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Nachhaltige Intensivierung von Fruchtfolgesystemen im Kontext des Klimawandels für die Biomasseproduktion zur anaeroben Vergärung

Dissertation

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vorgelegt von

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Wien, Oktober 2019

Darin besteht das Wesen der Wissenschaft.

Zuerst denkt man an etwas, das wahr sein könnte.

Dann sieht man nach, ob es der Fall ist

und im Allgemeinen ist es nicht der Fall.

Bertrand Russell (1872-1970)

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1 Einleitung

Die eingehende Forderung an Politik und Staaten, Industrie und Verkehr importunabhängige und klimaschonende Energieformen einzusetzen, wächst stetig. Mit zunehmendem Druck auf Regierungen und Entscheidungsträger in Österreich, Deutschland und Europa verfolgt man nun eine Reihe an Klimazielen. Wesentliche Aspekte der Klimaziele sind die Treibhausgasminimierung, der Ausbau der erneuerbaren Energieformen und die Steigerung von Energieeffizienz. In Österreich gilt derzeit die Bestrebung der im Juni 2018 vorgelegten Mission2030, Strom bis ins Jahr 2030 zu 100% aus erneuerbaren und CO_2 neutralen Energiequellen selbst zu produzieren (Bundesministerium für Nachhaltigkeit und Tourismus, 2018). Weiters wird neben Zielen für die erneuerbare Stromversorgung die klare und vielversprechende Absicht des ***„greening the gas“*** als zukunftsweisendes Schlagwort in der Strategie Mission2030 propagiert. Dahinter steht die Absicht zunehmender physischer Einspeisung von nachhaltig produzierten Gasen wie Methan und Wasserstoff in das derzeit vorrangig fossiles Erdgas führende Gasnetz. Die Einspeisung von lokal erzeugtem, erneuerbarem Methangas und Wasserstoff ermöglicht die direkte Substitution von fossilem Erdgas, welches im Falle Österreichs derzeit zum größten Teil aus Russland importiert werden muss. Die Erzeugung nachhaltiger Gase soll beispielsweise mit dem aus Biogas zu Erdgasqualität aufgereinigtem Biomethan, sowie mit Methan und Wasserstoff aus Power-to-Gas Anlagen unter Umwandlung von Überschuss Strom bewerkstelligt werden (Bundesministerium für Nachhaltigkeit und Tourismus, 2018).

Neben der Produktion nachhaltiger Energieformen, wird auch die Verwertung biogener Ausgangsstoffe in Bioraffinerien künftig eine wesentliche Rolle spielen. Aus nachwachsenden Rohstoffen werden hierbei Wertstoffe extrahiert und Ausgangsstoffe für biobasierte Industrieprozesse (biogene Chemikalien und Werkstoffe) hergestellt.

Wie bei den oben genannten Zielen auf nationaler Ebene, gilt auch bei Klimazielen auf europäischer Ebene und weltweit, wie beispielsweise dem bekannten „Kyoto-Protokoll“, der Grundsatz der Reduktion jährlicher CO_2 Emissionen in die Atmosphäre. Nur unter Einbehalt der

Ziele zur Eindämmung klimarelevanter Gase verspricht man sich signifikante Gegenmaßnahmen zur umweltschädlichen Klimaerwärmung. Es gibt divergierende Strategien für das Erreichen von Klimazielen denen allerdings gemeinsam ist, dass ihre konsequente Einhaltung mit erheblichen Schwierigkeiten verbunden ist. Dies zeigen Zwischenberichte der Politik sowie Berichte aus Medien zu den beispielsweise 2009 festgesetzten Klimazielen der EU-Mitgliedstaaten, die bis ins Jahr 2020 zu erreichen sind. Eine **20**%ige Reduktion des Treibhausgasausstoßes auf Basis des Jahres 1990, eine Erhöhung der erneuerbaren Energie auf **20**% des gesamten Endenergieverbrauches, und eine **20**%ige Energieeffizienzsteigerung wurden in jenen ambitionierten Zielen festgesetzt (European Commission, 2006; European Parliament and Council, 2009).

Über das Jahr 2020 hinaus wird europaweit das Ziel verfolgt, die Treibhausgasemissionen um 40% bis ins Jahr 2030 und um 80-95% bis ins Jahr 2050 zu reduzieren. Der erneuerbare Anteil am Endenergieverbrauch soll 2030 die 30%-Marke erreichen (European Commission, 2018).

Aus all diesen Zielen leitet sich der steigende Bedarf am weiteren Ausbau der erneuerbaren Energieproduktion ab, worin Biogas bereits jetzt eine wesentliche Fassette im Energiemix darstellt (Weiland, 2010). Die anaerobe Vergärung von Energiepflanzen, Agrarnebenprodukten sowie anderer organischen Materialien ist ein schon lange Zeit bekannter Prozess zur Umwandlung von Biomasse in die Endprodukte Biogas und hochwertiger Gärrestdünger (Weiland, 2006).

Biogas als Beitrag zur Erreichung der Klimaziele

Aktuell stehen rund 17.000 Biogasanalagen europaweit in Betrieb (installierte Leistung von 8,3 GW), wovon alleine in Deutschland, als deutlich anlagenstärkstes Land Europas, rund 10.000 Anlagen mit einer installierten Leistung von etwa 5 GW betrieben werden (Stambasky et al., 2016).

Vor allem die Grundlastfähigkeit sowie die Fähigkeit Regel- und Ausgleichenergie zu produzieren, stellen anerkannte Vorteile von biogasbetriebenen Blockheizkraftwerken im Vergleich zu Windkraft und Photovoltaik dar (Wallmann et al., 2016). Die Bereitstellung des nachhaltig generierten Energieträgers Biomethan stellt eine weitere und vielversprechende Nutzungsmöglichkeit für Biogasanlagen im künftigen Primärenergiemix dar.

Die genannten Emissionen klimarelevanter Gase, allen voran CO_2, spielen die wesentliche Rolle im lange diskutierten Klimawandel. Die Zunahme von Wetterextremen in jenem Klimawandelaspekt (Hitze-Wellen, Dürren, Starkniederschläge und Stürme) macht sich mehr und mehr bemerkbar, was sich auch auf pflanzenbauliche Anforderungen in landwirtschaftlichen Fruchtfolgen auswirkt und oft Ertragseinbußen mit sich bringt.

Mit den Beschlüssen zur Vorrangstellung für Stromnetzeinspeisung von Biogasanlagen über Förderungen und Ökostrom-Einspeisetarife, geregelt in Ökostromgesetzen und EEG Gesetzesnovellen, erfuhr der Einsatz von Energiepflanzen in Biogasanalgen einen massiven Aufschwung. Der Ausbau der Stromproduktion und die Einspeisung in öffentliche Netze durch Biogas-Blockheizkraftwerke zur gekoppelten Strom- und Wärmeproduktion stieg nach der Jahrtausendwende in Österreichern und Deutschland stark an. Der rechtliche Rahmen für den Ausbau von Stromerzeugung aus Biogas und anderen erneuerbaren Energien wurde dazu in Österreich im Jahr 2002 mit dem Ökostromgesetz geschaffen. In den letzten Jahren gewann die Einspeisung von aufgereinigtem Biogas zu Biomethan ins Gasnetz oder für die Fahrzeugbetankung auch bei Anlagenbetreibern an Interesse und vermehrte sich in der politischen Diskussion sowie in Gesetzgebungen.

Grundzüge der Biogasproduktion

Die Grundzüge der Biogasproduktion liegen in der anaeroben Vergärung von biogenen Rohstoffen. Unter anaeroben Bedingungen entstehen die Gase CH_4 und CO_2, sowie eine Reihe weiterer Begleitgase. Der Prozess läuft in **4 Stufen** ab:

Mikroorganismen bilden im anaeroben Milieu landwirtschaftlicher und industrieller Biogasanlagen sowie unter Lichtabschluss wasserdampfgesättigtes Biogas mit seinen Hauptbestandteilen CH_4 und CO_2. Zumeist läuft der Prozess in volldurchmischten stehenden Fermentern bei mesophilen Temperaturen um 40° Grad Celsius ab.

