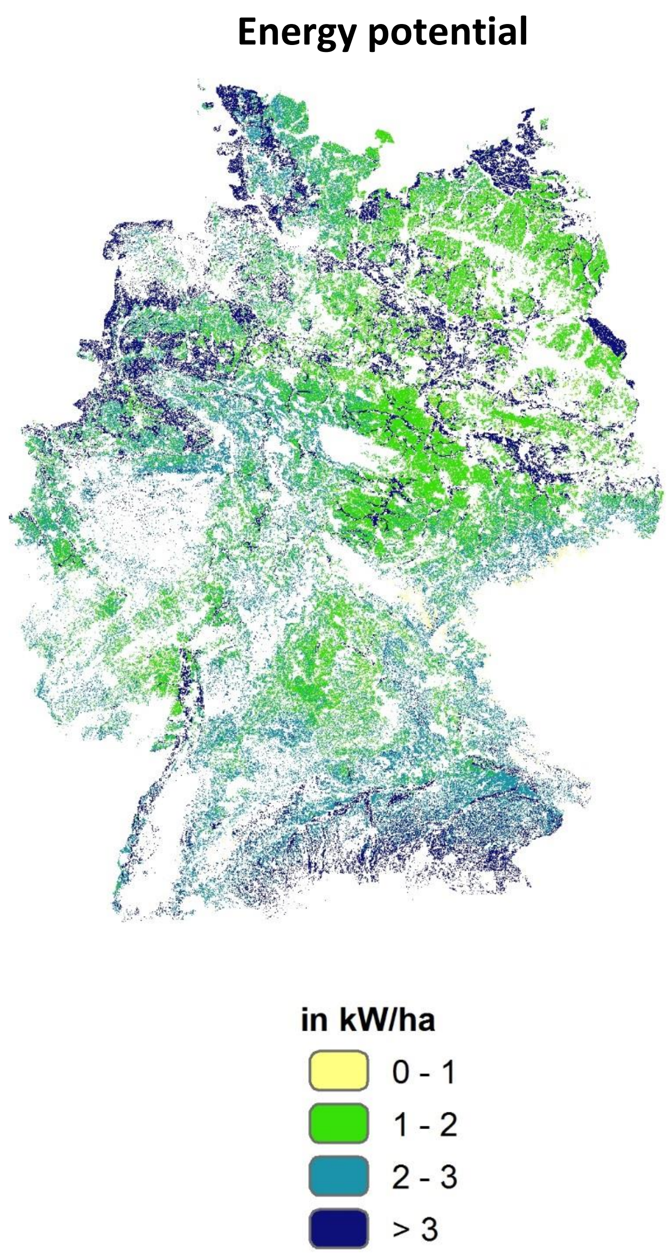

Figure 4-3: Spatial distribution of energy potentials on German farmland sites

The yield potential can also be mapped as energy potentials. In this context, Figure 4-3 confirms the previous results and illustrates the local or regional concentration of the energy potential. However, the Northern German lowland shown has a diverse spread, but in general has a very high energy potential. However, central Germany is characterized by homogeneous low potential, which significantly increases in the foothills of the Alps and the Alps in southern Germany.

Through the use of all economically suitable sites in Germany, about 117 million tons of woody biomass per year could be produced. If used for electricity generation, they could generate a power of about 19 GW. If used more efficiently in a power plant producing electricity and heat, this amount could be increased to 26 GW. Oil substituted as an energy carrier in this magnitude could save 189 Mt CO_2, corresponding to a share of approximately 20% of Germany's 2010 emissions (Statistisches Bundesamt 2012).

The full use of the arable land suitable for SRCs in Germany (a maximum case scenario) can be only a theoretical consideration. Scenarios that assume a significantly lower proportion of agricultural areas should be considered as much more realistic. According to this, in Table 4-3, proportions of 2.5, 5, and 10% of the suitable area with average PWA were taken into account. These scenarios should help to picture the future development.

Table 4-3: Values of energy conversion from suitable sites using the method of Andersen et al. (2005) [CHP = combined heat and power]

Proportion and type of power plant	Oven dry biomass [t a^{-1}]	energy equivalent [TJ]	Oil equivalent [Mt oe]	electrical power [GWh]	electrical power [GW]	substituted Mt C von Oil	Saved Mt CO_2	% of 2010 CO_2-emissions saved
100% SRC for energy	117,386,880	616,936	147.32	171,384.85	19.56	51.65	189.38	19.88
100% SRC for CHP	117,386,880	833,571	199.06	231,566.10	26.43	51.65	189.38	19.88
10% SRC for energy	11,738,688	61,693	14.73	17,138.48	1.96	5.17	18.94	1.99
10% SRC for CHP	11,738,688	83,357	19.91	23,156.61	2.64	5.17	18.94	1.99
5% SRC for energy	5,869,344	30,847	7.37	8,569.24	0.98	2.59	9.47	1
5% SRC for CHP	5,869,344	41,679	9.96	11,578.31	0.98	2.59	9.47	1
2,5% SRC for energy	2,934,672	15,423	3.68	4,284.62	0.49	1.29	4.73	0.5
2,5% SRC for CHP	2,934,672	20,839	4.98	5,789.15	0.66	1.29	4.73	0.5

In Germany, SRCs are established on over 10,000 hectares (Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz 2012, Internationales Institut für Wald und Holz NRW 2014). The Internationale Institut für Wald und Holz NRW (2014) predicts a need between 0.6 and 1.3 million ha in 2020, to meet the rising demand of wood fuel. The scenarios selected for this study are based on this future demand and cover a ratio between 0.3 million (2.5% scenario) to 1.2 million hectares (10% scenario).

Based on the Federal Statistical Office data for 2011, 40.1 million German households consume an average 3.490 kWh of electricity and 12.760 kWh of heat (heat is defined as a demand of 10.890 kWh heating and 1,870 kWh hot water generation) (Statistisches Bundesamt 2013 a, b). By taking these assumptions into consideration, a share of 2.5% of the suitable sites' 357,000 households could be provided with heat and electricity, or 1.2 million households could be supplied with just power. This would save 5 Mt of CO_2-emissions. Larger percentages, such as the 5% or 10% scenario would provide, respectively, 714,000 or 1.4 million households with electricity and heat. Or 2.4 to 4.8 million households would also be covered with electricity, saving up to 20 Mt of CO_2-emissions.

4.4 Discussion and Conclusion

This approach indicates a heterogeneous spatial distribution in terms of the SRC and biomass potential suitability in Germany. This includes both the economic use as well as effects on the water cycle in regions with negative climatic water balance. Nisbet et al. (2011) recommends against SRCs in region with water deficits, since this can lead to a significant decline of water resources for ecologically valuable wetlands or creeks.

In contrast, the discussion remains whether SRC cultivation would have positive effects if established on wet agricultural sites. Currently, heavily drained areas could benefit from a cultivation of SRCs, in which a surplus of water would serve the production of SRC. Plants used in SRCs are able to compete and profit from much higher water contents than conventional field crops when local drainage management is minimized. However, studies have not yet determined and quantified the effects.

Moreover, a reduction of CO_2-emissions can only be achieved if cultivation and transport of the biomass to the power station generate a minimum of additional CO_2-emissions. To achieve this, decentralized solutions for the utilization of biomass from SRC are necessary, which concentrate the cultivation and energy generation on a local or regional scale. The results presented show that this source of energy is not only locally, but also regionally, sensible and sustainable. This especially accounts for regions with a high yield potential. But for the primary energy supply in Germany, this energy carrier can only contribute with strong limitations. Moreover, the methodology used only generates an overview of the biomass potential in Germany, as seen in the initial data. Local conditions cannot be evaluated due to the scale of this approach, which does not allow validation by actual yield amounts.

But aspects match as shown in comparison with previous national studies. They confirmed that groundwater proximity is a key factor for a high biomass potential, whereas a continental climate implies an unfavorable location (Lindroth & Båth 1999, Murach et al. 2009, Aust 2012 & Stork et al. 2014). To achieve more detailed results, soil maps would be required, which provide additional information about available soil water content and groundwater proximity.

Taking into account the soil quality, infertile sites—according to annual crops—could be classified in a further step. A chipping of such areas with fields, which have high groundwater proximity, would result in locations with a low competition level between annual crops and SRC. In addition, this would serve to prevent a food versus fuel dilemma. However, additional studies are needed to enhance the regionalization aspect and site assessment regarding SRCs, by focusing on interception and soil evaporation as a share of evapotranspiration.

In addition, water use efficiency differences between calculated and actual values need to be observed. A much higher water use efficiency is reached by high-performance clones, but there are no studies at present which determine this (Schmidt et al. 2014). The yield performance of such high-performance clones also varies due to the weather conditions during the vegetation period. It is also recommended to use a diversification of plant material to prevent pests and minimize the impact of extreme weather conditions. Thus, the present work reasonably assumes a moderate to average yield potential.

This approach also refers to the yield expected by fertilization which assumes an increase of biomass. SRCs should only be fertilized if yield demands significantly reduce during the second or the following rotation, compensating a nutrient discharge due to the harvest (Quaye et al. 2011, Quaye & Volk 2013, Aronsson et al. 2014). However, this nutrient supply may result in eutrophication of soil and water bodies (Balasus et al. 2012). Considering the climate footprint, fertilizer application shows a significant deterioration in terms of sustainable management (Bottoms 2012, González-García et al. 2012). In a structure of a preferred and sustainable closed-loop economy, the ash from the combustion of biomass could be transferred back to the cultivation area to minimize the nutrient loss (Rademacher et al. 2013). In general, the fertilization of SRCs is controversial and numerous studies pointed out that it does not have a positive impact on yield amounts (Boelcke 2006, Burger 2010, Scholz et al. 2011, Balasus et al. 2012, Slazak et al. 2013, Sevel et al. 2014). However, the success of fertilization is also closely linked to the water supply (Hangs et al. 2012).

The intersection of the results of this approach with data about conservation areas could refine the assessment of suitable agricultural areas. Also, ecosystems could be excluded, which react sensitively to the SRC-indicated decrease of groundwater recharge. However, the cultivation of SRCs should focus on conditions optimized for landscape and humans as well as win-win situations (Hartwich et al. 2014c).

4.5 Summary

Our modeling approach shows that, from an economic perspective, 78% of the arable land in Germany is suitable for growing willow short rotation coppices. A theoretical total of 117 million tons of woody biomass could be harvested on this area annually. The biomass yield derived from a more realistic scenario, using only 2.5% of the arable land (300,000 ha) and a mean yield potential, would be sufficient to supply 1.2 million households with electricity or 357,000 households with thermal energy and electricity. The spatial distribution of preferential sites in Germany shows a significant concentration in the Northern German Plain. Other favorable areas for short rotation coppicing, according to our modeling approach, are located in the pre-Alps, Alps and the Upper Rhine Rift. In the Northern German Plain, these areas correspond to the glacial ancient river valleys (Urstromtal) and the lower reaches and plain tracts of the present-day river valleys, areas with a high groundwater table. A similar situation is found in the Upper Rhine area and partly in the Danube basin of southern Germany. In the pre-Alps and Alps, higher precipitation caused by orographic effects improves the biomass potential. However, undesirable effects on water resources of environmentally valuable wetlands and streams could occur in regions with a negative climatic water balance, due to the high water consumption of the plants. On the other hand, short rotation coppices could have a positive impact in regions where high groundwater levels are problematic, reducing the need for drainage systems. Finally, it is important to find efficient solutions for cultivation and energetic use, since long transportation distances lower the sustainability and revenue of such systems. In this context and considering the diverse distribution of the biomass potential across the country, cultivation and utilization should be local and decentralized.

Acknowledgements

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5 Hydrological modelling of changes in the water balance due to the impact of woody biomass production in the North German Plain

Abstract

Several studies implied that cultivation of willow and poplar short rotation coppice influence the water balance. Due to the high density of sites suitable for SRC in the Northern German Plain, this study focusses on four different model areas representative of the climatic, soil and morphological heterogeneity of this landscape. The river basins selected for the study are the Ems, Treene, Aland and Uecker-Randow-Welse basins. The water balance modelling was performed with the Soil Water Assessment Tool (SWAT), automatically calibrated with SWAT-CUP using parallelization by high performance computing. The implemented scenarios were set to 10% SRC cover, based on predictions for the area needed to meet the domestic demands for woody biomass by 2020. Additionally, an extreme scenario of 100% cultivation on all suitable sites was implemented to determine the maximum effect of SRC on the regional water balance and also to allow for a direct comparison with annual crops, pasture and deciduous forest. For parametrization, long-term measurements were used to characterize the key physiological parameters for willow and poplar in SWAT. The results for the 10% SRC scenarios did not show a substantial impact on the investigated water balance components at the water basin level. But, at the local level, the effect of conversion to SRC are more pronounced. In general, the actual evapotranspiration is compared with annual crops 16% higher and groundwater recharge decreases in average with 48%.

5.1 Introduction

Woody biomass represented 92% of the heat production from renewable resources in Germany in 2011 and is the major regenerative energy carrier (Umweltbundesamt 2013). In terms of the total energy mixture, biomass represented 7.6% of the total energy sources in 2013 (Fachagentur für Nachwachsende Rohstoffe 2014). Due to broad public debate and political support, renewable energy carriers are receiving increasing attention as a means to lower CO_2-emissions. This indicates that woody biomass will be in high demand in the near future. To meet these demands, and in order to conserve sustainable forestry, agricultural areas are being used to cultivate fast-growing tree species, such as willow or poplar. These trees are managed in short-rotation coppices (SRC), in which the trees are harvested aboveground repeatedly every three to five years. After being harvested in the winter, these tree species have the ability to regrow from the remaining rootstock during the next spring.

However, to implement SRCs in a sustainable framework, different hydrological factors have to be taken into account (Hartwich et al. 2014c). As described by several studies, willow and poplar, in contrast to herbaceous plants, have a much higher leaf area, which causes a reduction in effective precipitation (Ettala 1988, Hall & Allen 1997, Dimitriou et al 2009a, Nisbet 2005). Moreover, due to their physiological characteristics, willow and poplar show potential evapotranspiration rates that exceed those of grassland by 20% (Allen et al. 1998, Dimitriou et al. 2009a, Nisbet et al. 2011, Hartwich et al. 2015a). These characteristics underline the effect of SRCs on the water balance, an effect that has been anticipated by several previous studies (Petzold et al. 2009, Webb et al. 2009, Wahren et al. 2014).

Aust (2012) and Hartwich et al. (2015a) revealed a high suitability for SRCs in the Northern German Plain, owing mainly to high groundwater levels, contributing largely to the plant available water, which was also indicated by Murach et al. (2009) and Stork et al. (2014). Due to this high potential for the cultivation of SRCs, this study will primarily focus on this region and the impacts on the water balance that could arise in this area. Such effects could result in an increase in evapotranspiration, a reduction in groundwater recharge, a lessening of the base flow amount as well as a reduction of surface runoff. If these impacts reach a certain threshold, water-bound, semi-terrestrial ecosystems could be negatively affected, putting the sustainable cultivation of SRCs on such particular sites into question (Hartwich et al. 2014c).

The aim of this study therefore is to quantify the impact of willow and poplar SRCs on the water balance for basins located in the Northern German Plain. To analyze and quantify the impact of SRCs, hydrological models were set up for six selected river basins in the Northern German Plain, as current-state models. The Ems, Aland, Treene and Uecker-Randow-Welse river basins were selected to account for the differences in climate conditions as well as landscape evolution and soil properties. The 2012 version of the Soil and Water Assessment Tool (SWAT) was used to simulate the impact on the water balance generated by a land use change from annual crops to SRC. SWAT is a watershed model, which combines physically-based with empirical and conceptual approaches. It was developed to assess the impact of management and cultivation and changes thereof on hydrological factors on a basin-wide scale (Arnold et al. 1998, Srinivasan et al. 1998, Gassman et al. 2007). It was also used by Wahren et al. (2014, 2015) to estimate the effects of poplar SRC on a meso-scale basin.

