Institute of Crop Science, University of Hohenheim,
Department of Biobased Products and Energy Crops

Agricultural diversification of biogas crop cultivation

Cumulative Doctoral Thesis
Submitted in fulfilment of the requirements for the degree
'Doktor der Agrarwissenschaften' (Dr.sc.agr. / Ph.D. in Agricultural Sciences)
to the
Faculty of Agricultural Sciences of
University of Hohenheim

Date of acceptance of the dissertation: 29.10.2018
Date of oral exam: 16.11.2018
Submitted by Moritz von Cossel

Dean Faculty of Agricultural Science

Prof. Dr. Ralf T. Vögele

Thesis Committee

Supervisor

Prof. Dr. Iris Lewandowski

University of Hohenheim, Germany

Co-Supervisors

Prof. Dr. Carola Pekrun

Nuertingen-Geislingen University, Germany

Prof. Dr. Christian Zörb

University of Hohenheim, Germany

“A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise.”

Aldo Leopold (1949), The Land Ethic, A Sand County Almanac

Table of contents

List of figures

List of acronyms

ABS	Abstract
ADF	Acid detergent fibre
ADL	Acid detergent lignin
AGRI	Agricultural
app.	Approximately
BA	Biogas-amaranth
B.V.	Private limited liability company (in the Netherlands and Belgium)
C	Carbon
CL	Cellulose
CO_2	Carbon dioxide
CV	Cross validation
DM	Dry matter
DMC	Dry matter content
DMY	Dry matter yield
e.g.	Exempli gratia
ENVI	Environmental
FCC	Food crop cultivation
GHG	Greenhouse gas
HC	Hemicellulose
i.e.	Id est

ICC	Industrial crop cultivation
KEY	Keywords
MLR	Multiple linear regression
MYH	Methane yield per hectare
N	Nitrogen
N_2O	Nitrous oxide
NDF	Neutral detergent fibre
OECD	Organization for Economic Co-operation and Development
r	Correlation
R^2	Coefficient of determination
RB	Runner bean
RES	Non-lignocellulosic biomass fraction
rMSE	Square root of the mean square error
SBY	Specific biogas yield
SMY	Specific methane yield
SUBJAREA	Subject area
TKW	Thousand kernel weight
VS	Volatile solids
WC	White clover
WCC	Winter catch crop
WCCS	Whole crop cereal silage
WPM	Wild plant mixture
XP	Raw protein
yr	Year

Abstract

For all types of agricultural land-use, more diverse cropping systems are required, with respect to the maintenance of ecosystem values such as biodiversity conservation and climate change adaptation. This need for greater agricultural diversity is clearly illustrated by biogas crop cultivation. In Germany, maize currently dominates biogas crop cultivation due to its outstanding methane yield performance. However, the ecosystem value of maize cultivation decreases if good agricultural practices are ignored. Additionally, the poor aesthetical value of maize has led to biogas production gaining a negative reputation in society. To increase the diversity of biogas crop cultivation, alternative biogas crops such as amaranth and wild plant mixtures need to be investigated with respect to both yield performance and biogas substrate quality. The research objective of this study was the development of strategies for agricultural diversification of biogas crop cultivation. For this purpose, the following research questions were formulated:

1. How does amaranth perform as a biogas crop compared to maize and what are the major opportunities for and obstacles to the large-scale implementation of amaranth cultivation?
2. How does the spatial diversification 'legume intercropping' perform in amaranth compared to maize and what are the major opportunities for and obstacles to its practical implementation?
3. How do perennial wild plant mixtures perform in biomass production with respect to yield, quality and species diversity in the long term and what are the relevant agronomic factors?
4. How do available models perform in the prediction of specific methane yield of different crops based on their lignocellulosic biomass composition and how could they be improved?

To address research questions 1 and 2, field trials with amaranth and maize were conducted in southwest Germany in the years 2014 and 2015. Amaranth established well in both years. Its dark red inflorescences attracted many insects such as honeybees, wild bees and bumble bees. Therefore, a systematic implementation of amaranth into biogas crop rotations could significantly improve their socio-ecological value in terms of biodiversity conservation and landscape beauty. However, amaranth showed significantly lower dry matter yields (DMY) and specific methane yields (SMY), together resulting in lower methane yields than maize in both years. Therefore, breeding and an optimization of agricultural practices such as sowing density, planting geometry and fertilization management are required to make amaranth more competitive in comparison to maize.

To address research question 2, the amaranth field trials mentioned above also included treatments of legume intercropping with runner bean (RB, *Phaseolus vulgaris* L.) and white clover (WC, *Trifolium repens*, L.). The RB and WC developed equally well in amaranth and maize each year. For both amaranth and maize, the RB share of total DMY was low (5-10%) and did not significantly affect the total DMY. By contrast, WC had a significant negative effect on the DMY. Overall, the spatial diversification 'legume intercropping' could considerably improve the socio-ecological value of amaranth cultivation in terms of biodiversity conservation, greenhouse gas (GHG) mitigation and soil protection.

For research question 3, two different wild plant mixtures (WPM) were cultivated on three sites in southwest Germany from the years 2011 to 2015. At each location, the WPM showed great potential for both biodiversity conservation and ecosystem resilience. Numerous insect species were observed in the WPM stands each year, indicating WPM as a relevant cropping system for habitat networking. Furthermore, the aesthetic appearance of the WPM stands over the years demonstrated the potential positive effect WPM cultivation could have on the public perception of biogas production. The DMY of the WPM varied strongly depending on (i) the initial composition of species sown, (ii) the establishment procedure, (iii) the environmental conditions, (iv) the pre-crop, and (v) the number of predominant species. WPM were found to have low demands for fertilization and crop protection. Thus, WPM appear a promising low-input cropping system for the promotion of biodiversity conservation, habitat networking, soil and water protection, GHG mitigation and climate change adaptation. However, high DMY gaps remain a challenge for the practical inclusion of WPM in existing biogas cropping systems.

With respect to research question 4, a meta-analysis revealed that available models proved to be much less precise than expected. Although outperforming all available models, the correlation of the new models was still low (up to $r = 0.66$). It was also found that non-linear terms are of less importance than crop-specific regressors including the intercept. This indicates that across-crop models including crop-specific configurations could help to improve the identification of alternative crops and cropping systems for a more diverse biogas crop cultivation in the future.

Zusammenfassung

Für alle landwirtschaftlichen Nutzrichtungen werden vielfältigere Anbausysteme erfordert, insbesondere im Hinblick auf Ökosystemfunktionen wie die Förderung der Agrarbiodiversität und die Vorbereitung auf landwirtschaftlich relevante Folgen des Klimawandels. Dieser Mehrbedarf landwirtschaftlicher Vielfalt wird insbesondere beim Anbau von Biogaspflanzen in Deutschland deutlich, wo derzeit Mais aufgrund seiner hervorragenden Methanertragsleistung dominiert. Der Ökosystemwert des Maisanbaus nimmt jedoch ab, wenn die gute fachliche Praxis nicht eingehalten wird. Darüber hinaus führte der geringe ästhetische Wert von Mais zu einem negativen Ruf der Biogasproduktion in der Gesellschaft. Um die Vielfalt der Anbausysteme für die Biogasproduktion zu erhöhen, müssen alternative Biogaspflanzen wie Amaranth und Wildpflanzenmischungen hinsichtlich ihrer Ertragsleistung und der Biogassubstratqualität untersucht werden. Das Forschungsziel dieser Studie war die Entwicklung von Strategien zur landwirtschaftlichen Diversifizierung von Anbausystemen für die Biogasproduktion. Zu diesem Zweck wurden die folgenden Forschungsfragen formuliert:

1. Welches Potential bietet Amaranth als Biogaspflanze im Vergleich zu Mais und was sind die größten Chancen und Herausforderungen einer großflächigen Implementierung des Amaranthanbaus?
2. Wie ist die "Leguminosen-Mischkultur" als räumliche Diversifizierung bei Amaranth im Vergleich zu Mais zu beurteilen und was sind die größten Chancen und Herausforderungen für deren praktische Umsetzung?
3. Was leisten mehrjährige Wildpflanzenmischungen bei der Biomasseproduktion in Bezug auf Ertrag, Qualität und Artenvielfalt langfristig und was sind relevante agronomische Faktoren?
4. Wie eignen sich verfügbare Modelle zur Vorhersage des spezifischen Methanertrags verschiedener pflanzlicher Biogassubstratarten auf Grundlage ihrer Faserzusammensetzung und wie können die Modelle verbessert werden?

Um Forschungsfragen 1 zu beantworten, wurden Feldversuche mit Amaranth und Mais im Südwesten Deutschlands in den Jahren 2014 und 2015 durchgeführt. Der Amaranth hat sich in beiden Jahren gut etabliert. Seine dunkelroten Blütenstände zogen viele Insekten wie Honigbienen, Wildbienen und Hummeln an. Eine systematische Implementierung von Amaranth in bestehende Biogas-Fruchtfolgen könnte daher ihren sozial-ökologischen Wert im Hinblick auf Biodiversitätsschutz und Landschaftsästhetik deutlich verbessern. Amaranth zeigte jedoch deutlich niedrigere Trockenmasseerträge (TME) und spezifische Methanerträge als Mais, was in beiden Jahren zu niedrigeren Methan-Hektarerträgen führte. Daher sind weitere Züchtungsmaßnahmen sowie eine fortwährende Optimierung der Anbaumethode hinsichtlich

relevanter Anbaufaktoren wie Saatdichte, Pflanzgeometrie und Düngemanagement erforderlich, um Amaranth im Vergleich zu Mais wettbewerbsfähiger zu machen.

Um Forschungsfrage 2 zu beantworten, beinhalteten die oben genannten Amaranth-Feldversuche auch Leguminosen-Mischkultur-Varianten mit Stangenbohne (SB, *Phaseolus vulgaris* L.) und Weißklee (WK, *Trifolium repens*, L.). SB und WK entwickelten sich in Amaranth und Mais jedes Jahr gleichermaßen gut. Sowohl für Amaranth als auch für Mais war der SB-Anteil am gesamt-TME gering (5-10%) und hatte keinen signifikanten Einfluss auf den gesamt-TME. Im Gegensatz dazu hatte WK einen signifikanten negativen Einfluss auf den TME. Insgesamt könnte die Leguminosen-Mischkultur als räumliche Diversifizierung den sozial-ökologischen Wert des Amaranthanbaus in Bezug auf Biodiversitätsschutz, Treibhausgasminderung und Bodenschutz erheblich verbessern.

Für Forschungsfrage 3 wurden zwei verschiedene Wildpflanzenmischungen (WPM) an drei Standorten im Südwesten Deutschlands in den Jahren 2011 bis 2015 angebaut. An jedem Standort zeigten die WPM ein großes Potenzial für den Biodiversitätsschutz und die Resilienz der Ökosysteme. In den Pflanzbeständen der WPM wurden jedes Jahr zahlreiche Insektenarten beobachtet, was auf ein großes Potential von WPM für die Habitat-Vernetzung im Landwirtschaftlichen Raum hinweist. Darüber hinaus zeigte das ästhetische Erscheinungsbild der Pflanzbestände der WPM im Laufe der Jahre, welche potenziell positiven Auswirkungen der Anbau von WPM auf die öffentliche Wahrnehmung der Biogasproduktion haben könnte. Der TME der WPM variierte stark in Abhängigkeit von (i) der anfänglichen Kombination ausgesäter Arten, (ii) dem Etablierungsverfahren, (iii) den Umweltbedingungen, (iv) der Vorkultur und (v) der Anzahl dominanter Arten. Ferner wurde festgestellt, dass WPM einen geringen Bedarf an Düngung und Pflanzenschutz haben. Insgesamt zeigten sich beide WPM als vielversprechende Anbausysteme zur Biomasseproduktion unter Aspekten der Förderung des Biodiversitätsschutzes, der Habitatvernetzung, des Boden- und Gewässerschutzes, der Treibhausgasminderung und der Anpassung an den Klimawandel. Tendenziell niedrige TME bleiben jedoch eine Herausforderung für eine großflächige Implementierung von WPM in bestehende Biogas-Fruchtfolgen.

In Bezug auf Forschungsfrage 4 ergab eine Meta-Analyse, dass alle verfügbaren Modelle ungenauer waren als erwartet. Zwar waren die neu entwickelten Modelle besser, wiesen aber noch immer eine geringe Korrelation auf (bis r = 0,66). Es wurde auch festgestellt, dass nichtlineare Parameter von geringerer Bedeutung sind als pflanzenart-spezifische Regressoren einschließlich des Gesamteffekts. Dies deutet darauf hin, dass pflanzenart-übergreifende Modelle einschließlich pflanzenart-spezifischer Konfigurationen dazu beitragen könnten, die Identifizierung alternativer Pflanzenarten und Anbausysteme für eine Diversifizierung des Biogaspflanzenanbaus in Zukunft zu verbessern.

1. General Introduction

Over the past two centuries, the Earth's biosphere has entered its sixth fastest (Ceballos *et al.*, 2015) and most extensive mass extinction event (Barnosky *et al.*, 2011). This has been accompanied by a no less alarming loss of animal populations, especially among pollinators (Potts *et al.*, 2016), which has recently been proven to be much higher than ever expected (Ceballos *et al.*, 2017; Isbell *et al.*, 2017b). This devastating development is to a great extent caused by intensive agriculture (Benton *et al.*, 2003; Böhm *et al.*, 2013; Ceballos, 2002; Hooper *et al.*, 2005; McLaughlin and Mineau, 1995; Pereira *et al.*, 2012; Steffan-Dewenter and Tscharntke, 1999) and anthropogenic climate change (Pachauri *et al.*, 2014; Smith *et al.*, 2008; Thomas *et al.*, 2004). Both are mainly triggered by (i) the exponential growth of civilizations and their demand for agricultural products (Kremen and Miles, 2012; Lewandowski, 2015; Lewandowski *et al.*, 2018a; Tilman *et al.*, 2009) and (ii) their founding market paradigms primarily based on short- to mid-term economic feasibility (Altieri *et al.*, 2017; Blackmore *et al.*, 2011; Ragauskas *et al.*, 2006). Certain circumstances exacerbate future prospects for a global "trilemma" to reconcile *"biofuel production, food security and greenhouse-gas reduction*" in a socio-ecologically sustainable manner (Heaton *et al.*, 2013; Rockström *et al.*, 2009; Tilman *et al.*, 2009). These include: (i) the rapidly increasing demand for food, which is predicted to double by 2050 (Kremen and Miles, 2012), (ii) the high demand for animal food products from industrial livestock farming being responsible for about 70% of deforestation and about 15% of greenhouse gas emissions (Stoll-Kleemann and Schmidt, 2017), (iii) the U-turn of the US government on climate policy (Costanza, 2017; McGuire and Lynch, 2017; Reardon *et al.*, 2017; Tollefson, 2017), and (iv) an EU agricultural reform that "*fails on biodiversity*" (Grethe *et al.*, 2018; Pe'er *et al.*, 2014). The increasing demand for both food (Kremen and Miles, 2012) and biomass (Lewandowski, 2017; Lewandowski *et al.*, 2018a) is expected to intensify the competitive pressure on biodiversity conservation strategies because the land surface available for agriculture is decreasing as a result of erosion, salinization, contamination, degradation, desertification, sea-level rise and for other reasons (Wood *et al.*, 2000). This increasing demand for food and biomass accompanied by a decreasing land surface available for crop cultivation on the one hand, and a lack of societal awareness of biodiversity losses on the other hand, render the consideration of all aspects of the current major challenges by modern agriculture impossible (Dale *et al.*, 2010; Fritsche *et al.*, 2010; Tilman *et al.*, 2009). Thus, the necessity of biodiversity conservation strategies remains underrated and modern arable cropping systems are still dominated by just a few common crops cultivated mainly in short crop rotation systems or monocultures. This situation is mainly driven by markets, politics and agro-industrial progress (Fraser, 2006; Stein and Steinmann, 2018). However, there is a broad consensus that biodiversity conservation strategies, i.e. wildlife-friendly farming (Tscharntke *et al.*, 2012), are necessary to maintain the vital basis of ecosystem services, on which both humankind and wildlife depend (Altieri *et al.*, 2017; Foley *et al.*, 2005; Hallmann *et al.*, 2017; Hooper *et al.*, 2005; Isbell *et al.*, 2017b; Weisser *et al.*, 2017). Thus, only those more holistic concepts of modern arable cropping that also include biodiversity conservation strategies such as "*polyculture management*" and the *"management of field-margin vegetation*" as a high priority task will enable the implementation of an environmentally sustainable agriculture in the long term (Altieri *et al.*, 2017; Altieri and Letourneau, 1982). Agricultural diversification through "*spatial and temporal combinations of crops*" (Altieri and Letourneau, 1982) is seen as a key element in this context, since it supports agro-biodiversity at both temporal and spatial scale (Isbell *et al.*, 2017a; Lin, 2011; Stein and Steinmann, 2018; Theisen *et al.*, 2017; Tilman *et al.*, 2014; Weisser *et al.*,

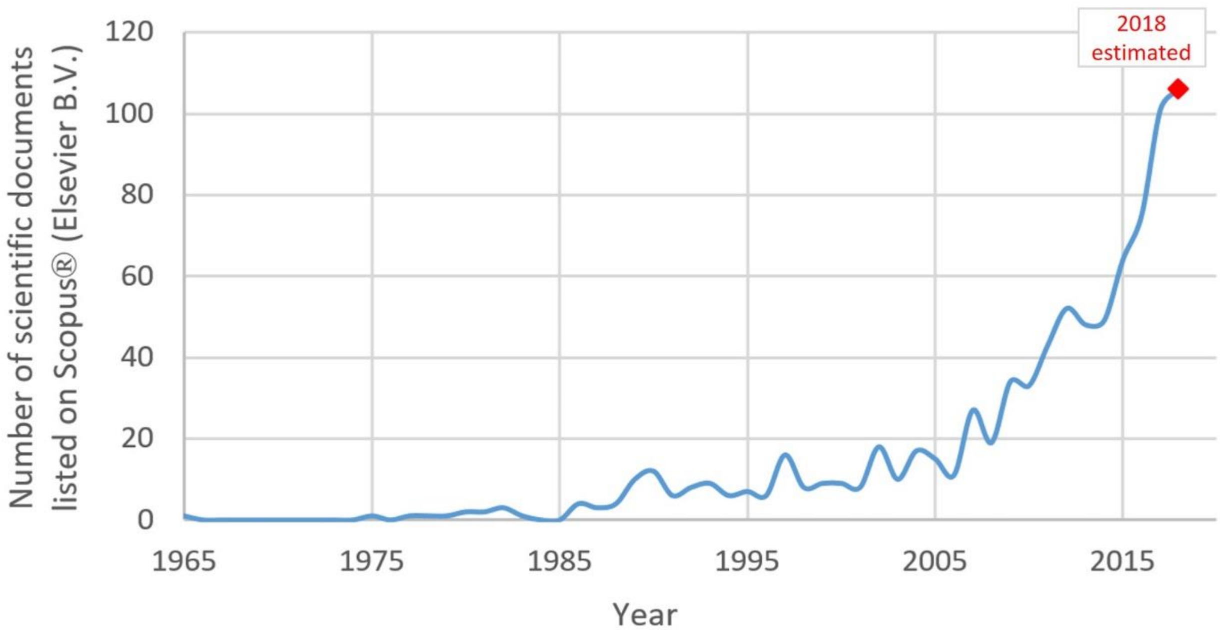

Figure 1: Number of scientific documents published per year between 1960 and mid-2018 available via Scopus® (Elsevier B.V.) (accessed 06.14.2018) with either the term "agricultural diversification" or "crop diversification" in title, abstract or keywords and belonging to either the subject area "Agricultural and Biological Sciences" or "Environmental Science". The total number of documents found was 813 (plus estimated 53 for second half of 2018). The search term read: "TITLE-ABS-KEY ("agricultural diversification" OR "crop diversification") AND (LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "ENVI"))".

2017). Accordingly, the number of scientific documents that can be found using Scopus® (Elsevier B.V.) with the terms "agricultural diversification" or "crop diversification" in the abstract, keywords or title points to the increasing scientific relevance of agricultural diversification worldwide (Fig. 1).

1.1. Agricultural diversification

Agricultural diversification can be described as the intentional inclusion of '*functional biodiversity at multiple spatial and/or temporal scales'* (Kremen *et al.*, 2012). This inclusion of functional biodiversity can mainly be realized by increasing the temporal and spatial variation of crop species (Altieri *et al.*, 2017; Kremen *et al.*, 2012). Numerous studies have shown that more diverse cropping systems can provide higher yield levels and a higher yield stability than less diverse systems in the long term (Andrews, 1972; Andrews and Kassam, 1976; Cardinale *et al.*, 2007; Gaudin *et al.*, 2015; Hector *et al.*, 1999; Hooper *et al.*, 2005; Isbell *et al.*, 2017a; Nunes *et al.*, 2018; Perrin, 1976; Stein and Steinmann, 2018; Theisen *et al.*, 2017; Tilman, 1999; Tilman *et al.*, 2014; Weisser *et al.*, 2017; Willey and Osiru, 1972; Zhang and Li, 2003). These positive agronomic effects of high diverse cropping systems mainly stem from an optimization of both (i) their collective resource use efficiency (Cardinale *et al.*, 2007) and (ii) their faunistic diversity (including soil microbial community) (Altieri *et al.*, 2015; Altieri and Letourneau, 1982). The underlying synergistic mechanisms form a complex causal network that depends on a number of temporal and spatial factors (Fig. 2, 3). The relevant factors for developing more diverse cropping systems can be categorized as follows:

a) **plant morphological traits** such as canopy height, canopy structure, rooting depth (Díaz and Cabido, 2001) and flower abundance (Stang *et al.*, 2006),
b) **plant physiological traits** such as nutrient uptake efficiency, drought/heat resistance/tolerance, time of flowering and secondary plant metabolites (Díaz and Cabido, 2001; Singer *et al.*, 2003), and
c) **landscape structures** such as field sizes and arrangements (Bianchi *et al.*, 2006; Holzschuh *et al.*, 2016; Steffan-Dewenter and Tscharntke, 1999), hedge sizes and arrangements (Batáry *et al.*, 2010; Biala *et al.*, 2007) and both sources and quantities of food and shelter for above- and below-ground animals (Altieri *et al.*, 2017; Altieri and Letourneau, 1982; Benton *et al.*, 2003; Potting *et al.*, 2005).

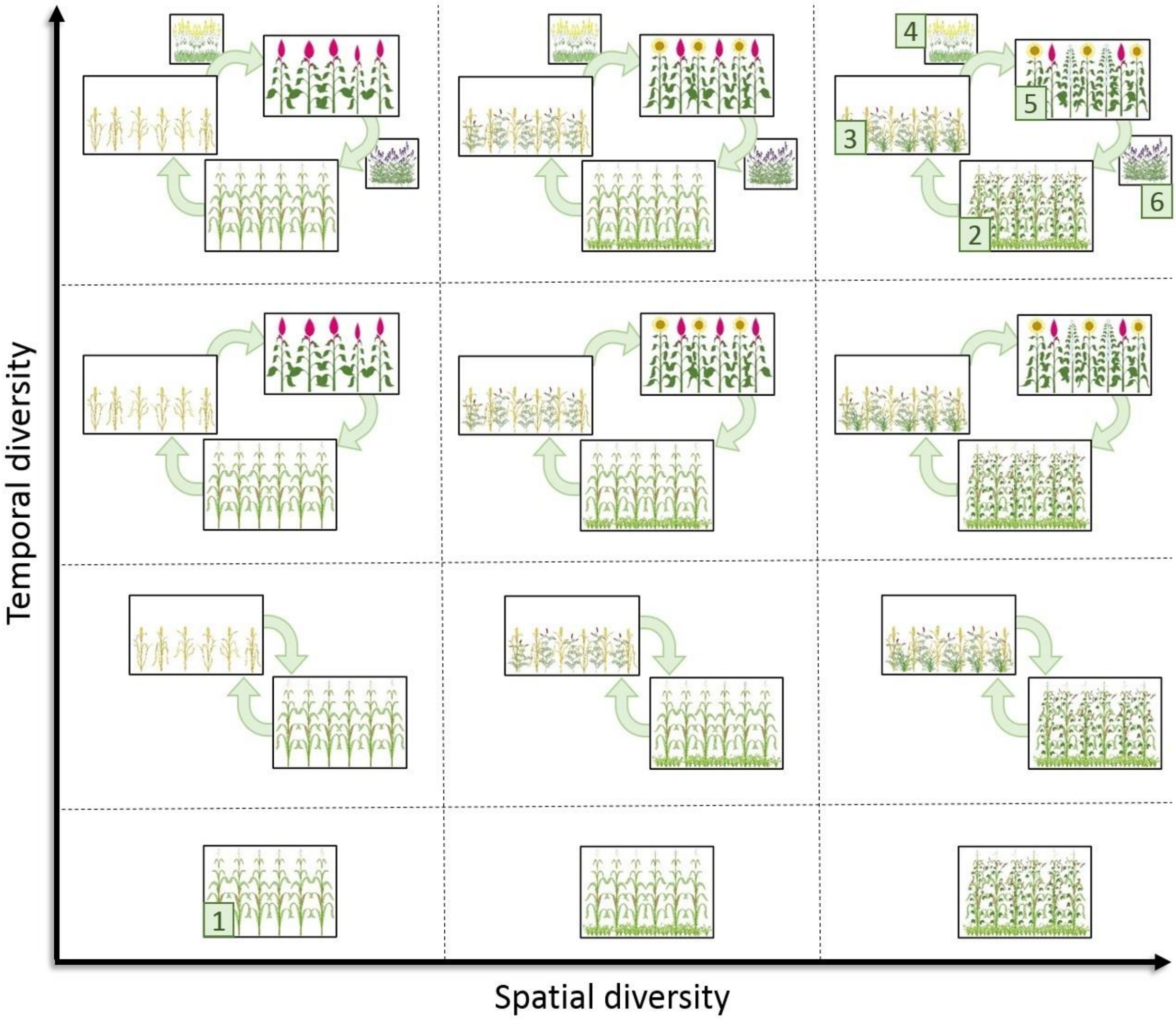

Figure 2: Schematic illustration of 12 theoretical combinations of temporal and spatial diversification measures for a biogas cropping system. The term 'temporal diversity' describes the number of crops over time. It can be increased through the implementation of crop rotations (green arrows) or catch crops (smaller pictures attached to arrows). 'Spatial diversity' describes the number of crops growing simultaneously on the same area. The lowest combined diversity level is represented by maize monoculture (1, bottom left corner) and the highest by a 3-year polycrop rotation of three different annual polycultures (top right corner): maize/grass/runner bean (2), wheat/common vetch/ryegrass (3) followed by winter catch crop (WCC) white mustard (4), sunflower/amaranth/mallow (5) followed by WCC phacelia (6). This figure does not represent the full complexity of all potential combinations and extensions of temporal and spatial diversification. Technical diversification measures such as variations of soil tillage and fertilizers are also not included.