Im Prozess fungieren hydrolytische, acidogene und acetogene Bakterien sowie die methanogenen Archea. Das fermentative Milieu liegt bei Hydrolyse und Acidogenese im Bereich 4,5 – 6,3 pH und bei Methanogenese und Acetogenese im Bereich 6,8- 7,5 pH. Die erste Phase der Biogasbildung wird als **Hydrolyse** bezeichnet, wobei hochmolekulare organische Substanzen (Eiweiße, Kohlehydrate, Fette und Zellulose) enzymatisch in niedermolekulare Verbindungen (Einfachzucker, Aminosäuren, Fettsäuren) abgebaut werden. Während der **Acidogenese**, der 2. Phase, werden Spaltprodukte der Hydrolyse zu reduzierten Verbindungen wie Carbonsäuren, Alkohol und Gasen abgebaut. In der dritten Phase namens **Acetogenese** werden Carbonsäuren und Alkohole bakteriell in Acetat, Wasserstoff und Kohlendioxid umgewandelt. In der letzten und eigentlich methanbildenden Phase, der **Methanogenese,** passiert schlussendlich die Bildung von CH_4 und CO_2. Während des gesamten Prozesses entsteht auch Wasserdampf, sodass das entstehende Biogas aus den 4 Schritten Wasserdampfgesättigt vorliegt. Die vier Phasen laufen in unterschiedlichen Geschwindigkeiten in den Fermentern einer Biogasanlage zumeist gleichzeitig ab. (Kaltschmitt und Hartmann, 2001; Madigan et al., 2008)

Für die Nutzung von nachwachsenden Rohstoffen und flüssigem Wirtschaftsdünger wurde das kontinuierlich betriebene, einphasige Nassfermentationsverfahren im volldurchmischten stehenden Reaktor (so genannte „Rührkesselfermenter“) zum dominierenden Anlagensystem (Weiland, 2010).

Die seit der Jahrtausendwende mit dem fortschreitenden Ausbau von Biogasanalgen einhergehend gestiegene anaerobe Vergärung von Energiepflanzenbiomasse, stellt auch heute noch die geringsten technologischen Anforderungen an die Biogas-Anlagentechnik und daher den mengenmäßig größten Anteil der eingesetzten Rohstoffe dar.

Aufgrund der kommerziell guten Vergärbarkeit und der monetär mit geringeren Kosten behafteten Verarbeitung in klassischen „Rührkesselfermentern“, beschränkte sich die Biogasproduktion zunehmend auf einige wenige ertragreiche Pflanzenkulturen wie Mais und Zuckerrüben (Stambasky et al., 2016). Die Verarbeitung von Energiepflanzen in Biogasanlagen ist eine weitgehend geprüfte und bewährte Technologie. Im Allgemeinen werden die Energiepflanzen, wie aus der Tierhaltung bekannt, zumeist als Silage konserviert in Fahrsilos gelagert. Maissilage weist sowohl gute Vergärbarkeit, hohe spezifische Gasausbeuten, einen geringen Ligningehalt, als auch hohe Flächenerträge und fortgeschrittene Sortenzüchtungen auf und ist noch heute die meistbenutzte Pflanzenbiomasse in Biogasanlagen (Graß et al., 2015). Rund 75% der in Deutschland genutzten Biomasse für die Biogasproduktion stammen aus Mais, vorrangig als Monokultur angebaut (Graß et al., 2013; Multerer, 2014).

Notwendigkeit der Suche nach alternativen Substraten

Kritiken an ökologisch schwer vertretbaren Mais-Monokulturen für die Stromproduktion, der Flächenkonkurrenz in der lebens- & futtermittelproduzierenden Landwirtschaft und der dadurch hervorgerufenen so genannten Teller-Trog-Tank-Diskussion ergeben ökologische Herausforderungen an die Energiepflanzenproduktion.

Neben der anaeroben Vergärung von Energiepflanzen wie Mais, Sorghum, Roggen, Sonnenblumen, Zuckerrübe und anderer silierfähiger Pflanzenbiomasse, besteht auch die Möglichkeit der Agrarrestoff- und Abfallvergärung in Biogasprozessen (Nasir et al., 2012). Letztere neigen mehr als Energiepflanzen zur Produktion von Gas mit erhöhtem Anteil an unerwünschten Begleitgasen wie NH_3 und H_2S, welche in zu hoher Konzentration rasch Schäden an nachfolgenden Aggregaten und Blockheizkraftwerken nach sich ziehen können.

Sowohl Flüssigmist als auch Festmist aus der Tierhaltung stellen grundsätzlich ein großes Potenzial an fermentierbaren Rohstoffen dar. Festmist ist jedoch aufgrund der komplexen Verwertbarkeit und des erhöhten Störstoffaufkommens (Pferdemist, Rindermist) mit wesentlich höheren und kostenintensiveren Anforderungen an die Anlagentechnik gepaart (Moench – Tegeder et al., 2014).

Durch die standardisierte und zumeist störstofffreie Stückgröße von Biomassesilage aus Energiepflanzen ergeben sich im Vergleich zur Abfall- und Reststoffvergärung wesentlich geringere prozess- und anlagentechnische Herausforderungen. Trotz der höheren Rohstoffpreise für eingesetzte Energiepflanzen, welche von der Stromproduktion gedeckt werden müssen, ergeben sich hinsichtlich der Gesamtrentabilität in landwirtschaftlichen Biogasanlagen oft ökonomische Vorteile. Abfall- und Reststoffvergärung zeigen im Wesentlichen geringere monetäre Aufwendungen für Inputstoffe, jedoch höhere Aufwände und Anforderungen in der anaeroben Fermentation auf.

Auch die gemeinsame Vergärung (Co-Fermentation) von Energiepflanzen mit Wirtschaftsdüngern, Rest- und Abfallstoffen findet zunehmend Eingang bei bestehenden und neuen Biogasanalgen und stellt eine vielversprechende Möglichkeit dar, da hierbei monetäre und technische Vorteile der Teilbereiche kombiniert werden können.

Die Vergärung von Energiepflanzenbiomasse wird nicht zuletzt deshalb weiterhin einen essenziellen Bestandteil als Ausgangsstoff zur Herstellung von Energie und Energieträgern unter Einsatz von Biogasanlagen darstellen.

Es ist notwendig, jene nachwachsenden Rohstoffe künftig in Form nachhaltiger Produktionssysteme und ökologisch gut verträglicher Fruchtfolgesysteme bereitzustellen, welche es ermöglichen, die positiven Effekte der Biogastechnologie zu erhalten und zu unterstreichen.

Das trotz eingehender pflanzenbaulicher Bemühungen bereits im Ausmaß reduzierte, jedoch noch immer vorrangig praktizierte Szenario ist wie Eingangs genannt der intensivierte Maisanbau, der zumeist in großflächigen Monokulturen angebaut wird. Dieses System weist zwar monetäre Vorteile, jedoch eine Reihe bekannter und nicht vertretbarer Umweltbelastungen bzw. ökologische Nachteile auf. Auch hinsichtlich der begrenzten Ressourcen, wie landwirtschaftliches Ackerland und pflanzenverfügbares Wasser, ist die Steigerung der Flächeneffizienz jedenfalls im Kontext der Nachhaltigkeit eine unabdingbare Notwendigkeit (Herrmann et al., 2011).

Mehrkultursysteme mit trockenheitsresistenten und anpassungsfähigen Pflanzen, welche in Sommer- und Winterkulturen verfügbar sind, stellen eine mögliche Lösung zur ökologisch verträglichen und nachhaltigen Effizienzsteigerung in der Biomasseproduktion dar.

Aus dem Klimawandel ergeben sich für den Energiepflanzenanbau die generellen Anforderungen, dass Fruchtfolgen nicht nur hohe Erträge erzielen, sondern auch gegen extreme Wetterlagen Widerstandsfähigkeit und Ertragsstabilität aufweisen (Lobell et al., 2013; Semenov et al., 2014).

Eine sowohl in ökologisch verträglichen Fruchtfolgen gut verwendbare und hinsichtlich der Trockenstressresistenz vielversprechende Kulturpflanze stellt die C4-Pflanze Sorghum (*Sorghum bicolor, Sorghum sudanese*) dar (Farré et al., 2006; Zegada-Lizarazu et al., 2012).