After model setup, the calibration was based on the automatic calibration tool SWAT-CUP v. 5.1.6 (Calibration and Uncertainty Programs [CUP]) and the statistical method of Sequential Uncertainty Fitting, Version 2 (SUFI-2) (Abbaspour et al. 2007). Also, plant-specific parameters for poplar and willow for Central European conditions were extracted from dedicated measurements as well as from the literature and used to parameterize the model. Afterwards, a direct comparison with annual crops, pasture and deciduous forest was drawn. Finally, scenarios for willow and poplar SRCs with different proportions on the suitable arable land (excluding pasture) were analyzed for their hydrological impact on a basin scale.

5.2 Materials and Methods

5.2.1 Study area

In order to characterize the hydrology and water balance of the North German Plain, basins in different areas were selected to represent the heterogeneous environmental conditions, namely climatic, soil and morphogenetic conditions (Figure 5-1). The Treene in Schleswig-Holstein and the Ems in Lower Saxony and North Rhine-Westphalia were selected as river basins characteristic of maritime conditions. Uecker, Randow and Welse in Brandenburg and Mecklenburg-Vorpommern, treated as one modeling area, were chosen to represent continental conditions. The Aland basin marks a transition zone between both climatic regimes.

The soil and morphological nature of the Northern German Plain has been shaped by past glaciation processes. These processes created basically two distinct glacial landscapes: young Weichselian and Pre-Weichselian. The Ems and Aland are representative of the Pre-Weichselian landscape and Uecker, Randow and Welse are considered young Weichselian. The Treene river basin covers both morphological and soil genetic regions.

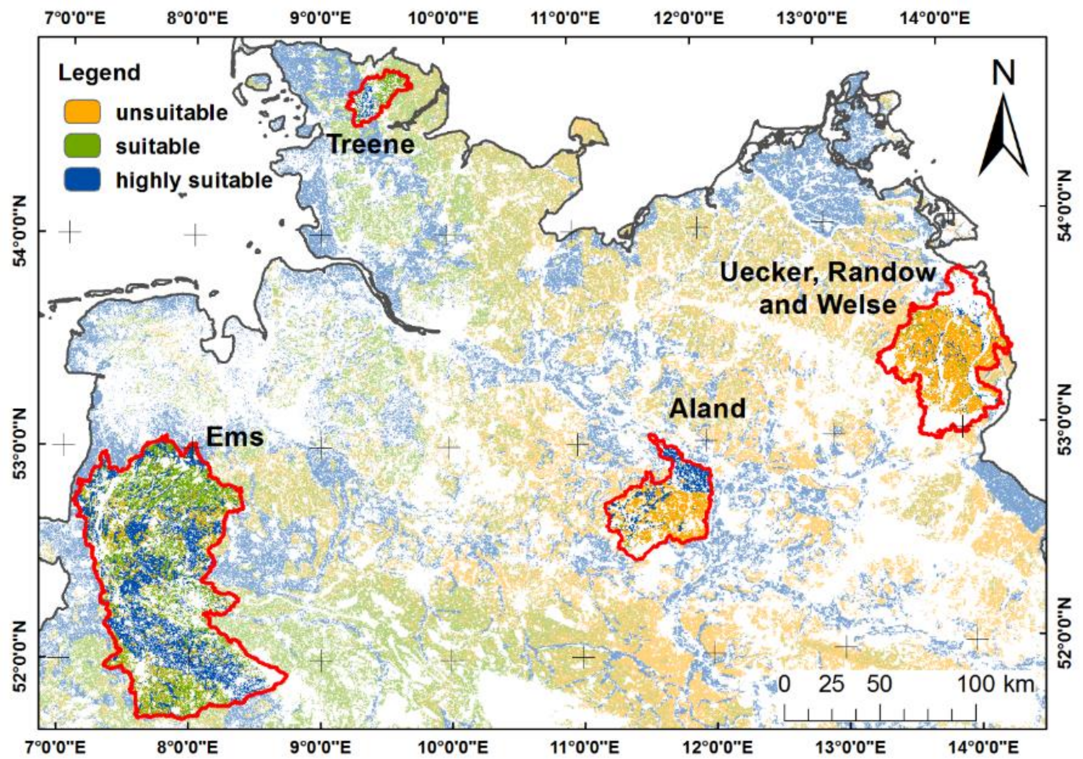

Figure 5-1: Selected basins and their suitability level for willow SRC, based on Hartwich et al. (2015a). Given the similar water use efficiency of willow and poplar SRC (see text), areas suitable for willow can be assumed to be suitable for poplar SRC as well.

As shown in Figure 5-1 and Hartwich et al. (2015a), the North German Plain is generally suitable for cultivation of SRC (poplar and willow), but with a high spatial variability. These differences in suitability result mainly from variations in climate conditions and groundwater availability for the cultivated tree species, whereas soil and relief conditions only have a minor influence. The suitability assessment by Hartwich et al. (2015a) only considered willow SRC. However, given the similar rooting depth and range of water use efficiency of willow and poplar cultivars grown in SRC in Central Europe (Bungart & Hüttl 2004, Linderson et al. 2007, Tallis et al. 2013, Schmidt & Murach 2015), it can be assumed that sites suitable for willow will also be suitable for poplar.

Table 5-1 illustrates the distribution of suitable agricultural land in the different basins. In addition, the table shows the area assigned to SRC in different scenarios, as explained below ('Scenarios'). Note that the Uecker, Randow and Welse basin is characterized by only a minor percentage of suitable sites (7% of the basin area). The basin was nevertheless chosen as test area in order to describe the hydrology of the northern German Plain in its breadth.

Table 5-1: Agricultural area suitable for SRC, and area under SRC in the different scenarios, see below.

Basin	Area, in km²	Agricultural land, in % of the basin area	Suitable agricultural land, in % of the basin area	SRC scenarios as percentage of suitable area, in km² (change of the basin area in %)	
				10%	100%
Treene	477	48	48	23 (5)	228 (48)
Ems	9,093	74	67	608 (7)	6,083 (67)
Uecker, Randow, Welse	3,290	47	7	23 (1)	233 (7)
Aland	1,907	54	22	41 (2)	409 (21)

5.2.2 The model system and parametrization

As a model system, the Soil and Water Assessment Tool, version 2012 ('SWAT 2012') was used to investigate the hydrological effects of SRC on the water balance of the different basins. SWAT is a semi-distributed watershed model, which uses physical as well as empirical and conceptual approaches. Different studies have proven that SWAT 2012 is a suitable method for evaluating different management strategies and for assessing their influences on various hydrological aspects (Arnold et al. 1998, Srinivasan et al. 1998, Gassman et al. 2007, Wahren et al. 2014).

SWAT 2012 uses hydrotopes, which characterize the hydrological properties of a specific area, to calculate the water balance. Within the model, these units are described as Hydrologic Response Units (HRU) and combine areas of sub-basins that share unique slope, soil and land use attributes (Arnold et al. 1998). In this way, the spatial heterogeneity of the landscape is implemented in the model.

Table 5-2 lists the data and their sources used to set up the model with a daily time step from 01/01/1990 to 12/31/2013. A three-year warm-up period was used, which reduces the model output to the period from 01/01/1993 to 12/31/2013. To calculate potential evapotranspiration, the Hargreaves-method was used during the model setup. The resulting values for potential evapotranspiration matched the values reported for the Northern German Plain by Neumann & Wycisk (2003). For surface runoff estimation, the curve number method was used.

Table 5-2: Model setup datasets and their sources

Datasets	**Source**
Relief information Digital Elevation Model, resolution 25 m	Federal Agency for Cartography and Geodesy, Frankfurt am Main
Land-use data Digital land cover model 2009, equal area Statistical agricultural data (period 1995-2013)	Federal Agency for Cartography and Geodesy, Frankfurt am Main Federal Statistical Office
Soil information Soil survey maps 1: 200,000 (Germany) Soil database of the soil survey map 1: 1,000,000 (Germany) Soil database of the soil survey map 1: 300,000 (Brandenburg)	Federal Institute for Geosciences and Natural Resources State Office for Mining, Geology and Minerals Brandenburg
Climate data (time series) Precipitation data of 117 stations Temperature data of 33 stations Relative humidity data of 33 stations Solar radiation data of 8 stations Wind speed data of 24 stations	German Weather Service
Discharge data of 30 runoff gauges	Lower Saxony State Office for Water Management, Coastal and Nature Conservation State Office for Environment, Health and Consumer Protection Brandenburg State Office for the Environment, Nature Conservation and Geology Mecklenburg Vorpommern State Agency for Nature, Environment and Consumer Protection North Rhine-Westphalia State Agency for Coastal Defense, National Park and Marine Reserve Schleswig-Holstein

The data preprocessing was done with ArcSWAT, which is an implementation to ESRI ArcGIS. In general, 64 different soil types and 12 land use classes could be defined by the datasets. These datasets were implemented to characterize the individual SWAT models for each of the basins.

The different datasets resulted in the model characteristics shown in Table 5-3. To keep model complexity and data volume on a workable level, the area for stream definition in the model setup was adjusted in relation to the watershed area. Due to this adjustment, the model runtime was 30 minutes at most.

Table 5-3: Model characteristics

Basin	Area in km²	Number of sub-basins	Number of HRUs	Area for stream definition in ha
Treene	477	34	4,574	1,000
Ems	9,093	86	4,486	8,000
Uecker, Randow and Welse	3,290	56	6,271	4,000
Aland	1,907	36	6,630	4,000

5.2.3 Calibration

The daily streamflow data of 30 gauging stations was used in calibration and validation. Table 5-4 shows the stations used in the individual basins, their data length as well as the specific periods of calibration and validation. These periods differ partially due to data availability. The station data and the SWAT models of the river basins were integrated into the automatic calibration tool SWAT-CUP (v. 5.1.6). Within this software, the calibration method SUFI-2 was used because of its ability to run parallel simulations in one iteration step (Abbaspour et al. 2007; Rouholahnejad et al. 2012).

Table 5-4: Runoff gauges per basin, their data length as well as calibration and validation period. Periods of calibration and validation differ due to data availability.

Basin	Station name	Length of the data series in years	Calibration period	Validation period
Treene	Soltfeld	18	1993-2006	2007-2010
	Mühlenbrück	19	1993-2006	2007-2011
	Oeversee	19	1993-2006	2007-2011
	Eggebek	19	1993-2006	2007-2011
	Soller Mühle	20	1993-2006	2007-2012
	Treier*	20	1993-2006	2007-2012
Ems	Versen-Wehrdurchstich*	20	1998-2006	2007-2012
	Bunnen	21	1993-2006	2007-2013
	Uptloh	21	1993-2006	2007-2013
	Bokeloh	21	1993-2006	2007-2013
	Herzlake	21	1993-2006	2007-2013
	Haselünne	21	1993-2006	2007-2013
	Augustmühle	21	1993-2006	2007-2013
	Bersenbrück	21	1993-2006	2007-2013
	Lingen-Darme	21	1993-2006	2007-2013
	Bramsche	21	1993-2006	2007-2013
	Rheine	21	1993-2006	2007-2013

	Greven	21	1993-2006	2007-2013
	Coermühle	15	1993-2000	2001-2007
	Wibbeltstraße	15	1993-2000	2001-2007
	Albertsloh	21	1993-2006	2007-2013
Uecker, Randow and Welse	Ueckermünde*	15	1998-2006	2007-2012
	Pasewalk	21	1993-2006	2007-2013
	Löcknitz, Eisenbahnbrücke	21	1993-2006	2007-2013
	Prenzlau, Wehr	21	1993-2006	2007-2013
	Sukow	21	1993-2006	2007-2013
Aland	Klein Wanzer*	7	2006-2010	2011-2013
	Dobbrun	21	1993-2006	2007-2013
	Hagenau	21	1993-2006	2007-2013
	Goldbeck	21	1993-2006	2007-2013

* major basin outlets

In the calibration, hydrological parameters and their ranges were adjusted according to findings from other studies using/applying SWAT in the Northern German Plain (Schmalz et al. 2008, Pfannerstill et al. 2014, Guse et al. 2014, Abbaspour et al. 2015). Table 5-5 lists the used calibration parameters, the type of variation as well as their initial and final ranges. All four basin models were calibrated independently, which results in different final calibration ranges. More detailed descriptions of the calibration procedure and setup are given by Abbaspour et al. (2007), Rouholahnejad et al. (2012), Abbaspour et al. (2015) and Hartwich et al. (2015b).

Table 5-5: Calibration parameters, type of variation as well as initial and final parameter ranges. Parameters and ranges were selected according to the approaches of Schmalz et al. (2008), Pfannerstill et al. (2014), Guse et al. (2014) and Abbaspour et al. (2015). Type of variation is specified as “v – value change” and “r – relative value change as absolute proportion”.

Parameter [Type of variation]	**Description**	**Initial range**	**Final range**			
			Treene	**Ems**	**Uecker, Randow and Welse**	**Aland**
SURLAG.bsn [v]	Surface runoff lag coefficient [-]	0.1-10	7.41-8.71	0.10-1.20	1.25-1.72	1.53-1.86
EVRCH.bsn [v]	Reach evaporation adjustment factor [-]	0.5-1	0.62-0.68	0.74-0.95	0.80-0.88	0.89-0.95
SOL_K.sol [r]	Saturated hydraulic conductivity [mm/h]	-0.5-0.5	0.21-0.33	-0.28-0.33	-0.20-0.10	0.18-0.32

SOL_BD.sol [r]	Moist bulk density [g/cm³]	-0.5-0.5	-0.04-0.12	-0.26-0.24	-0.13-0.11	0.12-0.24
SOL_AWC.sol [r]	Available water capacity of the soil layer [mm H_2O/mm soil]	-0.5-0.5	-0.17-(-0.01)	-0.33-0.24	-0.40-(-0.10)	-0.08-0.14
CN2.mgt [r]	Curve number for soil moisture conditions [-]	-0.5-0.5	-0.37-(-0.16)	-0.33-0.28	-0.10-0.13	-0.11-(-0.02)
ALPHA_BF.gw [v]	Baseflow alpha factor [d]	0.01-1	0.28-0.46	0.25-0.70	0.48-0.73	0.51-0.68
GWQMN.gw [v]	Threshold depth of water in the shallow aquifer required for return flow to occur [mm]	700-4,000	2,207-3,284	1,029-1,622	986.6-1,259	1,077-1,260
GW_REVAP.gw [v]	Groundwater "revap" coefficient [-]	0.02-0.2	0.11-0.14	0.06-0.15	0.09-0.13	0.08-0.10
REVAPMN.gw [v]	Threshold depth of water in the shallow aquifer for "revap" to occur [mm H_2O]	0-500	233.3-317.8	2.01-7.15	4.88-6.76	4.86-6.63
RCHRG_DP.gw [v]	Deep aquifer percolation fraction [-]	0.15-0.6	0.48-0.57	0.21-0.33	0.27-0.32	0.23-0.26
GW_DELAY.gw [v]	Groundwater delay [d]	3-50	27.11-43.31	14.20-35.36	18.41-30.65	21.42-26.05
LAT_TTIME.hru [v]	Lateral flow travel time [d]	10-160	75.94-119.3	61.05-127.0	52.78-92.76	77.74-106.9
OV_N.hru [r]	Manning's "n" value for overland flow [-]	-0.5-0.5	-0.02-0.25	-0.16-0.38	0.00-0.29	-0.35-(-0.11)
ESCO.hru [v]	Soil evaporation compensation factor [-]	0.3-1	0.49-0.64	0.79-0.92	0.81-0.91	0.78-0.83
EPCO.hru [v]	Plant uptake compensation factor [-]	0.7-1	0.51-0.7	0.76-0.91	0.83-0.90	0.82-0.88
CANMX.hru [v]	Maximum canopy storage [mm H_2O]	5-80	43.60-56.43	22.02-55.56	26.53-50.74	32.87-45.49
CH_N2.rte [v]	Manning's "n" value for the main channel [-]	0.01-0.3	0.13-0.19	0.16-0.29	0.06-0.12	0.18-0.22
PND_FR.pnd [v]	Fraction of sub-basin area that	0-0.6	0.40-0.60	0.003-0.009	0.004-0.03	0.007-0.008

	drains into ponds [-]					
PND_ESA.pnd [v]	Surface area of ponds when filled to emergency spillway [ha]	0-200	77.95-114.9	60.29-141.4	100.4-156.8	63.85-87.97
PND_PSA.pnd [v]	Surface area of ponds when filled to principal spillway [ha]	0-1000	502.2-635.3	247.1-674.6	459.3-750.6	575.9-817.0
PND_PVOL.pnd [v]	Volume of water needed to fill ponds to the principal spillway [10^4 m³ H_2O]	0-100	46.92-62.84	23.64-69.77	44.02-65.05	68.40-79.37
PND_EVOL.pnd [v]	Volume of water stored in ponds when filled to the emergency spillway [10^4 m³ H_2O]	0-200	74.47-111.0	36.91-110.7	62.36-131.9	82.01-131.6
PND_K.pnd [v]	Hydraulic conductivity through bottom of ponds [mm/hr]	0-1	0.58-0.69	0.33-0.78	0.33-0.48	0.55-0.69

The evaluation was primarily done with the Nash-Sutcliffe efficiency approach (NSE, Nash & Sutcliffe 1970). According to the studies of Gupta et al. (1999), Singh et al. (2004) and Moriasi et al. (2007), the percentage bias (PBIAS) and the standard deviation ratio of the root mean square error (RSR) should be considered when estimating quality levels. This set of objective functions was used to specify a new combination of parameter ranges, which was applied afterwards in the next iteration. In total, five to eight iterations, with 2,000 simulation runs each, were done to reach sufficient calibration results.