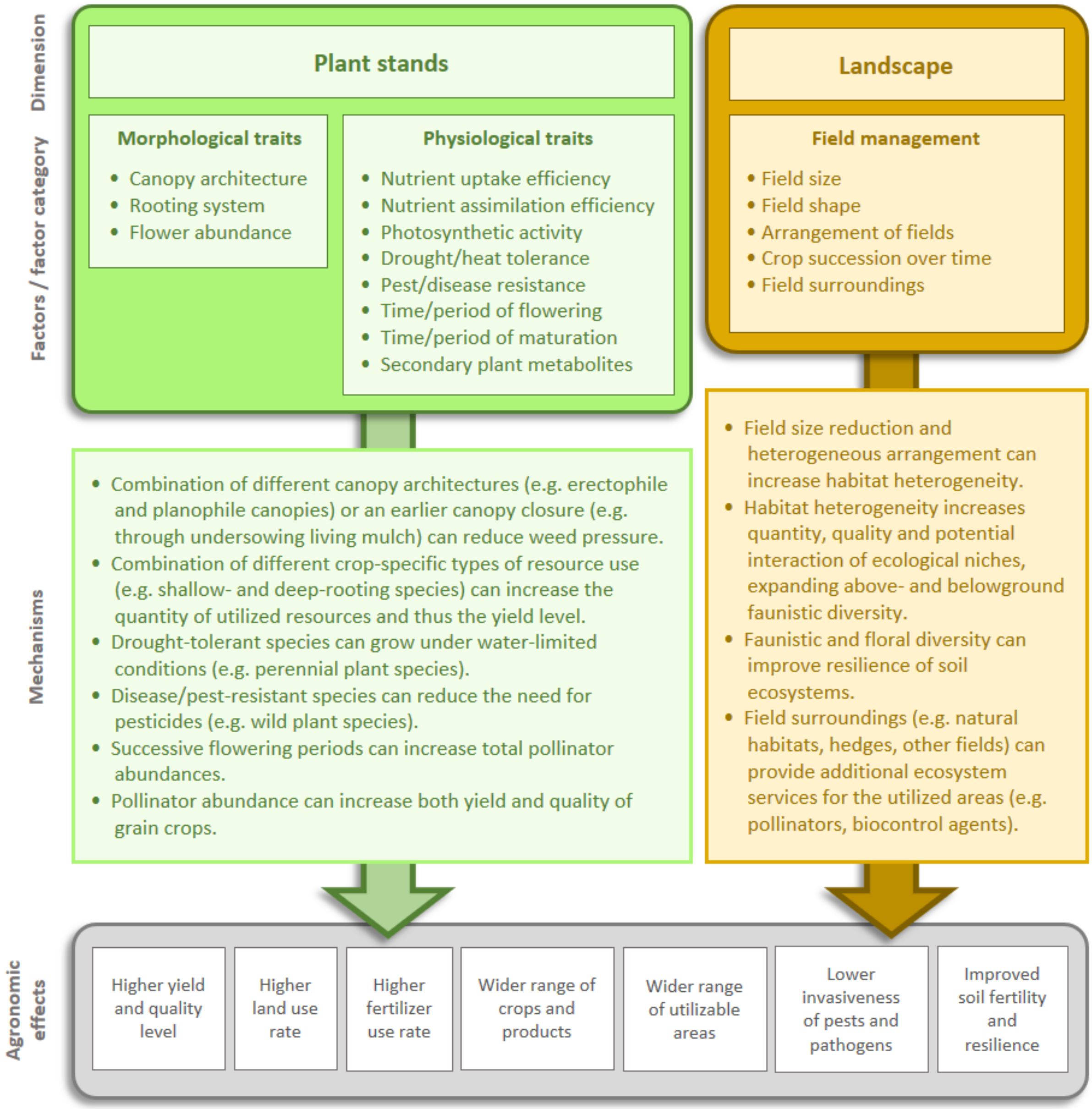

Figure 3: Overview of relevant factors and mechanisms potentially facilitating agronomic effects of agricultural diversification both within (green boxes) and between the plant stands/over time (brown boxes). The agronomic effects show the potential outcome for a best-case scenario.

Whereas morphological and physiological traits mainly influence yield and quality parameters, landscape structure can have yield-relevant effects on both natural pest control (Fig. 3) (Bianchi *et al.*, 2006; Perrin, 1975; Tscharntke *et al.*, 2016) and pollinator abundances (Holzschuh *et al.*, 2016; Kremen and Miles, 2012). When combined, temporal and spatial diversification strategies (Fig. 2) allow a higher habitat heterogeneity for above- and below-ground macro- and micro-fauna within agroecosystems (Altieri *et al.*, 2017; Benton *et al.*, 2003; Isbell *et al.*, 2017a; Liebman and Dyck, 1993; Van Der Heijden *et al.*, 2008). An increase in habitat heterogeneity is economically relevant because it enables a more balanced relation between plant herbivores and their antagonists (Potting *et al.*, 2005). This can improve natural pest control (Bianchi *et al.*, 2006; Tscharntke *et al.*, 2016) and thus reduce the need for synthetic or technical pest control.

Furthermore, it was found that crop diversity has a direct positive effect on ecosystem conditions (Hector and Bagchi, 2007; Weisser *et al.*, 2017), indicating that crop diversity may be more important for agroecosystem functioning than so far anticipated (Tscharntke *et al.*, 2005; Weisser *et al.*, 2017). Thus, the lower the temporal and spatial diversity (Fig. 2) of a specific cropping system, the higher the potential benefit of suitable diversification strategies for increasing it (Meyer *et al.*, 2016). Surprisingly, this is also true for mass-flower crops (MFC) such as sunflower (*Helianthus annuus* L.) and oilseed rape (*Brassica napus* L.). Once the field exceeds a certain size, these two crops lose their functional trait of supporting/increasing pollinator abundance through the supply of large quantities of nectar and pollen (Holzschuh *et al.*, 2016). This is mainly because of both a disproportional quantity of nest sites and flowering crops before and after the flowering periods of the MFC (Holzschuh *et al.*, 2016). Thus, field size is an important technical diversification factor. Hence, the various biological and technical categories of agricultural diversification have to be managed together as a system to mutually support agronomic (Fig. 3) and ecosystem functions (Altieri *et al.*, 2017; Hooper *et al.*, 2005; Potting *et al.*, 2005; Tscharntke *et al.*, 2005). Only then will agricultural diversification allow the devastating loss of biodiversity to be curtailed without compromising food security (Mockshell and Kamanda, 2017; Nicholls and Altieri, 2013). Accordingly, this study comprises three categories of diversification as follows:

1. The most common strategy of agricultural diversification is to replace monocultures with crop rotations (Fig. 2) or to adjust existing crop rotations to include alternative crops or additional crops (Bullock, 1992; Liebman and Dyck, 1993; McLaughlin and Mineau, 1995; Reheul *et al.*, 2017). This basic diversification strategy allows the crop species heterogeneity to be increased over time. It is therefore defined as 'temporal diversification'. Temporal diversification induces intentional negative feedback effects (disturbance) on the response diversity (Elmqvist *et al.*, 2003) of the "*complex adaptive systems*" (Folke, 2006) they are involved in. These more or less 'controlled disturbances' can increase the "*ecosystemic stability*" (Díaz and Cabido, 2001) against sudden alterations or disturbances due to climate change or invasive pests (Altieri *et*

al., 2015; Gaudin *et al.*, 2015; Tscharntke *et al.*, 2005). Thus, a continuous disturbance of the agroecosystem ensures the maintenance of its resilience, i.e. its "*capacity to reorganize after disturbance*" (Tscharntke *et al.*, 2005) on a high level in the long term (Chapin Iii *et al.*, 2000; Deutsch *et al.*, 2003; Elmqvist *et al.*, 2003; Weisser *et al.*, 2017) rendering a better yield stability (Gaudin *et al.*, 2015) compared to less resilient ecosystems. Adding catch crops before spring crops can increase ecosystem services such as reduction of erosion and nitrate leaching (Beaudoin *et al.*, 2005; Constantin *et al.*, 2010).

2. The potential sum of ecosystem services (Díaz and Cabido, 2001) can be further facilitated through the simultaneous cultivation of two or more crops on the same area, as can be found in double cropping (Heggenstaller *et al.*, 2008), intercropping (Liebman and Dyck, 1993; Ofori and Stern, 1987; Vandermeer, 1992) and other types of multiple cropping systems (Andrews and Kassam, 1976; Anex *et al.*, 2007; Isbell *et al.*, 2017a). These strategies are defined as 'spatial diversification' (Fig. 2) (Liebman and Dyck, 1993). Some key factors contributing to the collective performance of polycultures are: (i) plant morphology (Fig. 3), (ii) plant physiology (Fig. 3), (iii) species composition (Weißhuhn *et al.*, 2017), and (iv) planting geometry (Yang *et al.*, 2015).
3. Another strategy that can be classified as spatial diversification is the implementation or optimization of perennial cropping systems (Emmerling, 2014; Lewandowski *et al.*, 2003; Mast *et al.*, 2014) or perennial polycultures (Weißhuhn *et al.*, 2017). Perennial crops require less tillage and some of the most relevant perennial crops such as miscanthus, switchgrass and short rotation coppice can be harvested in winter when the topsoil is frozen. Thus, even when grown in monocultures, perennial crops increase soil biodiversity, inter alia due to the absence of soil disturbance and a continuous input of organic matter to the soil (Felten and Emmerling, 2011). Furthermore, perennial cropping systems can potentially improve the mid- to long-term sustainability of agronomic and environmental aspects of: (i) soil fertility (Emmerling, 2014; Weißhuhn *et al.*, 2017), (ii) erosion prevention (Cosentino *et al.*, 2015; Sanderson and Adler, 2008; Wiesenthal and Mourelatou, 2006), (iii) balance and structure of soil organic carbon (John *et al.*, 2005; Lal, 2004), (iv) GHG mitigation (Kiesel *et al.*, 2016; Lal, 2004; Rowe *et al.*, 2009), and (v) utilization of certain types of land defined as marginal and therefore unsuitable for annual crops due to biophysical,

socio-economic or environmental constraints (Edrisi and Abhilash, 2016; Lewandowski *et al.*, 2003; Mehmood *et al.*, 2017).

Consequently, agricultural diversification covers a wide range of both temporal and spatial measures to overcome biodiversity losses caused by agriculture. Although there are many comprehensive reviews on potential diversification strategies for feed and food crops (Altieri *et al.*, 2015; Andrews and Kassam, 1976; Liebman and Dyck, 1993; Perrin, 1976), research focusing on industrial crop cultivation (ICC) for biogas production in particular (Amon *et al.*, 2007a; Herrmann *et al.*, 2016b) has only just begun.

1.2. The role of industrial crop cultivation and biogas production

The key challenge for the diversification strategies mentioned above is the achievement of both long-term productivity and yield stability at least comparable to those of less diverse cropping systems. This challenge is especially important in the context of negative future climate change effects on agriculture (Pachauri *et al.*, 2014). It requires comprehensive investigation of resource-efficient and highly productive cultivation strategies for both food crops (including pasture and feed crops) and industrial crops the two main types of crops in arable cropping (Foley *et al.*, 2005). Currently, FCC has higher impacts on biodiversity than ICC due to its much higher (and further increasing) share of land surface (Foley *et al.*, 2005) and resource use. Conversely, the feasibility of ICC will increase because of (i) its GHG mitigation potential through the substitution of fossil-resource consumption (Edenhofer *et al.*, 2013; Rowe *et al.*, 2009), especially in times of increasing negative externalities mainly due to anthropogenic climate change (Pachauri *et al.*, 2014) and (ii) its suitability for marginal lands unfavorable for FCC (Krasuska *et al.*, 2010), such as contaminated (Didier *et al.*, 2012) and drought-affected sites (Lewandowski *et al.*, 2003). Accordingly, the global demand for biomass-based renewable energy and bio-based products are expected to further increase in the future (Berndes *et al.*, 2003) despite the fact that fossil resources still dominate the markets (Weiland, 2010; Witt *et al.*, 2012).

Nevertheless, the limitations of fossil resources (GHG mitigation) and the climatic impact of their ongoing use (climate-change adaptation) (Edenhofer *et al.*, 2013) have already become crucial political issues worldwide. The intention of finding a sustainable solution to this fundamental problem has led to the development of the bioeconomy (Birner, 2018; BMBF and BMEL, 2015; Lewandowski, 2015), also called “Biobased Economy” by the OECD in 2002

(Sheppard *et al.*, 2011). The paradigm of the bioeconomy includes sustainable ICC as an indispensable component of agricultural policies aiming to ensure sustainable biomass production, in particular with respect to biodiversity conservation (Blackmore *et al.*, 2011; Lewandowski, 2017) and climate change (Cosentino *et al.*, 2012). ICC generally allows the implementation of all the major diversification strategies mentioned above, since numerous industrial crops (Amon *et al.*, 2007a; Bauer *et al.*, 2010; Diamantidis and Koukios, 2000; Herrmann *et al.*, 2016b; Krasuska *et al.*, 2010; Mast *et al.*, 2014; Seppälä *et al.*, 2013; Venendaal *et al.*, 1997) and conversion routes (Edenhofer *et al.*, 2013; Prochnow *et al.*, 2009a, 2009b) are available. In Germany, biogas production is currently the most relevant biomass conversion route (Witt *et al.*, 2012). As such, this sector urgently requires more diverse and yet profitable cropping systems. This is described in the following section.

Biogas production is capable of providing a storable and continuously generated source of energy (German Council of Environmental Advisors, 2007; Weiland, 2010), both at large-scale commercial level and at small-scale household level (Winkler *et al.*, 2017). The integration of biogas production into organic farming systems can further improve the overall economic and socio-ecological benefits (Blumenstein *et al.*, 2018). In Germany, it has been demonstrated that all technical and economic adaptations to energy policies required to enable an expansion of ICC for biogas production could be realized within a decade (Weiland, 2006; Witt *et al.*, 2012). However, the rapid development of the biogas sector over the past two centuries also showed (i) that state incentives are required to allow for such fast implementations (Federal Ministry of Justice and Consumer Protection, 2017), (ii) which mistakes can occur in such interventions (Emmann *et al.*, 2013; Witt *et al.*, 2012), and (iii) to which types of environmental impacts (Verdade *et al.*, 2015) these mistakes can lead. The German Renewable Energy Act (Federal Ministry of Justice and Consumer Protection, 2017; Lang and Lang, 2015) failed to implement socio-ecological "*sustainability requirements of biomass*" as one of its targets (BMWi, 2014). Consequently, the concept of biogas production in Germany switched from being an environmentally oriented conversion route for organic residues (Holm-Nielsen *et al.*, 2009) to being a high-performance bioenergy pathway predominantly depending on biomass exclusively cultivated for biogas production (Amon *et al.*, 2007b; Witt *et al.*, 2012). This resulted in increased rents for arable land and thus both direct and indirect competition with food and feed production. The shift was mainly facilitated through an increase in maize proportions in existing crop rotations over 45% in many regions (Karpenstein-Machan and

Weber, 2010; Otte, 2010), due to the generally high methane yield performance of maize (Herrmann, 2013; Herrmann and Rath, 2012; Otte, 2010; Witt *et al.*, 2012). Maize cultivation has a comparatively low methane yield related nitrate N-load (Svoboda *et al.*, 2015). However, high proportions of maize in crop rotations can have negative impacts on biodiversity (Otte, 2010) accompanied by further negative externalities such as erosion or decreasing soil organic matter (Meyer *et al.*, 2016; Svoboda *et al.*, 2013; Vogel *et al.*, 2016) if good agricultural practices are ignored. This trend goes in the opposite direction to what was initially intended by the implementation of the German Renewable Energy Act (German Council of Environmental Advisors, 2007). However, the high energy-related proportion of maize (over 60%) in the substrate used for biogas production (Witt *et al.*, 2012) also indicates that biomass from agricultural, urban and livestock wastes alone is not sufficient to supply the amount of biomass required from biogas production to balance out other renewable energies such as wind energy and photovoltaics. For Germany, this implies that crops exclusively cultivated for biogas production are more relevant than alternative residue-based resources (Witt *et al.*, 2012).

The principles of good ICC practice for biogas production has not yet been implemented adequately in Germany because it does not meet the major agricultural challenges of (i) biodiversity conservation, (ii) climate change adaptation, (iii) GHG mitigation, (iv) food security, and (v) environmental protection (Heaton *et al.*, 2013; Tilman *et al.*, 2009). Maize-dominated cropping systems often lack relevant ecosystem services such as feed sources for pollinators (Höcherl *et al.*, 2012), soil erosion protection and nitrogen leach mitigation (due to late canopy closure). Potential diversification strategies to fill these gaps in ecosystem services could be:

- The expansion of crop rotations through annual crops, e.g. sunflower and amaranth, that provide high quantities of nectar and pollen over longer periods than maize (Höcherl *et al.*, 2012; Isbell *et al.*, 2017a; Tilman *et al.*, 2014) (Fig. 2).
- The intercropping of maize (or other annual biogas crops with comparably late canopy closure, e.g. sorghum ((*Sorghum bicolor* L. MOENCH) and amaranth) with living mulch or legumes to achieve an earlier canopy closure (Duchene *et al.*, 2017; Ofori and Stern, 1987; Wall *et al.*, 1991) (Fig. 2).
- The cultivation of perennial polycultures such as perennial wild plant mixtures (WPM) (Emmerling *et al.*, 2017; Von Cossel and Lewandowski, 2016; Weißhuhn *et al.*, 2017).

Although a few studies have addressed the strategies mentioned above, many technical questions on the realization of specific diversification measures still remain unanswered. Additionally, the breeding of new varieties or crossings is required for certain cropping systems, such as multiple cropping or low-input systems (Phillips and Wolfe, 2005). This leads to the very basic economical challenge of evaluating the biogas substrate quality of all the various genotypes and polyculture combinations with limited resources in the future, since biogas substrate quality is a very complex parameter to access (Angelidaki *et al.*, 2009, 1999, 1993; Weiland, 2010). While promising biogas substrate quality prediction models based on chemical composition are available for maize (Rath *et al.*, 2015, 2013), only little information exists on other biogas crops (than the most prevalent maize and WCCS) such as amaranth or substrate mixtures (Herrmann *et al.*, 2016b) such as wild plant mixtures. Despite high coefficients of correlation, none of the available models for biogas substrate quality prediction across crops are completely convincing. There are several reasons for this including low numbers of crop species in the dataset (Alaru *et al.*, 2011; Triolo *et al.*, 2011), a low total number of observations (Alaru *et al.*, 2011; Dandikas *et al.*, 2014; Thomsen *et al.*, 2014; Triolo *et al.*, 2011), and the exclusion of an intercept in the model (Thomsen *et al.*, 2014). Thus, the implementation of more diverse biogas cropping systems not only requires an improved understanding of biomass yield and yield stability performance from alternative crops and cropping systems, but also more reliable and cost-efficient methods to predict their biogas substrate quality. The accuracy of these substrate quality prediction methods becomes even more relevant for economic feasibility studies at regional scale. Such studies have recently been conducted by Niu *et al.* (2016) but these remain somewhat deficient for a number of reasons such as an insufficient model setup and an unrepresentative range of crops used for the model generation (Von Cossel *et al.*, 2018b).

1.3. Aims of this study

On this background, the defined research objective of this study was the development of strategies for agricultural diversification of biogas crop cultivation. To address this objective, the cultivation and evaluation of alternative crops and cropping systems were considered due to the following reasons:

On the one hand, further diversification strategies are required for improving the development of a more sustainable crop-based biogas production in the long-term. The broader the knowledge about potential biogas crops and biogas cropping systems the higher the chance to develop those not only performing economically feasible but also contributing to biodiversity conservation. For example, there is little knowledge on the performance of amaranth as a biogas crop or the long-term performance of WPM as biomass source for biogas production, even though both amaranth and WPM provide important functional traits such as high flower abundances, high nectar supply and long flower periods rendering them as potential diversification strategies for biogas cropping systems. There is also no information on the suitability of legume intercropping for amaranth cultivation, although it could increase its ecosystem value as in maize cultivation. On the other hand, the predictability of biogas substrate quality from more diverse cropping systems remains unclear. This creates a fundamental knowledge-gap because biogas substrate quality is relevant for the economic performance of a biogas crop and is a major selection criterion in the management of biogas cropping systems. Therefore, this study not only addresses alternative biogas crops and biogas cropping systems, but it also includes a meta-analysis of a recently discussed method for predicting biogas substrate quality.

The following research questions were formulated:

1. How does amaranth perform as a biogas crop compared to maize and what are the major opportunities for and obstacles to the large-scale implementation of amaranth cultivation?
2. How does the spatial diversification ‘legume intercropping’ perform in amaranth compared to maize and what are the major opportunities for and obstacles to its practical implementation?
3. How do perennial wild plant mixtures perform in biomass production with respect to yield, quality and species diversity in the long-term and what are the relevant agronomic factors?
4. How do available models perform in the prediction of specific methane yield of different crops based on their lignocellulosic biomass composition and how could they be improved?

2. The investigation of temporal and spatial diversification strategies for biogas cropping systems

This section addresses research questions 1 – 3 and provides new insights on both temporal and spatial diversification strategies to improve the environmental sustainability of biogas cropping systems. Overall, different life-cycles (annual, biennial and perennial species) and combinations of crops (sole cultivation, intercropping and mixed cropping) were investigated under field conditions in southwest Germany within the years 2011-2015. These experiments led to two peer-reviewed articles (Von Cossel *et al.*, 2017a; Von Cossel and Lewandowski, 2016) which are presented in this section:

- (2.1) Von Cossel, M., J. Möhring, A. Kiesel and I. Lewandowski. 2017. „Methane yield performance of amaranth (*Amaranthus hypochondriacus* L.) and its suitability for legume intercropping in comparison to maize (*Zea mays* L.).” *Industrial Crops & Products* 103: 107-121. Doi: 10.1016/j.indcrop.2017.03.047. http://dx.doi.org/10.1016/j.indcrop.2017.03.047,
- (2.2) Von Cossel, M. and I. Lewandowski. 2016. “Perennial wild plant mixtures for biomass production: Impact of species composition dynamics on yield performance over a five-year cultivation period in southwest Germany” *European Journal of Agronomy* 79: 74-89. Doi: 10.1016/j.eja.2016.05.006. http://dx.doi.org/10.1016/j.eja.2016.05.006.

These articles demonstrate how various alternative crops and cropping systems could perform in terms of agricultural diversification of biogas crop cultivation. Along with the discussion of the empirical results, potential chances and research needs for practical implementations of the investigated crops and cropping systems were derived.

2.1. Methane yield performance of amaranth and its suitability for legume intercropping

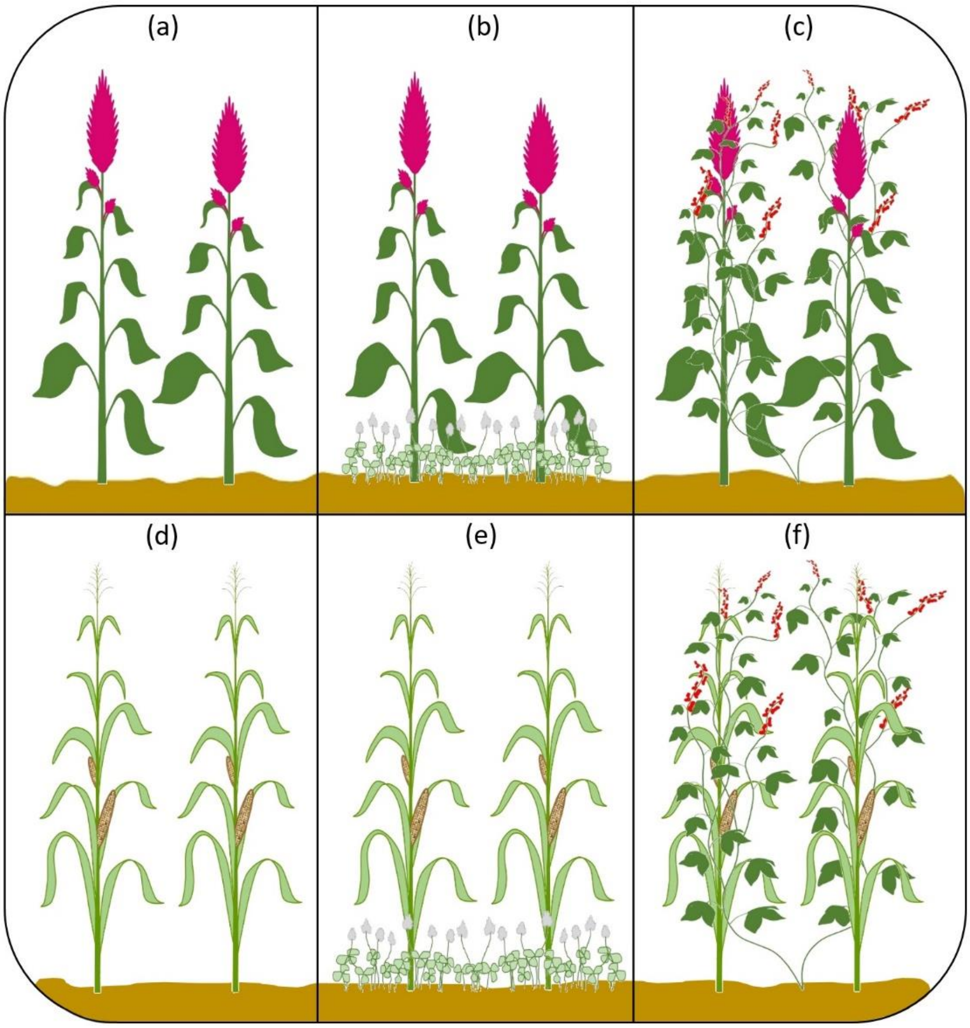

Figure 4: Schematic overview of cropping systems investigated by Von Cossel et al. (2017). A: Amaranth sole cultivation; B: Amaranth with undersown white clover; C: Amaranth intercropped with runner bean. For D-F, maize instead of amaranth.

Amaranth (*Amaranthus hypochondriacus* (L.)) is a promising alternative annual plant species for a closer investigation as biogas crop (Adamovics *et al.*, 2015; Brenner *et al.*, 2010; Eberl *et al.*, 2014; Gaduš *et al.*, 2012; Kaul *et al.*, 1996; Kodriková and Kolomazník, 2006). The implementation of amaranth into existing biogas cropping systems as an elementary measure of temporal diversification (Fig. 2) promises to support pollinators such as native/honey bees (*Apis* ssp. Linnaeus, 1758) and bumblebees (*Bombus* ssp. Latreille, 1802). These are the prevalent insect species being implicated by the ongoing biodiversity losses (Hallmann *et al.*, 2017). However, current knowledge about the agronomic performance of amaranth as biogas crop is poor compared to maize, especially in terms of diversification measures such as intercropping and mixed cropping (Eberl *et al.*, 2014; Gaduš *et al.*, 2012; Mursec *et al.*, 2009). The following article addresses research question 1 as it reports on the overall methane yield performance of a monocropped novel amaranth genotype (‘E2013’, Zeno-Projekte, Austria) in comparison to maize (‘Carolinio’, KWS, Germany) under plot trial conditions in Hohenheim, southwest Germany, from 2014 to 2015. Additionally, legume intercropping treatments with white clover (*Trifolium repens* L.; cv. RD84, Becker-Schoell, Germany) and runner bean (*Phaseolus vulgaris* L. cv. Gruenes Posthoernli, Sativa, Switzerland) were included to the field trials for investigating their suitability for biogas-amaranth (Fig. 4). These legume intercropping treatments were chosen for investigation due to their potential socio-economic effects on amaranth cultivation in context of nitrogen fixation (Cardoso *et al.*, 2007; Fujita *et al.*, 1992; Kaci *et al.*, 2018; Matson *et al.*, 1997), land equivalent ratio (Agegnehu *et al.*, 2006; Karpenstein-Machan and Stuelpnagel, 2000; Stoltz *et al.*, 2013) and landscape beauty (Borin *et al.*, 2010; Hodgson and Thayer, 1980). These positive effects of legume intercropping were also known for maize (Drinkwater *et al.*, 1998). Hence, the following article also addresses research question 2. Here, only the basic information on the article is provided, because the article was not published open access.

Methane yield performance of amaranth (*Amaranthus hypochondriacus* L.) and its suitability for legume intercropping in comparison to maize (*Zea mays* L.)