An die jeweiligen Pflanzensorten ergeben sich zusätzliche Anforderungen hinsichtlich der Ertragsentwicklung und des Abreifeverhaltens, um eine optimale Fruchtfolge für Ein- und Mehrkultursysteme zu generieren.

Nachwachsende Rohstoffe in Biogasanlagen werden in Zukunft in jedem Fall den so genannten „*2nd-generation*“ Rohstoffen, wie es Zwischenfrüchte, Zweitfrüchte und agrarische Reststoffe darstellen, angehören müssen, um ökologischen Aspekten und der politischen Diskussion betreffend Lebens-Futtermittelkonkurrenz Sorge zu tragen (Stürmer, 2017; Drljo et al., 2014; Leible et al., 2015). Auch in Bioraffinerien lässt sich jene ökologisch produzierte Pflanzenbiomasse gut einsetzen, was eine weitere Form der Biomassenutzung darstellt und die Substitution fossiler Ausgangsstoffe ermöglicht.

Hinsichtlich der nachhaltigen Intensivierung im Energiepflanzenbau ergibt sich daraus die Möglichkeit des Zwischenfrucht- und Zweitfruchtanbaues. Bei dieser Form der Biomasseerzeugung parallel zur Lebens- und Futtermittelproduktion besteht aufgrund der begrenzten Vegetationszeit zwischen zwei Hauptkulturen, die Notwendigkeit des Einsatzes schnellwüchsiger Pflanzen, wie es beispielsweise Sorghum, Mais und Roggen darstellen. Nennenswerte Erträge sind auch hier notwendig, um die spezifischen Erzeugungskosten zu optimieren.

Deshalb erfährt Sorghum zunehmend an Bedeutung für Zweit- und Zwischenfruchtanbau in Ein- und Mehrkultursystemen. Trotz geringerer Wachstumsgradtage (Growing degree days – GDD), welche im Vergleich zum herkömmlichen Anbau (Einkultursystem) nach Hauptfrüchten für Sommerzwischenfrüchte noch zur Verfügung stehen, birgt Sorghum das Potenzial, noch nennenswerte Erträge bis in den Herbst zu erreichen.

Die Vorzüge von Sorghum ergänzen sich weiters durch beste Trockenresistenz und Anpassungsfähigkeit auf verschiedenen Bodenbeschaffenheiten im Vergleich zu klassischen landwirtschaftlichen Kulturpflanzen wie Mais. (Farré et al., 2006; Zegada-Lizarazu et al., 2012).

Neben Sorghum, als gut an Klimaveränderung anpassungsfähige Sommerzwischenfurcht, wird Roggen erfolgreich als Winterzwischenfrucht vor beispielsweise Mais im Frühjahr angesät. Mit der Nutzung von Roggen, Sorghum und Mais in vielfältigen Fruchtfolgen könnte somit nachwachsender Rohstoff in nachhaltig intensivierten Mehrkultursystemen (zu Englisch: Double Cropping System, abgekürzt DCS) erzeugt werden. Eine Konkurrenz zu Nahrungs- und Futtermittel entsteht in einem solchermaßen vielfältig gestaltetet Fruchtfolgesystem nicht, da nur ein geringer, definierter Anteil (z.B. 10-20 %) der erzeugten Biomassen für die Energieerzeugung verwendet wird.

Dass Zweikultursysteme, je nach Sortentyp und Kulturkombination, ähnliche oder sogar höhere Erträge als herkömmliche Einkulturfruchtfolgen erzielen können, ließ sich bereits in mehreren Studien feststellen (Graß et al., 2013; Tang et al., 2018). Eine gesteigerte Landnutzungseffizienz sowie verbesserte Diversifikation können in Mehrkultursystemen gemeinsam mit gesteigerter Biomasseproduktion pro Jahr und verbessertem Schutz der Umwelt anhand positiver

Zwischenfruchteffekte erreicht werden (Andrade et al., 2017; Fang et al., 2006; Goff et al., 2010; Martinez-Feria et al., 2016).

Darüber hinaus ist bewiesen, dass eine Diversifikation der Kulturen in Zweinutzungssystemen eine langfristig positive Auswirkung auf Effizienz und Produktivität in der Fruchtfolge hat (Andrade et al., 2017).

Eine nachhaltige Energieproduktion in Form der Biogastechnologie unter Einsatz von Energiepflanzen als Biomasse, setzt somit die Nutzung der beschriebenen nachhaltigen und ökologischen Fruchtfolgesysteme voraus.

Zu diesem Zweck werden in gegenständlicher Arbeit und in den angeführten Publikationen Sortenunterschiede und Erträge von Ein- und Zweikultursystemen mit Roggen, Mais und Sorghum untersucht. Qualitative Eigenschaften, Erträge, Ertragsstabilität und agronomische Möglichkeiten zur Optimierung der nachhaltigen Fruchtfolgen gilt es im Detail zu untersuchen und zu optimieren.

2 Zielsetzung und Abgrenzung der Fragestellung

In der vorliegenden Arbeit wurden die Eigenschaften von Sorghum, Roggen und Mais in deren Ertragsentwicklung und Reifeverhalten für die Eignung der Kultivierung in nachhaltigen Ein- und Mehrkultursystemen zur Biomasseproduktion untersucht. Die Versuche dazu wurden in Parzellenversuchen über 3 Vegetationsperioden beziehungsweise 4 Jahren am Versuchsstandort Groß-Enzersdorf (Ost-Österreich, 151 m Seehöhe, 48°20‘N, 16°56’O) vorgenommen.

Ziel war es entscheidende quantitative und qualitative Merkmale der untersuchten Pflanzenarten und Sorten auf deren Eignung zum Anbau in nachhaltig intensivierten Fruchtfolgesystemen zur untersuchen. Die Fruchtfolgen wurden dabei im Kontext der Anforderungen des fortschreitenden Klimawandels (Wassernutzungseffizienz und Hitzestresstoleranz) behandelt.

Kernaufgabe stellte auch die Flächenintensivierung unter Nutzung von Zweikultursystemen mit dem Aspekt der Ertragsoptimierung unter gleichzeitigem Einbehalt der Nachhaltigkeit und Umweltverträglichkeit dar.

Die vorliegende Arbeit untersucht in mehrjährigen Feldversuchen **zum einen** Sorghum als Hauptfrucht im Einkultursystem und hierbei insbesondere:

I. die Eignung 5 unterschiedlicher Sorten zur Ertragsbildung in Abgängigkeit der Vegetationsdauer, sowie deren Reifeverhalten und Wachstumsdynamik. Weiter wird das absolute Biomassebildungsvermögen ermittelt.

II. Die Optimierung des Erntezeitpunktes bei optimaler Reife hinsichtlich der Silagequalität soll zur Ertragsmaximierung untersucht werden.

III. Eine Sortenbewertung zur Nutzung der Sorghum-Typen in Ein- und Mehrkultursystemen hinsichtlich Ertrags- und Reifeverhalten wird angestellt.

IV. Weiters werden Untersuchungen zum spezifischen Methanertrag in Abhängigkeit des Reifezustandes durchgeführt, sowie Methanhektarerträge bestimmt.

Zum anderen wird in der vorliegenden Arbeit das Potenzial von Sorghum in Mehrkulturfruchtfolgen beziehungsweise Zweikultursystemen untersucht und bewertet. Als trockenresistente Alternative zu Mais, wird die C4-Pflanze Sorghum gemeinsam mit Roggen dem Zweikultursystem Mais/Roggen gegenübergestellt und:

V. die Wachstumsdynamik von beiden Kulturpartnern (Mais/Roggen: Sorghum/Roggen) sowie deren optimaler Erntezeitpunkt ermittelt.

VI. Weiters wird unter Einbezug von Untersuchungen zum spezifischen Gasertrag der Biomasseproben ermittelt, welche Flächenerträge an Methan maximal zu erreichen sind.