Following the procedure of Moriasi et al. (2007), rankings were established and assigned to every gauging station to classify the results from the calibration and validation (Table 5-6).

Table 5-6 : Classification of hydrological model performance, according to Moriasi et al. (2007), and combined gauge assessment by rank

Classes	Rank	NSE	PBIAS	RSR
Very good	1.0	0.75 < NSE ≤ 1.00	PBIAS < ±10	0.00 ≤ RSR ≤ 0.50
Good	2.0	0.65 < NSE ≤ 0.75	±10 ≤ PBIAS < ±15	0.50 < RSR ≤ 0.60
Satisfactory	3.0	0.50 < NSE ≤ 0.65	±15 ≤ PBIAS < ±25	0.60 < RSR ≤ 0.70
Unsatisfactory	4.0	NSE ≤ 0.50	PBIAS ≥ ±25	RSR > 0.70

5.2.4 Parameterization of SRC

In order to create scenarios of land use and land use change, species-specific plant parameters for SWAT were derived from long-term data sets and dedicated experiments on poplar and willow SRC plantations established and/or monitored by the Eberswalde University for Sustainable Development in the Northern German Plain, mostly Brandenburg. Data from plantations managed in three-year rotation cycles were used, supplemented by literature surveys. The definition and estimation of the parameters followed the SWAT Theoretical Documentation (Neitsch et al. 2011).

Parameters concerning the leaf area index were derived from measurements in SRC plantations in NE Brandenburg from 2012 till 2014. A standard optical method was used to estimate LAI (LAI2000 Plant Canopy Analyzer, LI-COR, Inc., USA). Maximum and seasonal development of LAI was assessed in several plots in up to four poplar and five willow plantations. Planting density in the plots was around 15.000 trees per hectare, typical for a two to four year harvesting cycle in the region. Measurements were carried out on up to 18 dates per year to follow the seasonal dynamics of the leaf area development. Data from all plots were combined to construct a curve of optimal leaf area index development. As the base temperature, 5°C was chosen, the typical value for temperate tree species (see e.g. Fu et al. 2015, Vitasse & Basler 2013 and literature cited therein). Parameter values listed in Table 5-7 are suggested and implemented in the hydrologic models.

Table 5-7: Values suggested for willow and poplar SRC parametrization based on own measurements and literature, see text; definition and estimation parameters based on the SWAT Theoretical Documentation (Neitsch et al. 2011).

Changed crop parameter	**implemented values**		**Former values in SWAT database**
	Willow	**Poplar**	**Willow and Poplar***
Optimal Temperature (T_OPT) [°C]	18	18	30
Base Temperature (T_BASE) [°C]	5	5	10
Maximum potential LAI (BLAI) [m²/m²]	6.2	8.8	5
Fraction of growing season when growth declines (DLAI) [-]	0.701	0.87	0.99
Minimum LAI for plant during dormant period (ALAI_MIN or WAI) [m²/m²]	0.9	0.8	0.75
First point fraction of BLAI for optimum growth curve (LAIMX1) [-]	0.225	0.123	0.05
Second point fraction of BLAI for optimum growth curve (LAIMX2) [-]	0.916	0.899	0.95
Fraction of growing season coinciding LAIMX1 (FRGRW1) [-]	0.04	0.04	0.05
Fraction of growing season coinciding LAIMX2 (FRGW2) [-]	0.228	0.228	0.4
Max. Canopy Height (CHTMX) [m]	8	8	7.5
Max. Rooting Depth (RDMX) [m]	2	2	3.5
Number of years for tree to reach full development (MAT_YRS) [years]	3	3	10

*Willow and Poplar are separate in the SWAT database, but the values selected are equal for both tree genera

Compared to the existing parameters in the SWAT database, which distinguish willow and poplar trees but offer no differences in major parameters, the new parameter set better represents the plant-specific variables. One major difference between poplar and willow is illustrated in Figure 5-2, which shows the optimal LAI development curve during the vegetation period, expressed as fraction of potential heat units (accumulated degree days above the bases temperature of 5°C).

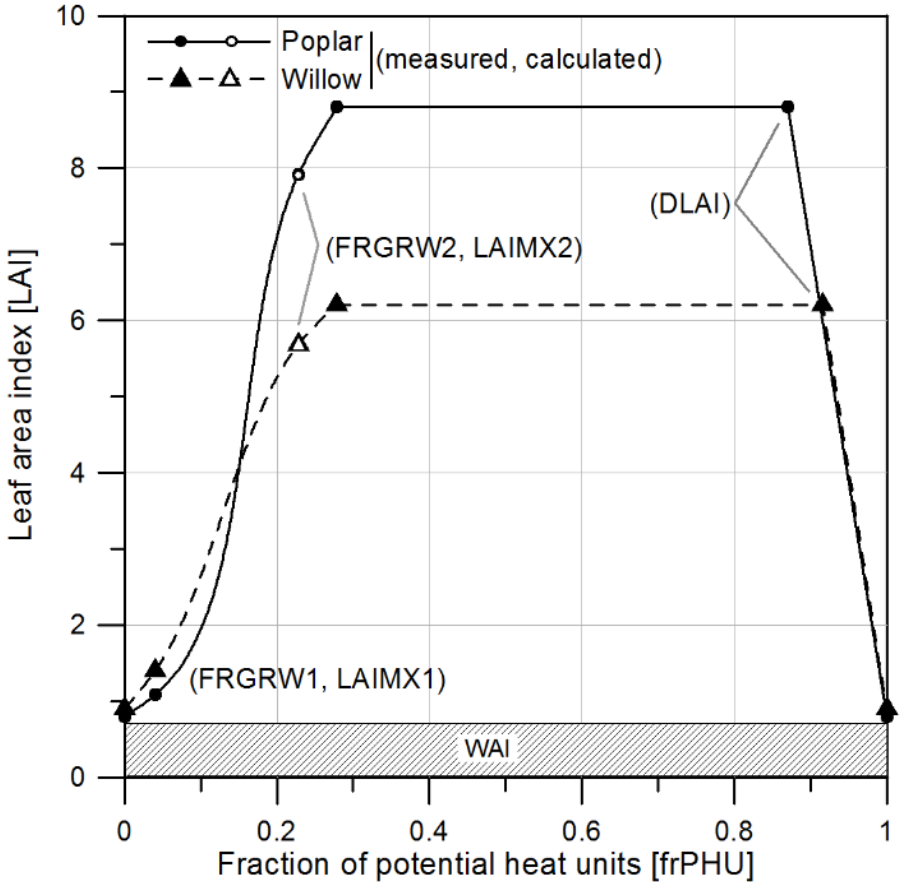

Figure 5-2: Leaf area development of willow and poplar as a function of fraction of vegetation period (frPHU). Values shown are based directly on own measurements or derived from regressions on the measured data and were used as model input parameters; parameters as defined by Neitsch et al. (2011). Table 5-6 defines the acronyms.

5.2.5 Scenarios

Based on our previous study (Hartwich et al. 2015a) and the values shown in Table 5-1 and Table 5-7, different land use scenarios were calculated with the calibrated model setup. To identify and quantify the general impact of willow and poplar SRC, a hypothetical 100% scenario (W_100 for willow and P_100 for poplar) was tested, where the total agricultural area suitable for SRC (see above) was assigned to SRC, representing 15 to 99% of the total agricultural area (cf. Table 5-1). However, to implement more realistic scenarios with regard to proportions of areas used for SRC, a projection of the Internationales Institut für Wald und Holz NRW [International Institute of Forestry and Wood Industries, North Rhine-Westphalia] (2014) was used. This projection predicts that by 2020 a share between 2.5% (0.3 Mio. ha) and 10% (1.2 Mio. ha) of the agricultural area in Germany must be transformed into SRCs in order to meet the demands for wood fuel. Based on this projection, scenarios were applied where 10% of the agricultural area of each river basin suitable for SRC were allocated to willow or poplar SRC in order to estimate their impact on the water balance. In total, four scenarios (W_100, W_10, P_100, _P10) were calculated for each model (basin). Due to the different basin sizes and the different proportions of the suitable agricultural area on the total agricultural area, the absolute land cover changes vary between basins and are given in the scenario names in square brackets.

5.3 Results

5.3.1 Calibration

Figure 5-3 shows the Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) of monthly data of the evaluated runoff gauges in calibration and validation. In calibration, NSE ranges from 0.75 to 0.96. In validation, the values vary from 0.48 to 0.94. According to Moriasi et al. (2007), the majority is ranked as "very good" for NSE in validation and calibration. The same is true of the PBIAS rankings. Only one gauge has a PBIAS ranking of "unsatisfactory" for validation, but it has a "very good" ranking in NSE. Another gauge is classified as "unsatisfactory" in validation but it received a "satisfactory" PBIAS ranking. However, this behavior is not related to the area coved by the gauging stations in the model.

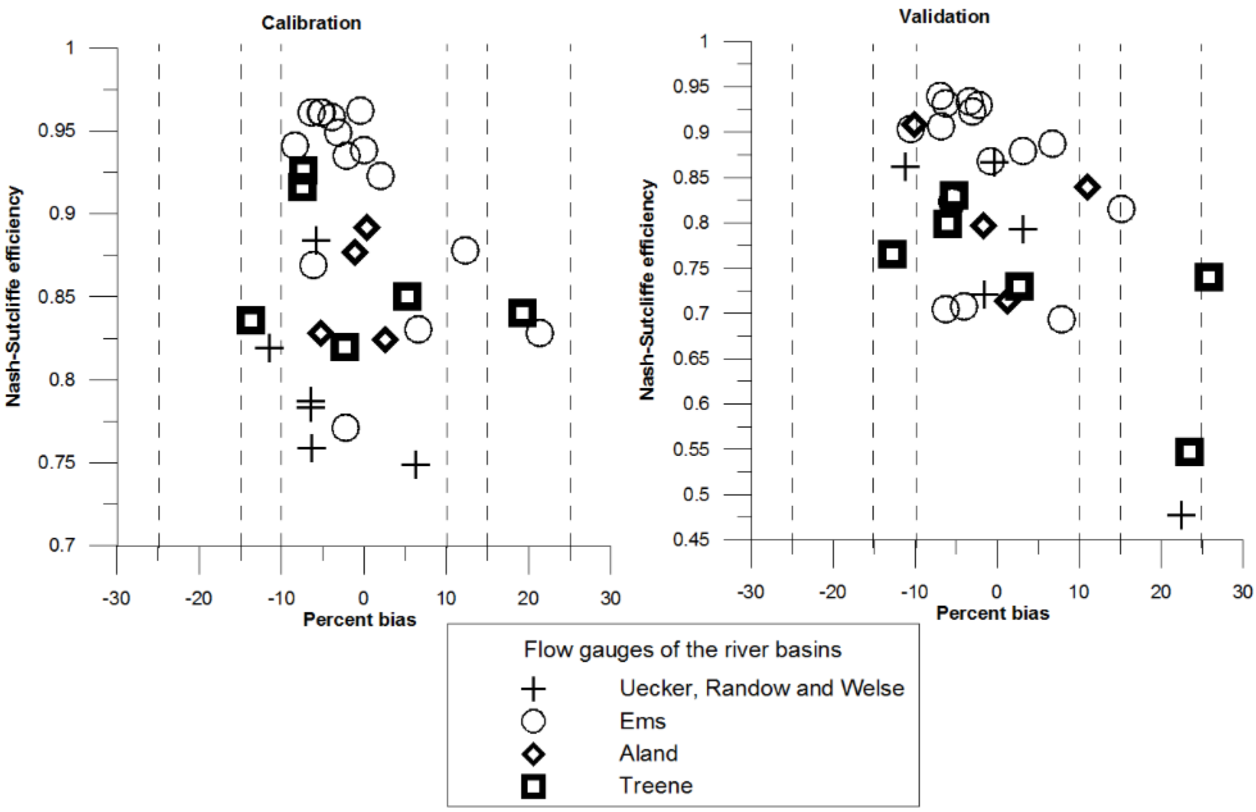

Figure 5-3: Nash-Sutcliffe efficiency and percent bias on the monthly data of the used 30 runoff gauges in calibration and validation; the dotted lines are indicating the percent goodness-of-fit classification by Moriasi et al. (2007), see Table 5-6, (URW – Uecker, Randow and Welse)

Corresponding to the model performance calculated by the different objective functions, Figure 5-4 illustrates the model results for the monthly discharge of the major basin outlets compared to observed values for the calibration and validation period. The simulated stream flow mostly captures the observed intra-annual dynamics, but with sporadic mismatches in high and low flow situations. Due to data availability, calibration and validation periods differ between gauges and watersheds. Nevertheless, the periods used were sufficient to establish an appropriate calibration and validation result for every model. For validation, at least one third of the measured timespan was used (gauge Treier / Treene). Table 5-8 summaries the values of the objective functions and the applied ranking according to Table 5-6. The rankings shown in Table 5-8 are all in the range of 1.0 to 1.3.