Moritz von Cossel[#a], Jens Möhring[b], Andreas Kiesel[a], Iris Lewandowski[a]

[#] Corresponding Author, E-Mail: mvcossel@gmx.de
[a] University of Hohenheim, Institute of Crop Science, Biobased Products and Energy Crops, Fruwirthstr. 23, 70599 Stuttgart, Germany
[b] University of Hohenheim, Institute of Crop Science, Biostatistics, Fruwirthstr. 23, 70599 Stuttgart, Germany, E-Mail: jens.moehring@uni-hohenheim.de
Industrial Crops and Products 103 (2017) 107-121;
http://dx.doi.org/10.1016/j.indcrop.2017.03.047

The use of amaranth as an alternative crop in biogas crop rotations has raised scientific interest Europe-wide over the past decade. However, the findings of available studies on its overall performance are contradictory. This study aims to examine both the performance of amaranth (*Amaranthus hypochondriacus* L.) as a biogas crop in comparison to maize (*Zea mays* L.) and to investigate its suitability for legume intercropping. Therefore, field trials were conducted in southwest Germany in 2014 and 2015. Two legumes (common bean (*Phaseolus vulgaris* L.) and white clover (*Trifolium repens* L.)) were selected for intercropping with amaranth and maize as main crops. Aboveground fresh matter yield, dry matter content (DMC), ash content and specific methane yield (SMY) were measured each year. The average methane yield per hectare (MYH) of amaranth was 3030.6 ± 87.3 m^3_N ha^{-1} in 2014 and 2265.6 ± 243.4 m^3_N ha^{-1} in 2015, about half that of maize each year. In 2015, the low MYHs resulted from low dry matter yields (DMYs) caused by drought conditions. For maize, this drought effect was much stronger than for amaranth. Over the two years, the average SMY was lower for amaranth (266.0 ± 1.7 l_N kg^{-1} of volatile solids (VS)) compared with maize (330.0 ± 1.5 l_N kg^{-1} of VS) due to high contents of both ash (> 13% of VS) and lignin (> 6% of VS). In both years, there was no significant effect of common bean intercropping on either the DMY or SMY of the main crops. White clover intercropping by contrast led to a significant decrease in DMY of both main crops in 2015. Overall, amaranth was found to be equally suitable for legume intercropping as maize. However, new genotypes and improved agricultural practices are needed to turn amaranth into a more productive biogas crop.

2.2. Perennial wild plant mixtures for biomass production

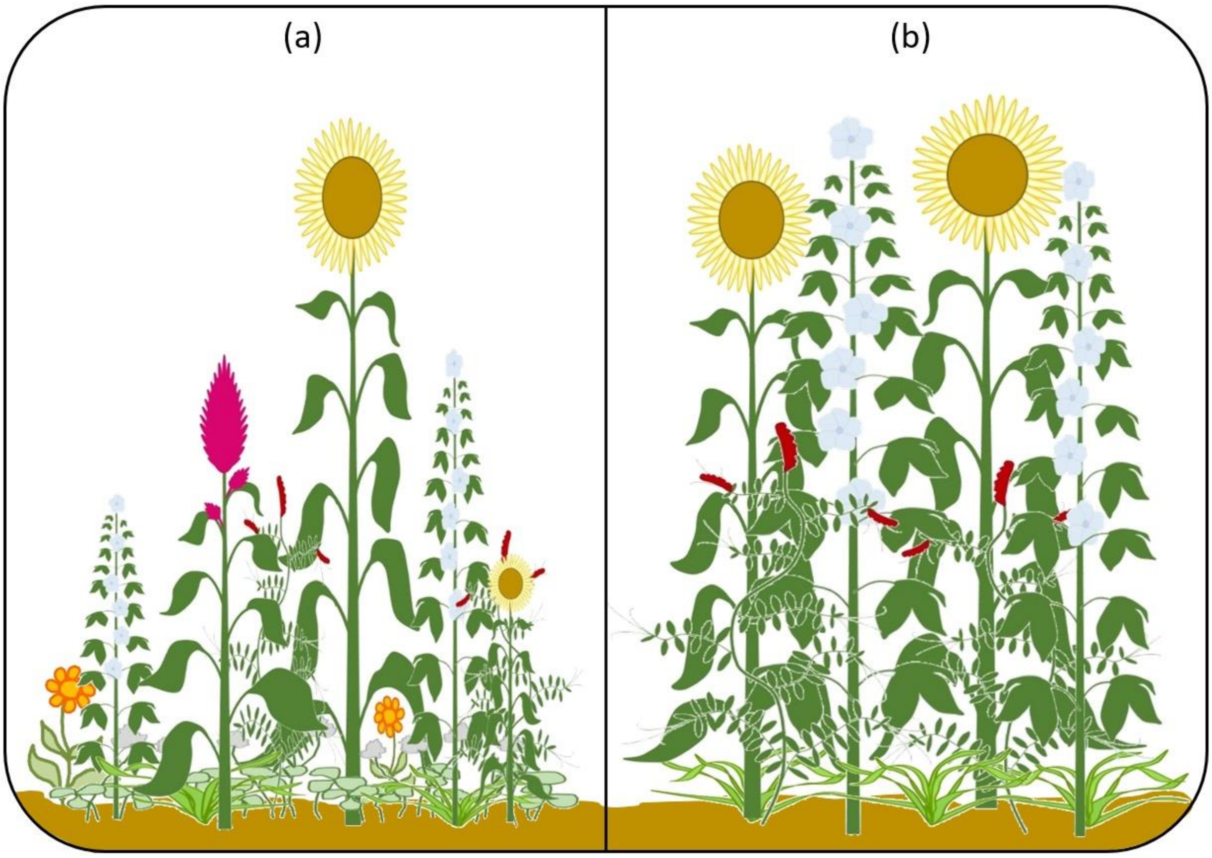

Figure 5: Schematic illustration of the two different wild plant mixtures S1 (A) and S2 (B) in the year of establishment. While S1 was expected to have higher species diversity than S2, S2 was expected to generate higher biomass yields.

Perennial wild plant mixtures (WPM; Fig. 5) are mixed cropping systems for biogas production developed by the Bavarian State Research Centre for Viticulture and Horticulture (LWG, Veitshöchsheim, Germany) in cooperation with the breeding company Saaten-Zeller GmbH & Co. KG (Eichenbühl, Germany) from 2008 to 2011 (Vollrath *et al.*, 2012). In 2011, the first WPM ("BG70", Saaten-Zeller) was available for farmers. It was a mixture of 25 mainly native wild annual, biennial and perennial plant species which were selected and combined according to (i) their suitability for anaerobic digestion, (ii) their biomass yield and (iii) their ecosystemic functions (Vollrath *et al.*, 2012). Hence, the cultivation of WPM was proposed to ensure both profitable annual methane yields and high spatial diversity over a cultivation period of at least 5 years, without any tillage or sowing required from the second year onwards. The diversity of the WPM plant stands was meant (i) to provide food and shelter for numerous open land animals, wild game, insects and birds, and (ii) to enable a high adaptability to site-specific biophysical constraints (Vollrath *et al.*, 2012). However, there was no information on both the long-term yield performance and species composition dynamics of the WPM so far, when the underlying field trials of the following article (Von Cossel and Lewandowski, 2016) were established at Hohenheim, Renningen and Sankt Johann (all sites in southwest Germany) in summer 2011. Therefore, the aim was to gather first insights into both the biomass yield performance and the species composition dynamics of WPM over a long time to improve the knowledge about both optimal composition and cultivation of WPM. Here, only the basic information on the article is provided, because the article was not published open access.

Perennial wild plant mixtures for biomass production: Impact of species composition dynamics on yield performance over a five-year cultivation period in southwest Germany

Moritz von Cossel[#] and Iris Lewandowski

[#] Corresponding author
University of Hohenheim, Institute of Crop Science, Dept. Biobased Products and Energy Crops, Fruwirthstr. 23, D-70599 Stuttgart, Phone: +4971145923557, Fax: +4971145924344, moritz.cossel@uni-hohenheim.de
European Journal of Agronomy 79 (2016) 74-89
http://dx.doi.org/10.1016/j.eja.2016.05.006

Wild plant mixtures (WPMs) are a promising perennial cropping system for biogas production with numerous ecological advantages. However, there is currently little information available on their long-term performance. To acquire such information, two different WPMs (S1, S2) of up to 27 endemic, predominantly wild species with a combination of annual, biennial and perennial life cycles were sown at three sites in southwest Germany in 2011. At Hohenheim (HOH), fertilization was varied (0, 50, 100 kg ha^{-1} nitrogen) and a split-plot design with three replications was applied. At Renningen (REN) and Sankt Johann (SJO), individual plots were used and fertilized with 50 kg ha^{-1}. Harvesting and sample testing was carried out each year over a five-year cultivation period. The development of dry matter yield (DMY), dry matter content (DMC) and species composition dynamics of WPMs were examined. There was wide variation in DMY between mixtures, sites and years ranging from 2.9–22.5 Mg ha^{-1} yr^{-1}. Significant mixture effects ($P < 0.001$) and site-age interactions ($P < 0.05$) were found. Over the five years, S2 had about 55% higher DMY than S1 (S2 accumulated DMY: 50.2-74.2 Mg ha^{-1}). For both mixtures, a high number (up to 19) of WPM species was observed, which then decreased over the cultivation period at all sites. The DMYs in REN and SJO increased over time, whereas in HOH they decreased due to the high weed pressure from the grassland pre-cultivation. At the site, the nitrogen mineralization of the grassland residues was sufficiently high to mask the effects of fertilization. A good substrate quality for ensiling (DMC > 28%) was achieved at all sites every year except for 2011. Therefore, we can recommend the WPM concept based on the S2 mixture as a practicable cultivation system with potentially high ecological benefits, especially for marginal sites.

3. Optimized models for the prediction of biogas substrate quality of alternative crops and cropping systems

This section is about the determination of crop-specific biogas substrate quality. A relevant improvement of biogas substrate quality prediction could on the one hand facilitate the progress in breeding and agronomy concerning alternative biogas crops, varieties and cropping systems. On the other hand, it could help optimizing practical implementation of biogas substrate quality prediction. These approaches can be found at farm scale in online measurements at harvest or in biogas plant process control and at regional scale in policy assessments (Niu *et al.*, 2016). For breeding and agronomy purposes, biogas substrate quality prediction methods are generally required since biogas batch assays are cost-intensive and time consuming (Dandikas *et al.*, 2014). In many cases, large numbers of samples have to be analyzed (Herrmann *et al.*, 2016b). One of the most common methods for biogas substrate quality assessment is the prediction of specific methane yield (SMY) of biomass using its lignocellulosic components (acid detergent lignin (ADL), cellulose (CL), hemicellulose (HC) and non-lignocellulose (RES)) as input variables. Several available studies on such SMY-prediction models report promising accuracies. Here, seven relevant models were evaluated within a meta-analysis based on a comparatively large dataset (n = 678). Additionally, this dataset was used for developing new SMY-prediction models to significantly improve the accuracy of SMY-prediction. This section includes the following publication:

- Von Cossel, M., J. Möhring, A. Kiesel and I. Lewandowski. 2018. „ Optimization of specific methane yield prediction models for biogas crops based on lignocellulosic components using non-linear and crop-specific configurations.” *Industrial Crops & Products* 120: 330-342. Doi: 10.1016/j.indcrop.2018.04.042. https://doi.org/10.1016/j.indcrop.2018.04.042.

Here, only the basic information on the article is provided, because the article was not published open access.

Optimization of specific methane yield prediction models for biogas crops based on lignocellulosic components using non-linear and crop-specific configurations

Moritz von Cossel*#a, Jens Möhring*b, Andreas Kiesel[a], Iris Lewandowski[a]

* First authors
[#] Corresponding author
[a] University of Hohenheim, Institute of Crop Science, Biobased Products and Energy Crops, Fruwirthstr. 23, 70599 Stuttgart, Fax: +49 (0) 711 459-22297, E-Mail: mvcossel@gmx.de
[b] University of Hohenheim, Institute of Crop Science, Biostatistics, Fruwirthstr. 23, 70599 Stuttgart, E-Mail: jens.moehring@uni-hohenheim.de
Industrial Crops and Products 120 (2018) 330-342
https://doi.org/10.1016/j.indcrop.2018.04.042

The prediction of the specific methane yield (SMY) of crop biomass based on its lignocellulosic composition is a promising tool in biogas plant management and bioenergy policies. The majority of studies on SMY prediction have found linear or non-linear models across crops with lignin content as major regressor variable. To investigate the effect of crop-specific regressions, a meta-analysis was conducted covering data from 14 published studies (518 observations) and three of the authors' own experiments (160 observations). This dataset includes a total of 678 observations of SMY and biomass components from 13 potential biogas crop species. These observations were used to (i) validate seven published models and (ii) both develop and cross-validate new linear and non-linear models with and without crop-specific regressions. The correlations of the available models ranged between r=0.12 and 0.51. New models showed higher correlations of up to r=0.66. Both crop-specific intercepts and slopes as well as the non-linear regressions led to a significant increase in the model predictability. Of these, the crop-specific intercepts resulted in the greatest improvement but at the same time remained easy to use and interpret. Therefore, it was shown that the inclusion of biomass source information contributes to the optimization of the SMY prediction precision.

4. General Discussion

In the general discussion, the basic findings of the articles presented in sections 2 and 3 (Von Cossel *et al.*, 2018b; Von Cossel *et al.*, 2017a; Von Cossel and Lewandowski, 2016) are controversially reviewed with regard to the research questions outlined in the introduction of this thesis.

The first research question addresses the performance of amaranth as an additional annual biogas crop in comparison to maize. This study has identified several qualitatively and quantitatively challenging factors that are decisive for the practical implementation of amaranth cultivation such as the dry matter yield level and the biogas substrate quality. Section 4.1 discusses in greater detail the most important factors and derives recommendations for breeders and agronomists.

The second research question concerns the suitability of biogas-amaranth for the spatial diversification 'legume intercropping' compared to maize. Here, it was found, that legume intercropping with runner bean (RB) and white clover (WC), respectively, has similar effects on biogas-amaranth and maize. Section 4.2 briefly analyzes the chances and challenges for future implementations of legume-intercropping in biogas-amaranth from both technical and eco-systemic perspectives.

The third research question is about the long-term performance of perennial wild plant mixtures (WPM) with respect to dry matter yield, substrate quality and species diversity. As shown in section 2.2, the WPM have revealed a wide range of dry matter yields over five years of cultivation, whereas a large variation of species compositions was observed. Section 4.3 synthetizes the potential links between agronomic and ecological aspects of WPM cultivation and derives recommendations for further improving the concept of WPM cultivation. Furthermore, it is discussed, where WPM should be cultivated for taking socio-ecological requirements such as food security, an environmentally benign production and vital wildlife habitats into account.

After several different alternative biogas crops and cropping systems were investigated (section 2), the question arose, how the biogas substrate quality of these various biogas-substrates could be assessed in a time- and cost-efficient way to enhance the progress in breeding and agronomic research. Here, the prediction of the biogas substrate quality is considered to be the most promising method, whereas many uncertainties on its applicability to alternative crops can be found in the literature. Therefore, the purpose of research question four is to test and improve available models for the prediction of the crop-specific biogas substrate quality. In section 4.4, the basic findings on this will be discussed in context of the potential role of SMY prediction for improving the assessment of more diverse biogas cropping systems in the future.

Finally, sections 4.5 and 4.6 aim at drawing a holistic picture of the chances and challenges of agricultural diversification of biogas crop cultivation under socio-ecological aspects (section 4.5) and the role of agricultural diversification within a growing bioeconomy (4.6).

4.1. Amaranth as an additional annual biogas crop for crop rotations

In the article entitled "*Methane yield performance of amaranth (Amaranthus hypochondriacus L.) and its suitability for legume intercropping in comparison to maize (Zea mays L.)*" (Von Cossel *et al.*, 2017a) (Section 2.1.) it was demonstrated how the introduction of amaranth (Fig. 6a) could perform as an additional temporal diversification measure in comparison to the most common biogas crop maize (Fig. 6b) in both mono- and intercropping regimes. Two field trials were conducted at the Ihinger Hof in southwest Germany in 2014 and 2015. For both

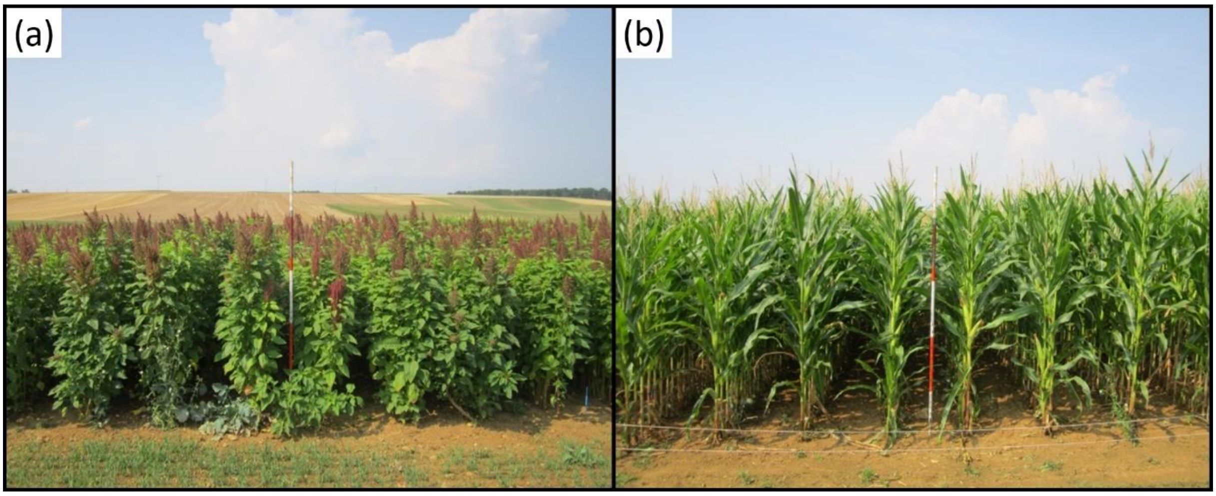

Figure 6: Monocropping treatments of amaranth 'E2013' (a) and maize 'Carolinio' (b) at Renningen on 12^th^ August 2015.

main crops (maize ('Carolinio', KWS, Germany) and amaranth ('E2013', G. Dobos, Zeno-Projekte, Austria), three nitrogen fertilization levels and four legume intercropping treatments were tested in 2014. The same was applied in 2015 except that two of the legume intercropping species (i) common vetch (*Vicia sativa* L.), and (ii) faber bean (*Vicia faba* L.) were excluded because their cultivation failed in 2014. Two additional amaranth genotypes (‘No.17’ and ‘Plaisman’, Slowenia) also failed in 2014 (field emergence rates ranged from 0 to 1 %) for unknown reasons and thus, they were not sown in 2015.

From an economic perspective, it was shown that the cultivation of amaranth and its use for biogas production is associated with both crucial qualitative and quantitative challenges. Four parameters have been identified which limit the economical suitability of amaranth crop for biogas production:

1. The dry matter yield (DMY),
2. the dry matter content (DMC),
3. the specific methane yield (SMY), and
4. the morphological development.

All these parameters were proven to be less preferable for amaranth compared to maize (Von Cossel *et al.*, 2017a). This was in line with the findings in the literature (Eberl *et al.*, 2014; Fritz *et al.*, 2012; Mursec *et al.*, 2009; Sitkey *et al.*, 2013). For the DMY and SMY, the economic relevance appears to be clear since (theoretically) the product of DMY and SMY is the methane yield per hectare (MYH), whereas the MYH is the key determinant for describing the performance of a crop or cropping system for biogas production. Consequently, if both DMY and SMY are low, the MYH will also be low. However, the DMY was found to be much more important for MYH than the SMY (Von Cossel *et al.*, 2017a). Additionally, the DMC and the morphological development indirectly affected the economic performance of amaranth as a biogas crop. Several technical, biological and morphological reasons lead to a minimum (about 28%) and a maximum (about 40%) threshold (Eberl *et al.*, 2014; Gebrehanna *et al.*, 2014) for an optimal DMC of biogas crops. This seems to be hardly manageable within amaranth cultivation:

1. The lower the DMC (below app. 28%), the higher the costs for processing the same quantities of biomass and the lower the quality of the silage (technical reason). Superfluous amounts of water within the biomass increase both the production costs and the silage effluent (Gebrehanna *et al.*, 2014). Additionally, negative effects of low DMC on ensilaging processes (Gebrehanna *et al.*, 2014; Haag *et al.*, 2015; Herrmann *et al.*, 2016b) increase the risk of ensilaging failure or a decrease in SMY of the silage (biological reason).

2. The higher the DMC (app. > 40%), the higher the indigestible fractions of lignocellulosic composition, i.e. lignin and lignin-bound cellulose due to the progressed maturation (morphological reason) (Herrmann *et al.*, 2016b).

For amaranth, the water content decreases rather slowly over the vegetation period (Eberl *et al.*, 2014; Fritz *et al.*, 2012; Von Cossel *et al.*, 2017a) compared to other crops such as maize (Von Cossel *et al.*, 2017a), *Miscanthus* × *giganteus* (J.M. Greef & Deuter ex Hodk. & Renvoize) (Kiesel and Lewandowski, 2017; Mayer *et al.*, 2014), *Sida hermaphrodita* (L.) (Jablonowski *et al.*, 2017) or even *Silphium perfoliatum* (L.) (Gansberger *et al.*, 2015). Whereas, the contents of lignin and ash were already much higher for amaranth than for maize at the same harvest date (Von Cossel *et al.*, 2017a). Thus, the low DMC (25.0%) was combined with high contents of constituents which negatively affect the SMY (266 l_N kg^{-1} VS^{-1}) (Von Cossel *et al.*, 2017a). In particular, these constituents were ash (13.6% of VS), lignin (6.5% of VS) (Von Cossel *et al.*, 2017a) and cellulose (32.9% of VS) (not published yet). This was in line with findings by Eberl *et al.* (2014) who reported a poor suitability of amaranth for ensilaging due to an average DMC of 23.6% at harvest accompanied by high contents of ash (13.7% of VS), ADL (5.8% of VS) and cellulose (26% of VS), which caused a much lower SMY (270 l_N kg^{-1} VS^{-1}) compared to maize (350 l_N kg^{-1} VS^{-1}). Additionally, some fractions of amaranth potentially increasing the SMY such as seeds and leaves are shed immediately after first frost nights in autumn (unpublished observations). This means that the harvest date of amaranth should not be delayed until the DMC is above 28% to avoid severe decrease of SMY caused by outstanding high lignin and ash contents as well as frost damages (leave losses). Therefore, in this study, amaranth was harvested two (2014) and four (2015) weeks later than maize, but its DMC was still lower than that of maize. It was no option to wait longer with the harvest of amaranth due to the occurrence of night frost, which causes amaranth leaves to shed. It was observed that amaranth biomass is even more lignified without leaves while the DMC remains rather low. However, amaranth also yielded significantly lower than maize even though it is also a C4-plant (Sage and Sage, 2013; Stallknecht and Schulz-Schaeffer, 1993) and was fertilized at the same N rates (Von Cossel *et al.*, 2017a). This could mainly be traced back to two relevant differences in planting material and cultivation method between amaranth and maize:

1. The amaranth genotype ‘E2013’ was only a prototype for biogas production from a small breeding company (ZENO PROJEKTE, Wien, Austria). Other studies on biogas-amaranth were also based on genotypes which have only recently been bred for biogas

purpose (Eberl *et al.*, 2014; Fritz *et al.*, 2012). Whereas, the maize genotype ('Carolinio') used as reference was an intensively bred variety especially tailored for biogas production from a globally operating company (KWS SAAT SE, Einbeck, Germany).

2. The knowledge about the cultivation of biogas-amaranth (i.e. with 'mass-growth' being the major trait instead of 'grain yield') under temperate climate was far less developed than for maize. Maize has already been cultivated for forage use (Struik, 1983) in Europe for green foddering since the early 18th century and for silage use since the late 1950s (Barrière *et al.*, 2006) – long before it was initially used for biogas production. Similar requirements for biogas production and silage for forage use regarding the qualitative composition of the biomass encouraged a rapid implementation of silage maize for biogas production. Thus, there were many uncertainties about optimal biogas-amaranth cultivation such as sowing technique, planting geometry, fertilizer requirements and harvest determination when the field trials for this study were prepared. Whereas for biogas maize cultivation, the best agronomic practices under temperate climate conditions were well known (Herrmann *et al.*, 2005, 2009; Herrmann and Taube, 2005; Svoboda *et al.*, 2015).

This indicates that both the genetic and the eco-physiological potentials - which together form the key elements of primary production (Lewandowski *et al.*, 2018b) – are insufficiently known for amaranth. Therefore, not only high-bred varieties but also a better agronomic understanding are recommended for a better implementation of amaranth as a biogas crop. It was concluded that the following relevant plant morphological and physiological traits are relevant for future breeding of biogas amaranth varieties (in alphabetical order):

- <u>Drought tolerance</u> improves the growth-suitability of amaranth on drought affected areas which helps reducing conflicts with food crop cultivation for good quality land,
- <u>Early maturation</u> avoids late harvest in autumn when (i) both trafficability and chances for establishing a winter-crop decline, and (ii) the risk of frost damage increases,
- <u>Frost tolerance</u> enables earlier sowing and increases field emergence rate,
- <u>Cold-tolerance</u> allows for both earlier sowing and the cultivation in areas with temperature or growth season limitations, e.g. in the Swabian Jura in south-western

Germany where amaranth (as part of a WPM) did not emerge (Von Cossel and Lewandowski, 2016),

- High thousand kernel weight enables a higher germination rate and a better homogeneity of the plant stands,
- Mass growth increases biomass yield, and
- Optimal quality and ratio of stem, leaves and flower (likely a high proportion (> 40%) of dry matter yield of flower combined with thin (0.5 – 2 cm) stems improves dry matter content and biogas substrate quality.

Furthermore, future investigations of biogas-amaranth cultivation should aim at both closing agronomic yield gaps and ensuring more environmentally sound production. Therefore, the following agronomic research questions are supposed to be worth being (further) investigated in more detailed, whereas some of them are already under investigation for grain-amaranth (in alphabetical order):

- No-till or reduced tillage suitability to reduce GHG emissions, sequestrate CO_2 and increase soil fertility,
- Optimal harvest time determination according to optimal leaf-N-content (Kaul *et al.*, 1996) and stem-lignin-content aiming at optimizing the biogas substrate quality for both ensilaging and anaerobic digestion,
- Planting geometry such as row width and row distance (Gimplinger *et al.*, 2008; Pospišil *et al.*, 2011; Stallknecht and Schulz-Schaeffer, 1993) to improve the composition, yield and harvestability of amaranth biomass,
- Soil- and climate-specific sowing density to avoid agronomic yield gaps through too high or too low plant densities,
- Crop rotation effects in terms of N return (Aufhammer *et al.*, 1995) and adequate weeding strategies.

Additionally, high contents of essential micro-nutrients such as manganese (Mn), iron (Fe), cobalt (Co) or nickel (Ni) in amaranth dry matter (Eberl *et al.*, 2014; Eberl and Fritz, 2018) could render amaranth as an important co-substrate in biogas plants mainly fed with silage maize, because it could (i) substitute synthetic additives, (ii) stabilize the fermentation process, and (iii) reduce the GHG emissions of biogas production (Eberl *et al.*, 2014). On the contrary, amaranth should not be grown on heavy metal contaminated soils due to its high uptake rates for heavy metals such as cadmium (Cd) or lead (Pb) (Alam *et al.*, 2003; Bian *et al.*, 2014). High contents of heavy metal within the biogas substrate could (i) reduce the efficiency of anaerobic digestion processes, and (ii) accumulate within the digestate, which would contaminate areas with heavy metals when being applied. Instead, on heavy metal contaminated sites, amaranth could perhaps be an option for phytoremediation (Franco-Hernandez *et al.*, 2010; Sauer and Ruppert, 2011) as long as the risk of heavy metal leaching remains low (Ali *et al.*, 2013). Either way, amaranth biomass from contaminated sites requires a good quality management (Al Seadi *et al.*, 2013) and biogas production could still be an option as has been supposed for maize (Meers *et al.*, 2010). However, amaranth biomass from contaminated sites should rather not be used for biogas production, if there are no adequate disposal or treatment strategies for the heavy metal contaminated digestate (Meers *et al.*, 2010).