VII. Ebenfalls wird der Einfluss von unterschiedlichen Ernte- und Anbauzeitpunkten der Fruchtfolgepartner Sorghum, Mais und Roggen auf den Biomasseertrag und das Reifeverhalten im Zweikultursystem untersucht.

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3 Publikation 1 – Wannasek et al. 2017

Research paper:

Biomass and Bioenergy 106 (2017) 137-145

Title:

Sorghum, a sustainable feedstock for biogas production? Impact of climate, variety and harvesting time on maturity and biomass yield

Autoren:

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Keywords:

Sorghum; crop maturity; biomass yield; growing degree days; crop rotation; anaerobic digestion

ABSTRACT

In the search for alternative raw materials for biogas production, sorghum is currently of a growing interest. Five selected sorghum cultivars, more or less representing the current sorghum variety market, were cultivated for 3 years at a test field in the Pannonian Plain (East Austria). Parameters such as maturity, biomass yield and harvest time were investigated and correlated with growing degree days. Highest biomass yield of average 18.9 t/ha was obtained by types SOR 3, 4 and 5 whereas the maximum yield (20.67 t/ha) was achieved by SOR 4 in the first year. The dry matter content depending on harvest date varied between 15 (SOR 4, 98d, year 3) and 51% (SOR 2, 170d, year 1). Among the 5 varieties, SOR 2 achieved exceptional fast high maturity levels within short cultivation period. Sorghum silage was used to determine the methane potential applying batch fermentation tests. An average methane yield of 338.0 $Nm^3 \cdot t\ VS^{-1}$ (± 9.9%) within an optimal maturity range of 27-35 % was obtained resulting in a methane per hectare yield of 2,300 (SOR 1) and 6,500 $Nm^3 \cdot ha^{-1}$ (SOR 4). Through an in-depth analysis of the results of the experiments, it becomes clear that the cultivation of sorghum for biogas production still offers high optimization potentials for varietal selection and the choice of the optimum harvesting time. Up to 50% methane per hectare yield losses can be compensated with good varietal selection. Furthermore, up to 14% higher yields can only be achieved by choosing the optimum harvesting time.

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Research paper

Sorghum, a sustainable feedstock for biogas production? Impact of climate, variety and harvesting time on maturity and biomass yield

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Growing degree days
Crop rotation
Anaerobic digestion

ABSTRACT

The experiments comprised three vegetation periods of five sorghum varieties. Novel data on the development of biomass yield, maturity level and biogas production were gained. Dry matter (DM) biomass yield ranged between 15.7 and 20.67 t ha^{-1} when sorghum was grown as main crop. The variety SOR 4 achieved a methane yield of 6500 m^3 ha^{-1}. The suitability of different sorghum varieties as summer catch crops was measured and assessed by combining growing degree days (GDD; temperatures > 10 °C) and maturity stage. This paper introduces a correlation of yields in course of the vegetation period with GDD values which enables to transfer yield and economic efficiency predictions from present results to other sites.

Sorghum is able to provide high-yields when used as catch crop, whereby an adapted varietal selection is indispensable. The sorghum variety SOR 2 (year2) of 1100 growing degree days (GDD) proofed to be fast ripening and is especially suitable as a summer catch crop. This variety achieved mean DM yields of 12.4 t ha^{-1} when used as summer catch crop.

Within this study crop maturities between 20 and 45% DM were investigated. Within this range, no decrease in specific methane yield with the increase in maturity and DM yield was observed.

The three year experimental data also included one year with low precipitation. The statistical analysis did not reveal a significant influence of the precipitation on the biomass yield which confirms the drought resistance of sorghum. This result is especially important in view of adaptation to climate change.

1. Introduction

Anaerobic digestion (AD) of energy crops has seen a startling series of developments since the late 90s. Due to various developments in the recent past (energy and commodity prices, food/fuel discussions, climate change, etc.) the use of a wider spectrum of energy crops and organic biomass has gained a growing importance. Up to date about 17 000 AD-plants with a total installed electric capacity of about 8.3 GW are operated within the EU. Germany, a leading country in this field, generates 5 GW from 10 000 AD plants [1].

Maize is currently the most predominant cultivated energy crop for biogas production in Central Europe. In Germany, maize represents about 73% of the total biomass used for AD [2]. According to a number of estimates 25% of total bioenergy production in Europe will be covered by biogas production in the near future [3]. Considering these estimates the demand for the cultivation of energy crops will consequently increase [4]. Outside Europe especially China and India are intensifying the establishment of renewable energies and technologies such as biogas production will play an

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important role in the future [5,6].

Since the cultivation of energy crops is usually carried out in parallel with agricultural food and feed production on the same arable land solutions are required for the competition between agricultural crops.

The sustainable production of food and feed must be a priority. The cultivation of energy crops on former forest and pastures as proposed by some authors, would lead to a significant increase in greenhouse gas emissions in the long run and is therefore not a sustainable alternative to overcome the aforementioned issues [7]. The growing demand for biomass cannot be covered by an increase in cultivation areas.

The development towards increased prices of agricultural commodities in the recent past has led to a rethink of regulatory framework conditions in various European countries. As a result AD plants solely accepting main crops will be restricted in the future, so called 2nd generation AD plants are underway favouring alternative feedstocks such as agricultural residues and catch crops [8–10]. Catch crops have short growth periods and can be cultivated between the vegetation periods of the main crops. Typical time periods for catch crops in Europe range from June to October (summer catch crops) and from October to April (winter catch crops). Furthermore, they are usually not used for food production and thus they positively contribute to solving the food vs. fuel debate. The selection of a suitable cultivar adapted to given climate conditions as well as the efficient cultivation in an integrated crop rotation systems is crucial in order to achieve high biomass yields [11]. The increase in efficiency in cultivation with regard to limited resources such as agricultural areas and plant-available water in the context of climate change, is therefore an indispensable necessity [12].

In the search for alternative biogas raw materials, sorghum is currently of a growing interest. It is a fast growing crop and is characterised by a wide adaptability to different environments and soil conditions and by an improved drought resistance compared to typical energy crops used in agriculture [13–15].

In several cultivation studies it could be shown that sorghum is able to provide biomass yields similar to the one of maize. It was demonstrated that sorghum can be cultivated in various climatic regions such as in Southeast China, central USA, Brazil and Europe. Typical biomass dry matter yields ranged between 10 and 23 t ha^{-1} [16–24]. Typical varieties investigated in long time field tests were *sorghum bicolor* and *sorghum sudanese*.

Although not many data on early and late maturing sorghum cultivars are available, varieties such as *Bovital* showed average yields between 11.6 t ha^{-1} and 15.2 t ha^{-1}. In a one year cultivation study of various sorghum varieties *Maja* and *Cerberus* achieved at two different locations biomass yields of 15.4–20.7 and 18.6–22.7 t ha^{-1}, respectively [18,19,23]. In the frame of a field study in Shanghai applying sorghum in constructed wetlands to treat pig manure, biomass yields between 10.0 and 17.6 t ha^{-1} DM could be achieved [20]. Similar yields could be observed in a cultivation study at two sites in Brazil with different rainfall impact (774 mm vs. 1352 mm annual rainfall) [24].

A few studies also examined the potential of sorghum as a feedstock for biogas production. Methane yields from sorghum biomass ranged from 207 to 387 m^3 t^{-1}.

Pazderu et al. tested the influence of row spacing on biomass yield and methane yield, respectively. For the sorghum cultivars *Bovital, Sucrosorgo* and *Goliath* methane yields between 207 and 246 m^3 t^{-1} were achieved [19]. A similar study by Mahmood et al. who compared five different sorghum varieties (*Goliath, Bovital, Aron, Rona 1* and *Akklimat*) showed methane yields between 232 and 282, except Aron und *Rona 1*, where yields of 316 and 387 m^3 t^{-1} were observed [25]. A methane yield of 279 m^3 t^{-1} of sorghum variety *Rona 1* was determined by Wünsch et al. [26].

The aforementioned studies investigated the influence of different parameters such as row spacing, type of cultivar as well as irrigation on the biomass and biogas yield, respectively. However, in order to achieve optimal productivity with regard to land efficiency and biomass yield in existing crop rotations, there is a need to determine also plant and site specific parameters such as growth and maturity dynamics of individual cultivars considering also climate and soil conditions.