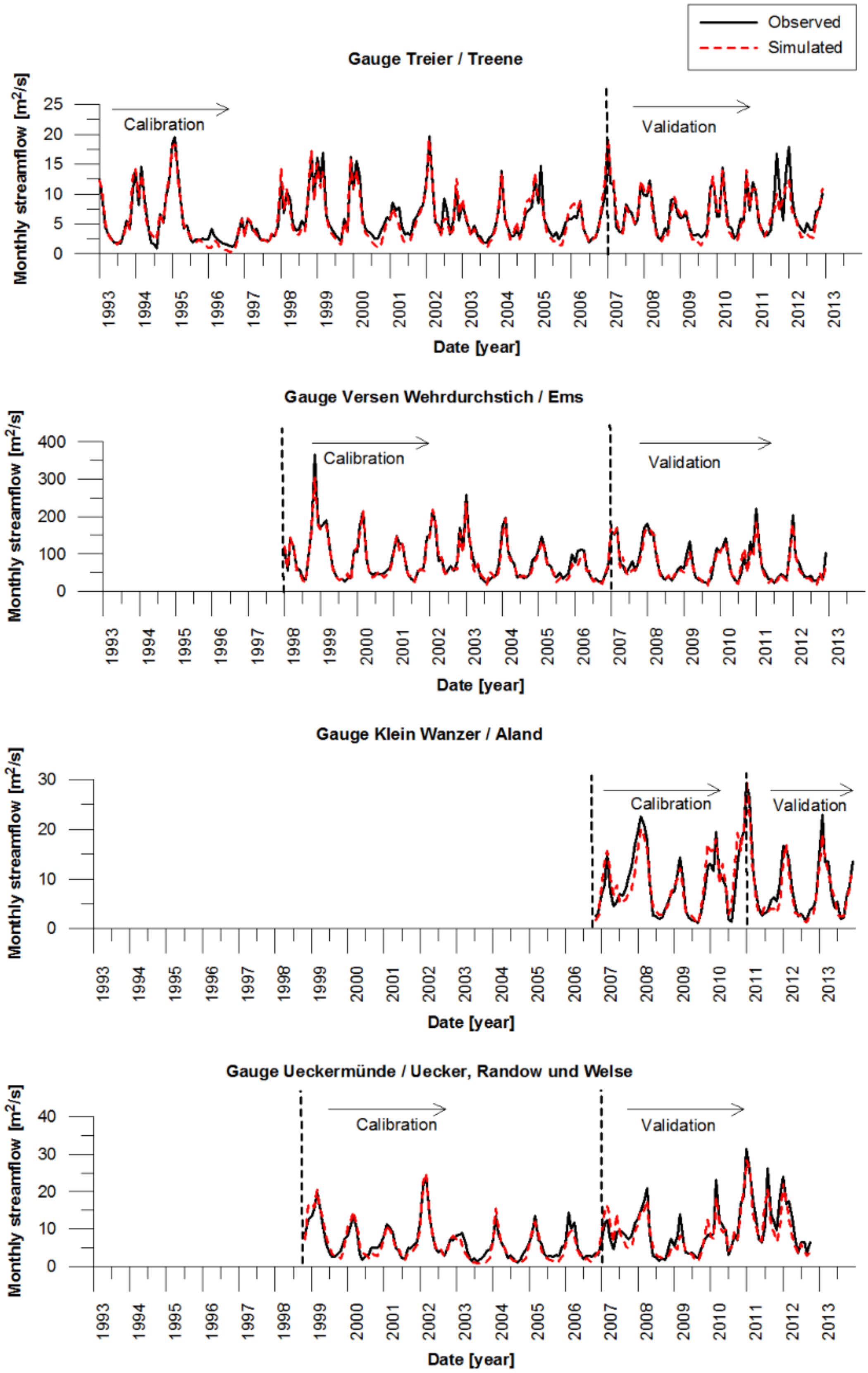

Figure 5-4: Model results of the major basin outlets for calibration and validation compared to the measured monthly streamflow.

Table 5-8: Values of objective functions from gauges at major basin outlets for calibration and validation

Gauge on basin outlet for calibration	Period	NSE	PBIAS	RSR	Rank
Treier / Treene	1993-2006	0.926	-7.4	0.27	1.0
Versen Wehrdurchstich / Ems	1998-2006	0.961	-5.1	0.196	1.0
Klein Wanzer / Aland	2006-2010	0.824	2.6	0.415	1.0
Ueckermünde / Uecker, Randow und Welse	1998-2006	0.884	-5.8	0.339	1.0
Gauge on basin outlet for validation	**Period**	**NSE**	**PBIAS**	**RSR**	**Rank**
Treier / Treene	2007-2012	0.83	-5.3	0.405	1.0
Versen Wehrdurchstich / Ems	2007-2012	0.932	-6.3	0.259	1.0
Klein Wanzer / Aland	2011-2013	0.908	-10.1	0.296	1.3
Ueckermünde / Uecker, Randow und Welse	2007-2012	0.862	-11.2	0.368	1.3

By calculating and comparing the observed and simulated probability of exceedance of daily discharge events, it is shown in Figure 5-5 that the highest 10% of events are not well covered by the models. However, all other discharge occurrences, and especially low flow events, are well represented by the simulation. This serves the aim of this study to estimate the influence of the conversion of annual crops to SRC on the water balance, since effects are expected effects will mainly occur at low discharge ranges.

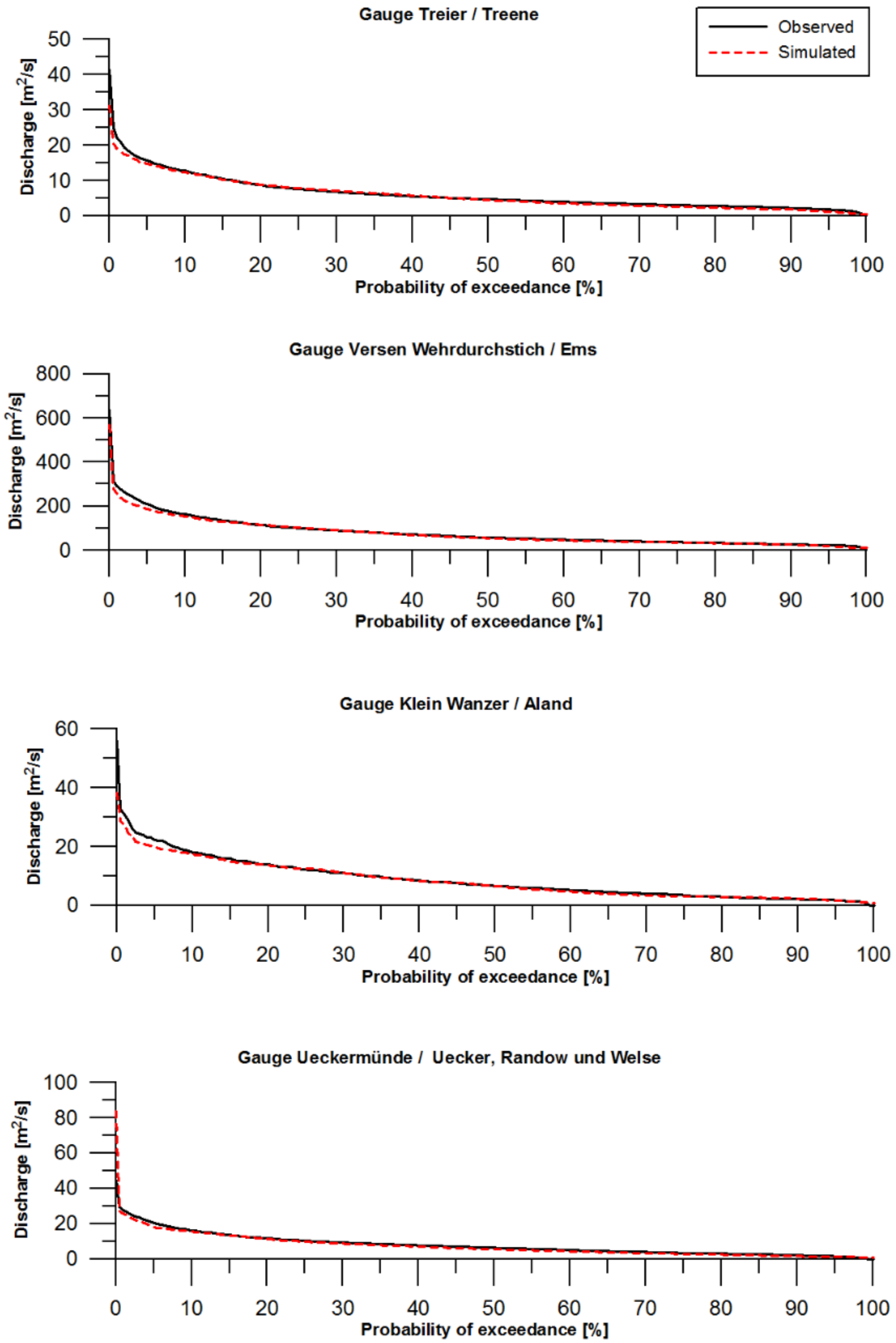

Figure 5-5: Flow duration curves of the major basin outlets for the combined calibration and validation period compared to the daily discharge occurrence observed.

5.3.2 Comparison of SRC with conventional annual crops, pasture and deciduous forest

To compare annual water balance parameters of willow and poplar SRC with those of conventional, i.e. annual crops, pasture and deciduous forest, the model output from the different basins is listed in Table 5-9. For this comparison the area of arable land suitable for SRC was either parameterized as SRC or various annual crops, whereas pasture and forest grow in different locations, based on the land cover classification. This implies different site properties for forest, pasture and arable land, respectively. The modelled actual annual evapotranspiration (ET) of SRC ranges from 404 mm (willow SRC, Aland) to 503 mm (poplar SRC, Treene), with differences between willow and poplar being marginal in each basin. When a regular annual culture is applied a range of 322 mm (canola, Aland) to 466 mm (winter barley, Treene) is observed. The smallest variation is found for pasture, with 398 mm (Ems) to 414 mm (Treene). Deciduous forest ET ranges from 460 mm (Aland) to 510 mm (Treene), the highest value observed in all land use types.

In general, ET of willow and poplar SRC is always higher than ET of the annual crops (canola, corn, rye, winter barley, winter wheat and “annual crops” in SWAT) in each catchment. It is also always higher than ET of pasture, with only one exception (Aland). Relative to precipitation the proportion of ET of SRC is highest in the Uecker-Randow-Welse basin (87% of precipitation) and lowest in the Treene basin (56%).

Concerning groundwater recharge (GW_RCHG), SRC generally shows lower rates than annual crops, except in the Aland basin. In the Ems basin SRC and deciduous forest are similar. Groundwater recharge under SRC varies widely from 69 mm (poplar, Uecker-Randow-Welse) to 397 mm (willow, Treene). Annual crops range from 142 mm (corn, Aland) to 482 mm (general class for agricultural land in SWAT, Treene), similar to pasture (114 mm in Aland basin to 484 mm in Treene) and deciduous forest (87 mm in Uecker, Randow and Welse to 412 mm in Treene). The proportion of groundwater recharge under SRC to precipitation is highest in the Treene basin (43%) and lowest in the Uecker-Randow-Welse basin (12%).

In accordance with the behaviors of the groundwater recharge the base flow (GWQ) reacts similar. This implies a decrease if SRCs are applied in stat of annual cultures. Against this background, differences in base flow (GWQ) range for SRC from 23 mm (poplar SRC, Uecker-Randow-Welse) to 211 mm (willow and poplar SRC, Treene). For annual cultures a variation of 33 mm (winter barley, Uecker-Randow-Welse) to 292 mm (general class for agricultural land in SWAT, Treene) is covered. If pasture is applied ranges between 47 mm (Aland) and 264 mm (Treene) are shown as well as 22 mm (Uecker-Randow-Welse) to 203 mm (Treene) for deciduous forest. If annual cultures are compared in base flow to willow and poplar SRC, the values of the conventional crop are higher. In relation to the annual precipitation the base covers the highest proportion in the Treene catchment and the lowest in the Uecker, Randow and Welse basin.

Surface runoff (SURQ) is lowered by SRC compared to annual crops. However, a high variation is covered by the surface runoff (SURQ) under willow and poplar SRC from 4 mm (Treen as well as Uecker-Randow-Welse) to 127 mm (Ems). When annual crops are applied the range reaches from 3 mm (winter barley, Uecker, Randow and Welse) to 192 mm (canola, Ems). Further, pasture and deciduous forest showing ranges of 5 mm (Treene) to 162 mm (Ems) and 4 mm (Treene as well as Uecker-Randow-Welse) to 96 mm (Ems). In general, the surface runoff is higher if annual crops are applied instead of SRC. In relation to the annual precipitation the highest values of surface runoff are generated by the Ems basin, the lowest by the basins Treene as well as Uecker-Randow-Welse.

In general, the available water capacity in the soil (AWC) exceeds under SRC cultivation in contrast to annual crops. For willow and poplar SRC a range between 102 mm (Uecker-Randow-Welse) and 251 mm (Aland) was modeled. Regarding annual cultures, the values vary from 49 mm (winter wheat, Aland) to 170 mm (for all annual cultures, Treene). Values shown for pasture and deciduous forest covering ranges between 166 (Ems) mm and 395 mm (Uecker-Randow-Welse) as well as from 144 mm (Aland) to 216 mm (Treene). The available water capacity in the soil reaches higher values if SRC are applied, then under conventional corps. Further, it is shown that, if comparted to the precipitation, highest values are displayed by the Treene basin lowest by the Aland basin.

Table 5-9:The basin specific water balance parameters of willow and poplar SRC compared to those of conventional annual crops, pasture (PAST) and deciduous forest (FRSD). As conventional annual cultures canola (CANP), corn (CORN), rye (RYE), winter barley (WBAR) and winter wheat (WWHT) specified as well as agricultural land (AGRL), which is a general class for annual crops in SWAT. The annual water balance parameters are actual evapotranspiration (ET), groundwater recharge (GW_RCHG), base flow (GWQ), surface runoff (SURQ) and available water capacity in the soil (AWC).

Basin [Precipitation]	Water balance parameter	Willow SRC	Poplar SRC	AGRL	CANP	CORN	RYE	WBAR	WWHT	PAST	FRSD
Treene [903 mm]	ET [mm]	502	503	408	467	457	416	466	467	413	486
	GW_RCHG [mm]	397	395	482	427	436	478	429	428	484	412
	GWQ [mm]	211	211	292	251	259	289	253	253	264	203
	SURQ [mm]	4	4	13	10	10	9	8	8	5	4
	AWC [mm]	182	182	170	170	170	170	170	170	186	216
Ems [814 mm]	ET [mm]	482	484	372	349	424	390	408	391	398	510
	GW_RCHG [mm]	204	203	260	273	223	255	245	260	253	208
	GWQ [mm]	104	103	147	151	121	144	136	146	144	110
	SURQ [mm]	127	127	183	192	167	169	162	163	162	96
	AWC [mm]	161	161	161	158	159	157	156	161	166	157
Uecker, Randow and Welse [566 mm]	ET [mm]	492	493	418	397	418	426	444	337	419	474
	GW_RCHG [mm]	70	69	141	164	142	136	120	219	128	87
	GWQ [mm]	24	23	44	59	46	43	33	96	53	22
	SURQ [mm]	4	4	7	5	5	4	3	10	18	4
	AWC [mm]	251	251	144	141	144	141	142	144	395	189
Aland [572 mm]	ET [mm]	404	405	339	322	378	338	351	336	420	460
	GW_RCHG [mm]	150	150	201	217	166	206	193	207	114	100
	GWQ [mm]	58	59	88	99	68	92	85	93	47	40
	SURQ [mm]	18	18	32	33	27	28	29	30	39	11
	AWC [mm]	102	102	51	51	51	49	49	49	209	144

5.3.3 Scenarios

Simulating the 10% and 100% scenarios in all basin models resulted in similar effects on the water balance for all areas. Figure 5-6 shows the components most influenced by the land use change: surface runoff, base flow, groundwater recharge and actual evapotranspiration. In general, a decrease in surface runoff, base flow and groundwater recharge as well as an increase in actual evapotranspiration can be seen. However, the areas suitable for willow and poplar SRC differ in size between the catchments so a direct comparison is not proper. These defenses in the suitable area find expression in lower total changes Aland and Uecker, Randow and Welse basin, which have also a minor suitable area than Ems and Treene. Letter, shown larger total changes. Against this background the following explanations should be seen as not weighted but rather as ranges, in which a change take place. In general, changes of the 10% scenarios are always under 10 mm. Regarding the surface runoff, the Ems for example, which has the highest current state value (129 mm), also shows the largest effect in the 100% scenarios (ca. 22 mm for poplar and willow) as well as in 10% scenarios (ca. 2.8 mm). In

Uecker-Randow-Welse basin the 100% scenarios show a reduction of around 4 mm (at a current state runoff of approximately 46 mm). The Treene and Ems watersheds reveal similarly high effects of the 100% scenarios on the base flow, namely a reduction of ca. 18 mm, whereas the Aland watershed reacts with reduction of around 6 mm. The other scenarios show reductions around 6 mm (Treene) or less than 5 mm (Ems) or 3 mm (Aland; Uecker-Randow-Welse less than 1 mm). Correspondently, the results for the groundwater recharge reflect those for the base flow or vice versa. Consistent with the former findings the actual evapotranspiration reacts most strongly with an increase in the 100% scenarios of ca. 45 mm in Ems basin and 23 mm in the Treene basin, approximately 12 mm in the Aland basin and 7 mm in Uecker-Randow-Welse basin.