Overall, amaranth showed great potential of ecosystemic benefit in this study under biodiversity aspects, because it provided both nectar and pollen over a much longer period than maize (only pollen) (Von Cossel *et al.*, 2017a). It was observed that the flowers of amaranth attracted numerous insect species such as wild bees, honey bees and bumble bees. Consequently, pollinators are expected to have a higher benefit of amaranth stands compared to maize stands, although it has to be mentioned, that maize pollen can at least function as 'primary care' (feeding source of lower quality) for pollinators as well (Höcherl *et al.*, 2012). Thus, it needs to be kept in mind, that amaranth should not replace maize completely. Instead, amaranth should be combined with maize and other crops following either good agricultural practices (FAO and WHO, 2014) or agri-environmental practices (Beaudoin *et al.*, 2005). Furthermore, the field size of amaranth stands must be considered in terms of negative agro-ecological effects through mass-flowering such as a decrease of pollinator populations (Holzschuh *et al.*, 2016) and the distances to field boundaries (Nicholls and Altieri, 2013). Hence, the cultivation of biogas-amaranth could be more environmentally beneficial on several smaller fields than on a few very large fields. This also implies the integration of amaranth into cropping systems with wide crop rotations (Figs. 2, 3) as well as the use of catch crops to avoid N losses due to the late harvest of amaranth (Aufhammer *et al.*, 1995). Additionally, the amaranth inflorescence could benefit pollinators in regions where oilseed rape, camelina or other early flowering crops are predominantly cultivated - especially in late summer when pollinators are preparing to overwinter (Gallinat *et al.*, 2015). Here, biogas-amaranth could become a high-quality source of feed for pollinators (Brenner *et al.*, 2000) when other sources have disappeared. Consequently, biogas-amaranth cultivation could generally help to increase the landscape heterogeneity and generate agronomic return (Fig. 3) if good agricultural practices (FAO and WHO, 2014) are considered. Moreover, the deep red inflorescences of amaranth (Fig. 7b and d) adds aesthetical value to the landscape. This could generally help to improve the public perception of biogas crop cultivation. On this background, it is highly recommended to continue research in the field of biogas-amaranth breeding which has just begun (Stetter *et al.*, 2015, 2016).

4.2. Spatial diversification of biogas-amaranth cultivation via 'legume intercropping'

In this study, it was concluded that the intercropping of biogas-amaranth with flower-rich legumes such as runner bean (RB) and white clover (WC) (Fig. 7) could add more ecosystemic functions to the cultivation of biogas-amaranth. These additional ecosystemic functions could be (i) an additional source of nectar and pollen, (ii) an earlier canopy closure (soil cover), (iii) a reduction of nitrogen leaching and N_2O emissions (Schmeer *et al.*, 2014), (iv) a substitution of synthetic nitrogen fertilizer via nitrogen fixation by rhizobium, and (v) a stimulation of soil microbial community followed by an increase in soil fertility (Song *et al.*, 2007; Zak *et al.*, 2003). Therefore, widening biogas crop rotation systems (Fig. 2) including legume-intercropped amaranth (Fig. 7) could contribute towards a more environmentally benign biogas crop cultivation at regional scale. Under aspects of biodiversity conservation, this would have several benefits such as a longer flowering period and a higher habitat heterogeneity (Benton *et al.*, 2003).

Nonetheless, the intercropping system of amaranth and RB needs further improvements similar to what has been reported for RB intercropping with maize (Nurk *et al.*, 2017a, 2015; Schmidt, 2013). For instance, both the planting geometry (sowing densities × row distances) and the sowing procedures of amaranth and RB need to be further investigated. Especially the sowing procedure presented in Von Cossel *et al.* (2017a) was rather experimental and not ready for practical implementation. It would be better to sow both species together in one sowing procedure instead of conducting two subsequent sowing procedures. However, the joint sowing of amaranth and RB could be challenging because of the different TKW of amaranth (< 1 g) (Brenner *et al.*, 2000) and RB (192 – 529 g) (Boros *et al.*, 2014). In this study, it was not investigated how RB influences the biogas substrate quality (i.e. DMC and SMY) of the substrate mixture of amaranth and RB. The reason of this was that (i) the share of RB was low each year compared to the findings of Nurk *et al.* (2017a) due to technical problems during the sowing procedures (Von Cossel *et al.*, 2017a) and (ii) no mixture-series were conducted as

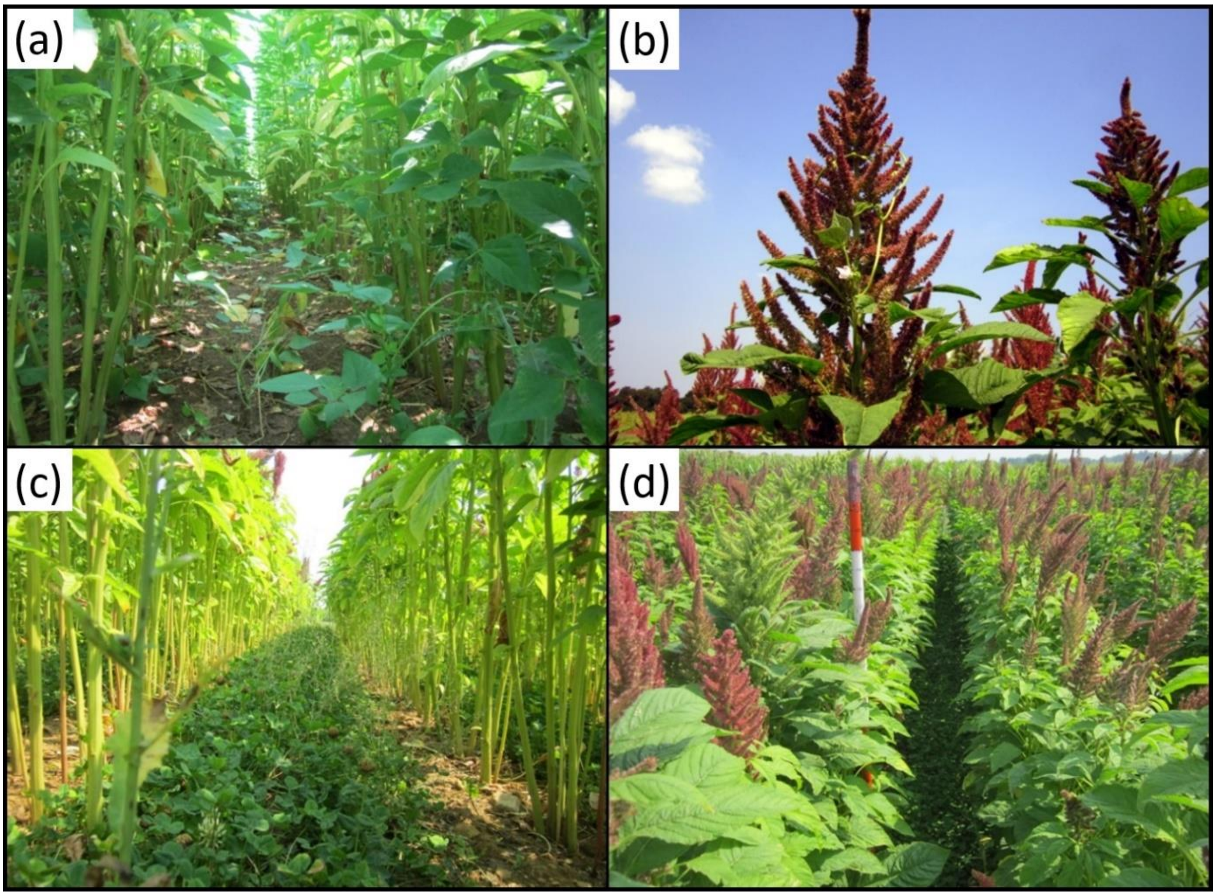

Figure 7: Amaranth intercropped with runner bean (a, b) and white clover (c, d) at Renningen on 12th August 2015.

has been reported for RB and maize (Nurk *et al.*, 2017b). Both DMC (Von Cossel *et al.*, 2017a) and SMY (Nurk *et al.*, 2017b) of RB are quite similar to those of amaranth (Von Cossel *et al.*, 2017a). Therefore, it can be assumed, that the negative effect of RB on the overall biogas substrate quality (Nurk *et al.*, 2017b) will be smaller for amaranth than for maize. However, the phasein contents of RB might limit the multi-functionality of amaranth-RB-silage because of their toxicity for vertebrates (Koyutürk, 2013). Thus, it needs to be investigated whether phasein gets destroyed during ensilaging or not. Furthermore, the optimal ratio of RB and amaranth for maximum DMY remains unclear. However, it was demonstrated that RB can grow within amaranth plant stands (Fig. 7b and d) and thus, that the planophil leaf architecture of amaranth does not cause too strong light deficient growth conditions for RB.

Contrary to RB, the largest part of the above-ground DM of WC is not harvested together with amaranth. This needs careful consideration for evaluating the intercropping of white clover (WC) and amaranth: White clover is not meant to increase the DMY or the substrate quality of amaranth. Instead, there are several socio-economic benefits through WC intercropping which may compensate for the significant negative effect of WC on both DMY and methane yield per hectare of the harvested amaranth biomass (Von Cossel *et al.*, 2017a). These benefits are

- winter-soil cover (reduced N leaching and erosion),
- post-harvest biodiversity conservation (source of food for pollinators, game etc.),
- SOM enrichment (CO_2 sequestration),
- nitrogen fixation (substitution of synthetic N fertilizer, GHG mitigation) and
- trafficability at harvest (workability).

4.3. Temporal and spatial diversification of biogas crop cultivation through perennial wild plant mixtures

Figure 8: Impression of the plant species diversity observed in a four year old plant stand of WPM ‘S1‘ at Hohenheim. Here, numerous plant species are flowering simultaneously such as greater knapweed (Centaurea scabiosa L.), viper’s bugloss (Echium vulgare L.), melilot (Melilotus officinalis L. Lam.), yellow chamomile (Cota tinctoria L. J. Gay ex Guss.), common yarrow (Achillea millefolium L.), oregano (Origanum vulgare L.), maidenstears (Silene vulgaris Moench Garcke), great mullein (Verbascum Thapsus L.), black mullein (Verbascum nigrum L.) and common Saint John’s wort (Hypericum perforatum L.).

The article entitled “*Perennial wild plant mixtures for biomass production: Impact of species composition dynamics on yield performance over a five-year cultivation period in southwest Germany*“ (Von Cossel and Lewandowski, 2016) (2.2.) reports on the five-year performance of two different WPM (S1, S2) grown in field trials at three different locations in southwest Germany from year 2011 onwards. With its five-year duration, this study was the first of its kind covering the whole cultivation period as has been recommended by the developers of the WPM cropping system (Kuhn *et al.*, 2014; Vollrath *et al.*, 2012). Fresh matter yield (FMY) and dry matter content (DMC) were determined species-specifically each year to enable an evaluation of the biomass productivity and the ensilage quality of the WPM at two levels: (i) the individual species, and (ii) the mixture. It was possible to interpret the influence of the species composition dynamics on the biomass productivity (DMY) and quality (DMC). The following sub-sections discuss the basic findings of Von Cossel and Lewandowski (2016) categorized into (i) the link between agronomic and ecological aspects of overall performance of the WPM, (ii) the aesthetical landscape upgrading / social effects, and (iii) the expected suitability of WPM cultivation for marginal lands in terms of a more environmental benign bioeconomy.

4.3.1. The links between agronomic and ecological aspects of the WPM

It was shown, that the agronomic performance of WPM links the number of species and the dynamics of the species composition over years (Mürle and Zuber, 2013; Von Cossel *et al.*, 2017a; Von Cossel and Lewandowski, 2016). This was concluded from the fact that both yield level and yield stability of the WPM decreased with increasing number of species as was the case for the WPM 'S1' (Fig. 8) at each location (Von Cossel and Lewandowski, 2016). This negative influence of WPM species diversity on both DMY level and stability has been observed when more than five species are dominating the stands from the third year onwards. This was not in line with Weisser *et al.* (2017) who found positive yield effects of increased biodiversity in grassland, and Carlsson *et al.* (2017) who reported non-significant yield effects of increased numbers of species sown within perennial species mixtures. These differences between the aforementioned studies and the findings for WPM by Von Cossel and Lewandowski (2016) are probably because Weisser *et al.* (2017) and Carlsson *et al.* (2017) investigated mixtures that were dominated by perennial grasses (Carlsson *et al.*, 2017; Weisser *et al.*, 2017) which were not included in the WPM. The perennial grasses have different growth requirements and are more competitive than the herbaceous plant species in the WPM. This is in line with findings of Bonin *et al.* (2018), who reported a significantly lower yield performance of a high diverse mixture of grasses and forbs compared with both a switchgrass monoculture and a three-species grass mixture (Bonin *et al.*, 2018). However, an intended reduction of WPM species diversity (Bleeker, 2018; Von Cossel *et al.*, 2017b) (or simply the preference of WPM S2 over WPM S1) could somewhat contradict the initial concept of WPM cultivation to increase both spatial and temporary biodiversity on arable lands (Janusch, 2014; Kuhn *et al.*, 2014; Vollrath, 2013).

Furthermore, the high diversity of WPM potentially provides a better flexibility of the WPM to the heterogeneous challenging growth conditions of marginal lands (Confalonieri *et al.*, 2014; Elbersen *et al.*, 2018a; Von Cossel *et al.*, 2018a). This becomes highly relevant in terms of land use conflicts with food crop cultivation. Thus, marginal land utilization could perhaps be the only reasonable option for WPM cultivation in the long-term, except field boundary concepts for favorable (non-marginal) sites in terms of habitat networking (Tschumi *et al.*, 2016). Nevertheless, WPM cultivation remains economically risky for the farms (Friedrichs, 2013), because most of the environmental benefits are common goods that cannot be monetized. Consequently, governmental interventions are required to reduce economic losses of the farm through WPM cultivation. These interventions should also be success-oriented. For example, the number of dominant species could be used as a key determinant to evaluate the ecosystemic value of the WPM. However, there are many other factors driving the overall environmental benefit of WPM cultivation than its species abundance such as the proportions of legume species (substitute synthetic N fertilizer) and night-blooming species (attract nocturnal insects bats depend on). Therefore, a more holistic evaluation system is required to allow for considering the additional ecosystemic benefits through a higher species diversity of the WPM. A key role for developing such more holistic evaluation systems could be the societal awareness of the biodiversity loss and other negative environmental impacts of less diverse cropping systems. This is because a change in societal awareness could force a change in the fundamental philosophy of policy makers towards the common good of both a clean environment and vital wildlife habitats. This is currently also discussed in context of the recent common agriculture policy reform in the European Union (Grethe *et al.*, 2018). Consequently, the societal awareness for the common good of both a clean environment and vital wildlife habitats could potentially promote most effectively through the appearance of WPM in the landscape.

4.3.2. The aesthetical landscape upgrade through WPM

Figure 9: Impression of the inflorescence of the perennial wild plant Centaurea scabiosa (L.) which is part of the WPM S1.

From an aesthetical point of view, WPM have shown an unsurpassable value as indicated by numerous types of flowers, colors, habitus (Fig. 8, 9), compositions and dynamics over time (Steberl, 2016; Von Cossel and Lewandowski, 2016). Even though this aspect was not directly empirically documented here, it deserves being mentioned and discussed because of its high relevance under social aspects such as

- the public discourse about the aesthetics of bioenergy crop cultivation (Janusch, 2014),
- the well-being of rural communities (Pfau *et al.*, 2014), and
- the conservation of traditional landscape through protection of wild game populations (Kuhn *et al.*, 2014).

Therefore, it was not surprising, that farms which cultivated WPM for biogas production received outstandingly positive feedback from the members of the communities in which they are living and economizing (Janusch, 2014). This positive feedback indicates that WPM cultivation provides the opportunity to improve the overall image of bioenergy in the society.

This issue has been recognized by many local politicians and hunting associations who have a great interest in projects involving WPM (Janusch, 2014; Kuhn *et al.*, 2014). The cooperation between farmers, local politicians and hunting associations is required to ensure a better organization of both effective habitat-networking (between the WPM stands and natural habitats) and an aesthetical upgrade of the landscape. Hence, it strongly depends on the local conditions how to integrate WPM to the existing cropping systems at regional scale most effectively. On this background, it is discussed in the following section whether WPM should be grown on marginal lands to avoid conflicts with other types of land use such as nature conservation and food crop cultivation.

4.3.3. The suitability of WPM for cultivation on marginal lands

Marginal lands are characterized by at least one agricultural constraint that impedes the cultivation of food crops – either in terms of the expected quantitative (yield level, agronomic effort) or qualitative (contamination with heavy metals) performance (Confalonieri *et al.*, 2014; Elbersen *et al.*, 2018a; Von Cossel *et al.*, 2018a). The European marginal land areas, which are available for agricultural utilization are mainly classified as marginal due to

1. adverse rooting conditions,
2. extreme climatic conditions and
3. excessive soil moisture (Elbersen *et al.*, 2018a; Von Cossel *et al.*, 2018a).

Consequently, those industrial crops which are able to deal with these constraints (in combination with the various environmental conditions) are highly relevant candidates for future utilization of marginal land for a growing bioeconomy (Von Cossel *et al.*, 2018a). However, the necessity of biodiversity conservation strategies for marginal land use concepts (Pedroli *et al.*, 2013; Tscharntke *et al.*, 2012) needs careful consideration within the site-specific crop-selection processes (Von Cossel *et al.*, 2018a). WPM show a great potential for an environmentally benign biomass supply under aspects of both biodiversity conservation and economic performance under low-input conditions. Here, it is further concluded that WPM could perform economically viable on marginal lands is based on the following observations by Von Cossel and Lewandowski (2016):

At Sankt Johann, a site defined as marginal in terms of low temperature, short vegetation period and shallow soils, some perennial wild plant species such as tansy, mugwort and common knapweed were found to be well performing. In 2015, a dry and hot year compared to the long-term climatology, especially tansy yielded nearly twice as high as silage maize even though it was only moderately fertilized (50 kg N ha^{-1}) (Von Cossel and Lewandowski, 2016). Additionally, WPM did not require any chemical phytosanitary measures. This low demanding nature of the WPM accompanied by high yield potentials is in line to the findings of Carlsson *et al.* (2017) who revealed a high GHG mitigation potential for unfertilized perennial species mixtures on marginal land. Thus, WPM cultivation is highly recommended for further investigations on marginal lands because it could allow for biomass production under low-input conditions. However, only well-known industrial crops such as miscanthus, giant reed and sorghum are considered within crop-suitability assessments conducted by currently running EU-projects (MAGIC, 2018; SEEMLA, 2018). This is due to (i) a better agronomic progress, (ii) existing industrial facilities for processing, and (iii) well-organized distribution channels of the major industrial crops. For WPM, there is only little knowledge on other conversion pathways than biogas production whereas the varying substrate quality of WPM biomass could be a key parameter (Steberl, 2016; Vollrath *et al.*, 2016). Moreover, the use as forage does also not seem to be an option for WPM biomass due to the high toxicity for cattle which was found for some perennial wild plant species such as common tansy (Roth *et al.*, 2008). However, it has not been investigated if ensilaging could reduce this toxicity level and make the WPM silage a suitable source for livestock production. Furthermore, WPM seem rather unsuitable for ethanol fermentation as an upstream process prior to biogas production (Zheng *et al.*, 2014) in terms of recalcitrance because of the high lignin contents of some wild plant species (Steberl, 2016). However, maybe these multi-functional use options are not required to incentivize a closer look on WPM as a potential option for marginal land utilization at larger scales: The suitability for biogas production, the high eco-systemic value and the potential suitability for low-input cultivation could render WPM feasible enough at both farm and regional scale in many cases.

At regional scale, the overall environmental benefit of WPM could be further enhanced through systematic cooperation between farms. This is because marginal lands are likely to be heterogeneously distributed (Elbersen *et al.*, 2018b) across farms. Thus, cross-farm coordination of WPM area arrangements could be required, for example to improve the habitat connection of the scattered marginal lands (Benton *et al.*, 2003). However, these scattered marginal lands also provide many options for other agricultural diversification strategies, because of numerous other cropping systems than WPM potentially suitable for marginal lands (Von Cossel *et al.*, 2018a). Crop-rotation systems including maize and biogas-amaranth could be among them, e.g. under aspects of drought-affected or contaminated sites (Section 4.1). For a systematic management of these crop-rotations, not only the soil fertility (Zegada-Lizarazu and Monti, 2011) but also the field surroundings deserve consideration. Fields near residential areas probably require different strategies than fields near nature reserves: While the presence of citizens likely affords a strategy that emphasizes on aesthetical values (Daniel, 2001), the field's proximity to nature reserves requires site-specific ecosystem services. Either way, WPM provide both high ecosystemic values and a high aesthetical value. Therefore, WPM are expected to become relevant for marginal land utilization policies in the future. However, WPM need to be further improved in terms of biomass productivity and substrate quality, as long as their potential socio-ecological benefits are not incentivized (Ang *et al.*, 2018; Grethe *et al.*, 2018). The improvement of WPM substrate quality however, is expected to be very time- and cost-intensive, because there is a high number of potential wild plant species and compositions of them to be investigated. Thus, there is a need for an efficient approach to evaluate the biogas substrate quality of novel biogas crops and crop mixtures such as WPM to make agricultural diversification of biogas crop cultivation a success.

4.4. Optimizing the prediction of biogas substrate quality for an efficient assessment of more diverse biogas cropping systems

The articles presented in section 2 revealed numerous potential temporal and spatial diversification strategies for biogas crop cultivation (Von Cossel *et al.*, 2017a; Von Cossel and Lewandowski, 2016). Most of them still need to be developed in terms of breeding biogas-amaranth genotypes, developing site-specific WPM compositions and the associated site-specific agricultural low-input strategies. It was further derived that biogas crops and cropping systems will predominantly face various biophysical constraints of marginal lands (e.g. shallow soil, saline soil, drought affected regions, etc.) (Confalonieri *et al.*, 2014; Elbersen *et al.*, 2018a; Von Cossel *et al.*, 2018a) in the future to avoid land-use conflicts with food production (Tilman *et al.*, 2009). Therefore, the pre-selection of alternative crops and cropping systems grown under the various conditions needs to be optimized to allow for a faster progress in the development of both new varieties (Phillips and Wolfe, 2005) and cropping systems. Hence, the question is raised of how to determine the biogas substrate quality of the numerous substrates and substrate mixes most effectively.

The prediction of specific methane yield (SMY) was dealt with by Von Cossel *et al.* (2018b), because of two reasons: (i) SMY forms one of the major parameters to evaluate the biogas substrate quality, and (ii) its determination via experimental biogas tests is expensive and time consuming. It has often been reported that there is a significant influence of chemical composition of the plant material on the SMY whereas lignocellulose based models are the most cited ones (Dandikas *et al.*, 2015, 2014; Niu *et al.*, 2016; Thomsen *et al.*, 2014; Triolo *et al.*, 2011). During conceptualization of their article, Von Cossel *et al.* (2018b) found, that both across-crop (Dandikas *et al.*, 2014; Herrmann *et al.*, 2016b; Thomsen *et al.*, 2014; Triolo *et al.*, 2011) and crop-specific models (Godin *et al.*, 2015; Rath *et al.*, 2015) were being discussed. Crop-specific models are much more reliable than across-crop approaches (Godin *et al.*, 2015; Rath *et al.*, 2015, 2013) but (i) they require a high number of variables and complicated equations which impede easy use and interpretability, (ii) until now, they are only available for maize and a few other main crops, and (iii) they are still far from high accuracy. Nevertheless, considering that the German Federal Plant Variety Office uses crop-specific models developed by Rath *et al.* (2013, 2015) (Bundessortenamt, 2016), there seems to be demand for crop-specific prediction models under aspects of breeding progress and screening process. For monocropped biogas-amaranth, it would be also helpful to develop a crop-specific model. For an optimal conceptualization of cropping systems at regional scale however, across-crop models are required. In many cases, this is because of the wide range of crops they have to cover (Dandikas *et al.*, 2014; Niu *et al.*, 2016; Thomsen *et al.*, 2014). In view of the scarcity of crop-specific models, the use of across-crop models is often the only option. This would also apply for both legume-intercropped biogas amaranth and WPM provided that respective shares of DMY can be estimated.

Von Cossel *et al.* (2018b) investigated the quality of promising available across-crop SMY-prediction models using a meta-analysis of individual participant data (Riley *et al.*, 2010). Although NIRS-based approaches are considered more accurate, here only those models based on the lignocellulosic fractions of the biomass were chosen because more of these models are available.

A high number of observations (678) was compiled for conducting a meta-analysis that represents a wider range of data and thus, allows for a better evaluation of existing models – especially those based on the lignin content as main or exclusive regressor variable (Alaru *et al.*, 2011; Dandikas *et al.*, 2014; Thomsen *et al.*, 2014; Triolo *et al.*, 2011). The dataset of available internal and external data provided by Von Cossel *et al.* (2018b) indicates, that both the tendency and the importance of the influence of lignin on SMY strongly depends on the crop (Fig. 10). There is a tendency of an increasing negative effect of the lignin content on the SMY with increasing lignin contents in the crops, which however is rather weak (> 0.6) or not even significant for most crops (Fig. 10). Therefore, it was doubted that lignin provides enough information for across-crop SMY-prediction models as has been applied in many published studies (Alaru *et al.*, 2011; Dandikas *et al.*, 2014; Triolo *et al.*, 2011). A five-fold cross-validation revealed that all published models perform worse (R^2 = 0.015 to 0.255) than expected (R^2 = 0.49 to 0.83) when a large dataset is being applied (Von Cossel *et al.*, 2018b).