The cultivation of sorghum in existing crop rotations offers the possibilities of efficient energy crop cultivation, both either as main crop or as two-crop even in dry climatic regions of Central Europe. In a comprehensive field study over 4 years the authors could show that applying crop combination in double cultivation can even achieve higher biomass yield compared to single cultivation. The combination e.g. winter barley/sorghum reached in average 5% higher yields as maize in single cultivation [27]. But also other crop rotations including early harvested crops such as bread cereals and rapeseed fast-growing with sorghum and hybrids of sorghum/Sudan grass as second crop are promising combinations to increase field utilisation efficiency.

Very often so called plant growth calendars (calendar days) are used in agriculture to predict plant development for management decisions. However, calendar days can be misleading, especially for early crop growth stages. For example, a cool May can significantly delay a plant reaching the four-leaf stage, which directly affects optimal plant control strategies [28]. By means of GDD, growth experiences of certain varieties can be better compared over several years at one location. In addition, appropriate cultivation strategies can also be transferred to colder or warmer regions. Up to date about 30 different sorghum varieties are available on the market. Detailed information on growth characteristics and biomass yield are usually unavailable and/or not sufficiently provided. In general, crops are characterised mainly by the following three categories: Biomass yield (high/low); Maturity (early/late); Resistance against droughts, disease (high/low).

The focus within this study was set to select cultivars which cover the commercially available spectrum of sorghum species. The present study examines (i) the biomass yield and maturity development in course of the vegetation period and the total biomass yield of five different types of sorghum in a three year field experiment. Based on the measured growth dynamics, (ii) the optimum harvesting time at optimum silage quality was determined. (iii) A varietal assessment for single and double cultivation was performed including biomass yield, maturity and growth dynamics. Finally (iv) the specific methane-producing capacity as a function of the vegetation stage and crop type was analysed.

2. Material and methods

2.1. Crop selection

The sorghum species used in the experiments are listed in Table 1. All crops are pure sorghum bicolor types except SOR 2, which is a hybrid between *sorghum bicolor* and *sorghum Sudanese*.

2.2. Crop cultivation

2.2.1. Field site

The cultivation experiments were carried out at an experimental field site of the University of Natural Resources and Life Sciences (BOKU) Vienna in Gross-Enzersdorf (East Austria, 151 m above sea level, 48°20′N, 16° 56′E).

The climate is characterised by an average annual rainfall of 550 mm and an annual average temperature of 9.9 °C (Central

Table 1
List of Sorghum crops applied in the field tests.

Name	Type	Biomass yield[a]	Maturity tendency[a]	Variety denomination
SOR 1	*Sorghum bicolor*	High	Medium/Late	Branco
SOR 2	*Sorghum bicolor x sorghum sudanese*	Medium	Early/Medium	Maja
SOR 3	*Sorghum bicolor*	High	Medium/Late	Zerberus
SOR 4	*Sorghum bicolor*	High	Late	Bulldozer
SOR 5	*Sorghum bicolor*	High	Late	Sucro Sorgho

[a] Manufacturer specification.

Institution for Meteorology and Geodynamics Austria, ZAMG; 48°12′N, 16° 34′E). The soil type can be characterised as chernozem, a black coloured fertile soil rich in humus, phosphorus and ammonium.

The three years experiment was carried out as a randomised block with 3 replicates of each variety and plot. Each plot was further divided into 6 rows with 1.5 × 8 m. The distance between the single rows was 37.5 cm. The sowing time was between May 3rd and 11th in every vegetation period. The depth of the sowing was 2.5 cm. The specific sowing density for seed was set to 22 m^{-2}. In order to eliminate boundary effects along the edges of the experimental field, a surrounding plot of 2 m was established.

All plots were fertilised with urea and NAC fertiliser with an annual nitrogen input of 93 kg ha^{-1}. Harvesting took place five times a year, earliest at day 98, latest at day 183.

2.2.2. Climate data

Rainfall and temperature data were provided by the Central Department for Meteorology (Central Institution for Meteorology and Geodynamics Austria, ZAMG).

Rainfall and temperature were monitored during the three experimental years parallel to the vegetation period and comprise a span of 209 days (25 days before and 183 days after sowing). Temperature was recorded hourly. Daily and monthly means including standard deviation were calculated.

2.3. Sampling and sample preparation

A defined size of 1 m^2 (0.37 m × 2.66 m) of each variety was harvested by hand. Each harvest was carried out in triplicate. Immediately before harvest, the plant height was determined by measuring the length of all plants within the defined plot from the soil surface to the base of the tallest leaf. Harvested biomass was crushed to an average particle size of 2.5 cm by a cutting mill. A minor part was used for chemical analysis, the major part was transferred to a 2 L container, compressed and kept there for 4 weeks to produce silage. Silage was further used for the determination of the biomethane potential (BMP tests).

2.4. Biomethane potential tests (BMP tests)

BMP tests were carried out in triplicate in 1 L eudiometer batch digesters according to the guidelines VDI 4630 [29]. The operation temperature was set to 37.5 °C. Inoculum used was taken from an AD plant digesting maize silage at a temperature of 38 °C. Before using it in the experiment it was transferred to a continuously stirred laboratory digester in order to degrade the residual biomass. To keep the microbial culture vital, the digester was fed with maize silage every 2 weeks (internal standardisation). Silage from the sorghum experiments was mixed with 600 g inoculum in the lab digester. The amount of silage was calculated in order to obtain a mass ratio of 0.5 between organic dry matter (volatile solids) of the feedstock and the inoculum applied. The experiments were operated for 4 weeks. The amount of biogas production was periodically monitored, whereas the biogas composition (CH_4, CO_2 and H_2S) was analysed with a portable gas analyser (Dräger X-am 7000).

2.5. Chemical analysis

2.5.1. Dry matter and volatile solids

Dry matter (DM also known as total solids (TS)), ash content and volatile solids (VS) of the harvested biomass were analysed according to standard methods DIN DEV 38 414 part 2 [30] and DIN DEV 38 414 part 3 [31].

2.6. Statistical analysis

The statistical analysis was carried out with statistical software programme SAS. Data were analysed by one-way ANOVA, followed by Tukey's test for post-hoc comparison. The level of significance was set at $P < 0.05$.

2.7. Growing degree-units (GDU)

Growing degree units (GDU) or growing degree days (GDD) are a measure of heat accumulation in order to predict crop development rates such as the date that the crop will reach maturity. "Growing degree days" is a way of assigning a heat value to each day. The values are added together to give an estimate of the amount of seasonal growth that plants have achieved. GDU are calculated by taking the integral of warmth above a base temperature (Tbase). The base temperature is commonly set to 10 °C. The calculation is shown in equation (1).

$$GDU = \int_{min}^{max} (T - Tbase)dt \qquad (1)$$

If the average daily temperature is lower than the base temperature then GDU is zero [32].

3. Results and discussion

3.1. Irrigation

In the course of the three year cultivation experiments (2009–2011) no constant climatic conditions were observed at the experimental site. Cultivation year 3 was characterised by low rainfall, especially during the sowing period in May (only 45 mm rainfall).

The total rainfall in cultivation year 3 but also in in year 1 was significantly lower (330 and 385 mm) compared to year 2 (554 mm).