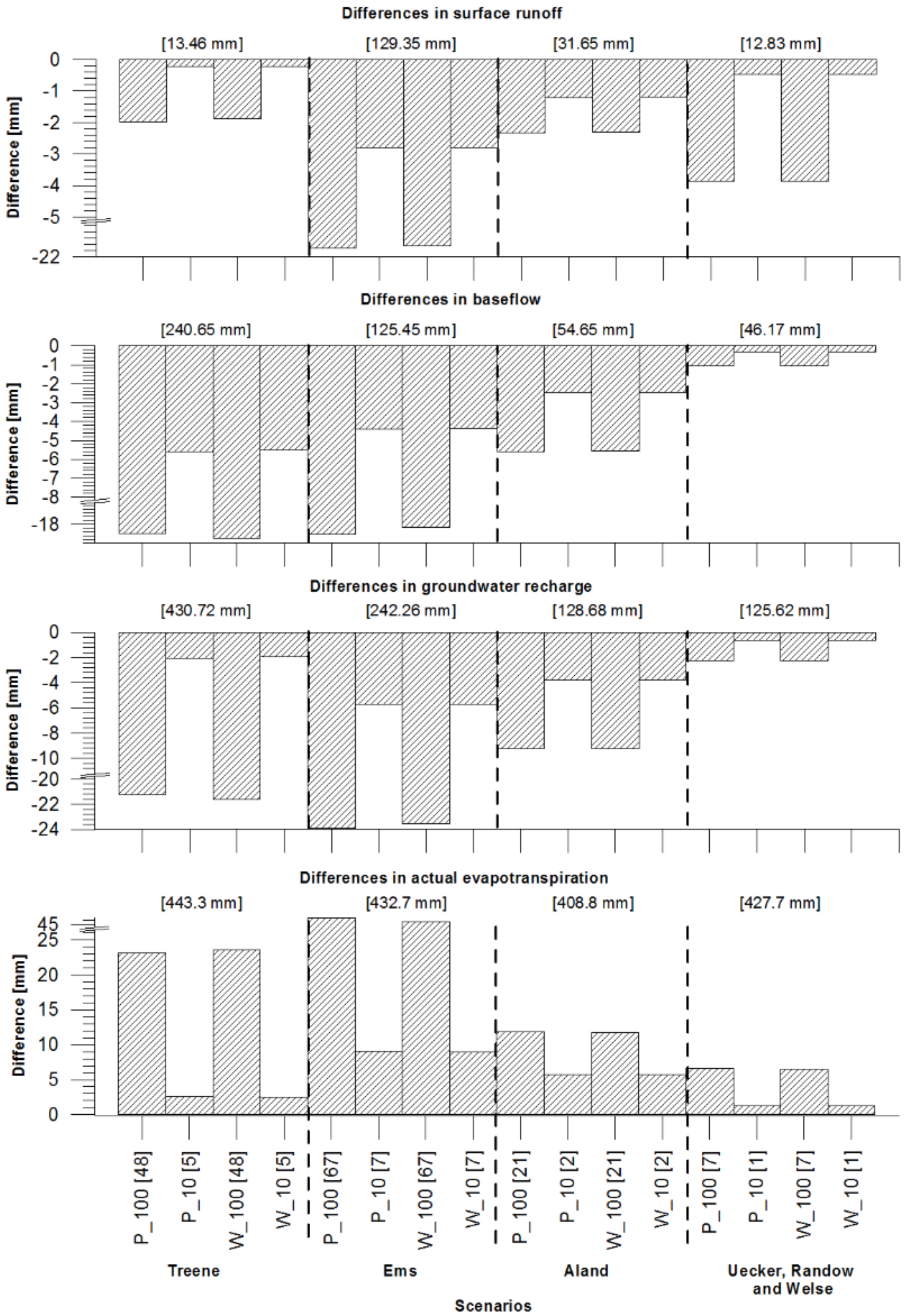

Figure 5-6: Differences in selected water balance components from the actual state to the scenarios (absolute values from the actual state in brackets; P = poplar SRC, W = willow SRC; the percentage of land use change is indicated by the number, e.g. 100 = 100% of suitable sites are converted to SRC, total percentage of land use change in the catchment in brackets). The sum of differences in surface runoff, baseflow and groundwater recharge do not balance out the differences in actual evapotranspiration, because base flow is a share of groundwater recharge.

5.4 Discussion

5.4.1 Calibration

With respect to the classification of Moriasi et al. (2007) and the implemented rankings, the calibration and validation periods showed good to very good results (Figure 5-3, Table 5-8). However, it has been demonstrated by several studies that calibration results are dependent on the parameters chosen for the model setup and the calibration setup. The relevant parameters in this respect include the kind, time span and quality of input data as well as the hydrologic model, the optimization method, the objective function and the general assumptions used in the process (Abbaspour et al. 1997, Abbaspour et al. 1999, Henriksen et al. 2003, Stisen et al. 2011, Arnold et al. 2012). Due to this, the model results are subject to uncertainties and cannot be considered as absolute. However, the specific uncertainties were not estimated in this study, given that the major aim was to test the influences of SRC cultivation on water balance parameters. But, due to the use of the SUFI-2 procedure the final parameter ranges (Table 5-5) are comparable to uncertainty ranges (Strauch et al. 2012). Nevertheless, the determined discharge functions can be considered as reasonable, as the presented results demonstrate and also shown in numerous studies (Nash & Sutcliffe 1970, Sevat & Dezetter 1991, Singh et al. 2005, Moriasi et al. 2007, Van Liew et al. 2007).

The simulated monthly streamflow values of the basin outlets (Figure 5-4) also show a good fit to the intra-annual dynamics and to the absolute values of the observed data. In particular, the data from the "Versen Wehrdurchstich" gauging station of the River Ems illustrates a very good match. Only extreme events like high floods are not accurately simulated. This is also indicated by the flow duration curves (Figure 5-5), which show a mismatch in the top 10% events for every basin. However, these events are of minor significance for the long-term water balance.

Considering the uncertainties in hydrologic modelling, a major objective of this study could be achieved by setting up four different SWAT models to determine the current state water balance of each basin. This serves the further aim of this study to quantify the impact on the water balance of willow and polar SRC as well as in different land use scenarios.

5.4.2 HRU conversion from agriculture to SRC

In general, differences between willow and poplar SRC were only marginal. This is not surprising given the similarity of the parameter values determined in our study and applied here. Nevertheless, the results of this approach are in accordance with those of former studies. Thus, it is shown that the actual evapotranspiration of willow and poplar SRC exceeds the values of conventional crops on an average of 16%. This behavior is also indicated by several approaches (Ettala 1988, Hall & Allen 1997, Dimitriou et al 2009a, Nisbet 2005, Wahren et al. 2015). If compared to pasture (14% higher) and deciduous forest (6% higher) the tendency continues, but no longer in every case observed. This behavior is primarily related to site-specific characteristics, which differ between arable land, pasture and forest. Earlier studies indicated as well that ground water recharge will decrease substantially, if SRC are planted instead of annual cultures (Wahren et al. 2014, 2015). Similar reactions were identified by the approach presented in this study, which determines an average reduction of 48% compared to annual cultures. Furthermore, the results indicate a comparable relation between SRC and pasture (39% lower) as well as deciduous forest (19% lower). In relation to a reduction of groundwater recharge a decrease of base flow was estimated as well, with an average minoring of 60%. Further a reduction of surface runoff (71% lower) and an increase in available water capacity in the soil (26% increase) were modeled for SRC in comparison to annual crop, which was also observed in other studies (Wahren et al. 2012, 2015).

Against this background, the estimated changes in water balance components are in consistency with the relevant processes. This finds its expression in higher water consumption, transpiration rates and LAI than annual crops, which enhances the actual evaporation and decreases the effective rainfall as well as groundwater recharge (Ettala 1988, Hall & Allen 1997, Dimitriou et al 2009a, Nisbet 2005, Wahren et al. 2015). Willow and Poplar also differ in their root system development, which is deeper and denser in comparison to conventional cultures. This increases infiltration capacity and reduces surface runoff and average soil water content (Lamersdorf et al. 2010, Wahren et al. 2014, 2015). However, if the values of pasture and deciduous forest are compared with SRC, site-specific condition and their influence on processes have to be taken into account.

5.4.3 Scenarios

As indicated by the results of the direct comparison of land use types in the models to willow and poplar SRC and literature (Petzold et al. 2009, Webb et al. 2009, Wahren et al. 2015) an effect on regional water balance was observed, due to the scenarios. These show also an increase of evapotranspiration for all river basins and a decrease in surface runoff, base flow and groundwater recharge. Only the extreme scenarios (100% SRC) show a high influence on all the components. The other scenarios change the single components by less than 10 mm. Differences between the scenarios and the current state of the basins are related to the various factors, explained above. Further, they are in accordance with findings of Wahren et al. (2015) which reported comparable results for the influences of willow and poplar SRCs in a mesoscale catchment in Germany. However, a direct comparison of the scenarios between the basins is hardly possible, due to the differences in scale of the suitable area. This variation makes it also discussable if the pictured scenarios are equally realistic to all basins. For example, a higher degree of establishment would be easier in the catchments with a minor proportion on suitable areas. However, the chosen dimension is oriented on prediction made of the Internationales Institut für Wald und Holz NRW [International Institute of Forestry and Wood Industries, North Rhine-Westphalia] (2014) as well as the approach of Hartwich et al. (2015a). Having said that, however, the conversion to SRC at a realistic level – between up to 10% of the suitable agricultural area – results only in marginal changes to the regional water balance. But, a certain level of suitable agricultural area at which a drastic change in the landscape water balance would appear was not determined by this approach. The definition of such a break point or rather interval should be focused in upcoming research. In the project lower scenarios with a use of 5 and 2.5% of suitable sides were tested as well, but as shown by the 10% scenario their results did not show considerable effects on the water balance.

If on a regional scale the effects are not substantial, this does not imply that there will be no considerable effects on the local scale, because the hydrologic processes often have a much higher influence on the water balance for local areas, as shown by the direct comparison of SRC and other land use types (Table 5-9). Furthermore, the cultivation of SRC is currently restricted to arable land, but if grassland was released for cultivation – which from a conservation and biodiversity point of view is not desirable (BUND 2010) - the potential area for cultivation would change in quantity and quality, which may influence the overall effects of SRC. Rising temperatures and shifts in precipitation regimes and quantities would most likely also influence the results of these scenarios.

5.5 Conclusion

The results of the 10% scenarios showed changes of less than 10 mm for the observed water balance components, which can be considered as not substantial on the landscape level. Only the hypothetical 100% scenarios lead to considerable changes. At a local level such alteration in the water cycle may be possible. Based on the results of the modeling exercise the establishment of SRC on 10% of the suitable agricultural area poses no influence to the water balance on a basin level. However, the changes detected in the direct comparison of willow and poplar SRC indicates, that these plantations influence the local water balance condition considerably. But, this behavior does not specify necessarily a negative influence on the water cycle. If locations are chosen in accordance to create win-win situations, as described by Hartwich et al. (2014c), these abilities of SRC could for example be used to lower the maintenance costs of heavily drained agricultural areas. Future work should focus on aspects related to climate change and effects at the local scale as well as including parameters for the latest high-yielding poplar and willow cultivars.

Acknowledgements

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6 Synthesis

The focus of this dissertation is to assess framework conditions for the sustainability of SRC establishments. This is linked to finding win-win situations effects of cultivation, as well as to locate suitable sites for SRC. However, to satisfy the requirements of overall sustainability, the negative effects of the cultivation were also reflected. For this reason, the regional and local water cycle received particular focus.

6.1 Main conclusion

Hereafter, the main research questions were answered and integrated into the main conclusion.

1. *How is the sustainable use of SRCs in terms of land and water availability characterized?*

This question was reflected in Chapter 2 by determining the positive and negative effects of cultivation on land and water redistribution from their current use. However, a sound planning of SRC cultivation could counteract the possible dilemma between the renewable energy carrier and a sustainable land and water management. SRCs are able to implement ecosystem functions in regions intensely developed and cultivated by man, such as in central Europe, including Germany. This behavior enhances the habitat variety as well as the development of migration corridors. Further, wind erosion could be decreased by these plantations, if they were planted on large fields. Their canopy height increases the surface roughness and decreases the wind speed as well as the area exposed. Moreover, water erosion on such field sites is also decreased, which reduces the input of sediments, nutrients and pollutants into surface water bodies and enhances water quality. However, the water balance could be negatively influenced. Estimations show potential a lowered yield amount on field areas next to SRCs. Conclusions could exclude regions with a negative water balance. These behaviors are most often related to the high water abstraction rates of the tree species used. However, this approach could not confirm drastic influences on the water balance at a regional level by applying willow or poplar SRCs in realistic proportions to the landscape. But, it is also approved that SRC had a higher water abstraction than regular annual crop, which influences the local water cycle.
The characteristics of SRCs are closely linked to the efficiency of land and water use. This means sustainability is only achievable with an efficient treatment of these resources. SRC cultivation types serve multiple needs. Further, the cultivation practice is efficient and sustainable, if management conditions are set up properly. Such proper conditions refer most of all to transportation, cultivation and harvesting, which should not negatively influence the energy budget or environmental conditions.

2. In which conditions could SRCs achieve win-win situations?

The reflection of this question was managed in Chapter 2, which discusses the challenges of the establishment process as well as win-win situations. Win-win situations were characterized as circumstances in which both monetary and environmental needs are equally satisfied. To trigger a positive development in SRC establishment, such situations are needed. However, this also applies to the "Food versus Fuel – Dilemma". To counteract this conflict and create win-win situations, Pain et al. (1996) published three recommendations, which considers an establishment on (1) highly erosive land, (2) agricultural land with high water content and (3) less fertile land, which could not produce food efficiently. Furthermore, additional environmental objectives should also be focused on, such as the improvement of water quality, increase of habitat variety, and reduction of greenhouse gas emissions. Not least is the emission reduction goal—a central aspect of this kind of cultivation practice. This aspect could also be related to cultivation management. Management practices should not only focus on decentralized establishment to minimize transportation cost and CO_2-emissions, but also environmental conditions. This refers to the ability of the tree species cultivated in SRCs flourish on sites with high water availability. If agricultural areas with managed groundwater levels were used for cultivation, this could result in reduced costs and CO_2-emissions due to reduced drainage management. The enhancements to water quality as well as habitat variety also serve the objectives of the water framework directive. High suitability levels are linked to an area's close vicinity to riversides or surface water bodies. In this approach, these aspects can be combined to improve both.

3. How can the methodological concept of Aust (2012) and Murach et al. (2009) be improved in order to better comply with environmental conditions and enhance the determination of suitable sites?