For this reason, new models were developed based on the large dataset (678 observations) within the supplemental material of Von Cossel *et al.* (2018b). Additionally, various model setup combinations were tested including linear, non-linear and crop-specific configurations. It was found, that all newly developed models perform much better than the published models with coefficients of determination of up to R^2 = 0.481 (cross-validation: R^2 = 0.431). However, these values are far too low for practical implementations. Hence, the first relevant finding of this study was the need for carefully consideration of which model to use in practical implementations. For example, Niu *et al.* (2016) used a model of Thomsen *et al.* (2014) mainly because of the high R^2 of > 0.96. This high R^2 however, is a result of a specific model setup that automatically excludes the intercept. These models are accurate in terms of statistics but not applicable for practical use. A description of this paradox was another relevant result of Von

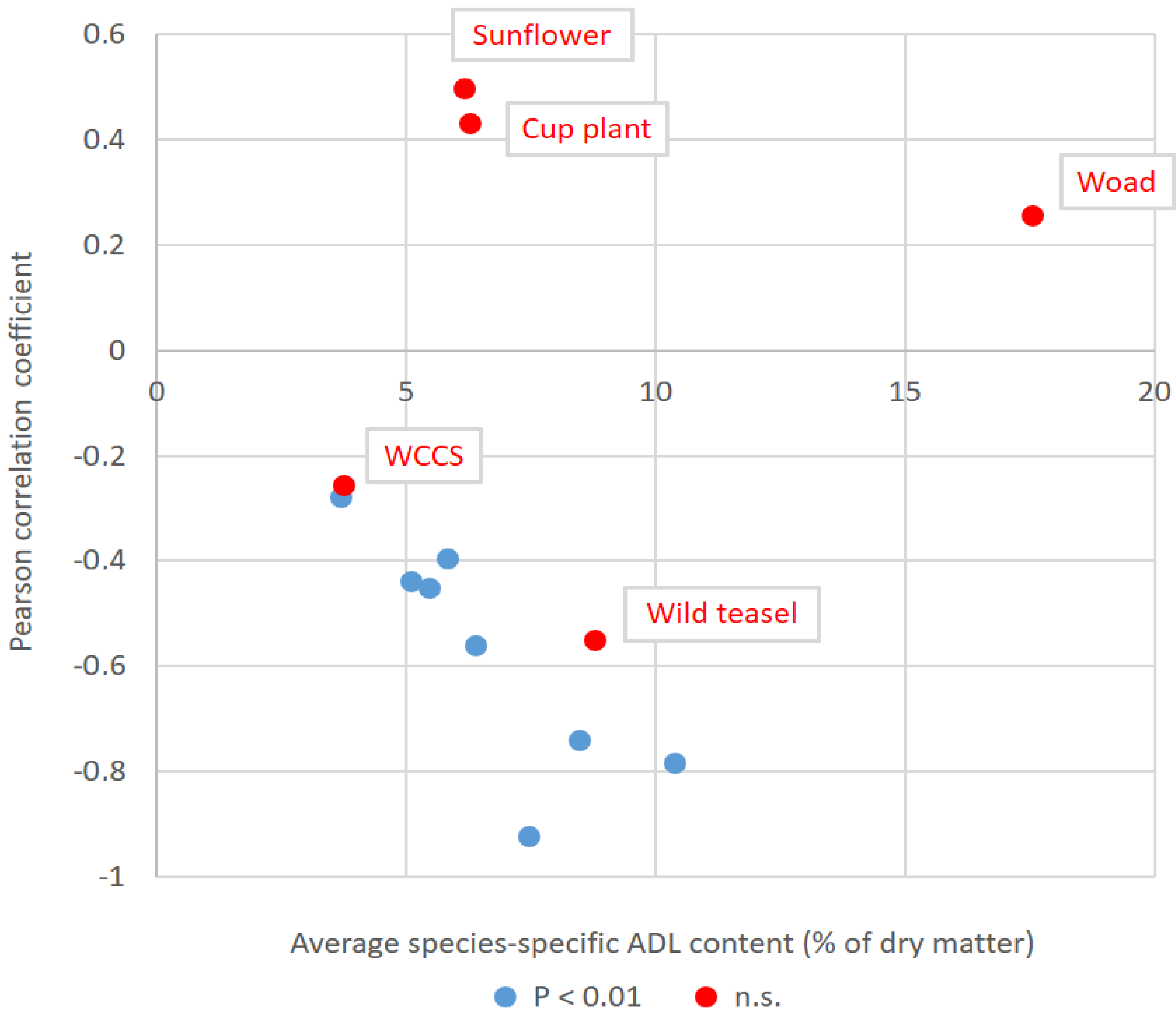

Figure 10: Influence of the average species-specific lignin (ADL) content on the ADL-based SMY predictability using the supplementary data of Von Cossel et al. (2018b). There is a clear tendency of decreasing predictability when the ADL content is higher. However, for some crops (indicated in red), no significant influence of ADL on SMY was found.

Cossel *et al.* (2018b). Furthermore, the effects of non-linear terms (including the squared terms) and crop-specific regressors (including the intercept) were tested, which has not been conducted that comprehensively before. The findings indicate, that the predictability increases most when the source of biomass, here the crop, is considered as an input variable, i.e. crop-specific regressors. Among crop-specific regressors, the intercept was found to have a major effect on the predictability while the slopes of the lignocellulosic fractions are selected across crop-species by the model. Their inclusion only marginally improves the predictability but complicates easy use and interpretability of the models (Von Cossel *et al.*, 2018b).

For both the development and the implementation of across-crop SMY prediction models at regional scale, as was done by Niu *et al.* (2016), the following recommendations were derived by Von Cossel *et al.* (2018b) (in alphabetical order):

- Check the basic model setup – Is an intercept required? And If so – is it automatically included to the model?
- Check the number of observations used for model development – Is the number in relation to the variance of both the independent and dependent variable?
- Check the source of the data – If external data has been used, is it available and was it used/copied appropriately?
- Check the sub-categories within the observations – Were the potential effects of the source (study) or type (crop) of data investigated?
- Check the validation method used – Has a cross-validation been performed?

If any of these check categories can be answered with 'no' or remains unclear, a closer look on the methods of the respective study is highly recommended to avoid misinterpretation of the results of the study. These recommendations are not strictly limited to the research field of SMY-prediction and could therefore also interdisciplinary contribute to a progress of both the understanding of existing studies on MLR and the development of new MLR approaches.

4.5 The socio-ecosystemic functions of agricultural diversification

Despite "*there is no universal functional type classification*" (Altieri *et al.*, 2017), the overall ecosystemic benefits of the agricultural diversification approaches for biogas crop cultivation investigated in this study were evaluated along two socio-ecosystemic categories:

- Biodiversity conservation and landscape heterogeneity,
- GHG mitigation and climate change adaptation.

4.5.1. The role of agricultural diversification for biodiversity conservation and landscape heterogeneity

There is an ongoing debate on whether agricultural utilization of abandoned or degraded land could, against expectations, be a chance for biodiversity conservation (Queiroz *et al.*, 2014; Tscharntke *et al.*, 2012). In many cases, the answer could be 'yes' because of the projected severely negative impacts of climate change on wildlife (Thomas *et al.*, 2004) which could hit un-utilized areas even worse than under strategical utilization for ICC (Smith *et al.*, 2008). This means, that strategical utilization of non-utilized areas through implementing diverse agricultural systems could help increasing the ecosystem resilience (Tscharntke *et al.*, 2012). In this way, strategical utilization of marginal land for ICC could contribute to preserving agrobiodiversity against the negative effects of climate change. However, neither annual monocropping systems nor perennial polycropping systems are generally most preferable for biodiversity conservation. This is because resilience, the "*response capability of ecosystems to resist disturbances and change*" (Walker *et al.*, 1999) itself needs intended disturbances from time to time in order to remain vital, i.e. to maintain its resilience at a high level (Elmqvist *et al.*, 2003; Folke *et al.*, 2004). Therefore, both the high species diversity of the WPM and the comparably labor-intensive cultivation of amaranth in combination with other crops within crop rotations could help to maintain the resilience of agroecosystems. This is highly relevant under aspects of biodiversity conservation because the implementation of species-rich ecosystems is only one of two important issues to be addressed (Hallmann *et al.*, 2017) - its long-term protection is the other one (Altieri *et al.*, 2017). WPM however, provide numerous possibilities to overcome several issues at once at a comparably low input level:

- WPM can be grown in form of wild flower stripes at field boundaries where they (i) function as elements of habitat networking, and (ii) increase the activity of natural biocontrol agents (Hatt *et al.*, 2015; Tschumi *et al.*, 2016).
- Small fields cultivated with WPM could be widely distributed and form some sort of island-landscape for wild pollinators and other insects, especially for wild bees most of which only have a small flying radius of some hundred meters or less (Fortel *et al.*, 2014).

Landscape heterogeneity, i.e. the temporal sequencing of crops and cropping systems at regional scale or the species diversity of poly cropping systems such as WPM at field scale, is not only a key element of biodiversity conservation (Benton *et al.*, 2003) but it also forms a cultural element of the modern society (Daniel, 2001). In Germany, the media-effective term 'Vermaisung' describes the considerable discrepancy between biomass productivity and the aesthetical value of the landscape. 'Vermaisung' vaguely means that maize dominates the cropping systems at regional scale resulting in a monotone landscape with a low aesthetical value. This has led to a notable decrease within the public acceptance of biogas production over the past decade. Controversially, a colorful and vital structure of landscape through more different types of plant species and a temporal sequencing of them helps improving the aesthetical value of the landscape (Borin *et al.*, 2010; Daniel, 2001; Janusch, 2014; Leopold, 1949). Therefore, agricultural diversification through the integration of amaranth or WPM into existing cropping systems could potentially increase both public awareness and acceptance of biomass production. This may lead to a better public support for research on biomass production and its' practical implementation, because the major positive effects of agricultural diversification for the public such as GHG mitigation and climate change adaptation are not so easy to comprehend.

4.5.2. Agricultural diversification in the context of climate change

Climate change presents a major challenge for primary production in view of the expected impacts on agriculture such as droughts, heat waves and extreme weather events (Pachauri *et al.*, 2014; Samaniego *et al.*, 2018; Stoy, 2018; Teuling, 2018). For agricultural diversification of ICC, this has several consequences: On the one hand, climate change adaptation is becoming more and more crucial in order to cope with the expected climate change impacts on agriculture. On the other hand, it is important to help slow down climate change, which can be done by (i) reducing GHG emissions from agriculture (Pachauri *et al.*, 2014), (ii) making better use of the agricultural potential to store CO_2 (Beerling *et al.*, 2018; Scurlock and Hall, 1998), and (iii) providing environmentally sustainably produced biofuels (Von Cossel *et al.*, 2018a). The latter helps to substitute fossil fuels. Considering these consequences, ICC is not only requiring strategies to cope better with the impacts of climate change, but also to reduce GHG emissions from agricultural production. Such strategies include reduced tillage (Frank *et al.*, 2015), site-specific N application (Kessel *et al.*, 2013; Smith *et al.*, 2008), legume-based N fertilization (Duchene *et al.*, 2017; Schmeer *et al.*, 2014; Smith *et al.*, 2008) and the selection of perennial cropping systems (Hudiburg *et al.*, 2015; Kiesel *et al.*, 2016; Ramirez-Almeyda *et al.*, 2017; Von Cossel *et al.*, 2018a).

On this background, the perennial WPM cropping system could provide a considerable GHG mitigation potential (Section 2.2). This GHG mitigation potential of WPM is expected because even low yield levels of perennial crops (3.6 - 9.2 Mg ha^{-1} yr^{-1}) were found to reduce the GHG fluxes by 0.5 - 1.0 Mg C ha^{-1} yr^{-1} more compared to annual cropping systems (Hudiburg *et al.*, 2015). Additionally, WPM could potentially also perform better than the reference energy-scenario based on fossil resources in terms of terrestrial acidification, freshwater eutrophication and marine eutrophication as has been proven for miscanthus by Kiesel *et al.* (2016). This is because WPM also (i) include high-yielding perennial species, (ii) do not require any phytosanitary measures, and (iii) show a high nitrogen use efficiency (Von Cossel and Lewandowski, 2016).

As far as annual crop rotations are concerned, several low-input practices should be considered for ICC to improve both its GHG mitigation potential and its climate-change adaptability, such as

- Reduced tillage (Frank *et al.*, 2015; Smith *et al.*, 2008),
- Undersown catch crop, e.g. WC (Dhillon and von Wuehlisch, 2013),
- Combination with an agroforestry system (Dhillon and von Wuehlisch, 2013; Smith *et al.*, 2008) and
- Precise N application (Kessel *et al.*, 2013; Smith *et al.*, 2008).

The above-mentioned low-input practices are assumed to be suitable for amaranth due the similarities between amaranth and maize reported by Von Cossel *et al.* (2017a) such as the suitability for legume-intercropping and the high biomass yield potential. However, new biogas-amaranth varieties are also required in terms of GHG mitigation (Smith *et al.*, 2008) because there is high evidence of large genetic yield gaps of amaranth as has already been explained above (Section 2.1.). Nevertheless, on degraded land (Smith *et al.*, 2008) the existing prototypes of biogas-amaranth such as ‘E2013’ could succeed because of the high water use efficiency of amaranth (Eberl *et al.*, 2014). This is relevant because the number of extreme weather events such as droughts and hurricanes are expected to increase (Pachauri *et al.*, 2014; Samaniego *et al.*, 2018; Teuling, 2018). In this context, highly resilient cropping systems such as wide crop rotations or perennial cropping systems are also required (Folke *et al.*, 2004; Tittonell, 2014). This is especially relevant for ICC on marginal land (Smith *et al.*, 2008; Von Cossel *et al.*, 2018a), because WPM can help agro-ecosystems to compete better with abiotic disturbances.

Overall, the findings on agricultural diversification of biogas crop cultivation presented in this study are also relevant in terms of climate-change adaptation:

- The dynamic concept of WPM aims at the development of site-specific plant mixtures depending on both the species-specific growth requirements and the inter-specific competition. This means that the given repertoire of the WPM provides a kind of 'multi-site-specialization'.

- Perennial wild plant species provide both direct and indirect resilience improving functions: (i) the permanent soil cover indirectly improves the resistance of the soil-ecosystem against disturbances such as heavy rains, droughts, and (ii) the deep rooting system and long vegetation periods of the perennial species such as tansy, mugwort or knapweed directly provide high resistance against disturbances such as droughts, erosion and heavy rain events.
- Amaranth provides opportunity of high yields under limited rain-fed conditions because of its C4-metabolism and its high water use efficiency (Eberl *et al.*, 2014). However, more breeding is required for closing the yield gaps.

4.6. The role of agricultural diversification for a growing bioeconomy

A growing global bioeconomy requires increasing amounts of biomass from agricultural production, forests and aquatic systems to overcome the dependency on fossil resources in the long-term (Lewandowski *et al.*, 2018a). Simultaneously, there is an increasing public awareness for socio-ecosystemic externalities of primary production in general due to biodiversity losses (Hallmann *et al.*, 2017), water contaminations (BMU, 2017) and land degradation (UBA, 2016). Hence, a reduction of these externalities has gathered high priority in bioeconomy research (Dornburg *et al.*, 2010; Lewandowski, 2015; Pfau *et al.*, 2014; Ronzon *et al.*, 2016; Wezel *et al.*, 2014). However, its implementation can only be managed via governmental interventions (Ahlheim, 2018; Staffas *et al.*, 2013) or a well-organized "*network of different actors*" (Birner, 2018) such as farmers associations, environmental organizations or hunting associations. The main reason for the requirement of governmental interventions is that the market failed *"in the environmental sector*" (Ahlheim, 2018) meaning today, the positive externalities of agricultural diversification are not sufficiently rewarded. This indicates a tremendous demand for a better understanding of

(i) how to integrate new diversification approaches into existing cropping systems with respect to the landscape heterogeneity (Benton *et al.*, 2003), and

(ii) how to manage agricultural diversification at regional scale given the latent demand of both governmental subsidies (Staffas *et al.*, 2013) and complex networking between practitioners and policy makers (Birner, 2018).

Providentially, agricultural research has already started to investigate more diverse and thus environmentally benign cropping systems decades ago (Altieri and Letourneau, 1982; Andrews and Kassam, 1976). Hence, there are numerous studies about the performance of various crops and cropping systems for providing agricultural products such as food, feed, bioenergy and biobased resources (Altieri, 2018; Altieri *et al.*, 2017; Borkowska and Molas, 2012; Corno *et al.*, 2015; Emmerling *et al.*, 2017; Herrmann *et al.*, 2016b, 2016a; Kalamaras and Kotsopoulos, 2014; Mayer *et al.*, 2014; Sims *et al.*, 2006; Theisen *et al.*, 2017; Wezel *et al.*, 2014; Zürcher, 2014). For some of these crops and cropping systems, several approaches and findings on agricultural diversification presented in this study could potentially be transferred if certain similarities are given. For instance, (i) legume intercropping could also be applied to other annual crops than amaranth and maize, if similar preconditions such as wide row-width, late canopy closure and high final plant height are given, (ii) perennial wild plant mixtures could be used for other utilization pathways than biogas production such as combustion or bioethanol production, if adequate wild plant species (e.g. those with a low ash content and a high DMY potential within spring harvest regimes) are selected, and (iii) the inclusion of crop-specific regressors to MLR approaches could improve the prediction of biomass quality within bioethanol or combustion pathways.

Consequently, this study contributes to an ongoing interdisciplinary progress in the research field of agricultural diversification within primary production (Altieri *et al.*, 2015; Wezel *et al.*, 2014) through providing new insights to both economic and socio-ecological performances of agricultural diversification measures, i.e. ‘legume intercropping’ and mixed cropping. This is highly relevant for meeting “*societal challenges such as* (…) *the loss of soil fertility and biodiversity*” (Knierim *et al.*, 2018). Therefore, this study not only answers specific agronomic and biostatistical questions. It also contributes to a progress in agricultural diversification of primary production at regional scale towards a more environmentally benign bioeconomy in the long-term.

5. References

Adamovics, A., Dubrovskis, V., Zeverte-Rivza, S., others, 2015. Anaerobic digestion of sunflowers and amaranths silages with catalyst Metaferm., in: “ Nordic View to Sustainable Rural Development”, Proceedings of the 25th NJF Congress, Riga, Latvia, 16-18 June 2015. NJF Latvia. llufb.llu.lv/conference/NJF/NJF_2015_Proceedings_Latvia-385-389.pdf (accessed 06.21.2018)

Agegnehu, G., Ghizaw, A., Sinebo, W., 2006. Yield performance and land-use efficiency of barley and faba bean mixed cropping in Ethiopian highlands. Eur. J. Agron. 25, 202–207. https://doi.org/10.1016/j.eja.2006.05.002

Ahlheim, M., 2018. Environmental Economics, the Bioeconomy and the Role of Government, in: Bioeconomy. Springer, Cham, pp. 315–327. https://doi.org/10.1007/978-3-319-68152-8_10

Al Seadi, T., Drosg, B., Fuchs, W., Rutz, D., Janssen, R., 2013. Biogas digestate quality and utilization, in: The Biogas Handbook. Elsevier, pp. 267–301. https://doi.org/10.1533/9780857097415.2.267

Alam, M.G.M., Snow, E.T., Tanaka, A., 2003. Arsenic and heavy metal contamination of vegetables grown in Samta village, Bangladesh. Sci. Total Environ. 308, 83–96. https://doi.org/10.1016/S0048-9697(02)00651-4

Alaru, M., Olt, J., Kukk, L., Luna del Risco, M., Lauk, R., Noormets, M., others, 2011. Methane yield of different energy crops grown in Estonian conditions, in: Agronomy Research. Estonian Research Institute of Agriculture, pp. 13–22. agronomy.emu.ee/vol09Spec1/p09s102.pdf (accessed 06.21.2018)

Ali, H., Khan, E., Sajad, M.A., 2013. Phytoremediation of heavy metals—concepts and applications. Chemosphere 91, 869–881. https://doi.org/10.1016/j.chemosphere.2013.01.075

Altieri, M.A., 2018. Agroecology: the science of sustainable agriculture. CRC Press. https://www.taylorfrancis.com/books/e/9780429964015

Altieri, M.A., Letourneau, D.K., 1982. Vegetation management and biological control in agroecosystems. Crop Prot. 1, 405–430. https://doi.org/10.1016/0261-2194(82)90023-0

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-resilient farming systems. Agron. Sustain. Dev. 35, 869–890. https://link.springer.com/article/10.1007/s13593-015-0285-2

Altieri, M.A., Nicholls, C.I., Montalba, R., 2017. Technological Approaches to Sustainable Agriculture at a Crossroads: An Agroecological Perspective. Sustainability 9, 349. https://doi.org/10.3390/su9030349

Amon, T., Amon, B., Kryvoruchko, V., Machmüller, A., Hopfner-Sixt, K., Bodiroza, V., Hrbek, R., Friedel, J., Pötsch, E., Wagentristl, H., Schreiner, M., Zollitsch, W., 2007a. Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. Bioresour. Technol. 98, 3204–3212. https://doi.org/10.1016/j.biortech.2006.07.007

Amon, T., Amon, B., Kryvoruchko, V., Zollitsch, W., Mayer, K., Gruber, L., 2007b. Biogas production from maize and dairy cattle manure—influence of biomass composition on the methane yield. Agric. Ecosyst. Environ. 118, 173–182. https://doi.org/10.1016/j.agee.2006.05.007

Andrews, D.J., 1972. Intercropping with sorghum in Nigeria. Exp. Agric. 8, 139–150.

Andrews, D.J., Kassam, A.H., 1976. The Importance of Multiple Cropping in Increasing World Food Supplies. Mult. Crop. asaspecialpubli, 1–10. https://doi.org/10.2134/asaspecpub27.c1

Anex, R.P., Lynd, L.R., Laser, M.S., Heggenstaller, A.H., Liebman, M., 2007. Potential for enhanced nutrient cycling through coupling of agricultural and bioenergy systems. Crop Sci. 47, 1327–1335. https://doi.org/10.2135/cropsci2006.06.0406

Ang, F., Mortimer, S.M., Areal, F.J., Tiffin, R., 2018. On the Opportunity Cost of Crop Diversification. J. Agric. Econ. 69, 794–814. https://doi.org/10.1111/1477-9552.12272

Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J.L., Guwy, A.J., Kalyuzhnyi, S., Jenicek, P., Van Lier, J.B., 2009. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. Water Sci. Technol. 59, 927–934. https://iwaponline.com/wst/article-abstract/59/5/927/15563

Angelidaki, I., Ellegaard, L., Ahring, B.K., 1999. A comprehensive model of anaerobic bioconversion of complex substrates to biogas. Biotechnol. Bioeng. 63, 363–372. https://doi.org/10.1002/(SICI)1097-0290(19990505)63:3<363::AID-BIT13>3.0.CO;2-Z

Angelidaki, I., Ellegaard, L., Ahring, B.K., 1993. A mathematical model for dynamic simulation of anaerobic digestion of complex substrates: Focusing on ammonia inhibition. Biotechnol. Bioeng. 42, 159–166. https://doi.org/10.1002/bit.260420203

Aufhammer, W., Kaul, H.-P., Herz, P., Nalborczyk, E., Dalbiak, A., Gontarczyk, M., 1995. Grain yield formation and nitrogen uptake of amaranth. Eur. J. Agron. 4, 379–386. https://doi.org/10.1016/S1161-0301(14)80039-7

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., others, 2011. Has the Earth/'s sixth mass extinction already arrived? Nature 471, 51–57. https://doi.org/10.1038/nature09678

Barrière, Y., Alber, D., Dolstra, O., Lapierre, C., Motto, M., Ordas, A., Van Waes, J., Vlasminkel, L., Welcker, C., Monod, J.P., 2006. Past and prospects of forage maize breeding in Europe. II. History, germplasm evolution and correlative agronomic changes. Maydica 51, 435–449. https://library.wur.nl/WebQuery/wurpubs/372140

Batáry, P., Matthiesen, T., Tscharntke, T., 2010. Landscape-moderated importance of hedges in conserving farmland bird diversity of organic vs. conventional croplands and grasslands. Biol. Conserv. 143, 2020–2027. https://doi.org/10.1016/j.biocon.2010.05.005

Bauer, A., Leonhartsberger, C., Bösch, P., Amon, B., Friedl, A., Amon, T., 2010. Analysis of methane yields from energy crops and agricultural by-products and estimation of energy potential from sustainable crop rotation systems in EU-27. Clean Technol. Environ. Policy 12, 153–161. https://link.springer.com/article/10.1007/s10098-009-0236-1

Beaudoin, N., Saad, J.K., Van Laethem, C., Machet, J.M., Maucorps, J., Mary, B., 2005. Nitrate leaching in intensive agriculture in Northern France: Effect of farming practices, soils and crop rotations. Agric. Ecosyst. Environ. 111, 292–310. https://doi.org/10.1016/j.agee.2005.06.006

Beerling, D.J., Leake, J.R., Long, S.P., Scholes, J.D., Ton, J., Nelson, P.N., Bird, M., Kantzas, E., Taylor, L.L., Sarkar, B., 2018. Farming with crops and rocks to address global climate, food and soil security. Nat. Plants 4, 138–147. https://www.nature.com/articles/s41477-018-0108-y

Benton, T.G., Vickery, J.A., Wilson, J.D., 2003. Farmland biodiversity: is habitat heterogeneity the key? Trends Ecol. Evol. 18, 182–188. https://doi.org/10.1016/S0169-5347(03)00011-9

Berndes, G., Hoogwijk, M., van den Broek, R., 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenergy 25, 1–28. https://doi.org/10.1016/S0961-9534(02)00185-X

Biala, K., Terres, J.-M., Pointereau, P., Paracchini, M.L., 2007. Low Input Farming Systems: an opportunity to develop sustainable agriculture. Proc. JRC Summer Univ. Ranco 2–5. https://www.bezpecnostpotravin.cz/userfiles/file/publikace/low-input.pdf (accessed 06.21.2018)

Bian, B., Lv, L., Yang, D., Zhou, L., 2014. Migration of heavy metals in vegetable farmlands amended with biogas slurry in the Taihu Basin, China. Ecol. Eng. 71, 380–383. https://doi.org/10.1016/j.ecoleng.2014.07.026

Bianchi, F.J.J.A., Booij, C.J.H., Tscharntke, T., 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. Proc. R. Soc. Lond. B Biol. Sci. 273, 1715–1727. https://doi.org/10.1098/rspb.2006.3530

Birner, R., 2018. Bioeconomy Concepts, in: Bioeconomy. Springer, Cham, pp. 17–38. https://doi.org/10.1007/978-3-319-68152-8_3

Blackmore, S., Gibby, M., Rae, D., 2011. Strengthening the scientific contribution of botanic gardens to the second phase of the Global Strategy for Plant Conservation. Bot. J. Linn. Soc. 166, 267–281. https://doi.org/10.1111/j.1095-8339.2011.01156.x

Bleeker, W., 2018. Heimische Wildpflanzen als Grundlage zur Entwicklung ressourcenschonender Biomasseproduzenten (WaGBio) https://www.fnr.de/index.php?id=11150&fkz=22025015 (accessed 06.21.2018)

Blumenstein, B., Siegmeier, T., Selsam, F., Möller, D., 2018. A case of sustainable intensification: Stochastic farm budget optimization considering internal economic benefits of biogas production in organic agriculture. Agric. Syst. 159, 78–92. https://doi.org/10.1016/j.agsy.2017.10.016

BMBF, BMEL, 2015. Bioeconomy in Germany Opportunities for a bio-based and sustainable future. Federal Ministry of Education and Research (BMBF); Federal Ministry of Food and Agriculture (BMEL), Bonn and Berlin. https://ec.europa.eu/knowledge4policy/publication/bioeconomy-germany-opportunities-bio-based-sustainable-future_en

BMU, 2017. Nitratbericht 2016: Keine Entwarnung bei Gewässerbelastung [WWW Document]. https://www.bmu.de/pressemitteilung/nitratbericht-2016-keine-entwarnung-bei-gewaesserbelastung/ (accessed 6.21.18).

BMWi, 2014. BMWi - Federal Ministry for Economic Affairs and Energy - Act on the Development of Renewable Energy Sources (Renewable Energy Sources Act - RES Act 2014). http://www.bmwi.de/Redaktion/EN/Downloads/renewable-energy-sources-act-eeg-2014.html (accessed 11.1.17).