In Fig. 1, the cumulative rainfall distribution of all three years within the vegetation period (183 days) is shown. Furthermore, also the rainfall distribution 25 days before sowing start is included, indicated as negative vegetation days. This serves to illustrate the general water supply in the soil at the beginning of the vegetation

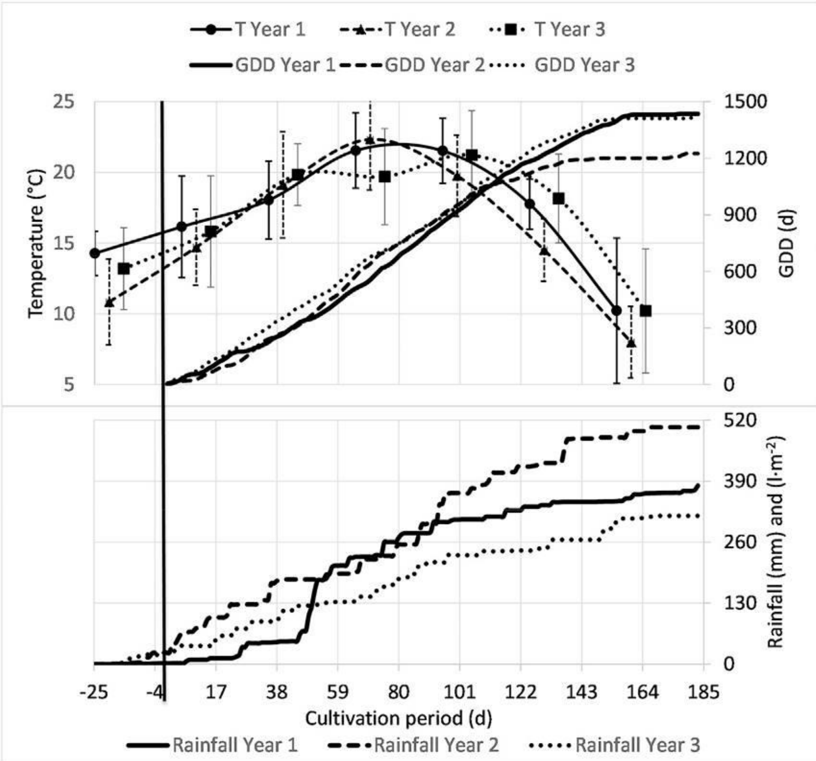

Fig. 1. Temperature and rainfall profile of the 3 year field test.

period. As illustrated in the figure, in year 1 rainfall was only 45 mm (day −25 until day 45) within a period of 2.5 months and was therefore significantly dryer compared to the other years. Although soil moisture was not measured, it can be assumed that water supply in this crucial period was not as sufficient as in year 2 and 3 (180 and 130 mm for the same period).

3.2. Temperature and heat accumulation (GDD)

In Fig. 1 (upper graph) the monthly average temperature profile of the 3 cultivation periods is illustrated. The average temperature in year 2 was significantly lower compared to year 1 and 3. The temperature course in year 3 showed a cold period between day 40 and 90, but towards to the end of the cultivation, temperatures were significantly higher.

A more accurate measure of the vegetation period is the use of growing degree days (GDD), which take aspects of local weather into account and allow to predict the crops' pace toward maturity.

The lower temperatures in year 2 were also confirmed calculating GDD, showing a 15% reduced heat accumulation (1225 vs 1414 (year 3)/1435 (year 1) GDD) during the cultivation period compared to year 1 and 3.

3.3. Growing degree days (GDD) classification

Five harvesting dates in each cultivation year were selected to quantify to the influence of the date of harvest and the GDD respectively on biomass yield as well as on the degree of maturity. The time intervals were about 14 days. The GDD and the harvesting dates of the 3 years were split into 5 classes, where classes 2, 3 and 4 (1068 up to 1323 GDD) were within an optimal range in terms of heat accumulation, class 1 and 5 were beyond this optimal range. Due to the low average temperature in year only two classes were available. Most of the data were accumulated in class 3. Table 2 lists the classification including GDD and the harvesting dates (in brackets).

It can be seen that year 2 was a cold year, therefore the 5th harvest (day 183) falls into a lower GDD class (class 3). In years 1 and 3, the 5th harvest took place after 170 and 160 days respectively, and falls into the highest GDD class (class 5). Although in year 1 and 3 the 5th harvest occurred between 2 and 3 weeks earlier compared to year 2, 200 more GDD could be accumulated which had a positive impact not only on maturity but also on biomass yield.

Table 2
Classification of harvest periods using growing degree days (GDD) and harvesting dates (days in brackets).

	YEAR 1	YEAR 2	YEAR 3
CLASS 1			922 (98)[1]
CLASS 2		1068 (114)[1]	
	1072 (113)[1]		
			1112 (113)[2]
		1135 (127)[2]	
CLASS 3		1193 (141)[3]	
		1201 (155)[4]	
	1202 (128)[2]		
		1225 (183)[5]	
			1226 (124)[3]
CLASS 4	1303 (140)[3]		
			1323 (138)[4]
CLASS 5			1411 (160)[5]
	1419 (157)[4]		
	1431 (170)[5]		

[1,2,3,4,5] Harvesting date.

There is only a little information available in literature using GDD values. Therefore an in depth discussion of our novel indicator is not possible with the currently available literature. Dolciotti et al. could show that dough maturity stage (between 30 and 35% TS) of the two investigated late maturing sorghum cultivars in Northern Italy can be observed after 1250 GDD [33].

3.4. Biomass yield

The biomass dry matter (DM) yields of all harvests ranged from 3.65 to 20.67 t ha^{-1} within the three cultivation periods. The highest biomass dry matter yield of average 18.9 t ha^{-1} was obtained by the cultivars SOR 3, 4 and 5. The individual and annual deviation over three years of cultivation ranged between 3% (SOR 3), 7% (SOR 5) and 10% (SOR 4).

The sorghum hybrid type (SOR 2) reached its maximum yield already on the 2nd harvesting date after 113 (year 3) and 128 (year 1 and 2) growth days. While SOR 2 had already reached its maximum at this time, the other varieties showed only yields in the range of about 85% of their maximum yields.

Significantly later, at the 4th or 5th harvest date the other cultivars reached their highest yields. In some cases even a decline in biomass yield occurred in later harvests. Fig. 2 illustrates maturity and biomass yields depending on the harvesting time.

Biomass dry matter yields generated in this study were similar compared to other studies [17–19] except the early/medium maturing SOR 2 and SOR 3 which reached yields between 15.7 and 18.9 t ha^{-1}. Although not much data on early maturing sorghum cultivars are available, comparable varieties such as e.g. Bovital showed considerable lower average yields of 11.6 t ha^{-1} [18] and 12.4 t ha^{-1} [19] in other studies. In a one year cultivation study of various sorghum varieties including the same cultivars as used in the present study, Maja and Cerberus achieved at two different locations biomass yields of 15.4–20.7 and 18.6–22.7 t ha^{-1}, respectively. Bovital reached compared to the aforementioned authors higher yields of 14.6 and 15.2 t ha^{-1} [23].

The experimental site in this study is influenced by the Pannonia climate and thus optimal for warmth loving C4 plants such as sorghum. A more recent study at the same location with other sorghum varieties confirmed the potential of sorghum cultivation with high biomass yields in this specific region [34]. Climate simulation including various relevant growth parameters showing that in the near future more regions in central Europe may become a potential cultivation area for sorghum with increased biomass yields [34,35].

However, in a comprehensive study testing different crops and various irrigation regimes [36] showed that sorghum is less affected by low water supply and dry periods in the vegetation phase than for instance maize. Nevertheless, water supply is also a major growth factor for sorghum. The aforementioned authors