In Chapter 3, this question was discussed and concluded, by developing an optimized approach to estimate yield and energy potentials of willow cultivated in SRCs. The progress was primarily caused by a combination of the methodological concepts of Murach et al. (2009) and Aust (2012). This research used the terrain correction implemented by Aust (2012), the utilization of the available water capacity in the uppermost 50 cm of the soil structure defined by Murach et al. (2009), as well as the groundwater availability in the rooting zone of 2 m. In addition, to estimate effective precipitation, the evapotranspiration calculated by the FAO Penman-Monteith approach was used and adjusted to the characteristics of a willow SRC with a crop coefficient of 1.2. However, by comparing the results of the former approaches to the new, the concept of Aust (2012) generally results in lower suitability while the Murach et al. (2009) approach results in a higher suitability. This is primarily due to differences in evaporation estimation. The approach of Aust (2012) uses the climatic water balance in the estimation, which causes a high water loss for the plant available water, if plant transpiration is not excluded from the calculation. In contrast, Murach at al. (2009) defines a fixed amount of 35% interception in the estimation, which does not take natural variability of vegetation and landscape conditions into account. However, in the new approach, 35% was linked to the adjusted FAO Penman-Monteith evapotranspiration with regard to the studies of Persson & Lindroth (1994), as well as Lindroth & Båth (1999). Finally, the new concept enhances the estimation of suitable sites and yield potentials, but only on a regional scale. These restrictions refer to the scale of input data which lowers the significance for local agricultural areas and limits the option of validation with actual yield amounts. However, in comparison with the other approaches (Lindroth & Båth 1999, Murach et al. 2009, Aust 2012, Stork et al. 2014), the established method covers a reasonable allocation of the total and spatial yield distribution.

4. *Which agricultural regions in Germany are suitable for SRC cultivation as well as associated with a certain bioenergy potential?*

To answer this question, the approach presented in Chapter 4 was used. The former method was utilized to estimate yield amounts, suitable sites and bioenergy potentials of agricultural regions. On the bases of the plant available water, the linear regression method of Lindroth & Båth (1999) was applied with a new water use efficiency level for willow presented by Linderson et al. (2007). This adjustment refers to a border species variety as well as the assumption of an overestimation in approach of Lindroth & Båth (1999) presented by Linderson et al. (2007). Nevertheless, high-performance clones will reach much higher values, which would result in an increase of the estimated yield amounts. But, on the other hand, this kind of plant material is often much more vulnerable to drought and pests than conventionally applied clones. To save the long-term yield of such plantation, a mixture of plant material, performance plants, or a less vulnerable plant are used.

The suitability of field sites was defined by an economic limitation estimated by Andersen et al. (2005) and Murach et al. (2009) with a minimum yield of 8 t/(ha*a) for a suitable site. Due to this value, all sites below are consequently excluded from further calculations. This implies that a change in the economic framework conditions would result in an increase or decrease in the limitation set, with all consequences to the estimated total and spatial information. Since studies are missing to determine such a limitation, in particular for Germany, this will have to be focused on in upcoming research. However, the applied estimation of the bioenergy potential was based on typical power stations used to produce electricity or a more effective combination of generating heat and power. Due to their high degree of efficiency, they represent the state-of-the-art in this matter.

With this information, the highest estimated biomass potentials for the cultivation are located at the Northern German Plain. Morphological units such as glacial valleys, depressions, and wide river valleys are characterized by high groundwater levels, which have a positive effect on plant growth. However, the gradient of continental climate decreases the estimated potentials to the east in Germany, which leads to a shift of unsuitable conditions for this region. The central and southern regions of Germany are classified by a generally suitable potential, which is restricted by rain shadow effects or extended in wide river valleys such as in the Northern German Plain.
Different bioenergy potential scenarios were estimated based on the prediction of the Internationales Institut für Wald und Holz NRW (2014), using 2.5, 5 and 10% of suitable sites. If 5% of the suitable sites with average yield in Germany would be transferred to willow SRCs, 714,000 households could be supplied with heat and electricity or 2.4 million only with electricity. This would reduce the CO_2-emssions by 9.5 Mt per year if oil is substituted.

5. Considering the impact on regional and local water balance, which quantities and effects could result in suitable regions?

Due to the high biomass potentials determined for the Northern Germany Lowlands, a hydrologic modelling approach was set up in Chapter 5, to quantify the influence of SRC land use change scenarios on water balance components. To determine this influence, the Soil Water Assessment Tool was used as software to construct hydrological models of the following river and river system catchments. These river catchments are Ems, Treene and Aland as well as the combined catchment of Ücker, Randow and Welse. To represent specific landscape conditions, these basins cover the environmental variety in the Northern German Plain, including climatic, soil and morphological conditions. However, for every study area, a current state model was set up to calculate the period of 01.01.1990 to 31.12.2013, as well as calibrate and validate by discharge data. In total, 30 stream gages were integrated into the automated calibration with SWAT-CUP using the statistical calibration method SUFI-2. Finally, according to the classification of Moriasi et al. (2007) and the applied ranking, a good to very good representation of the measured discharge values was found. To implement cultivation scenarios for willow and poplar SRCs, plant specific data were used, determined by the Faculty of Forest and Environment at Eberswalde University for Sustainable Development. Further the scenarios are oriented on predictions estimated by the Internationales Institut für Wald und Holz NRW (2014) as well as the determined suitable area. The extreme scenario was carried out to quantify the maximum impact on the water cycle by transferring all suitable agricultural sites to SRCs.
However, a significant effect on the observed components of surface runoff, base flow, groundwater recharge and actual evapotranspiration could not be observed under reasonable conditions. Just the

extreme scenario generates such an influence. This implies the assumption that willow and poplar SRCs would not have a significant and negative influence on the regional water cycle if established in the predicted amounts. However, this does not infer that local sites are without influence on the water balance or that influence could not arise due to climate change. In relation to the local conditions the comparison to conventional annual crops shows higher actual evaporation and a decrease in surface runoff, base flow as well as groundwater recharge. On one hand, this behavior implies a negative effect on locations with a geranial negative water balance and sides where ecological benefit is depending on wet soil conditions. On the other hand, the cultivation of poplar or willow SRCs could be an alternative on wet field sides where a conventional cultivation of annual crops relies on drainage systems. This alternative would also serve ecological aspects by implementing new habitat structures into a cultivated landscape. Moreover, the ecological and monetary maintaining cost for such drainage systems would be avoided.

6.2 Future perspectives

Climate change provides a need for alternative and renewable energy carriers. The discussion on how to achieve a sustainable transition of the energy sector is in progress as society has recognized the need for this change. This approach shows several aspects of one particular solution. But, in terms of SRC cultivation as well as other renewable energy carriers, further research is needed. This refers primarily to the future of this cultivation practice in Germany. If a sustainable cultivation and processing as a bioenergy carrier is proven, the next step of establishing a framework condition for this concept should be focused on a further diffusion of this concept. However, to achieve this goal, the qualitative and quantitative influences on the local water balance have to be further assessed. This would include evaluating the positive aspects of sediment, nutrient and pollutant output as well as further characteristics regarding the water framework directive. Nevertheless, an establishment of SRCs will be focused on suitable sites, since today the cultivation is driven by an economic concept without subventions. Even if this does not influence the positive or negative aspects of cultivation, it specifies the regions in which the characteristics have an effect. This makes it necessary to gain spatial information on this behavior. To enhance the spatial resolution of the bioenergy potential estimation, accurate data is needed, especially in terms of soil and groundwater information. Further, plant specific data have to be considered and adapted for Central Europe regarding water use efficiency, maximum water uptake for biomass production, evapotranspiration and interception amounts. Through this, the quality estimated yield amounts would enhance total and spatial values. If the spatial resolution covered local conditions, a validation of this method and further assessments would be possible. Nevertheless, the determination of an economic limitation has to be improved and updated.

Without such instruments, the distinction between suitable und unsuitable sites will become much more uncertain by time. However, the estimated yield amounts will consist of the selected cultures, since environmental conditions change. Climate change should be addressed in upcoming research about SRC establishment. The changing climate conditions will influence the results of plant available water and bioenergy estimation. They may also change the effects on the water balance on regional and local conditions.

7 References

Abbaspour K C, van Genuchten M Th, Schulin R, Schläppi E (1997) A sequential uncertainty domain inverse procedure for estimating subsurface flow and transport parameters. *Water Resources Research* 33 (8): 1879–1892.

Abbaspour K C, Sonnleitner M, Schulin R (1999) Uncertainty in estimation of soil hydraulic parameters by inverse modeling: example lysimeter experiments. *Soil Science Society of America Journal* 63 (3): 501–509.

Abbaspour K C, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R (2007) Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *Journal of Hydrology* 333(2-4): 413-430.

Abbaspour K D, Rouholahnejad E, Vaghef Si, Srinivasan R, Yang H, Kløve B (2015) A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology* 524: 733-752.

Ad-Hoc-Arbeitsgruppe Boden (1994) Bodenkundliche Kartieranleitung. 4. Auflage. Bundesanstalt für Geowissenschaften und Rohstoffe und Geologische Landesämter der Bundesrepublik Deutschland, Hannover.

Ad-Hoc-Arbeitsgruppe Boden (2005) Bodenkundliche Kartieranleitung. 5. Auflage. Bundesanstalt für Geowissenschaften und Rohstoffe in Zusammenarbeit mit den Staatlichen Geologischen Diensten der Bundesrepublik Deutschland, Hannover.

AG Energiebilanzen [AGEB] (2015): Auswertungstabellen zur Energiebilanz Deutschland 1990 bis 2014. Berlin, Köln. Retrieved from http://www.ag-energiebilanzen.de/index.php?article_id=29&fileName=ausw_25082015_ov.pdf [Accessed 6 January 2016]

Agora-Energiewende (2016): Die Energiewende im Stromsektor: Stand der Dinge 2015. Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2016. Berlin. Retrieved from http://www.agora-energiewende.de/fileadmin/Projekte/2016/Jahresauswertung_2016/Agora_Jahresauswertung_2015_web.pdf [Accessed 6 January 2016]

Ali W (2009) Modelling of Biomass Production Potential of Poplar in Short Rotation Plantations on Agricultural Lands of Saxony, Germany. Dissertation. Fakultät Forst-, Geo- und Hydrowissenschaften. Technische Universität Dresden.

Allen G, Pereira S, Raes D, Smith M (1998) Crop evapotranspiration-Guidelines for computing crop water requirements. *FAO Irrigation and drainage paper* 56. Rome, FAO. Retrieved from http://www.fao.org/docrep/x0490e/x0490e00.htm [Accessed 6 January 2016]

Andersen R, Towers W, Smith P (2005) Assessing the potential for biomass energy to contribute to Scotland's renewable energy needs. *Biomass and Bioenergy* 29 (2): 73-82.

Arnold J, Srinivasan R, Muttiah R S, Williams J R (1998) Large area hydrologic modeling and assessment part I: model development. *Journal of the American Water Resource Association* 34 (1): 73-89.

Arnold J G, Moriasi D N, Gassman P W, Abbaspour P W, White P W, Srinivasan R, Santhi C, van Harmel R D, Van Griensven A, Van Liew M W, Kannan N, Jha M K (2012) SWAT: model use, calibration, and validation. *Tansactions of American Society of Agricultural and Biological Engineers* 55 (4): 1491–1508.

Aronsson P, Rosenqvist H, Dimitriou I (2014) Impact of Nitrogen Fertilization to Short-Rotation Willow Coppice Plantations Grow in Sweden on Yield and Economy. *BioEnergy Research* 7: 993-1001.

Aust C (2012) Abschätzung der Nationalen und regionalen Biomassepotentiale von Kurzumtriebsplantagen auf landwirtschaftlichen Flächen in Deutschland. Dissertation. Fakultät für Forst- und Umweltwissenschaften. Albrecht-Ludwigs-Universität, Freiburg im Breisgau.

Baffes J, Haniotis T (2010) Placing the 2006/08 Commodity Price Boom into Perspective. *Policy Research Working Paper* 5371. Washington, DC, World Bank. Retrieved from http://www-wds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2010/07/21/000158349_20100721110120/Rendered/PDF/WPS5371.pdf [Accessed 6 January 2016]

Balasus A, Bischoff W A, Schwarz A, Scholz V, Kern J (2012) Nitrogen fluxes during the initial stage of willows and poplars in short-rotation coppices. *Journal of Plant Nutrition and Soil Science* 175 (5): 729-738.

Baum S, Weih M, Busch G, Kroiher F, Bolte A (2009) The impact of Short Rotation Coppice plantations on phytodiversity. Landbauforschung. *vTI Agriculture and Forestry Research* 3 (59): 163-170.

Beccali M, Columba P, D'Alberti V, Franzitta V (2009) Assessment of bioenergy potential in Sicily: A GIS-based support methodology. *Biomass and Bioenergy* 33 (1): 79-87.

Bechler K, Toth O (2010) Bewertung von Böden nach ihrer Leistungsfähigkeit - Leitfaden für Planungen und Gestattungsverfahren Bodenschutz. Landesanstalt für Umwelt, Messung und Naturschutz Baden-Württemberg, Karlsruhe.

Bemmann A, Knust C (2010) Agrowood - Kurzumtriebsplantagen in Deutschland und europäische Perspektiven. Weißensee-Verlage Ökologie, Berlin.

Biswas A (2009) Water management: some personal reflections. *Water International* 34 (4): 402-408.

Boelcke B (2006) Schnellwachsende Baumarten auf landwirtschaftlichen Flächen – Leitfaden zur Erzeugung von Energieholz. Ministerium für Ernährung, Landwirtschaft, Forsten und Fischerei, Mecklenburg-Vorpommern, Schwerin.

Bölscher J, Schulte A, Huppmann O (2010) Long-term flow field monitoring at the Upper Rhine floodplains. In: Dittrich A, Koll K, Aberle J, Geisenhainer P (Eds.) River Flow - Proceedings of the International Conference on Fluvial Hydraulics Vol. 1. Bundesanstalt für Wasserbau, Braunschweig: 477-485.

Börjesson P, Berndes G (2006) The prospects for willow plantations for wastewater treatment in Sweden. *Biomass and Bioenergy* 30 (5): 428-438.

Bottoms E L (2012) Soil Greenhouse Gas Emissions and Soil C Dynamics in Bioenergy Crops. Dissertation. University of Aberdeen, Aberdeen.

Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz [BMELV], Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU] (2010) Nationaler Biomasseaktionsplan für Deutschland -- Beitrag der Biomasse für eine nachhaltige Energieversorgung. Berlin, BMELV, BMU. Retrieved from http://www.bmel.de/SharedDocs/Downloads/Broschueren/Biomasseaktionspl-anNational.pdf?__blob=publicationFile [Accessed 6 January 2016]

Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz [BMELV] (2012): Pappeln und Weiden in Deutschland: Bericht der nationalen Pappelkommission. Zeitraum: 2008 bis 2011. BMELV, Bonn.

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit [BMU] (2011): Deutschland bei Klimaschutz-Zielen 2020 auf Kurs. Pressemitteilung Nr. 154/11. Berlin. Retrieved from http://www.bmub.bund.de/presse/pressemitteilungen/pm/artikel/deutschland-bei-klimaschutz-zielen-2020-auf-kurs/ [Accessed 6 January 2016]

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU] (2012) Erneuerbare Energien 2011. Daten des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit zur Entwicklung der erneuerbaren Energien in Deutschland im Jahr 2011 auf der Grundlage der Angaben der Arbeitsgruppe Erneuerbare Energie-Statistik (AGEE-Stat). Stuttgart, Zentrum für Sonnenenergie-Wasserstoff-Forschung Baden-Württemberg. Retrieved from http://www.hk24.de/linkableblob/hhihk24/innovation/downloads/1897454/.3./data/Entwicklung_der_Erneuerbaren_Energien_in_2011_Stand_Maerz_2012-data.pdf [Accessed 6 January 2016]

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU] (2013) Erneuerbare Energien in Zahlen. Nationale und internationale Entwicklung. BMU, Berlin.