Böhm, M., Collen, B., Baillie, J.E.M., Bowles, P., Chanson, J., Cox, N., Hammerson, G., Hoffmann, M., Livingstone, S.R., Ram, M., Rhodin, A.G.J., Stuart, S.N., van Dijk, P.P., Young, B.E., Afuang, L.E., Aghasyan, A., García, A., Aguilar, C., Ajtic, R., Akarsu, F., Alencar, L.R.V., Allison, A., Ananjeva, N., Anderson, S., Andrén, C., Ariano-Sánchez, D., Arredondo, J.C., Auliya, M., Austin, C.C., Avci, A., Baker, P.J., Barreto-Lima, A.F., Barrio-Amorós, C.L., Basu, D., Bates, M.F., Batistella, A., Bauer, A., Bennett, D., Böhme, W., Broadley, D., Brown, R., Burgess, J., Captain, A., Carreira, S., Castañeda,

M. del R., Castro, F., Catenazzi, A., Cedeño-Vázquez, J.R., Chapple, D.G., Cheylan, M., Cisneros-Heredia, D.F., Cogalniceanu, D., Cogger, H., Corti, C., Costa, G.C., Couper, P.J., Courtney, T., Crnobrnja-Isailovic, J., Crochet, P.-A., Crother, B., Cruz, F., Daltry, J.C., Daniels, R.J.R., Das, I., de Silva, A., Diesmos, A.C., Dirksen, L., Doan, T.M., Dodd, C.K., Doody, J.S., Dorcas, M.E., Duarte de Barros Filho, J., Egan, V.T., El Mouden, E.H., Embert, D., Espinoza, R.E., Fallabrino, A., Feng, X., Feng, Z.-J., Fitzgerald, L., Flores-Villela, O., França, F.G.R., Frost, D., Gadsden, H., Gamble, T., Ganesh, S.R., Garcia, M.A., García-Pérez, J.E., Gatus, J., Gaulke, M., Geniez, P., Georges, A., Gerlach, J., Goldberg, S., Gonzalez, J.-C.T., Gower, D.J., Grant, T., Greenbaum, E., Grieco, C., Guo, P., Hamilton, A.M., Hare, K., Hedges, S.B., Heideman, N., Hilton-Taylor, C., Hitchmough, R., Hollingsworth, B., Hutchinson, M., Ineich, I., Iverson, J., Jaksic, F.M., Jenkins, R., Joger, U., Jose, R., Kaska, Y., Kaya, U., Keogh, J.S., Köhler, G., Kuchling, G., Kumlutaş, Y., Kwet, A., La Marca, E., Lamar, W., Lane, A., Lardner, B., Latta, C., Latta, G., Lau, M., Lavin, P., Lawson, D., LeBreton, M., Lehr, E., Limpus, D., Lipczynski, N., Lobo, A.S., López-Luna, M.A., Luiselli, L., Lukoschek, V., Lundberg, M., Lymberakis, P., Macey, R., Magnusson, W.E., Mahler, D.L., Malhotra, A., Mariaux, J., Maritz, B., Marques, O.A.V., Márquez, R., Martins, M., Masterson, G., Mateo, J.A., Mathew, R., Mathews, N., Mayer, G., McCranie, J.R., Measey, G.J., Mendoza-Quijano, F., Menegon, M., Métrailler, S., Milton, D.A., Montgomery, C., Morato, S.A.A., Mott, T., Muñoz-Alonso, A., Murphy, J., Nguyen, T.Q., Nilson, G., Nogueira, C., Núñez, H., Orlov, N., Ota, H., Ottenwalder, J., Papenfuss, T., Pasachnik, S., Passos, P., Pauwels, O.S.G., Pérez-Buitrago, N., Pérez-Mellado, V., Pianka, E.R., Pleguezuelos, J., Pollock, C., Ponce-Campos, P., Powell, R., Pupin, F., Quintero Díaz, G.E., Radder, R., Ramer, J., Rasmussen, A.R., Raxworthy, C., Reynolds, R., Richman, N., Rico, E.L., Riservato, E., Rivas, G., da Rocha, P.L.B., Rödel, M.-O., Rodríguez Schettino, L., Roosenburg, W.M., Ross, J.P., Sadek, R., Sanders, K., Santos-Barrera, G., Schleich, H.H., Schmidt, B.R., Schmitz, A., Sharifi, M., Shea, G., Shi, H.-T., Shine, R., Sindaco, R., Slimani, T., Somaweera, R., Spawls, S., Stafford, P., Stuebing, R., Sweet, S., Sy, E., Temple, H.J., Tognelli, M.F., Tolley, K., Tolson, P.J., Tuniyev, B., Tuniyev, S., Üzüm, N., van Buurt, G., Van Sluys, M., Velasco, A., Vences, M., Veselý, M., Vinke, S., Vinke, T., Vogel, G., Vogrin, M., Vogt, R.C., Wearn, O.R., Werner, Y.L., Whiting, M.J., Wiewandt, T., Wilkinson, J., Wilson, B., Wren, S., Zamin, T., Zhou, K., Zug, G., 2013. The conservation status of the world's reptiles. Biol. Conserv. 157, 372–385. https://doi.org/10.1016/j.biocon.2012.07.015

Bonin, C.L., Fidel, R.B., Banik, C., Laird, D.A., Mitchell, R., Heaton, E.A., 2018. Perennial biomass crop establishment, community characteristics, and productivity in the upper US Midwest: Effects of cropping systems seed mixtures and biochar applications. Eur. J. Agron. 101, 121–128. https://doi.org/10.1016/j.eja.2018.08.009

Borin, M., Passoni, M., Thiene, M., Tempesta, T., 2010. Multiple functions of buffer strips in farming areas. Eur. J. Agron., Cropping Systems Design: new methods for new challenges 32, 103–111. https://doi.org/10.1016/j.eja.2009.05.003

Borkowska, H., Molas, R., 2012. Two extremely different crops, Salix and Sida, as sources of renewable bioenergy. Biomass Bioenergy 36, 234–240. https://doi.org/10.1016/j.biombioe.2011.10.025

Boros, L., Wawer, A., Borucka, K., 2014. Morphological, phenological and agronomical characterisation of variability among common bean (Phaseolus vulgaris L.) local populations from The National Centre for Plant Genetic Resources: Polish Genebank. J. Hortic. Res. 22, 123–130. https://doi.org/10.2478/johr-2014-0029

Brenner, D.M., Baltensperger, D.D., Kulakow, P.A., Lehmann, J.W., Myers, R.L., Slabbert, M.M., Sleugh, B.B., 2010. Genetic resources and breeding of Amaranthus. Plant Breed. Rev. 19, 227–285.

Brenner, D.M., Baltensperger, D.D., Kulakow, P.A., Lehmann, J.W., Myers, R.L., Slabbert, M.M., Sleugh, B.B., 2000. Genetic resources and breeding of Amaranthus. Plant Breed. Rev. 19, 227–285. https://www.cabdirect.org/cabdirect/abstract/20063179623

Bullock, D.G., 1992. Crop rotation. Crit. Rev. Plant Sci. 11, 309–326. https://doi.org/10.1080/07352689209382349

Bundessortenamt, 2016. Getreide, Mais, Öl- und Faserpflanzen, Leguminosen Rüben, Zwischenfrüchte 2016. Bundessortenamt, Hannover. https://docplayer.org/7886764-Beschreibende-sortenliste-getreide-mais-oel-und-faserpflanzen-leguminosen-rueben-zwischenfruechte-bundessortenamt.html (accessed 6.21.18)

Cardinale, B.J., Wright, J.P., Cadotte, M.W., Carroll, I.T., Hector, A., Srivastava, D.S., Loreau, M., Weis, J.J., 2007. Impacts of plant diversity on biomass production increase through time because of species complementarity. Proc. Natl. Acad. Sci. 104, 18123–18128. https://doi.org/10.1073/pnas.0709069104

Cardoso, E., Nogueira, M.A., Ferraz, S.M.G., 2007. Biological N 2 fixation and mineral N in common bean–maize intercropping or sole cropping in southeastern brazil. Exp. Agric. 43, 319–330. https://doi.org/10.1017/S0014479707005029

Carlsson, G., Mårtensson, L.-M., Prade, T., Svensson, S.-E., Jensen, E.S., 2017. Perennial species mixtures for multifunctional production of biomass on marginal land. GCB Bioenergy 9, 191–201. https://doi.org/10.1111/gcbb.12373

Ceballos, G., 2002. Mammal Population Losses and the Extinction Crisis. Science 296, 904–907. https://doi.org/10.1126/science.1069349

Ceballos, G., Ehrlich, P.R., Barnosky, A.D., García, A., Pringle, R.M., Palmer, T.M., 2015. Accelerated modern human–induced species losses: Entering the sixth mass extinction. Sci. Adv. 1, e1400253. https://doi.org/10.1126/sciadv.1400253

Ceballos, G., Ehrlich, P.R., Dirzo, R., 2017. Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. Proc. Natl. Acad. Sci. 201704949. https://doi.org/10.1073/pnas.1704949114

Chapin Iii, F.S., Zavaleta, E.S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L., Hooper, D.U., Lavorel, S., Sala, O.E., Hobbie, S.E., 2000. Consequences of changing biodiversity. Nature 405, 234–242. https://www.nature.com/articles/35012241

Confalonieri, R., Jones, R., van Diepen, K., Van Orshoven, J., 2014. Scientific contribution on combining biophysical criteria underpinning the delineation of agricultural areas affected by specific constraints: Methodology and factsheets for plausible criteria combinations. https://core.ac.uk/download/pdf/38629006.pdf (accessed 6.21.18)

Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., Beaudoin, N., 2010. Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. Agric. Ecosyst. Environ. 135, 268–278. https://doi.org/10.1016/j.agee.2009.10.005

Corno, L., Pilu, R., Tambone, F., Scaglia, B., Adani, F., 2015. New energy crop giant cane (Arundo donax L.) can substitute traditional energy crops increasing biogas yield and reducing costs. Bioresour. Technol. 191, 197–204. https://doi.org/10.1016/j.biortech.2015.05.015

Cosentino, S.L., Copani, V., Scalici, G., Scordia, D., Testa, G., 2015. Soil erosion mitigation by perennial species under Mediterranean environment. BioEnergy Research 8, 1538–1547. https://doi.org/10.1007/s12155-015-9690-2

Cosentino, S.L., Testa, G., Scordia, D., Alexopoulou, E., 2012. Future yields assessment of bioenergy crops in relation to climate change and technological development in Europe. Italian Journal of Agronomy 7, 22. https://doi.org/10.4081/ija.2012.e22

Costanza, R., 2017. Trump: a confluence of tipping points? Nature. https://doi.org/10.1038/542295b

Dale, V.H., Kline, K.L., Wiens, J., Fargione, J., 2010. Biofuels: implications for land use and biodiversity. Ecological Society of America Washington, DC. https://www.researchgate.net/profile/Virginia_Dale/publication/265485931_Biofuels_Implications_for_Land_Use_and_Biodiversity_Biofuels_Implications_for_Land_Use_and_Biodiversity/links/5416d23e0cf2fa878ad42beb/Biofuels-Implications-for-Land-Use-and-Biodiversity-Biofuels-Implications-for-Land-Use-and-Biodiversity.pdf (accessed 6.21.18)

Dandikas, V., Heuwinkel, H., Lichti, F., Drewes, J.E., Koch, K., 2015. Correlation between Biogas Yield and Chemical Composition of Grassland Plant Species. Energy Fuels 29, 7221–7229. https://doi.org/10.1021/acs.energyfuels.5b01257

Dandikas, V., Heuwinkel, H., Lichti, F., Drewes, J.E., Koch, K., 2014. Correlation between biogas yield and chemical composition of energy crops. Bioresour. Technol. 174, 316–320. https://doi.org/10.1016/j.biortech.2014.10.019

Daniel, T.C., 2001. Whither scenic beauty? Visual landscape quality assessment in the 21st century. Landsc. Urban Plan. 54, 267–281. https://doi.org/10.1016/S0169-2046(01)00141-4

Deutsch, L., Folke, C., Skånberg, K., 2003. The critical natural capital of ecosystem performance as insurance for human well-being. Ecol. Econ., Identifying Critical Natural Capital 44, 205–217. https://doi.org/10.1016/S0921-8009(02)00274-4

Dhillon, R.S., von Wuehlisch, G., 2013. Mitigation of global warming through renewable biomass. Biomass Bioenergy 48, 75–89. https://doi.org/10.1016/j.biombioe.2012.11.005

Diamantidis, N.D., Koukios, E.G., 2000. Agricultural crops and residues as feedstocks for non-food products in Western Europe. Ind. Crops Prod. 11, 97–106. https://doi.org/10.1016/S0926-6690(99)00045-X

Didier, T., Philippe, L.-G., Sonia, H., Amar, B., Claudia, M.-C., Marielle, D., Jairo, F., 2012. Prospects of Miscanthus x giganteus for PAH phytoremediation: A microcosm study. Ind. Crops Prod. 36, 276–281. https://doi.org/10.1016/j.indcrop.2011.10.030

Dı́az, S., Cabido, M., 2001. Vive la différence: plant functional diversity matters to ecosystem processes. Trends Ecol. Evol. 16, 646–655. https://doi.org/10.1016/S0169-5347(01)02283-2

Dornburg, V., van Vuuren, D., van de Ven, G., Langeveld, H., Meeusen, M., Banse, M., van Oorschot, M., Ros, J., van den Born, G.J., Aiking, H., 2010. Bioenergy revisited: key factors in global potentials of bioenergy. Energy Environ. Sci. 3, 258–267. https://doi.org/10.1039/B922422J

Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262. https://doi.org/10.1038/24376

Duchene, O., Vian, J.-F., Celette, F., 2017. Intercropping with legume for agroecological cropping systems: Complementarity and facilitation processes and the importance of soil microorganisms. A review. Agric. Ecosyst. Environ. 240, 148–161. https://doi.org/10.1016/j.agee.2017.02.019

Eberl, V., Fahlbusch, W., Fritz, M., Sauer, B., 2014. Screening und Selektion von Amarantsorten und -linien als spurenelementreiches Biogassubstrat (No. 37), Berichte aus dem TFZ. Technologie- und Förderzentrum im Kompetenzzentrum für Nachwachsende Rohstoffe, Straubing. www.tfz.bayern.de/mam/cms08/service/dateien/37_bericht.pdf (accessed 6.21.18)

Eberl, V., Fritz, M., 2018. Amarant als spurenelementreiches Biogassubstrat (No. 1), Biogas Forum Bayern. Technologie- und Förderzentrum (TFZ) im Kompetenzzentrum für Nachwachsende Rohstoffe, Bayern. www.tfz.bayern.de/mam/cms08/rohstoffpflanzen/dateien/amarant_als_biogassubstrat.pdf (accessed 6.21.18)

Edenhofer, O., Seyboth, K., Creutzig, F., Schlömer, S., 2013. On the Sustainability of Renewable Energy Sources. Annu. Rev. Environ. Resour. 38, 169–200. https://doi.org/10.1146/annurev-environ-051012-145344

Edrisi, S.A., Abhilash, P.C., 2016. Exploring marginal and degraded lands for biomass and bioenergy production: An Indian scenario. Renew. Sustain. Energy Rev. 54, 1537–1551. https://doi.org/10.1016/j.rser.2015.10.050

Elbersen, B., Van Eupen, M., Mantel, S., Alexopoulou, E., Bai, Z., Boogard, H., Carrasco, J., Ceccarelli, T., Ramos, C.C., Ciria, P., Cosentino, S.L., Elbersen, W., Eleftheriadis, I., Fritz, S., Gabrielle, B., Iqbal, Y., Lewandowski, I., McCallum, I., Monti, A., Mucher, S., Sanz, M., Scordia, D., Verzandvoort, S., Von Cossel, M., Zanetti, F., 2018b. Mapping Marginal land potentially available for industrial crops in Europe. Presented at the EUBCE 2018 - 26th European Biomass Conference & Exhibition, Copenhagen. https://www.researchgate.net/publication/325272893

Elbersen, B., Van Verzandvoort, M., Boogaard, S., Mucher, S., Cicarelli, T., Elbersen, W., Mantel, S., Bai, Z., MCallum, I., Iqbal, Y., Lewandowski, I., Von Cossel, M., Carrasco, J., Ramos, C.C., Sanz, M., Ciria, P., Monti, A., Consentino, S., Scordia, D., Eleftheriadis, I., 2018a. Definition and classification of marginal lands suitable for industrial crops in Europe. Deliverable 2.1, Horizon 2020 Project MAGIC, GA No 727698. Wageningen University and Research, Wageningen, The Netherlands. http://magic-h2020.eu/

Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J., Walker, B., Norberg, J., 2003. Response diversity, ecosystem change, and resilience. Front. Ecol. Environ. 1, 488–494. https://doi.org/10.1890/1540-9295(2003)001[0488:RDECAR]2.0.CO;2

Emmann, C.H., Guenther-Lübbers, W., Theuvsen, L., 2013. Impacts of biogas production on the production factors land and labour–current effects, possible consequences and further research needs. Int. J. Food Syst. Dyn. 4, 38–50. https://ageconsearch.umn.edu/record/164768 (accessed 6.21.18)

Emmerling, C., 2014. Impact of land-use change towards perennial energy crops on earthworm population. Appl. Soil Ecol. 84, 12–15. https://doi.org/10.1016/j.apsoil.2014.06.006

Emmerling, C., Schmidt, A., Ruf, T., von Francken-Welz, H., Thielen, S., 2017. Impact of newly introduced perennial bioenergy crops on soil quality parameters at three different locations in W-Germany. J. Plant Nutr. Soil Sci. 180, 759–767. https://doi.org/10.1002/jpln.201700162

FAO, WHO, 2014. The international code of conduct on pesticide management. World Health Organization and Food and Agriculture Organization of the United Nations.

Federal Ministry of Justice and Consumer Protection, 2017. EEG 2017 - German Renewable Energies Act. https://www.gesetze-im-internet.de/eeg_2014/BJNR106610014.html (accessed 11.1.17).

Felten, D., Emmerling, C., 2011. Effects of bioenergy crop cultivation on earthworm communities—A comparative study of perennial (Miscanthus) and annual crops with consideration of graded land-use intensity. Appl. Soil Ecol. 49, 167–177. https://doi.org/10.1016/j.apsoil.2011.06.001

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., 2005. Global consequences of land use. Science 309, 570–574. https://doi.org/10.1126/science.1111772

Folke, C., 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. Glob. Environ. Change 16, 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C.S., 2004. Regime shifts, resilience, and biodiversity in ecosystem management. Annu. Rev. Ecol. Evol. Syst. 35. https://doi.org/10.1146/annurev.ecolsys.35.021103.105711

Fortel, L., Henry, M., Guilbaud, L., Guirao, A.L., Kuhlmann, M., Mouret, H., Rollin, O., Vaissière, B.E., 2014. Decreasing abundance, increasing diversity and changing structure of the wild bee community (Hymenoptera: Anthophila) along an urbanization gradient. PloS One 9, e104679. https://doi.org/10.1371/journal.pone.0104679

Franco-Hernandez, M.O., Vásquez-Murrieta, M.S., Patiño-Siciliano, A., Dendooven, L., 2010. Heavy metals concentration in plants growing on mine tailings in Central Mexico. Bioresour. Technol. 101, 3864–3869. https://doi.org/10.1016/j.biortech.2010.01.013

Frank, S., Schmid, E., Havlík, P., Schneider, U.A., Böttcher, H., Balkovič, J., Obersteiner, M., 2015. The dynamic soil organic carbon mitigation potential of European cropland. Glob. Environ. Change 35, 269–278. https://doi.org/10.1016/j.gloenvcha.2015.08.004

Fraser, E.D.G., 2006. Crop diversification and trade liberalization: Linking global trade and local management through a regional case study. Agric. Hum. Values 23, 271–281. https://doi.org/10.1007/s10460-006-9005-5

Friedrichs, J.C., 2013. Wirtschaftlichkeit des Anbaus von Wildpflanzenmischungen zur Energiegewinnung - Kalkulation der erforderlichen Förderung zur Etablierung von Wildpflanzenmischungen (Opinion of experts). Rosdorf, Germany. https://lebensraum-brache.de/biogas-aus-wildpflanzen/wirtschaftlichkeit-des-anbaus-von-wildpflanzenmischungen/ (accessed 6.21.18)

Fritsche, U.R., Sims, R.E., Monti, A., 2010. Direct and indirect land-use competition issues for energy crops and their sustainable production–an overview. Biofuels Bioprod. Biorefining 4, 692–704. https://doi.org/10.1002/bbb.258

Fritz, M., Deiglmayr, K., Gehring, K., 2012. Amaranth, Energiepflanzen für Biogasanlagen. Fachagentur Nachwachsende Rohstoffe e. V., Gülzow. http://www.biogas-forum-bayern.de/media/files/0003/energiepflanzen-f-r-biogaserzeugung.pdf (accessed 6.21.18)

Fujita, K., Ofosu-Budu, K.G., Ogata, S., 1992. Biological nitrogen fixation in mixed legume-cereal cropping systems, in: Biological Nitrogen Fixation for Sustainable Agriculture. Springer, pp. 155–175. https://doi.org/10.1007/BF00011315

Gaduš, J., Giertl, T., Jančo, Š., Košík, L., Fodora, M., Civáňová, Ľ., 2012. Biogas production from amaranth through dry fermentation technology. http://agris.fao.org/agris-search/search.do?recordID=SK2013000032

Gallinat, A.S., Primack, R.B., Wagner, D.L., 2015. Autumn, the neglected season in climate change research. Trends Ecol. Evol. 30, 169–176. https://doi.org/10.1016/j.tree.2015.01.004

Gansberger, M., Montgomery, L.F.R., Liebhard, P., 2015. Botanical characteristics, crop management and potential of Silphium perfoliatum L. as a renewable resource for biogas production: A review. Ind. Crops Prod. 63, 362–372. https://doi.org/10.1016/j.indcrop.2014.09.047

Gaudin, A.C.M., Tolhurst, T.N., Ker, A.P., Janovicek, K., Tortora, C., Martin, R.C., Deen, W., 2015. Increasing Crop Diversity Mitigates Weather Variations and Improves Yield Stability. PLOS ONE 10, e0113261. https://doi.org/10.1371/journal.pone.0113261

Gebrehanna, M.M., Gordon, R.J., Madani, A., VanderZaag, A.C., Wood, J.D., 2014. Silage effluent management: a review. J. Environ. Manage. 143, 113–122. https://doi.org/10.1016/j.jenvman.2014.04.012

German Council of Environmental Advisors, 2007. Klimaschutz durch Biomasse - Sondergutachten, 1st ed. Erich Schmidt, Berlin. https://doi.org/10.1007/s12302-008-0008-2

Gimplinger, D.M., Dobos, G., Kaul, H.-P., others, 2008. Optimum crop densities for potential yield and harvestable yield of grain amaranth are conflicting. Eur. J. Agron. 28, 119–125. https://doi.org/10.1016/j.eja.2007.05.007

Godin, B., Mayer, F., Agneessens, R., Gerin, P., Dardenne, P., Delfosse, P., Delcarte, J., 2015. Biochemical methane potential prediction of plant biomasses: Comparing chemical composition versus near infrared methods and linear versus non-linear models. Bioresour. Technol. 175, 382–390. https://doi.org/10.1016/j.biortech.2014.10.115

Grethe, H., Arens-Azevedo, U., Balmann, A., Biesalski, H.K., Birner, R., Bokelmann, W., Christen, O., Gauly, M., Knierim, U., Latacz-Lohmann, U., Martínez, J., Offermann, F., Pischetsrieder, M., Qaim, M., Schmid, J.C., Spiller, A., Taube, F., Voget-Kleschin, L., Weingarten, P., 2018. For an EU Common Agricultural Policy serving the public good after 2020: Fundamental questions and recommendations. Berichte Über Landwirtsch. 225. https://doi.org/10.12767/buel.v0i225.220.g405

Haag, N.L., Nägele, H.-J., Fritz, T., Oechsner, H., 2015. Effects of ensiling treatments on lactic acid production and supplementary methane formation of maize and amaranth–An advanced green biorefining approach. Bioresour. Technol. 178, 217–225. https://doi.org/10.1016/j.biortech.2014.08.048

Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PloS One 12, e0185809. https://doi.org/10.1371/journal.pone.0185809

Hatt, S., Uyttenbroeck, R., Lopes, T.M., Paul, A., Danthine, S., Bodson, B., Piqueray, J., Monty, A., Francis, F., 2015. Do Wildflower Strips Favor Insect Pest Populations at Field Margins? Agric. Agric. Sci. Procedia 6, 30–37. https://doi.org/10.1016/j.aaspro.2015.08.034

Heaton, E.A., Schulte, L.A., Berti, M., Langeveld, H., Zegada-Lizarazu, W., Parrish, D., Monti, A., 2013. Managing a second-generation crop portfolio through sustainable intensification: Examples from the USA and the EU. Biofuels Bioprod. Biorefining 7, 702–714. https://doi.org/10.1002/bbb.1429

Hector, A., Bagchi, R., 2007. Biodiversity and ecosystem multifunctionality. Nature 448, 188–190. https://www.nature.com/articles/nature05947

Hector, A., Schmid, B., Beierkuhnlein, C., Caldeira, M.C., Diemer, M., Dimitrakopoulos, P.G., Finn, J.A., Freitas, H., Giller, P.S., Good, J., Harris, R., Högberg, P., Huss-Danell, K., Joshi, J., Jumpponen, A., Körner, C., Leadley, P.W., Loreau, M., Minns, A., Mulder, C.P.H., O'Donovan, G., Otway, S.J., Pereira, J.S., Prinz, A., Read, D.J., Scherer-Lorenzen, M., Schulze, E.-D., Siamantziouras, A.-S.D., Spehn, E.M., Terry, A.C., Troumbis, A.Y., Woodward, F.I., Yachi, S., Lawton, J.H., 1999. Plant Diversity and Productivity Experiments in European Grasslands. Science 286, 1123–1127. https://doi.org/10.1126/science.286.5442.1123

Heggenstaller, A.H., Anex, R.P., Liebman, M., Sundberg, D.N., Gibson, L.R., 2008. Productivity and Nutrient Dynamics in Bioenergy Double-Cropping Systems. Agron. J. 100, 1740–1748. https://doi.org/10.2134/agronj2008.0087

Herrmann, A., 2013. Biogas production from maize: current state, challenges and prospects. 2. Agronomic and environmental aspects. BioEnergy Res. 6, 372–387. https://doi.org/10.1007/s12155-012-9227-x

Herrmann, A., Kornher, A., Taube, F., 2005. A new harvest time prognosis tool for forage maize production in Germany. Agric. For. Meteorol. 130, 95–111. https://doi.org/10.1016/j.agrformet.2005.02.005

Herrmann, A., Rath, J., 2012. Biogas production from maize: current state, challenges, and prospects. 1. Methane yield potential. BioEnergy Res. 5, 1027–1042. https://doi.org/10.1007/s12155-012-9202-6

Herrmann, A., Taube, F., 2005. Nitrogen concentration at maturity—an indicator of nitrogen status in forage maize. Agron. J. 97, 201–210. https://dl.sciencesocieties.org/publications/aj/abstracts/97/1/0201

Herrmann, C., Heiermann, M., Idler, C., Hertwig, F., 2009. Einfluss von Trockenmassegehalt (Abreife), Häcksellänge und Silierung auf die Biogasausbeute von Mais. Optim. Futterwertes Von Mais Maisprodukten, Optimierung des Futterwertes von Mais und Maisprodukten 87–105. https://www.researchgate.net/publication/237621231

Herrmann, C., Idler, C., Heiermann, M., 2016a. Biogas crops grown in energy crop rotations: Linking chemical composition and methane production characteristics. Bioresour. Technol. 206, 23–35. https://doi.org/10.1016/j.biortech.2016.01.058

Herrmann, C., Plogsties, V., Willms, M., Hengelhaupt, F., Eberl, V., Eckner, J., Strauß, C., Idler, C., Heiermann, M., 2016b. Methane production potential of various crop species grown in energy crop rotations. Landtechnik 71, 194–209. https://www.researchgate.net/profile/Christiane_Herrmann/publication/310832718

Höcherl, N., Siede, R., Illies, I., Gätschenberger, H., Tautz, J., 2012. Evaluation of the nutritive value of maize for honey bees. J. Insect Physiol. 58, 278–285. https://doi.org/10.1016/j.jinsphys.2011.12.001

Hodgson, R.W., Thayer, R.L., 1980. Implied human influence reduces landscape beauty. Landsc. Plan. 7, 171–179. https://doi.org/10.1016/0304-3924(80)90014-3

Holm-Nielsen, J.B., Al Seadi, T., Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. Bioresour. Technol. 100, 5478–5484. https://doi.org/10.1016/j.biortech.2008.12.046