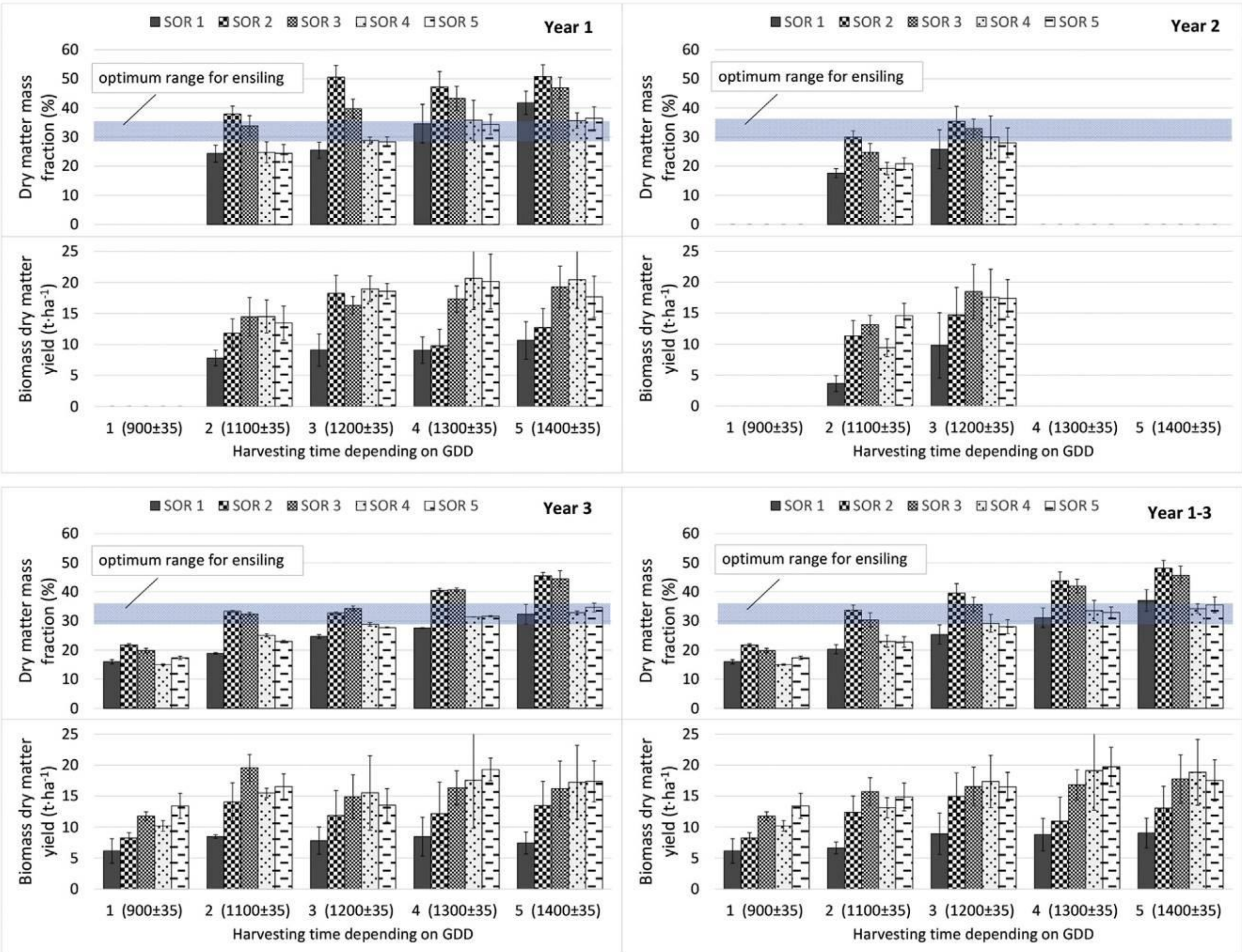

Fig. 2. Maturity, biomass dry matter yield and harvest time of five sorghum cultivars as a function of GDD and specific dry matter for each cultivation year and average of the whole period (year 1–3).

could successfully demonstrate, that if average irrigation is below 300 mm (and above 170 mm) and 170 mm (and above 50 mm) a significant reduction in plant height by about 15% and 45%, respectively was observed [36].

This shows the importance of gaining experimental data in a climate that specifically suits sorghum cultivation rather than relying on data gained in less suitable areas.

3.5. Maturity level

The dry matter mass fraction depending on the harvest date comprised values between 15% (SOR 4, 98 d, year 3) and 51% (SOR 2, 170 d, year 1). Among the five varieties, SOR 2 achieved high maturity levels exceptionally fast (see Fig. 2).

With regard to the ability for optimal ensiling, the dry matter is should to be in a range between 27 and 35% [37]. Other sources reported that the transition from lactic to dough ripeness (32–38% TS) is the optimal harvest date for whole crop ensiling [38].

A dry matter concentration below 27% usually results in a loss (up to 10%) due to an above average production of silage effluent liquids whereas an excessively high DM concentration would inhibit the ensiling process by formation of yeasts and moulds [39].

Although a loss of wet weight during ensiling can be observed, the energy impact of this is negligible, because ensiled biomass shows higher methane yields. Both facts have been intensively investigated by Herrmann et al. [9,39]. The authors investigated various crops and measured weight losses between 0.8% and 1.6% for maize and hemp respectively. The same authors showed an increase in specific methane yield caused by ensiling which compensates the aforementioned weight loss.

Among the 5 varieties sorghum-sudangrass hybrid SOR 2 achieved optimal maturity range already after 1100 GDD in year 1 and 3, and after 1200 GDD in year 2. Crop types SOR 1, SOR 4 and SOR 5 required significant higher heat impact in order to achieve the optimal maturity level. Fig. 3 illustrates the accumulated GDD of the five varieties for each cultivation year.

As we introduced the novel concept of relation maturity levels with GDD, it was not possible to compare our data with values from the literature.

In order to use sorghum as a second crop, it is important to achieve a high degree of maturity in the shortest possible time. The varieties SOR 2 and SOR 3 revealed to be suitable candidates. Additionally, SOR 3 can also be cultivated as main crop in regions with lower average temperature and GDD accumulation and will still provide high biomass DM yields as it was demonstrated in year 2 (13.1–18.5 t ha^{-1}).

3.6. Harvesting time

As already seen in the previous results, the harvesting date significantly affects the biomass yield and the dry matter mass fraction of the whole crops. Maximum biomass yields showed in most cases a dry matter mass fraction of above 35% (SOR 4, SOR 5) or did not even reach this level (SOR 1) when harvested. With cultivation of the higher yielding varieties SOR 4 and SOR 5, this degree of maturity of 35% was not reached until the end of the vegetation or only between the 170th and 183th vegetation day. The lower-yielding varieties SOR 2 and SOR 3 reached the optimum harvest time on the average before the 130th vegetation day. As can be seen in Fig. 1, the strong rainfall in year 2 delayed the maturation behaviour of the sorghum cultures. As expected, the dry matter, an indicator of the plant maturity, was at the lowest level ($p > 0.001$ *t*-test) and was at vegetation day 170 13% below that from year 1.

Variety SOR 2 reached the dry matter mass fraction of 50.57% already far above the optimum in the first experimental year on the 128^{th} day of the vegetation period.

Very little information was available in literature on harvesting time versus maturity level. For an exceptionally warm region in Indonesia (average Temperature >30 °C, low rainfall) the authors claimed 105 d after sowing as the optimal harvesting time, but did not quantify the maturity level [41]. The authors of a one year study conducted in Central Greece (dry and hot) suggested that in order to achieve maximum yield choosing the best harvesting time of the crop should be taken into consideration. For the investigated sorghum cultivar Keller the optimal harvesting time was between 120 and 130 days after sowing, but again no information on maturity level was given [42].

3.7. Methane yield

Biomethane potential (BMP) tests of 39 harvested and ensiled fractions with an initial range of dry matter between 20 and 46% (after harvest) were carried out. The VS/TS mass ratio was 93%. In Fig. 4, the results of the BMP tests as a function of dry matter are shown. The deviations including all values ($n = 39$) were 8.3%, including only the values in the dry matter range between 27 and 35% ($n = 20$) were 9.9%.

As a result an average methane yield on VS of 338.0 m^3 t^{-1} (±9.9%) out of 20 BPM test within DM range of 27–35% was obtained and used for further calculations. This corresponds very well with results from BMP tests of sorghum cultivars found in literature. Pazderu et al. tested the influence of row spacing on biomass yield and methane yield, respectively. Methane yields of three different sorghum cultivars (Bovital, Sucrosorgo and Goliath) ranged between 207 and 246 m^3 t^{-1} [19]. A similar test design was studied by Mahmood et al. who compared five different sorghum varieties (Goliath, Bovital, Aron, Rona 1 and Akklimat). The

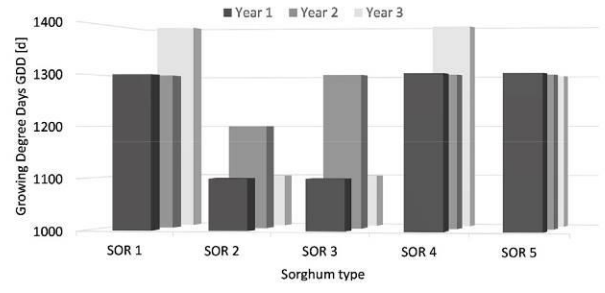

Fig. 3. Comparison of GDD required for optimal maturity (27–35% TS) obtained.