Bundesministerium für Wirtschaft und Energie [BMWE] (2014) Erneuerbare Energien in Zahlen - Nationale und internationale Entwicklung im Jahr 2013. Bundesministerium für Wirtschaft und Energie, Berlin.

Bund für Umwelt und Naturschutz Deutschland [BUND] (2010) Kurzumtriebsplantagen für die Energieholzgewinnung – Chancen und Risiken. *Positionen* 55. Berlin, Bund für Umwelt und Naturschutz Deutschland. Retrieved from http://www.bund.net/fileadmin/bundnet/pub-likationen/landwirtschaft/20100714_landwirtschaft_bund_position_55_KUP.pdf [Accessed 6 January 2016]

Bungart R, Hüttl R F (2004) Growth dynamics and biomass accumulation of 8-year-old hybrid poplar clones in a short-rotation plantation on a clayey-sandy mining substrate with respect to plant nutrition and water budget. *Eur. J. For. Res.* 123: 105-115.

Burger F J (2010) Bewirtschaftung und Ökobilanzierung von Kurzumtriebsplantagen. Dissertation. Lehrstuhl für Holzkunde und Holztechnik. Technische Universität München, München.

Busch G (2009) The impact of Short Rotation Coppice cultivation on groundwater recharge – a spatial (planning) perspective. *Landbauforschung - vTI Agriculture and Forestry Research* 3 (59): 207-221.

Busch G (2012) Agrarholz auf Ackerflächen – eine multikriterielle Bewertung des Einflusses auf Landschaftsfunktionen. Klimawandel: Was tun!. *IALE-D-Jahrestagung 2012, 24.-26. Oktober 2012*. Eberswalde, INKA BB - Klimawandel und Innovation: 148-150. Retrieved from http://www.iale.de/fileadmin/user_upload/PDFs/IALE-Jahrestagung_2012/IALE_Tagungsband_2012_Eberswalde.pdf [Accessed 6 January 2016]

Cocco D (2007) Comparative study on energy sustainability of biofuel production chains. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 221 (5), 637-645.

Dengiz O, Gol C, Sargioglu F, Edis S (2010) Parametric approach to land evaluation for forest plantation: a methodological study using GIS model. *African Journal of Agricultural Research* 5 (12): 1482-1496.

Dimitriou I, Busch G, Jacobs S, Schmidt-Walter P, Lamersdorf N (2009a) A review of the impacts of Short Rotation Coppice cultivation on water issues. *Landbauforschung - vTI Agriculture and Forestry Research* 3 (59): 162-197.

Dimitriou I, Baum C, Baum S, Busch G, Schulz U, Köhn J, Lamersdorf N, Leinweber P, Aronsson P, Weih M, Berndes G, Bolte A (2009b) The impact of Short Rotation Coppice (SRC) cultivation on the environment. *Landbauforschung – vTI Agriculture and Forestry Research* 3 (59): 159-206.

Duer H, Christensen P (2010) Socio-economic aspects of different biofuel development pathways. *Biomass and Bioenergy* 34 (2): 237-243.

Elowson S (1999) Willow as a vegetation filter for cleaning of polluted drainage water from agricultural land. *Biomass and Bioenergy* 16 (4): 281-290.

Ettala M O (1988) Evapotranspiration from Salix aquatic plantation at a sanitary landfill. *Aqua Fennica* 18 (1): 3-14.

European Environmental Agency [EEA] (2008) A review of the possible impact of biomass production from agriculture on water - Background paper for the conference "WFD meets CAP – Looking for a consistent approach". Kopenhagen, European Environmental Agency. Retrieved from http://icm.eionet.europa.eu/ETC_Reports/Biomass_WFD_report_V7_final260108-2.pdf [Accessed 6 January 2016]

European Parliament & Council (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA relevance). *Official Journal of the European Union* L 140: 16-62.

Food and Agricultural Organization of the United Nations [FAO]. (2009). The State of Food Insecurity in the World - Economic crises – impacts and lessons learned. Rome, FAO. Retrieved from: http://www.fao.org/docrep/012/i0876e/i0876e00.htm [Accessed 6 January 2016]

Fachagentur für Nachwachsende Rohstoffe [FNR] (2006) Analyse und Evaluierung der thermo-chemischen Vergasung von Biomasse. *Schriftenreihe „Nachwachsende Rohstoffe"* Band 29. Landwirtschaftsverlag GmbH, Münster.

Fachargentur für Nachwachsende Rohstoffe [FNR] (2014) Anteil erneuerbarer Energien am Endenergieverbrauch. Gülzow-Prüzen, FNR. Retrieved from http://mediathek.fnr.de/anteil-erneuerbarer-energien-am-endenergieverbrauch.html [Accessed 30 January 2015]

Fiorese G, Guariso G (2010) A GIS-based approach to evaluate biomass potential from energy crops at regional scale. *Environmental Modelling & Software* 25(6): 702-711.

Fu Y H, Piao S, Vitasse Y, Zhao H, De Boeck H J, Liu Q, Yang H, Weber U, Hänninen H, Janssens I A (2015) Increased heat requirement for leaf flushing in temperate woody species over 1980–2012: effects of chilling, precipitation and insolation. *Global Change Biology* 21: 2687–2697.

Gassman P, Reyes M, Green C, Arnold J G (2007) The soil and water assessment tool: historical development, applications, and future research directions. *Tansactions of American Society of Agricultural and Biological Engineers* 50 (4): 1211–1250.

Gerold D, Landgraf D, Wolf H, Schildbach M (2009) Bewirtschaftungsstrategien von Kurzumtriebsplantagen. In: Reeg T, Bemmann A, Konold W, Murach D, Spiecker H (Eds.) Anbau und Nutzung von Bäumen auf landwirtschaftlichen Flächen. Wiley-VCH Verlag, Weinheim: 73–82.

Gleick P (2000) The Changing Water Paradigm - A Look at Twenty-first Century Water Resources Development. *Water International* 25 (1): 127-138.

Gleick P, Christian-Smith J, Cooley H (2011) Water-use efficiency and productivity: rethinking the basin approach. *Water International* 36 (7): 784-798.

González-García S, Mola-Yudego B, Dimitriou I, Aronsson P, Murphy R (2012): Environmental assessment of energy production based on long term commercial willow plantations in Sweden. *Science of the Total Environment* 421-422: 210-219.

Graham R L (1994) An analysis of the potential land base for energy crops in the conterminous United States. *Biomass and Bioenergy* 6 (3): 175-189.

Graham R L, English B C, Noon C E (2000) A Geographic Information System-based modeling system for evaluating the cost of delivered energy crop feedstock. *Biomass and Bioenergy* 18 (4): 309-329.

Guidi W, Piccioni E, Bonari E (2008) Evapotranspiration and crop coefficient of poplar and willow short-rotation coppice used as vegetation filter. *Bioresource technology* 99 (11): 4832-4840.

Gupta H V, Sorooshian S, Yapo P O (1999) Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering* 4 (2): 135-143

Guse B, Reusser D E, Fohrer N (2014) How to improve the representation of hydrological processes in SWAT for a lowland catchment – temporal analysis of parameter sensitivity and model performance. *Hydrological Processes* 28 (4): 2651-2670.

Hall R L (2003) Short rotation coppice for energy production - Hydrological guidelines. *Report of the DTI New and Renewable Energy Programme* (B/CR/00783/GUIDELINES/SRC URN 03/883). Wallingford, Oxfordshire, Centre for Ecology and Hydrology. Retrieved from: http://nora.nerc.ac.uk/2631/1/HallShortRotationReport.pdf [Accessed 6 January 2016]

Hall R L, Allen S J (1997) Water use of poplar clones grown as short-rotation coppice at two sites in the United Kingdom. *Aspects of Applied Biology* 49: 163-172.

Hanegraaf M, Biewingam E, van der Bijl G (1998) Assessing the ecological and economic sustainability of energy crops. *Biomass and Bioenergy* 15 (4-5): 345-355.

Hangs D R, Schoenau J J, Van Rees K C J, Knight J D (2012) The effect of irrigation on nitrogen uptake and use efficiency of two willow (Salix spp.) biomass energy varieties. *Canadian Journal of Plant Science* 92 (3): 563-575.

Hartmann T, Needham B (2012) Introduction: Why reconsider planning by law and property rights?. In: Hartmann T, Needham B (Eds.) Planning by law and property rights reconsidered. Ashgate, Farnham, Surrey: 1–23.

Hartmann T, Spit T (2014) Frontiers of land and water governance in urban regions. *Water International* 39 (6): 791-797.

Hartwich J, Bölscher J, Schulte A (2014a) Die Menge des pflanzenverfügbaren Wassers als Kriterium zur Abschätzung des Bioenergiepotentials von KUP-Standorten in Deutschland. In: Chifflard P, Karthe D, Grashey-Jansen S, Wetzel K-F (Eds.) Beiträge zum 45. Jahrestreffen des Arbeitskreises Hydrologie vom 21.-23. November 2013 in Augsburg. *Geographica Augustana* 16: 29-34.

Hartwich J, Bölscher J, Schulte A (2014b) Wasserverfügbarkeit als Kriterium zur Potenzialabschätzung für die Produktion holzartiger Biomasse in Deutschland. Eichstätt, Tag der Hydrologie. Retrieved from http://www.geo.fu-berlin.de/geog/fachrichtungen/angeog/projekte/AGENT/Hartwich_Boelscher_Schulte_Poster-TdH-2014.pdf?1405009162#%20Hartwich_Boelscher_Schulte_Poster-TdH-2014 [Accessed 6 January 2016]

Hartwich J, Bölscher J, Schulte A (2014c) Impact of short-rotation coppice on water and land resources. *Water International* 39 (6): 813-825.

Hartwich J, Bölscher J, Schulte A, Schmidt M, Pflugmacher C, Murach D (2015a) Das Transpirationswasserdargebot als steuernder Faktor für die Produktion von Energie aus Weiden in Kurzumtriebsplantagen – Abschätzung des Bioenergiepotentials für Deutschland. *Hydrologie und Wasserbewirtschaftung* 59 (5): 217-226.

Hartwich J, Reinhardt-Imjela C, Bölscher J, Schulte A (2015b) The impact of woody biomass production on the water balance of the North German Lowlands - Model setup and calibration. In: Conference Proceedings. International Soil & Water Assessment Tool Conference, Pula, Sardinia, Italy: 1-13.

Hartwich J, Schmidt M, Bölscher J, Reinhardt-Imjela C, Murach D, Schulte A (2016): Hydrological modelling of changes in the water balance due to the impact of woody biomass production in the North German Plain. *Environmental Earth Sciences* 75 (14). DOI: 10.1007/s12665-016-5870-4

Hashimoto T, Stedinger J, Loucks P (1982) Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resources Research* 18 (1): 14-20.

Haufe H-K, Augenstein I, Vogelgsang W, Lehle M (1998) Bewertung von Böden als „Standort für die natürliche Vegetation". *Naturschutz und Landschaftsplanung* 30 (7): 214-219.

Healy R W (2010) Estimating groundwater recharge. The Cambridge University Press, Cambridge.

Heller M C, Keoleian G A, Mann M K, Volk T A (2004) Life cycle energy and environmental benefits of generating electricity from willow biomass. *Renewable Energy* 29 (7): 1023-1042.

Henriksen H J, Troldborg L, Nyegaard P, Sonnenborg T O, Refsgaard J C, Madsen B (2003) Methodology for construction, calibration and validation of a national hydrological model for Denmark. *Journal of Hydrology* 280 (1-4): 52–71.

Internationales Institut für Wald und Holz NRW (2014) Entwicklung eines Nachhaltigkeitszertifikats für den Agrarholzanbau, AZ 29927-01/-02 - Schlussbericht. Band 1. Deutsche Bundesstiftung Umwelt, Münster.

Köhn J (2009) Socio-economics in SRC – a review on concepts and the need for transdisciplinary research. *Landbauforschung – vTI Agriculture and Forestry Research* 3 (59): 223-232.

Krotscheck C, Konig F, Obernberger I (2000) Ecological assessment of integrated bioenergy systems using the Sustainable Process Index. *Biomass and Bioenergy* 18 (4): 341-368.

Lamersdorf N, Petzold R, Schwärzel K, Feger K-H, Köstner B, Moderow U, Bernhofer C, Kunst C (2010) Bodenökologische Aspekte von Kurzumtriebsplantagen. In: Bemmann A, Knust C (Eds.) Agrowood - Kurzumtriebsplantagen in Deutschland und europäische Perspektiven. Weißensee Verlag, Berlin: 170-188.

Linderson M-L, Iritz Z, Lindroth A (2007) The effect of water availability on stand-level productivity, transpiration, water use efficiency and radiation use efficiency of field-grown willow clones. *Biomass and Bioenergy* 31 (7): 460-468.

Lindroth A, Båth A (1999) Assessment of regional willow coppice yield in Sweden on basis of water availability. *Forest Ecology and Management* 121 (1-2): 57-65.

Lindroth A, Cienciala E (1996) Water use efficiency of short-rotation Salix viminalis at leaf, tree and stand scales. *Tree Physiology* 16 (1-2): 257-262.

Lindroth A, Verwijst T, Halldin S (1994) Water-use efficiency of willow: variation with season, humidity and biomass allocation. *Journal of Hydrology* 156 (1): 1-19

Marland G, Schlamadinger B (1997) Forests for carbon Sequestration or fossil fuel substitution? A sensitivity analysis. *Biomass and Bioenergy* 13 (6): 389-397.

Mirck J, Volk T A (2009) Seasonal sap flow of four Salix varieties growing on the Solvay Wastebeds in Syracuse, NY, USA. *International journal of phytoremediation* 12 (1): 1-23.

Mitchell C P (2000) Development of decision support systems for bioenergy applications. *Biomass and Bioenergy* 18 (4): 265-278.

Mitchell D (2008) A Note on Rising Food Prices. *Policy Research Working Paper* 4682. Washington, DC, World Bank. Retrieved from https://openknowledge.worldbank.org/ bitstream/handle/10986/6820/WP4682.pdf?sequence=1 [Accessed 6 January 2016]

Monteith J (1978) Reassessment of maximum growth rates for C3 and C4 crops. *Experimental Agriculture* 14 (01): 1-5.

Moriasi D N, Arnold J G, Van Liew M W, Bingner R L, Harmel R D, Veith T L (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *American Society of Agricultural and Biological Engineers* 50 (3): 885-900.

Murach D., Hartmann H, Murn Y, Schultze M, Wael A, Röhle H (2009) Standortsbasierte Leistungsschätzung in Agrarholzbeständen in Brandenburg und Sachsen. In: Reeg T, Bemmann A, Kondold W, Murach D, Spiecker H (Eds.) Anbau und Nutzung von Bäumen auf Landwirtschaftlichen Flächen. Wiley, Weinheim: 29-40.

Nash J E, Sutcliffe J V (1970) River flow forecasting through conceptual models. Part I: Discussion of principles. *Journal of Hydrology* 10: 282-290.

Neitsch S L, Arnold J G, Kiniry J R, Williams J R (2011) Soil and Water Assessment Tool theoretical documentation version 2009. *Texas Water Resources Institute Technical Report* No. 406. College Station, Texas Water Resources Institute. Retrieved from http://twri.tamu.edu/reports/2011/tr406.pdf. [Accessed 26 November 2015]

Neumann, J, Wycisk P (2003) Mittlere jährliche Grundwasserneubildung. In: Liedtke H, Mäusbacher R, Schmidt K H (Eds.) Bundesrepublik Deutschland Nationalatlas – Relief, Boden und Wasser. Spektrum Akademischer Verlag, Heidelberg, Berlin: 144-145.

Nisbet T (2005) Water Use by Trees. *Forestry Commission Information Note* 65. Forestry Commission, Edinburgh.