Holzschuh, A., Dainese, M., González-Varo, J.P., Mudri-Stojnić, S., Riedinger, V., Rundlöf, M., Scheper, J., Wickens, J.B., Wickens, V.J., Bommarco, R., Kleijn, D., Potts, S.G., Roberts, S.P.M., Smith, H.G., Vilà, M., Vujić, A., Steffan-Dewenter, I., 2016. Mass-flowering crops dilute pollinator abundance in agricultural landscapes across Europe. Ecol. Lett. 19, 1228–1236. https://doi.org/10.1111/ele.12657

Hooper, D.U., Chapin, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Symstad, A.J., Vandermeer, J., Wardle, D.A., 2005. Effects of Biodiversity on Ecosystem Functioning: A Consensus of Current Knowledge. Ecol. Monogr. 75, 3–35. https://doi.org/10.1890/04-0922

Hudiburg, T.W., Davis, S.C., Parton, W., Delucia, E.H., 2015. Bioenergy crop greenhouse gas mitigation potential under a range of management practices. Gcb Bioenergy 7, 366–374. https://doi.org/10.1111/gcbb.12152

Isbell, F., Adler, P.R., Eisenhauer, N., Fornara, D., Kimmel, K., Kremen, C., Letourneau, D.K., Liebman, M., Polley, H.W., Quijas, S., 2017a. Benefits of increasing plant diversity in sustainable agroecosystems. J. Ecol. 105, 871–879. https://doi.org/10.1111/1365-2745.12789

Isbell, F., Gonzalez, A., Loreau, M., Cowles, J., Díaz, S., Hector, A., Mace, G.M., Wardle, D.A., O'Connor, M.I., Duffy, J.E., Turnbull, L.A., Thompson, P.L., Larigauderie, A., 2017b. Linking the influence and dependence of people on biodiversity across scales. Nature 546, 65–72. https://doi.org/10.1038/nature22899

Jablonowski, N.D., Kollmann, T., Nabel, M., Damm, T., Klose, H., Müller, M., Bläsing, M., Seebold, S., Krafft, S., Kuperjans, I., Dahmen, M., Schurr, U., 2017. Valorization of Sida (Sida hermaphrodita) biomass for multiple energy purposes. GCB Bioenergy 9, 202–214. https://doi.org/10.1111/gcbb.12346

Janusch, C., 2014. Potentiale und Grenzen des Anbaus von mehrjährigen Wildpflanzenmischungen als Biogassubstrat. Bachelor Thesis. University of Hohenheim, Biobased products and Energy Crops. Stuttgart, Germany. http://docplayer.org/33660771-Potentiale-und-grenzen-des-anbaus-von-mehrjaehrigen-wildpflanzenmischungen-als-biogassubstrat.html

John, B., Yamashita, T., Ludwig, B., Flessa, H., 2005. Storage of organic carbon in aggregate and density fractions of silty soils under different types of land use. Geoderma 128, 63–79. https://doi.org/10.1016/j.geoderma.2004.12.013

Kaci, G., Blavet, D., Benlahrech, S., Kouakoua, E., Couderc, P., Deleporte, P., Desclaux, D., Latati, M., Pansu, M., Drevon, J.-J., 2018. The effect of intercropping on the efficiency of faba bean–rhizobial symbiosis and durum wheat soil-nitrogen acquisition in a Mediterranean agroecosystem. Plant Soil Environ. 64, 138–146. https://doi.org/10.17221/9/2018-PSE

Kalamaras, S.D., Kotsopoulos, T.A., 2014. Anaerobic co-digestion of cattle manure and alternative crops for the substitution of maize in South Europe. Bioresour. Technol. 172, 68–75. https://doi.org/10.1016/j.biortech.2014.09.005

Karpenstein-Machan, M., Stuelpnagel, R., 2000. Biomass yield and nitrogen fixation of legumes monocropped and intercropped with rye and rotation effects on a subsequent maize crop. Plant Soil 218, 215–232. https://doi.org/10.1023/A:1014932004926

Karpenstein-Machan, V.M., Weber, C., 2010. Energiepflanzenanbau für Biogasanlagen. Naturschutz Landschaftsplanung 42, 312–320. https://www.nul-online.de/Magazin/Archiv/Energiepflanzenanbau-fuer-Biogasanlagen,QUlEPTE4MDcyNjUmTUlEPTgyMDMw.html (accessed 06.21.2018)

Kaul, H.E., Aufhammer, W., Nalborczyk, E., Pirog, S., Wasiak, K., Laible, B., 1996. The suitability ofamaranth genotypes for grain and fodder use in Central Europe. Bodenkult. 173, 3. https://diebodenkultur.boku.ac.at/volltexte/band-47/heft-3/Kaul.pdf

Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., Groenigen, K.J., 2013. Climate, duration, and N placement determine N2O emissions in reduced tillage systems: a meta-analysis. Glob. Change Biol. 19, 33–44. https://doi.org/10.1111/j.1365-2486.2012.02779.x
Kiesel, A., Lewandowski, I., 2017. Miscanthus as biogas substrate – cutting tolerance and potential for anaerobic digestion. GCB Bioenergy 9, 153–167. https://doi.org/10.1111/gcbb.12330
Kiesel, A., Wagner, M., Lewandowski, I., 2016. Environmental Performance of Miscanthus, Switchgrass and Maize: Can C4 Perennials Increase the Sustainability of Biogas Production? Sustainability 9, 5. https://doi.org/10.3390/su9010005
Knierim, A., Laschewski, L., Boyarintseva, O., 2018. Inter- and Transdisciplinarity in Bioeconomy, in: Bioeconomy. Springer, Cham, pp. 39–72. https://doi.org/10.1007/978-3-319-68152-8_4
Kodriková, K., Kolomazník, K., 2006. The modelling of the amaranth biomass fermentation and the measurement of biogas micro flow. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.462.7908
Koyutürk, M., 2013. Charakterisierung von Buschbohnensorten aus dem Sortenarchiv der Arche Noah (PhD Thesis). Universität für Bodenkultur, Wien. http://search.obvsg.at/primo_library/libweb/action/dlDisplay.do?vid=OBV&docId=OBV_alma71427922140003331&fn=permalink
Krasuska, E., Cadórniga, C., Tenorio, J.L., Testa, G., Scordia, D., 2010. Potential land availability for energy crops production in Europe. Biofuels, Bioproducts and Biorefining 4, 658–673. https://doi.org/10.1002/bbb.259
Kremen, C., Iles, A., Bacon, C., 2012. Diversified farming systems: An agroecological, systems-based alternative to modern industrial agriculture. Ecol. Soc. 17. https://doi.org/10.5751/ES-05103-170444
Kremen, C., Miles, A., 2012. Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. Ecol. Soc. 17. https://doi.org/10.5751/ES-05035-170440
Kuhn, W., Zeller, J., Bretschneider-Herrmann, N., Drenckhahn, K., 2014. Energy from wild plants - Practical tips for the cultivation of wild plants to create biomass for biogas generation plants. Berlin. https://lebensraum-brache.de/wp-content/uploads/2014/04/Flyer_NLFlur_1213_Englisch_klein.pdf (accessed 06.21.2018)
Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. science 304, 1623–1627. 10.1126/science.1097396
Lang, M., Lang, A., 2015. The 2014 German renewable energy sources act revision–from feed-in tariffs to direct marketing to competitive bidding. J. Energy Nat. Resour. Law 33, 131–146. https://doi.org/10.1080/02646811.2015.1022439
Leopold, A., 1949. A sand county almanac. Oxford University Press. https://faculty.ithaca.edu/mismith/docs/environmental/leopold.pdf (accessed 06.21.2018)
Lewandowski, I., 2017. Increasing Biomass Production to Sustain the Bioeconomy, in: Knowledge-Driven Developments in the Bioeconomy, Economic Complexity and Evolution. Springer, Cham, pp. 179–203. https://doi.org/10.1007/978-3-319-58374-7_10
Lewandowski, I., 2015. Securing a sustainable biomass supply in a growing bioeconomy. Glob. Food Secur. 6, 34–42. https://doi.org/10.1016/j.gfs.2015.10.001

Lewandowski, I., Gaudet, N., Lask, J., Maier, J., Tchouga, B., Vargas-Carpintero, R., 2018a. Context, in: Bioeconomy. Springer, Cham, pp. 5–16. https://doi.org/10.1007/978-3-319-68152-8_2

Lewandowski, I., Lippe, M., Castro-Montoya, J., Dickhöfer, U., Langenberger, G., Pucher, J., Schließmann, U., Derwenskus, F., Schmid-Staiger, U., Lippert, C., 2018b. Primary Production, in: Bioeconomy. Springer, Cham, pp. 95–175. https://doi.org/10.1007/978-3-319-68152-8_6

Lewandowski, I., Scurlock, J.M., Lindvall, E., Christou, M., 2003. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass Bioenergy 25, 335–361. https://doi.org/10.1016/S0961-9534(03)00030-8

Liebman, M., Dyck, E., 1993. Crop Rotation and Intercropping Strategies for Weed Management. Ecol. Appl. 3, 92–122. https://doi.org/10.2307/1941795

Lin, B.B., 2011. Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change. BioScience 61, 183–193. https://doi.org/10.1525/bio.2011.61.3.4

MAGIC, 2018. Marginal Lands for Growing Industrial Crops - Turning a burden into an opportunity. Horizon 2020 Project, GA No. 727698. http://magic-h2020.eu/ (accessed 6.20.18).

Mast, B., Lemmer, A., Oechsner, H., Reinhardt-Hanisch, A., Claupein, W., Graeff-Hönninger, S., 2014. Methane yield potential of novel perennial biogas crops influenced by harvest date. Ind. Crops Prod. 58, 194–203. https://doi.org/10.1016/j.indcrop.2014.04.017

Matson, P.A., Parton, W.J., Power, A.G., Swift, M.J., 1997. Agricultural Intensification and Ecosystem Properties. Science 277, 504–509. https://doi.org/10.1126/science.277.5325.504

Mayer, F., Gerin, P.A., Noo, A., Lemaigre, S., Stilmant, D., Schmit, T., Leclech, N., Ruelle, L., Gennen, J., von Francken-Welz, H., Foucart, G., Flammang, J., Weyland, M., Delfosse, P., 2014. Assessment of energy crops alternative to maize for biogas production in the Greater Region. Bioresour. Technol. 166, 358–367. https://doi.org/10.1016/j.biortech.2014.05.054

McGuire, C.J., Lynch, D., 2017. The Need for Environmental Justice Never Ends Because Externalities Persist. Environ. Justice 10, 68–71. https://doi.org/10.1089/env.2017.0013

McLaughlin, A., Mineau, P., 1995. The impact of agricultural practices on biodiversity. Agric. Ecosyst. Environ. 55, 201–212. https://doi.org/10.1016/0167-8809(95)00609-V

Meers, E., Van Slycken, S., Adriaensen, K., Ruttens, A., Vangronsveld, J., Du Laing, G., Witters, N., Thewys, T., Tack, F.M.G., 2010. The use of bio-energy crops (Zea mays) for 'phytoattenuation'of heavy metals on moderately contaminated soils: a field experiment. Chemosphere 78, 35–41. https://doi.org/10.1016/j.chemosphere.2009.08.015

Mehmood, M.A., Ibrahim, M., Rashid, U., Nawaz, M., Ali, S., Hussain, A., Gull, M., 2017. Biomass production for bioenergy using marginal lands. Sustain. Prod. Consum. 9, 3–21. https://doi.org/10.1016/j.spc.2016.08.003

Meyer, S.T., Ebeling, A., Eisenhauer, N., Hertzog, L., Hillebrand, H., Milcu, A., Pompe, S., Abbas, M., Bessler, H., Buchmann, N., 2016. Effects of biodiversity strengthen over time as ecosystem functioning declines at low and increases at high biodiversity. Ecosphere 7. https://doi.org/10.1002/ecs2.1619

Mockshell, J., Kamanda, J., 2017. Beyond the Agroecological and Sustainable Agricultural Intensification Debate: Is Blended Sustainability the Way Forward? International Journal of Agricultural Sustainability, 16:2, 127–149. https://doi.org/10.1080/14735903.2018.1448047

Mürle, R., Zuber, J., 2013. Analyse wichtiger Einflussfaktoren auf Bestandesentwicklung und Ertragsbildung von Wildpflanzenmischungen im Hinblick auf die Verwertung als Biogassubstrat - Ein Freilandversuch. Project work. University of Hohenheim, Biobased Products and Energy crops, Stuttgart, Germany.

Mursec, B., Vindis, P., Janzekovic, M., Brus, M., Cus, F., 2009. Analysis of different substrates for processing into biogas. J. Achiev. Mater. Manuf. Eng. 37, 652–659. https://www.researchgate.net/publication/44444986 (accessed 06.21.2018)

Nicholls, C.I., Altieri, M.A., 2013. Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review. Agron. Sustain. Dev. 33, 257–274. https://doi.org/10.1007/s13593-012-0092-y

Niu, W., Han, L., Liu, X., Huang, G., Chen, L., Xiao, W., Yang, Z., 2016. Twenty-two compositional characterizations and theoretical energy potentials of extensively diversified China’s crop residues. Energy 100, 238–250. https://doi.org/10.1016/j.energy.2016.01.093

Nunes, M.R., van Es, H.M., Schindelbeck, R., Ristow, A.J., Ryan, M., 2018. No-till and cropping system diversification improve soil health and crop yield. Geoderma 328, 30–43. https://doi.org/10.1016/j.geoderma.2018.04.031

Nurk, L., Graß, R., Hubert, S., Pekrun, C., Wachendorf, M., 2015. Mischanbau von Silomais mit Stangenbohnen. Poster. Am Mut hängt der Erfolg - Rückblicke und Ausblicke auf die ökologische Landbewirtschaftung. Beiträge zur 13. Wissenschaftstagung Ökologischer Landbau, Hochschule für nachhaltige Entwicklung Eberswalde, 17.-20. März 2015, Verlag Dr. Köster, Berlin. http://orgprints.org/26888/ (accessed 06.21.2018)

Nurk, L., Graß, R., Pekrun, C., Wachendorf, M., 2017a. Effect of sowing method and weed control on the performance of maize (Zea mays L.) intercropped with climbing beans (Phaseolus vulgaris L.). Agriculture 7, 51. https://doi.org/10.3390/agriculture7070051

Nurk, L., Graβ, R., Pekrun, C., Wachendorf, M., 2017b. Methane yield and feed quality parameters of mixed silages from maize (Zea mays L.) and common bean (Phaseolus vulgaris L.). BioEnergy Res. 10, 64–73. https://doi.org/10.1007/s12155-016-9779-2

Ofori, F., Stern, W.R., 1987. Cereal–legume intercropping systems. Adv. Agron. 41, 41–90. https://doi.org/10.1016/S0065-2113(08)60802-0

Otte, A., 2010. Biogas und Biodiversität-ein Gegensatz. Oral presentation. Symposium Energiepflanzen-Landschaft der Zukunft. Neu-Anspach, Germany.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N.K., Edenhofer, O., Elgizouli, I., Field, C. B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Jimenez Cisneroz, B., Kattsov, V., Lee, H., Mach, K.J., Marotzke, J., Mastrandrea, M.D., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pereira, J.J., Pichs-Madruga, R., Plattner, G.K., Pörtner, H.O., Power, S.B., Preston, B., Ravindranath, N. H., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T.F., Tschakert, P., van Vuuren, D. and van Ypserle, J.P., 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change / R. Pachauri and L. Meyer (Editors) , Geneva, Switzerland. IPCC, 151 p., ISBN: 978-92-9169-143-2. https://epic.awi.de/id/eprint/37530/

Pedroli, B., Elbersen, B., Frederiksen, P., Grandin, U., Heikkilä, R., Krogh, P.H., Izakovičová, Z., Johansen, A., Meiresonne, L., Spijker, J., 2013. Is energy cropping in Europe compatible with biodiversity?–Opportunities and threats to biodiversity from land-based production of biomass for bioenergy purposes. Biomass Bioenergy 55, 73–86. https://doi.org/10.1016/j.biombioe.2012.09.054

Pe'er, G., Dicks, L.V., Visconti, P., Arlettaz, R., Báldi, A., Benton, T.G., Collins, S., Dieterich, M., Gregory, R.D., Hartig, F., Henle, K., Hobson, P.R., Kleijn, D., Neumann, R.K., Robijns, T., Schmidt, J., Shwartz, A., Sutherland, W.J., Turbé, A., Wulf, F., Scott, A.V., 2014. EU agricultural reform fails on biodiversity. Science 344, 1090–1092. https://doi.org/10.1126/science.1253425

Pereira, H.M., Navarro, L.M., Martins, I.S., 2012. Global biodiversity change: the bad, the good, and the unknown. Annual Review of Environment and Resources, Vol. 37:25-50 https://doi.org/10.1146/annurev-environ-042911-093511

Perrin, R.M., 1976. Pest management in multiple cropping systems. Agro-Ecosyst. 3, 93–118. https://doi.org/10.1016/0304-3746(76)90110-4

Perrin, R.M., 1975. The role of the perennial stinging nettle, Urtica dioica, as a reservoir of beneficial natural enemies. Ann. Appl. Biol. 81, 289–297. https://doi.org/10.1111/j.1744-7348.1975.tb01644.x

Pfau, S.F., Hagens, J.E., Dankbaar, B., Smits, A.J., 2014. Visions of sustainability in bioeconomy research. Sustainability 6, 1222–1249. https://doi.org/10.3390/su6031222

Phillips, S.L., Wolfe, M.S., 2005. Evolutionary plant breeding for low input systems. J. Agric. Sci. 143, 245–254. https://doi.org/10.1017/S0021859605005009

Pospišil, A., Pospišil, M., Matotan, S., 2011. Grain amaranth (Amaranthus spp.) seed and total biomass yield as influenced by plant density. University of Zagreb Faculty of Agriculture, pp. 631–634. https://www.cabdirect.org/cabdirect/abstract/20123323802

Potting, R.P.J., Perry, J.N., Powell, W., 2005. Insect behavioural ecology and other factors affecting the control efficacy of agro-ecosystem diversification strategies. Ecol. Model. 182, 199–216. https://doi.org/10.1016/j.ecolmodel.2004.07.017

Potts, S.G., Imperatriz-Fonseca, V.L., Ngo, H.T., Biesmeijer, J.C., Breeze, T.D., Dicks, L.V., Garibaldi, L.A., Hill, R., Settele, J., Vanbergen, A.J., 2016. Summary for policymakers of the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. http://nora.nerc.ac.uk/id/eprint/519227/ (accessed 06.21.2018)

Prochnow, A., Heiermann, M., Plöchl, M., Amon, T., Hobbs, P.J., 2009a. Bioenergy from permanent grassland – A review: 2. Combustion. Bioresour. Technol. 100, 4945–4954. https://doi.org/10.1016/j.biortech.2009.05.069

Prochnow, A., Heiermann, M., Plöchl, M., Linke, B., Idler, C., Amon, T., Hobbs, P.J., 2009b. Bioenergy from permanent grassland–A review: 1. Biogas. Bioresour. Technol. 100, 4931–4944. https://doi.org/10.1016/j.biortech.2009.05.070

Queiroz, C., Beilin, R., Folke, C., Lindborg, R., 2014. Farmland abandonment: threat or opportunity for biodiversity conservation? A global review. Front. Ecol. Environ. 12, 288–296. https://doi.org/10.1890/120348

Ragauskas, A.J., Williams, C.K., Davison, B.H., Britovsek, G., Cairney, J., Eckert, C.A., Frederick, W.J., Hallett, J.P., Leak, D.J., Liotta, C.L., Mielenz, J.R., Murphy, R., Templer, R.,

Tschaplinski, T., 2006. The Path Forward for Biofuels and Biomaterials. Science 311, 484–489. https://doi.org/10.1126/science.1114736
Ramirez-Almeyda, J., Elbersen, B., Monti, A., Staritsky, I., Panoutsou, C., Alexopoulou, E., Schrijver, R., Elbersen, W., 2017. "Assessing the Potentials for Nonfood Crops" in Modeling and Optimization of Biomass Supply Chains (Elsevier), 219–251. https://doi.org/10.1016/B978-0-12-812303-4.00009-4
Rath, J., Heuwinkel, H., Herrmann, A., 2013. Specific biogas yield of maize can be predicted by the interaction of four biochemical constituents. BioEnergy Res. 6, 939–952. https://doi.org/10.1007/s12155-013-9318-3
Rath, J., Heuwinkel, H., Taube, F., Herrmann, A., 2015. Predicting specific biogas yield of maize-validation of different model approaches. BioEnergy Res. 8, 832–842. https://doi.org/10.1007/s12155-014-9562-1
Reardon, S., Tollefson, J., Witze, A., Ross, E., 2017. US science agencies face deep cuts in Trump budget. Nature 543, 471–472. https://doi.org/10.1038/nature.2017.21652
Reheul, D., Cougnon, M., Kayser, M., Pannecoucque, J., Swanckaert, J., De Cauwer, B., van den Pol-van Dasselaar, A., De Vliegher, A., 2017. Sustainable intensification in the production of grass and forage crops in the Low Countries of north-west Europe. Grass Forage Sci. 72, 369–381. https://doi.org/10.1111/gfs.12285
Riley, R.D., Lambert, P.C., Abo-Zaid, G., 2010. Meta-analysis of individual participant data: rationale, conduct, and reporting. Bmj 340, c221. https://doi.org/10.1136/bmj.c221
Rockström, J., Steffen, W., Noone, K., Persson, Å., III, F.S.C., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., Wit, C.A. de, Hughes, T., Leeuw, S. van der, Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity [WWW Document]. Nature. https://doi.org/10.1038/461472a
Ronzon, T., Lusser, M., Klinkenberg, M., Landa, L., Sanchez Lopez, J., M'Barek, R., Hadjamu, G., Belward, A., Camia, A., Giuntoli, J., Cristobal, J., Parisi, C., Ferrari, E., Marelli, L., Torres de Matos, C., Gomez Barbero, M., Rodriguez Cerezo, E., 2016. Bioeconomy Report 2016 (JRC Scientific and Policy Report No. EUR 28468 EN). European Commision. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/bioeconomy-report-2016
Roth, L., Daunderer, M., Kormann, K., 2008. Giftpflanzen-Pflanzengifte : Vorkommen, Wirkung, Therapie ; allergische und phototoxische Reaktionen : neu: mit Sonderteil über Gifttiere. Nikol. Hamburg, Germany. https://www.tib.eu/de/suchen/id/zbmkm%3AHBZTHT015565481/Giftpflanzen-Pflanzengifte-Vorkommen-Wirkung-Therapie/ (accessed 06.21.2018)
Rowe, R.L., Street, N.R., Taylor, G., 2009. Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. Renew. Sustain. Energy Rev. 13, 271–290. https://doi.org/10.1016/j.rser.2007.07.008
Sage, R.F., Sage, T.L., 2013. C4 Plants, in: Levin, S.A. (Ed.), Encyclopedia of Biodiversity (Second Edition). Academic Press, Waltham, pp. 361–381. https://doi.org/10.1016/B978-0-12-384719-5.00192-1
Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E.F., Marx, A., 2018. Anthropogenic warming exacerbates European soil moisture droughts. Nat. Clim. Change 8, 421. https://www.nature.com/articles/s41558-018-0138-5

Sanderson, M.A., Adler, P.R., 2008. Perennial forages as second generation bioenergy crops. Int. J. Mol. Sci. 9, 768–788. https://doi.org/10.3390/ijms9050768

Sauer, B., Ruppert, H., 2011. Bioenergetische Nutzungskonzepte für kontaminierte landwirtschaftliche Standorte (Poster). Interdisziplinäres Zentrum für Nachhaltige Entwicklung der Universität Göttingen & Geowissenschaftliches Zentrum der Georg-August-Universität Göttingen, Göttingen. http://www.bioenergie.uni-goettingen.de/fileadmin/user_upload/admin/tagung_2013/Poster_2013/Sauer_KontaminierteStandorte.pdf (accessed 06.21.2018)

Schmeer, M., Loges, R., Dittert, K., Senbayram, M., Horn, R., Taube, F., 2014. Legume-based forage production systems reduce nitrous oxide emissions. Soil Tillage Res. 143, 17–25. https://doi.org/10.1016/j.still.2014.05.001

Schmidt, W., 2013. Erhöhung der Diversität im Energiepflanzenanbau am Beispiel Mais-Bohnen-Gemenge, in: 4. Symposium Energiepflanzen. pp. 77–104. https://docplayer.org/75863537-Erhoehung-der-diversitaet-im-energiepflanzenanbau-am-beispiel-mais-bohnen-gemenge.html (accessed 06.21.2018)

Scurlock, J.M.O., Hall, D.O., 1998. The global carbon sink: a grassland perspective. Glob. Change Biol. 4, 229–233. https://doi.org/10.1046/j.1365-2486.1998.00151.x

SEEMLA, 2018. Sustainable exploitation of biomass for bioenergy from marginal lands. Horizon 2020 Project, GA No. 691874. http://www.seemla.eu/de/horizon-2020-programme-4/ (accessed 6.20.18).