Nisbet T, Thomas H, Shah N (2011) Short Rotation Forestry and Water. In: McKay H (Eds.) Short Rotation Forestry: Review of growth and environmental impacts. *Forest Research Monograph* 2. Forest Research, Surrey: 13-34.

Pacaldo R, Volk T, Briggs R (2013) Greenhouse Gas Potentials of Shrub Willow Biomass Crops Based on Below- and Aboveground Biomass Inventory Along a 19-Year Chronosequence. *BioEnergy Research* 6 (1): 252-262.

Pain L, Peterson T, Undersander D, Rineer K, Bartelt G, Temple S, Sample D, Klemme R (1996) Some ecological and socio-economic considerations for biomass energy crop production. *Biomass and Bioenergy* 10 (4): 231-242.

Palmas C, Abis E, von Haaren C, Lovett A (2012) Renewables in residential development: an integrated GIS-based multicriteria approach for decentralized micro-renewable energy production in new settlement development: a case study of the eastern metropolitan area of Cagliari, Sardinia, Italy. *Energy, Sustainability and Society* 2 (1): 1-15.

Perry C H, Miller R C, Brooks K N (2001) Impacts of short-rotation hybrid poplar plantations on regional water yield. *Forest Ecology and Management* 143 (1-3): 143-151.

Persson G (1995) Willow stand evapotranspiration simulated for Swedish soils. *Agricultural water management* 28 (4): 271-293.

Persson G, Lindroth A (1994) Simulating evaporation from short-rotation forest: variations within and between seasons. *Journal of Hydrology* 156 (1): 21-45.

Petzold R, Feger K H, Schwärzel K (2009) Wasserhaushalt von Kurzumtriebsplantagen. In: Reeg T, Bemmann A, Konold W, Murach D, Spiecker H (Eds.) Anbau und Nutzung von Bäumen auf landwirtschaftlichen Flächen. Wiley-VCH Verlag, Weinheim: 181-192.

Pfannerstill M, Guse B, Fohrer N (2014) A multi-storage groundwater concept for the SWAT model to emphasize nonlinear groundwater dynamics in lowland catchments. *Hydrological Processes* 28 (22): 5599-5612.

Pistocchi C, Guidi W, Piccioni E, Bonari E (2009) Water requirements of poplar and willow vegetation filters grown in lysimeter under Mediterranean conditions: Results of the second rotation. *Desalination* 246 (1): 137-146.

Pretzsch J, Skodawessely C (2010) Sozio-ökonomische und ethische Aspekte der Kurzumtriebswirtschaft. In: Bemmann A, Knust C (Eds.) Agrowood - Kurzumtriebsplantagen in Deutschland und europäische Perspektiven. Weißensee Verlag, Berlin: 230-242.

Quaye A K, Volk T A, Hafner S, Leopold D J, Schirmer C (2011) Impacts of paper sludge and manure on soil and biomass production of willow. *Biomass and Bioenergy* 35 (7): 2796-2806.

Quaye A K, Volk T A (2013) Biomass production and soil nutrients in organic and inorganic fertilized willow biomass production systems. *Biomass and Bioenergy* 57: 113-125.

Rademacher P, Schmidt M, Mollnau C, Soren K, Hartmann H, Murach D (2013) Nutrition of fast growing tree species and effects of land use change on agricultural soils. *Verhandlungen der Gesellschaft für Ökologie* Vol. 43.

Reeg T (2009) Anbau und Nutzung von Bäumen auf landwirtschaftlichen Flächen. Wiley-VCH-Verlag, Weinheim.

Richter D (1995) Ergebnisse methodischer Untersuchungen zur Korrektur des systematischen Meßfehlers des Hellmann-Niederschlagsmessers. *Berichte des Deutschen Wetterdienstes* 194. Deutscher Wetterdienst, Offenbach am Main.

Robinson D, Acemoglu J (2012) Why Nations Fail: The Origins of Power, Prosperity, and Poverty. Crown Business, New York.

Roger P, Hall A (2003) Effective Water Governance. *TEC Background Papers* No. 7. Global Water Partnership Technical Committee (TEC). Elanders Novum, Sweden.

Roesch C, Aust C, Knapp M, Joerissen J (2011) Sustainability criteria to identify grassland for short rotation coppice. *19th European Biomass Conference and Exhibition*: 409-415.

Roos A, Rakos C (2000) The limits of modelling. Experiences with bioenergy in practice - could models have predicted this outcome? *Biomass and Bioenergy* 18 (4): 331-340.

Rouholahnejad E, Abbaspour K C, Vejdani M, Srinivasan R, Schulin R, Lehmann A (2012) A parallelization framework for calibration of hydrological models. *Environmental Modelling & Software* 31: 28-36.

Schänger J (2009) Monetäre Bewertung ökologischer Leistungen des Agrarholzanbausn. In: Reeg T, Bemmann A, Konold W, Murach D, Spiecker H (Eds.) Anbau und Nutzung von Bäumen auf landwirtschaftlichen Flächen. Wiley-VCH Verlag, Weinheim: 171–180.

Schmalz B, Tavares F, Fohrer N (2008) Modelling hydrological processes in mesoscale lowland river basins with SWAT - capabilities and challenges. *Hydrological Sciences Journal* 53 (5): 989-1000.

Schmidt M, Böhme T, Krämer S, Rademacher P, Murach D (2014) Water use and productivity of poplar and willow in SRC plantations in NE Germany along gradients of groundwater depth. *Proceedings, 2nd European Agroforestry Congress.* Cottbus: 237-240.

Schmidt P, Glaser T (2009) Kurzumtriebsplantagen aus Sicht des Naturschutzes. In: Reeg T, Bemmann A, Konold W, Murach D, Spiecker H (Eds.) Anbau und Nutzung von Bäumen auf landwirtschaftlichen Flächen. Wiley-VCH Verlag, Weinheim: 161–170.

Schmidt P, Gerold D (2010) Nachhaltig bewirtschaftete Wälder versus Kurzumtriebsplantagen versus Agroforstsysteme. In: Bemmann A, Knust C (Eds.) Agrowood - Kurzumtriebsplantagen in Deutschland und europäische Perspektiven. Weißensee Verlag, Berlin: 208-216.

Schmidt M, Murach D (2015) Wassernutzungseffizienz von Gehölzen im Kurzumtrieb auf Ackerstandorten in Brandenburg. In: Kage H, Sieling H, Francke-Weltmann L (ed.): Multifuntionale Agrarlandschaften – Pflanzenbaulicher Anspruch, Biodiversität, Ökosystemdienstleistungen. Verlag Liddy Halm, Göttingen: 41-42.

Schmidt T, Röder N, Dauer J, Klimek S, Laggner A, de Witte T, Offermann F, Osterburg B (2014) Biodiversitätsrelevante Regelungen zur nationalen Umsetzung des Greenings der Gemeinsamen Agrarpolitik der EU nach 2013. *Thünen Working Paper* No. 20. Braunschweig, Johann Heinrich von Thünen-Institut. Retrieved from http://nbn-resolving.de/urn:nbn:de:gbv:253-201403-dn053406-9 [Accessed 6 January 2016]

Scholz V G, Heiermann M, Kern J, Balasus A (2011) Environmental impact of energy crop cultivation, Umweltwirkungen des Energiepflanzenanbaus. *Archives of Agronomy and Soil Science* 57 (8): 805-837.

Servat E, Dezetter A (1991) Selection of calibration objective functions in the context of rainfall-runoff modelling in a Sudanese savannah area. *Hydrological Sciences Journal* 36 (4): 307-330.

Sevel L, Nord-Larsen T, Ingerslev M, Jørgensen U, Raulund-Rasmussen K (2014) Fertilization of SRC Willow, I: Biomass Production Response. *BioEnergy Research* 7 (1): 319-328.

Singh J, Knapp H V, Demissie M (2004) Hydrologic modeling of the Iroquois River watershed using HSPF and SWAT. *Illinois State Water Survey Contract Report* 2004-08. Champaign, Illinois State Water Survey. Retrieved from http://swat.tamu.edu/media/90101/singh.pdf [Accessed 6 January 2015]

Singh J, Knapp H V, Arnold J G, Demissie M (2005) Hydrologic modeling of the Iroquois River watershed using HSPF and SWAT. *J. American Water Resources Assoc.* 41 (2): 361-375.

Slazak A, Böhm C, Veste M (2013) Kohlenstoffspeicherung, Nährstoff- und Wasserverfügbarkeit. In Wagener F, Heck P, Böhmer J (Eds.) Nachwachsende Rohstoffe als Option für den Naturschutz… - Naturschutz durch Landbau?. Schlussbericht zu ELKE III. Hochschule Trier, Umwelt-Campus Birkenfeld: 130-149.

Söderbaum P, Tortajada C (2011) Perspectives for water management within the context of sustainable development. *Water International* 36 (7): 812-827.

Solomon S, Qin D, Manning M, Alley R, Berntsen T, Bindoff N, Chen Z, Chidthaisong A, Gregory J M, Hegerl G (2007) Climate change 2007: the physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, New York.

Srinivasan R, Ramanarayanan T S, Arnold J G, Bednarz S T (1998) Large area hydrologic modeling and assessment part II: model application. *Journal of the American Water Resources Association* 34 (1): 91-101

Statistisches Bundesamt (2012): Umweltnutzung und Wirtschaft. Tabellen zu den Umweltökonomischen Gesamtrechnungen. Teil 3: Luftemission. Statistisches Bundesamt, Wiesbaden.

Statistisches Bundesamt (2013a): Energie, Rohstoffe, Emissionen - Energieverbrauch der privaten Haushalte für Wohnen (temperaturbereinigt). Wiesbaden, Statistisches Bundesamt. Retrieved from https://www.destatis.de/DE/ZahlenFakten/GesamtwirtschaftUmwelt/Umwelt/UmweltoekonomischeGesamtrechnungen/EnergieRohstoffeEmissionen/Tabellen/EnergieverbrauchHaushalte.html [Accessed 29 January 2013]

Statistisches Bundesamt (2013b): Haushalte & Familien – In drei Viertel der Haushalte leben höchstens zwei Personen. Wiesbaden, Statistisches Bundesamt. Retrieved from https://www.destatis.de/DE/ZahlenFakten/GesellschaftStaat/Bevoelkerung/HaushalteFamilien/Aktuell.html [Accessed 29 January 2013]

Stephens W, Hess T, Knox J (2001) Review of the effects of energy crops on hydrology. Bedford, Institute of Water and Environment, Cranfield University Silsoe. Retrieved from https://dspace.lib.cranfield.ac.uk/handle/1826/3368 [Accessed 6 January 2016]

Stisen S, Sonnenborg T O, Hojberg A L, Troldborg L, Refsgaard J C (2011) Evaluation of climate input biases and water balance issues using a coupled surface–subsurface model. *Vadose Zone Journal* 10 (1): 37–53.

Stork M, Schulte A, Murach D (2014) Large-scale fuelwood production on agricultural fields in mesoscale river catchments – GIS-based determination of potentials in the Dahme river catchment (Brandenburg, NE Germany). *Biomass and Bioenergy* 64: 42-49

Strauch M, Bernhofer C, Koide S, Lorz C, Volk M, Makeschin F (2012) Using precipitation data ensemble for uncertainty analysis in SWAT streamflow simulation. *Journal of Hydrology* 414–415: 413–424.

Strohm K, Schweinle J, Liesebach M, Osterburg B, Rödl A, Baum S, Nieberg H, Bolte A, Walter K (2012) Kurzumtriebsplantagen aus ökologischer und ökonomischer Sicht. *Arbeitsberichte aus der vTI-Agrarökonomie*. Institut für Betriebswirtschaft, Braunschweig.

Styles D, Jones M (2007) Energy crops in Ireland: Quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. *Biomass and Bioenergy* 31 (11-12): 759-772.

Tallis M J, Casella E, Henshall P A, Aylott M J, Randle T J, Morison J I L, Taylor G (2013) Development and evaluation of ForestGrowth-SRC, a process-based model for short rotation coppice yield and spatial supply reveals poplar uses water more efficiently than willow. *Global Change Biol. Bioenergy* 5: 53–66.

Tenerelli P, Carver S (2012) Multi-criteria, multi-objective and uncertainty analysis for agro-energy spatial modelling. *Applied Geography* 32 (2): 724-736.

Uchida S, Hayashi K (2012) Comparative life cycle assessment of improved and conventional cultivation practices for energy crops in Japan. *Biomass and Bioenergy* 36: 302-315.

Ugarte D G D, Ray D E (2000) Biomass and bioenergy applications of the POLYSYS modeling framework. *Biomass and Bioenergy* 18 (4): 291-308.

Umweltbundesamt [UBA] (2013) Strom- und Wärmeversorgung einer Siedlung bei unterschiedlichen Energieeffizienz-Standards. Umweltbundesamt, Dessau-Roßlau

Van Liew M, Veith T, Bosch D, Arnold J (2007) Suitability of SWAT for the Conservation Effects Assessment Project: Comparison on USDA Agricultural Research Service Watersheds. *Journal of Hydrologic Engineering* 12 (2): 173-189.

Venturi P, Venturi G (2003) Analysis of energy comparison for crops in European agricultural systems. *Biomass and Bioenergy* 25 (3): 235-255.

Viana H, Cohen W B, Lopes D, Aranha J (2010) Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. *Applied Energy* 87 (8): 2551-2560.

Vitasse Y, Basler D (2013) What role for photoperiod in the bud burst phenology of European beech. *European Journal of Forest Research* 132: 1-8.

Volk T A, Abrahamson L, White E (2001) Root dynamics in willow biomass crops. New York, NY: SUNY College of Environmental Science and Forestry. United States Department of Energy Syracuse.

Wahren A, Julich S, Feger K-H (2014) Modellgestützte Untersuchung zum Einfluss von Energieholz-Anbau auf ein mesoskaliges Einzugsgebiet (Hoyerswerdaer Schwarzwasser, Sachsen). In: Cyffka B (ed) Wasser – Landschaft – Mensch in Vergangenheit, Gegenwart und Zukunft. Beiträge zum Tag der Hydrologie am 20./21. März 2014 an der Katholischen Universität Eichstät-Ingolstadt. Forum für Hydrologie und Wasserbewirtschaftung Heft 34 (14): 245-252

Wahren A, Richter F, Julich S, Jansen M, Feger K H (2015) The influence of more widespread cultivation of short rotation coppice on the water balance–from the site to regional scale. In: D. B. Manning, A. Bemmann, M. Bredemeier, N. Lamersdorf and C. Ammer (eds.) Bioenergy from Dendromass for the Sustainable Development of Rural Areas. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany: 45-61

Walsh M E (2000) Method to estimate bioenergy crop feedstock supply curves. *Biomass and Bioenergy* 18(4): 283-289

Webb J, Cook P, Skiba U, Levy P, Sajwaj T, Parker C, Mouat A (2009) Investigation of the Economics and Potential Environmental Impacts of the Production of Short Rotation Coppicing on Poorer Quality Land. *Report to the Scottish Government* ED45623 (1). Harwell, AEA Technology plc. Retrieved from: http://www.scotland.gov.uk/Publications/2009/10/21091129/0 [Accessed 6 January 2016]

Wendling U (2001) Berechnung der Grasreferenzverdunstung mit der FAO Penman-Montheit-Beziehung. In: Deutscher Wetterdienst (Eds.) Klimaatlas Bundesrepublik Deutschland – Teil 2. Offenbach am Main: 602-604.

Zichy M, Dürnberger C, Formowitz B, Uhl A (2011) Energie aus Biomasse ein ethisches Diskussionsmodell. Eine Studie des Institutes Technik-Theologie-Naturwissenschaften und des Technologie- und Förderzentrums. Vieweg+Teubner Verlag, Springer Fachmedien, Wiesbaden.