Seppälä, M., Laine, A., Rintala, J., 2013. Screening novel plants for biogas production in northern conditions. Bioresour. Technol. 139, 355–362. https://doi.org/10.1016/j.biortech.2013.04.014

Sheppard, A.W., Gillespie, I., Hirsch, M., Begley, C., 2011. Biosecurity and sustainability within the growing global bioeconomy. Curr. Opin. Environ. Sustain. 3, 4–10. https://doi.org/10.1016/j.cosust.2010.12.011

Sims, R.E., Hastings, A., Schlamadinger, B., Taylor, G., Smith, P., 2006. Energy crops: current status and future prospects. Glob. Change Biol. 12, 2054–2076. https://doi.org/10.1111/j.1365-2486.2006.01163.x

Singer, A.C., Crowley, D.E., Thompson, I.P., 2003. Secondary plant metabolites in phytoremediation and biotransformation. Trends Biotechnol. 21, 123–130. https://doi.org/10.1016/S0167-7799(02)00041-0

Sitkey, V., Gaduš, J., Kliskỳ, L., Dudák, A., 2013. Biogas production from amaranth biomass. Acta Reg. Environ. 10, 59–62. https://doi.org/10.2478/aree-2013-0013

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., 2008. Greenhouse gas mitigation in agriculture. Philos. Trans. R. Soc. Lond. B Biol. Sci. 363, 789–813. https://doi.org/10.1098/rstb.2007.2184

Song, Y.N., Zhang, F.S., Marschner, P., Fan, F.L., Gao, H.M., Bao, X.G., Sun, J.H., Li, L., 2007. Effect of intercropping on crop yield and chemical and microbiological properties in rhizosphere of wheat (Triticum aestivum L.), maize (Zea mays L.), and faba bean (Vicia faba L.). Biol. Fertil. Soils 43, 565–574. https://doi.org/10.1007/s00374-006-0139-9

Staffas, L., Gustavsson, M., McCormick, K., 2013. Strategies and policies for the bioeconomy and bio-based economy: An analysis of official national approaches. Sustainability 5, 2751–2769. https://doi.org/10.3390/su5062751

Stallknecht, G.F., Schulz-Schaeffer, J.R., 1993. Amaranth rediscovered, In: J. Janick and J.E. Simon (eds.), New crops, p. 211-218. Wiley, New York.

https://hort.purdue.edu/newcrop/proceedings1993/V2-211.html (accessed 06.21.2018)
Stang, M., Klinkhamer, P.G.L., Van Der Meijden, E., 2006. Size constraints and flower abundance determine the number of interactions in a plant–flower visitor web. Oikos 112, 111–121. https://doi.org/10.1111/j.0030-1299.2006.14199.x
Steberl, K., 2016. Mehrjährige Wildpflanzenmischungen im Systemvergleich mit anderen ein- und mehrjährigen Anbauverfahren für die Biogasproduktion. Master thesis. University of Hohenheim, Biobased Products and Energy Crops. Stuttgart, Germany.
Steffan-Dewenter, I., Tscharntke, T., 1999. Effects of habitat isolation on pollinator communities and seed set. Oecologia 121, 432–440. https://doi.org/10.1007/s004420050949
Stein, S., Steinmann, H.-H., 2018. Identifying crop rotation practice by the typification of crop sequence patterns for arable farming systems–A case study from Central Europe. Eur. J. Agron. 92, 30–40. https://doi.org/10.1016/j.eja.2017.09.010
Stetter, M. G., Müller, T., and Schmid, K.J., 2015. Incomplete domestication of South American grain amaranth (*Amaranthus caudatus*) from its wild relatives. bioRxiv, 025866. https://doi.org/10.1101/025866.
Stetter, M.G., Zeitler, L., Steinhaus, A., Kroener, K., Biljecki, M., and Schmid, K.J., 2016. Crossing methods and cultivation conditions for rapid production of segregating populations in three grain amaranth species. Front. Plant Sci. 7, 816. https://doi.org/10.3389/fpls.2016.00816
Stoll-Kleemann, S., Schmidt, U.J., 2017. Reducing meat consumption in developed and transition countries to counter climate change and biodiversity loss: a review of influence factors. Reg. Environ. Change 17, 1261–1277. https://doi.org/10.1007/S10113-016-1057-5
Stoltz, E., Nadeau, E., Wallenhammar, A.-C., 2013. Intercropping maize and faba bean for silage under Swedish climate conditions. Agric. Res. 2, 90–97. https://doi.org/10.1007/s40003-012-0048-0
Stoy, P.C., 2018. Deforestation intensifies hot days. Nat. Clim. Change 8, 366. https://www.nature.com/articles/s41558-018-0153-6
Struik, P.C., 1983. Physiology of forage maize (*Zea mays* L.) in relation to its production and quality. Dissertation. Wageningen University and Research, Laboratory of Field Crops and Grassland Science. Wageningen, The Netherlands. https://library.wur.nl/WebQuery/wurpubs/77534
Svoboda, N., Taube, F., Kluß, C., Wienforth, B., Kage, H., Ohl, S., Hartung, E., Herrmann, A., 2013. Crop production for biogas and water protection—A trade-off? Agric. Ecosyst. Environ. 177, 36–47. https://doi.org/10.1016/j.agee.2013.05.024
Svoboda, N., Taube, F., Kluß, C., Wienforth, B., Sieling, K., Hasler, M., Kage, H., Ohl, S., Hartung, E., Herrmann, A., 2015. Ecological Efficiency of Maize-Based Cropping Systems for Biogas Production. BioEnergy Res. 8, 1621–1635. https://doi.org/10.1007/s12155-015-9614-1
Teuling, A.J., 2018. A hot future for European droughts. Nat. Clim. Change 8, 364. https://www.nature.com/articles/s41558-018-0154-5
Theisen, G., Silva, J.J.C., Silva, J.S., Andres, A., Anten, N.P., Bastiaans, L., 2017. The birth of a new cropping system: towards sustainability in the sub-tropical lowland agriculture. Field Crops Res. 212, 82–94. https://doi.org/10.1016/j.fcr.2017.07.001
Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B.,

van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Townsend Peterson, A., Phillips, O.L., Williams, S.E., 2004. Extinction risk from climate change. Nature 427, 145–148. https://doi.org/10.1038/nature02121

Thomsen, S.T., Spliid, H., Østerg\a ard, H., 2014. Statistical prediction of biomethane potentials based on the composition of lignocellulosic biomass. Bioresour. Technol. 154, 80–86. https://doi.org/10.1016/j.biortech.2013.12.029

Tilman, D., 1999. The ecological consequences of changes in biodiversity: a search for general principles. Ecology 80, 1455–1474. https://doi.org/10.1890/0012-9658(1999)080[1455:TECOCI]2.0.CO;2

Tilman, D., Isbell, F., Cowles, J.M., 2014. Biodiversity and Ecosystem Functioning. Annu. Rev. Ecol. Evol. Syst. 45, 471–493. https://doi.org/10.1146/annurev-ecolsys-120213-091917

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., 2009. Beneficial biofuels—the food, energy, and environment trilemma. Science 325, 270–271. https://doi.org/10.1126/science.1177970

Tittonell, P., 2014. Ecological intensification of agriculture—sustainable by nature. Curr. Opin. Environ. Sustain. 8, 53–61. https://doi.org/10.1016/j.cosust.2014.08.006

Tollefson, J., 2017. Fears rise for US climate report as Trump officials take reins. Nat. News 548, 15. https://doi.org/10.1038/548015a

Triolo, J.M., Sommer, S.G., Møller, H.B., Weisbjerg, M.R., Jiang, X.Y., 2011. A new algorithm to characterize biodegradability of biomass during anaerobic digestion: influence of lignin concentration on methane production potential. Bioresour. Technol. 102, 9395–9402. https://doi.org/10.1016/j.biortech.2011.07.026

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., Whitbread, A., 2012. Global food security, biodiversity conservation and the future of agricultural intensification. Biol. Conserv. 151, 53–59. https://doi.org/10.1016/j.biocon.2012.01.068

Tscharntke, T., Karp, D.S., Chaplin-Kramer, R., Batáry, P., DeClerck, F., Gratton, C., Hunt, L., Ives, A., Jonsson, M., Larsen, A., 2016. When natural habitat fails to enhance biological pest control–Five hypotheses. Biol. Conserv. 204, 449–458. https://doi.org/10.1016/j.biocon.2016.10.001

Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I., Thies, C., 2005. Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. Ecol. Lett. 8, 857–874. https://doi.org/10.1111/j.1461-0248.2005.00782.x

Tschumi, M., Albrecht, M., Bärtschi, C., Collatz, J., Entling, M.H., Jacot, K., 2016. Perennial, species-rich wildflower strips enhance pest control and crop yield. Agric. Ecosyst. Environ. 220, 97–103. https://doi.org/10.1016/j.agee.2016.01.001

UBA, 2016. Erosion. Dessau-Roßlau, Germany https://www.umweltbundesamt.de/en/topics/soil-agriculture/land-a-precious-resource/erosion#textpart-1 (accessed 6.21.18)

Van Der Heijden, M.G.A., Bardgett, R.D., Van Straalen, N.M., 2008. The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol. Lett. 11, 296–310. https://doi.org/10.1111/j.1461-0248.2007.01139.x

Vandermeer, J.H., 1992. The ecology of intercropping. Cambridge University Press. https://www.cabdirect.org/cabdirect/abstract/19890724948

Venendaal, R., Jørgensen, U., Foster, C.A., 1997. European energy crops: a synthesis. Biomass Bioenergy 13, 147–185. https://doi.org/10.1016/S0961-9534(97)00029-9

Verdade, L.M., Piña, C.I., Rosalino, L.M., 2015. Biofuels and biodiversity: Challenges and opportunities. Environ. Dev. 15, 64–78. https://doi.org/10.1016/j.envdev.2015.05.003

Vogel, E., Deumlich, D., Kaupenjohann, M., 2016. Bioenergy maize and soil erosion — Risk assessment and erosion control concepts. Geoderma 261, 80–92. https://doi.org/10.1016/j.geoderma.2015.06.020

Vollrath, B., 2013. Wildpflanzen als Biogassubstrat. https://docplayer.org/83281835-Wildpflanzen-als-biogassubstrat-fachvortrag-zum-projekt-energie-aus-wildpflanzen.html (accessed 06.21.2018)

Vollrath, B., Werner, A., Degenbeck, M., Illies, I., Zeller, J., Marzini, K., 2012. Energetische Verwertung von kräuterreichen Ansaaten in der Agrarlandschaft und im Siedlungsbereich - eine ökologische und wirtschaftliche Alternative bei der Biogasproduktion (Schlussbericht), Energie aus Wildpflanzen. Bayerische Landesanstalt für Weinbau und Gartenbau, Veitshöchheim. https://www.lwg.bayern.de/mam/cms06/landespflege/dateien/energie_aus_wildpflanzhen_fnr_abschlussbericht_22005308_in.pdf (accessed 6.21.18)

Vollrath, B., Werner, A., Degenbeck, M., Marzini, K., 2016. Energetische Verwertung von kräuterreichen Ansaaten in der Agrarlandschaft - eine ökologische und wirtschaftliche Alternative bei der Biogasproduktion (Phase II) (Schlussbericht), Energie aus Wildpflanzen. Bayerische Landesanstalt für Weinbau und Gartenbau, Veitshöchheim. https://doi.org/10.2314/GBV:866552227

Von Cossel, M., Iqbal, Y., Scordia, D., Cosentino, S.L., Elbersen, B., Staritsky, I., Van Eupen, M., Mantel, S., Prysiazhniuk, O., Maliarenko, O., Lewandowski, I., 2018a. Low-input agricultural practices for industrial crops on marginal land (D4.1). In: MAGIC project reports, supported by the EU's Horizon 2020 programme under GA No. 727698, University of Hohenheim, Stuttgart, Germany.

Von Cossel, M., Lewandowski, I., 2016. Perennial wild plant mixtures for biomass production: Impact of species composition dynamics on yield performance over a five-year cultivation period in southwest Germany. Eur. J. Agron. 79, 74–89. https://doi.org/10.1016/j.eja.2016.05.006

Von Cossel, M., Möhring, J., Kiesel, A., Lewandowski, I., 2018b. Optimization of specific methane yield prediction models for biogas crops based on lignocellulosic components using non-linear and crop-specific configurations. Ind. Crops Prod. 120, 330–342. https://doi.org/10.1016/j.indcrop.2018.04.042

Von Cossel, M., Möhring, J., Kiesel, A., Lewandowski, I., 2017a. Methane yield performance of amaranth (Amaranthus hypochondriacus L.) and its suitability for legume intercropping in comparison to maize (Zea mays L.). Ind. Crops Prod. 103, 107–121. https://doi.org/10.1016/j.indcrop.2017.03.047

Von Cossel, M., Steberl, K., Möhring, J., Kiesel, A., Lewandowski, I. (2017b) Etablierungs-verfahren mehrjähriger Biogas-Wildpflanzenmischungen im Vergleich: Ohne Mais geht's nicht? Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften (Witzenhausen: Liddy Halm), 58–59. Available at: https://www.researchgate.net/publication/325477300 (accessed 11.05.2018).

Walker, B., Kinzig, A., Langridge, J., 1999. Plant attribute diversity, resilience, and ecosystem function: the nature and significance of dominant and minor species. Ecosystems 2, https://doi.org/95–113. 10.1007/s100219900062

Wall, G.J., Pringle, E.A., Sheard, R.W., 1991. Intercropping red clover with silage corn for soil erosion control. Can. J. Soil Sci. 71, 137–145. https://doi.org/10.4141/cjss91-013

Weiland, P., 2010. Biogas production: current state and perspectives. Appl. Microbiol. Biotechnol. 85, 849–860. https://doi.org/10.1007/s00253-009-2246-7

Weiland, P., 2006. Biomass Digestion in Agriculture: A Successful Pathway for the Energy Production and Waste Treatment in Germany. Eng. Life Sci. 6, 302–309. https://doi.org/10.1002/elsc.200620128

Weisser, W.W., Roscher, C., Meyer, S.T., Ebeling, A., Luo, G., Allan, E., Beßler, H., Barnard, R.L., Buchmann, N., Buscot, F., 2017. Biodiversity effects on ecosystem functioning in a 15-year grassland experiment: Patterns, mechanisms, and open questions. Basic Appl. Ecol. 23, 1–73. https://doi.org/10.1016/j.baae.2017.06.002

Weißhuhn, P., Reckling, M., Stachow, U., Wiggering, H., 2017. Supporting Agricultural Ecosystem Services through the Integration of Perennial Polycultures into Crop Rotations. https://doi.org/10.3390/su9122267

Wezel, A., Casagrande, M., Celette, F., Vian, J.-F., Ferrer, A., Peigné, J., 2014. Agroecological practices for sustainable agriculture. A review. Agron. Sustain. Dev. 34, 1–20. https://doi.org/10.1007/s13593-013-0180-7

Wiesenthal, T., Mourelatou, A., 2006. How much bioenergy can Europe produce without harming the environment? EEA Report 7/2006. ISSN: 1725-9177. https://trid.trb.org/view/790822

Willey, R.W., Osiru, D.S.O., 1972. Studies on mixtures of maize and beans (Phaseolus vulgaris) with particular reference to plant population. J. Agric. Sci. 79, 517–529. https://doi.org/10.1017/S0021859600025909

Winkler, B., Lemke, S., Ritter, J., Lewandowski, I., 2017. Integrated assessment of renewable energy potential: Approach and application in rural South Africa. Environ. Innov. Soc. Transit. 24, 17–31. https://doi.org/10.1016/j.eist.2016.10.002

Witt, J., Thrän, D., Rensberg, N., Hennig, C., Naumann, K., Billig, E., Sauter, P., Daniel-Gromke, J., Krautz, A., Weiser, C., 2012. Monitoring zur Wirkung des Erneuerbare-Energien-Gesetz (EEG) auf die Entwicklung der Stromerzeugung aus Biomasse, DBFZ Report Nr. 12. Deutsches Biomasseforschungszentrum, Leipzig. https://www.dbfz.de/fileadmin/eeg_monitoring/berichte/06_Monitoring_EB_Maerz_2012.pdf (accessed 06.21.2018)

Wood, S., Sebastian, K., Scherr, S.J., 2000. Pilot analysis of global ecosystems: agroecosystems, a joint study by International Food Policy Research Institute and World Resources Institute. Int. Food Policy Res. Inst. World Resour. Inst. Wash. DC. https://www.cabdirect.org/cabdirect/abstract/20013036518 (accessed 06.21.2018)

Yang, F., Wang, X., Liao, D., Lu, F., Gao, R., Liu, W., Yong, T., Wu, X., Du, J., Liu, J., Yang, W., 2015. Yield Response to Different Planting Geometries in Maize–Soybean Relay Strip Intercropping Systems. Agron. J. 107, 296–304. https://doi.org/10.2134/agronj14.0263

Zak, D.R., Holmes, W.E., White, D.C., Peacock, A.D., Tilman, D., 2003. Plant diversity, soil microbial communities, and ecosystem function: are there any links? Ecology 84, 2042–2050. https://doi.org/10.1890/02-0433

Zegada-Lizarazu, W., Monti, A., 2011. Energy crops in rotation. A review. Biomass Bioenergy 35, 12–25. https://doi.org/10.1016/j.biombioe.2010.08.001

Zhang, F., Li, L., 2003. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. Plant Soil 248, 305–312. https://doi.org/10.1023/A:1022352229863

Zheng, Y., Zhao, J., Xu, F., Li, Y., 2014. Pretreatment of lignocellulosic biomass for enhanced biogas production. Prog. Energy Combust. Sci. 42, 35–53. https://doi.org/10.1016/j.pecs.2014.01.001

Zürcher, A., 2014. Dauerkulturen als Alternativen zu Mais - Wildartenmischungen, Topinambur, Durchwachsene Silphie, Virginiamalve und Riesenweizengras. 7. Workshop "Pflanzliche Rohstoffe zur Biogasgewinnung" LTZ Augustenberg, Rheinstetten-Forchheim, Germany. https://docplayer.org/53901435-Dauerkulturen-als-alternativen-zu-mais-wildartenmischungen-topinambur-durchwachsene-silphie-virginiamalve-und-riesenweizengras.html (accessed 06.21.2018)

6. Acknowledgements

First, I would like to express my deepest gratitude to my supervisor Prof. Dr. Iris Lewandowski for giving me the chance to participate in her team. During the past five years, her professional mentoring substantially helped me shaping my sense of science. Furthermore, I am very grateful to the co-supervisors Prof. Dr. Carola Pekrun and Prof. Dr. Christian Zörb for reviewing my thesis.

I would also like to thank my colleagues in the Department Biobased Products and Energy Crops (340b), in particular Andrea Ehmann, Dr. Moritz Wagner, Bastian Winkler, Anja Mangold, Dr. Ulrich Thumm, Andreas Kiesel and Dr. Yasir Iqbal for their encouragement and inspiring discussions. It has been an honor to work with you and I look forward to future collaborations.

Furthermore, I would like to express my gratitude to the technicians Thomas Ruopp, Dagmar Metzger, Astrid Stadtaus, Kathrin Steberl, Johanna Class, Sebastian Böckle, Marianne Häfner, Thomas Truckses, Andreas Lohrer, Herbert Grötzinger, Martin Zahner, Helmut Bimek, Peter Weckherlin, Martin Trautner, Walter Schneider and everyone else who was involved in field or laboratory works. In many cases, your ideas considerably improved the experiments.

Special thanks go to Dr. Jens Hartung for developing the field trial designs and improving the statistical sections of the papers.

Many thanks go to Nicole Gaudet for spending weeks on spell-checking my documents during the last five years. I would also like to thank her for organizing the English learning group, which was certainly a great help for all participants.

In addition, I would like to acknowledge the research funding by the German Federal Ministry of Education and Research (BMBF) under the BioProFi framework (GOBi, project number: 03EK3525A).

Finally, I would like to offer a very special gratitude to my friends and family, especially to Viktoria and Maximilian. In so many ways, you have given me exactly the support I needed during my promotion phase. I owe you so much.

7. Curriculum Vitae

Moritz von Cossel

Personal Details

Date of Birth: 24 September 1980

Nationality: German

Mail: moritz.cossel@uni-hohenheim.de

Professional experience

Since 09/2013
University of Hohenheim, Institute of Crop Science, Department of Biobased Products and Energy Crops, Stuttgart, Germany
Doctoral Student

- PhD. Thesis: "Agricultural diversification of biogas crop cultivation"

07/2009 – 08/2013
Christian-Albrechts-University of Kiel, Institute of Agricultural Engineering, Kiel, Germany
Research Assistant

- Organization and implementation of a large-scale soil mapping project using an EM38 MK1 (Geonics, Canada)

06/2008 – 07/2008
Bioland Hof: Hof Hafkamp, Bad Malente-Gremsmühlen, Germany

- Internship on an organic farm

04/2008 – 05/2008
Demeterhof: Gut Wulfsdorf, Ahrensburg, Germany

- Internship on an organic vegetable farm

2006 – 2008
Christian-Albrechts-University of Kiel, Institute of Crop Science and Plant Breeding, Grass and Forage Science/ Organic Agriculture, Kiel, Germany
Research Assistant

	• Initial experience of exact field trials
2005 – 2006	**Rudolf Behr AG, Ohlendorf, Seevetal, Germany**
	• Employment as a vegetable grower

Voluntary work

2008 – 2009	**Christian-Albrechts-University of Kiel, Student Parliament Member**
2007 – 2008	**Christian-Albrechts-University of Kiel, General Student Committee Environmental Speaker**
	• Cooperation in the initiation of an environmental management system (EMAS) at the Christian-Albrechts-University of Kiel
09/2007 – 09/2009	**Student Services Schleswig-Holstein, Kiel, Germany Dorm tutor**
	• Bicycle repairs and provision of tools

Community service

09/2001 – 07/2002	**Hilfe im Haus e.V., Hamburg, Germany**
	• Community service for a severely disabled person

Education

2010 – 2012	**Christian-Albrechts-University of Kiel, Faculty of Agricultural and Nutritional Sciences, Kiel, Germany** **Master of agricultural science**
	• Master Thesis: "In situ pH-Beprobung landwirtschaftlich genutzter Böden als Schnittstelle zwischen ECa-Kartierung und teilflächenspezifischer Kalkung" • Master of Science in Agriculture: Grade "Good"
2006 – 2010	**Christian-Albrechts-University of Kiel, Faculty of Agricultural and Nutritional Sciences, Kiel, Germany** **Bachelor of agricultural science**
	• Bachelor Thesis: "Das EM38: Einflußfaktoren auf Aussagekraft und Reproduzierbarkeit der scheinbaren elektrischen Leitfähigkeit landwirtschaftlicher Nutzflächen" • Bachelor of Science in Agriculture: Grade "Good"
2003 – 2005	**Georgsanstalt – Vocational schools II, Uelzen, Germany**
	• Training as a vegetable grower

2002 – 2003	**Christian-Albrechts-University of Kiel, Faculty of Mathematics and Natural Sciences, Kiel, Germany** • Study courses in the field of chemistry
1990 – 2001	**Internatsgymnasium Schloss Plön, Germany** • Certificate: General qualification for university entrance

Skills

Language	**German:** Native **English:** Fluent **Polish:** Basic
Computing	Good knowledge of ArcView, SAS, OpenOffice, MS Office, Zotero, Paint.net Basic knowledge of DASYLab, SPSS
Technical	EM38 MK1 (Geonics, Canada)

Conference contributions

09/2018	**Oral presentation** at the conference "*13th Global Summit and Expo on Biomass and Bioenergy*": Von Cossel, M. (2018) How to meet the needs of bees – Diversification of industrial crop cultivation for a more environmentally benign bioeconomy
05/2018	**Poster** at the conference "*26th European Biomass Conference & Exhibition*": Elbersen, B., van Eupen, M., Mantel, S., Alexopoulou, E., Iqbal, Y., Lewandowski, I., von Cossel, M., Zanetti, F. *et al.* (2018) Mapping marginal land potentially available for industrial crops in Europe
09/2017	**Oral presentation** at the conference "*Annual Meeting of the German Society for Plant Science*": Von Cossel, M., Steberl, K., Möhring, J., Kiesel, A., Lewandowski, I. (2017) Etablierungs-verfahren mehrjähriger Biogas-Wildpflanzenmischungen im Vergleich: Ohne Mais geht's nicht?
03/2017	**Poster** at the conference "*Progress in Biogas IV*": Von Cossel, M., Steberl, K., Möhring, J., Kiesel, A., Lewandowski, I. (2017) Methane yield performance and biogas substrate quality of wild plant mixtures and *Amaranthus hypochondriacus* (L.) - Just a hype or true flower power?
03/2017	**Poster** at the conference "*Progress in Biogas IV*": von Cossel, M., Steberl, K., Möhring, J., Kiesel, A., Lewandowski, I. (2017) Perennial wild plant mixtures as biogas substrate - The establishment matters

03/2017	**Poster** at the conference "*Progress in Biogas IV*": Meissner, K., Awiszus, S., Reyer, S., Grumaz, C., Bach, M., von Cossel, M., Steinbrenner, J., Müller, T., Oechsner, H., Lewandowski, I., Sohn, K., Müller, J. (2017) Gobi - General Optimization of Biogas Processes
09/2015	**Poster** at the conference "*Perennial Biomass Crops for a Resource-Constrained World*": von Cossel, M., Lewandowski, I. (2015) Perennial wild plant mixtures as biogas substrate
09/2014	**Poster** at the conference "*Progress in Biogas III*": von Cossel, M., Lewandowski, I. (2014) Effects of nitrogen fertilization and strip cultivation with legumes on methane yield and sustainability of maize and amaranth

Publications

Von Cossel, M., Iqbal, Y., Scordia, D., Cosentino, S. L., Elbersen, B., Staritsky, I. *et al.* (2018) Low-input agricultural practices for industrial crops on marginal land (D4.1). In: MAGIC project reports, supported by the EU's Horizon 2020 programme under GA No. 727698, University of Hohenheim, Stuttgart, Germany.

Elbersen, B., Eupen van E., Mantel, S., Verzandvoort, S., Boogaard, H., Mucher, S., Cicarreli, T. & Elbersen, W., Bai, Z., Iqbal, Y., Von Cossel, M., Ian MCallum, I., Carrasco, J., Ciria Ramos, C., Monti, A., Scordia, D., Eleftheriadis, I. (2018). Methodological approaches to identify and map marginal land suitable for industrial crops in Europe (D2.6). In: MAGIC project reports, supported by the EU's Horizon 2020 programme under GA No. 727698. Wageningen University and Research, Wageningen, The Netherlands.

Elbersen, B., Eupen van E., Mantel, S., Verzandvoort, S., Boogaard, H., Mucher, S., Cicarreli, T. & Elbersen, W., Bai, Z., Iqbal, Y., Von Cossel, M., Lewandowski, I., Ian MCallum, I., Carrasco, J., Ciria Ramos, C., Sanz, M., Ciria, P., Monti, A., Cosentino, S. L., Scordia, D., Eleftheriadis, I. (2018). Definition and classification of marginal lands suitable for industrial crops in Europe (D2.1). In: MAGIC project reports, supported by the EU's Horizon 2020 programme under GA No. 727698. Wageningen University and Research.

Von Cossel, M., Möhring, J., Kiesel, A. and Lewandowski, I. (2018) Optimization of specific methane yield prediction models for biogas crops based on lignocellulosic components using non-linear and crop-specific configurations. *Industrial Crops & Products* 120: 330-342. Doi: 10.1016/j.indcrop.2018.04.042.

Von Cossel, M., Steberl, K., Möhring, J., Kiesel, A., Lewandowski, I. (2017) Etablierungs-verfahren mehrjähriger Biogas-Wildpflanzenmischungen im Vergleich: Ohne Mais geht's nicht? *Mitteilungen der Gesellschaft für Pflanzenbauwissenschaften* (Witzenhausen: Liddy Halm), 58–59. Available at: https://www.researchgate.net/publication/325477300 (accessed 11.05.2018).

Von Cossel, M., Möhring, J., Kiesel, A. and Lewandowski, I. (2017) Methane yield performance of amaranth (Amaranthus hypochondriacus L.) and its suitability for legume intercropping in comparison to maize (Zea mays L.). *Industrial Crops & Products* 103: 107-121. Doi: 10.1016/j.indcrop.2017.03.047.

Von Cossel, M. and Lewandowski, I. (2016) Perennial wild plant mixtures for biomass production: Impact of species composition dynamics on yield performance over a five-year cultivation period in southwest Germany. *European Journal of Agronomy* 79: 74-89. Doi: 10.1016/j.eja.2016.05.006.

Publications under preparation

Von Cossel, M., Mangold, A., Kiesel, A., Hartung, J., Lewandowski, I. When a giant needs help – *Miscanthus × giganteus* (Greef et Deuter) establishment under maize (*Zea mays* L.).

Von Cossel, M., Mohr, V., Elbersen, B., Staritsky, I., Van Eupen, M., Mantel, S., Happe, S., Iqbal, Y., Warrach-Sagi, K., Wulfmeyer, V., Lewandowski, I. Climate change-forced shifts in growth suitability distribution of industrial crops in Europe until 2100 based on high resolution EUROCORDEX simulations.

Von Cossel, M., Steberl, K., Hartung, J., Kiesel, A., Lewandowski, I. The establishment of perennial wild plant mixtures under maize (*Zea mays* L.) reduces the trade-off between social-ecological and economic performance of biogas production.

Von Cossel, M., Hartung, E. The estimation of site-specific lime demand based on apparent soil electrical conductivity (EM38) and in-situ determined topsoil pH.

Von Cossel, M., Iqbal, Y., Elbersen, B., Staritsky, I., Van Eupen, M., Mantel, S., Scordia, D., Cosentino, S.L., Maliarenko, O., Lewandowski, I., Crop selection for low-input industrial cropping on marginal lands in Europe

Reviewing activities

African Journal of Biotechnology; Agronomy; Applied Energy; Biotechnology for Biofuels; European Journal of Agronomy; GCB Bioenergy; International Agrophysics; International Journal of Biodiversity and Conservation; Journal of Ecology and The Natural Environment; Journal of Medicinal Research and Biological Studies; Journal of Plant Science: Current Research; Proceedings of The World Sustainability Forum

https://publons.com/author/1350319/moritz-von-cossel#profile

Hohenheim, 18.07.2018

Moritz von Cossel