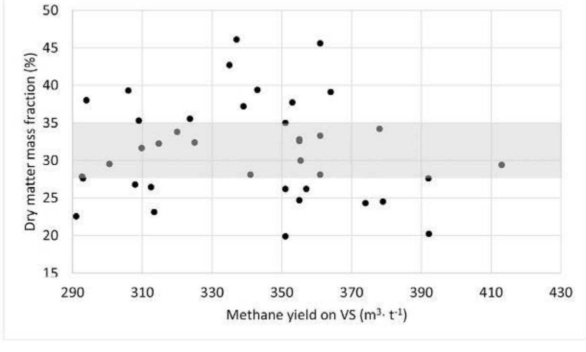

Fig. 4. BMP Tests: Methane yields as a function of dry matter mass fraction. The shadowed area indicates the dry matter mass fraction (27–35%) for optimal ensiling. Methane yields are converted to standard conditions (273 K, 101.3 kPa).

methane yields ranged between 232 and 282, except Aron und Rona 1, which achieved yields of 316 and 387 $m^3\ t^{-1}$, respectively [25]. A methane yield of 279 $m^3\ t^{-1}$ of sorghum variety Rona 1 was determined by Wünsch et al. [26].

In Fig. 5 the specific methane yield per hectare of 5 sorghum types at optimal maturity level (27–35% DM) are illustrated.

SOR 4 and SOR 5 were able to provide highest specific methane yield on VS between 5500 and 6500 $m^3\ ha^{-1}$ followed by SOR 3 with yields between 4500 and 6150 $m^3\ ha^{-1}$. Sorghum type SOR 2 showed lower yields of about 3700–4630 $m^3\ ha^{-1}$, but achieved this in shortest time of growing, requiring between 200 and 300 less GDD compared to the other varieties. SOR 1 was one of the slowest growing varieties providing a methane yield between 2300 and 3100 $m^3\ ha^{-1}$.

It seems that the amount of lignocellulosic (and thus non degradable) compounds in the plant did not differ significantly between the various maturity stages. This fact was also confirmed by Ref. [43] investigating parameters such as growing stage and harvest time of maize plants affecting the ensiling and biomethanisation process. The chemical composition of different plant varieties and harvest times only differs marginally within variants tested, whereas most remarkable differences have been determined for the fibrous ingredients. Differences in methane yield within maize varieties and harvest times investigated were marginally but the methanisation rate was clearly influenced by the degree of comminution and the ensiling process. An average increase of methane yield of about 8% was only achieved by reduction of chopping length <5.5 mm, but from the technical and economical point of view not recommended [43].

Similar studies also on maize found again relatively small differences in the methane yield of medium-to-late silo maize cultivars, each with 4 different harvesting dates. The differences within a variety at different harvesting periods were 3–9% [44]. A stronger effect of the harvesting date on the methane yield was found by Ref. [45] in studies of 13 different early to late maize varieties. From the milk maturity (about 20% DM) to full maturity, methane yields decreased by 7–27%.

Most of the values found tend to be lower than the average methane yield in this study. Beside the nature of variety one reason might be that some of the crops were harvested with a dry matter mass fraction below 30%, which is not optimal for subsequent ensiling process.

According to literature, the harvest date and maturity level, chopping length as well as ensiling can affect the methane yield. Ensiling is seen by the majority of authors as a kind of pretreatment, hydrolysing structural polymers to easy available and degradable organic acids. Comparing methane yields of various energy plants an increase of up to 9% for maize, forage rye and sorghum hybrid was achieved by ensiling [12]. Lowering chopping lengths can further increase methane yield up to 13% [17].

3.8. *Sorghum – single and double cultivation*

The cultivation of catch crops after early harvested crops represents a good possibility for the cultivation of energy crops, but presupposes a harvesting yield in only a few months of vegetation (<4 months). From the results presented, the suitability of sorghum, depending on the type of cultivar, can be derived for both, single and double cultivation.

As demonstrated within this study, some sorghum varieties (SOR 3) as well as individual hybrids (SOR 2), are able to achieve high degree of maturity within less than a vegetation period, even in Central European climates.

The sorghum-Sudan grass hybrid SOR 2 investigated in this study but also SOR 3 enable the formation of biomass at optimal maturity level in less than 4 months of vegetation time.

In terms of biomass yield and maturity, SOR 2 and SOR 3 are best suited for use as a second crop compared to the other varieties examined within this study. The biomass DM yield in this short growth period reached for SOR 2 and SOR 3 an average of 12.4 and 15.7 $t\ ha^{-1}$ after 114 vegetation days, with the highest order in year 3 of 14.04 and 19.6 $t\ ha^{-1}$ for SOR 2 and SOR 3, respectively.

Among these two types, SOR 2 showed significantly higher maturity levels after 114 days (38.0, 29.9 and 33.4%) compared to 33.9, 24.8 and 32.4% for SOR 3. Especially in year 2, which was compared to year 1 and 3 characterised by higher rainfall and lower temperatures, SOR 2 was able to reach the optimal maturity level (29.9%) already after 1200 GDD, while SOR 3 only achieved 24.8%. Nevertheless, SOR 3, if cultivated as main crop is able to achieve high biomass DM yields (13.1–18.5 $t\ ha^{-1}$) also in colder regions (as

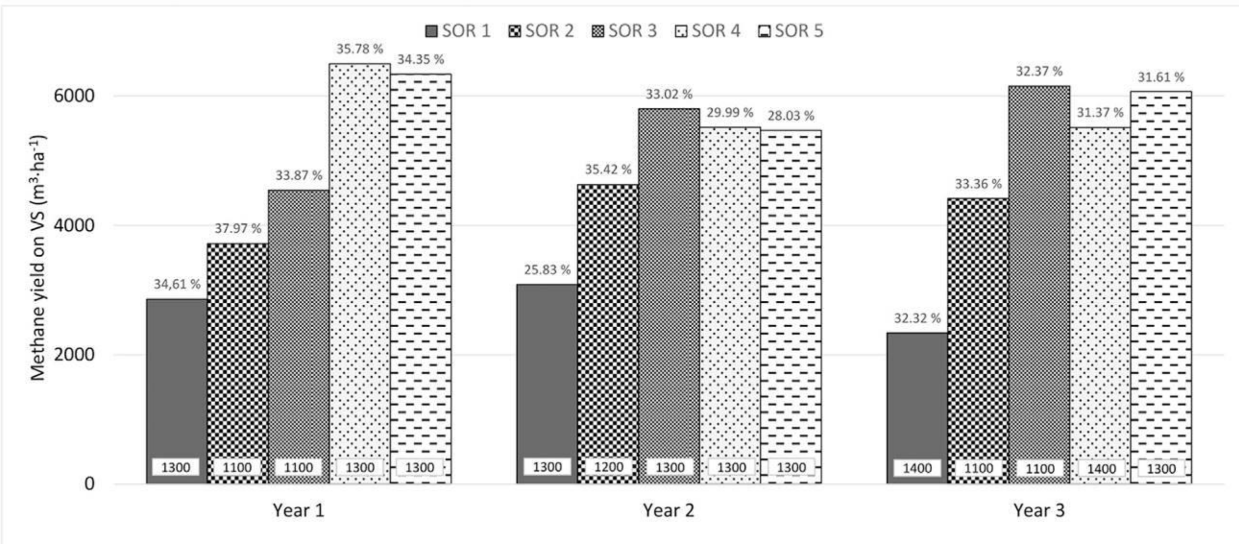

Fig. 5. Comparison of specific methane yield of five sorghum varieties harvested at optimal maturity level. Values above bars are % DM, values on the bottom are growing degree days (GDD).

demonstrated in year 2).

In view of the short vegetation period described (<4 months), the cultivation of sorghum and sorghum – Sudan grass hybrids in Central European climatic areas can be carried out as second crops after early clearing crops (e.g. winter barley, green grass, rape). Sorghum types with this or similar maturity and yield characteristics enable the production of on average 12–15 t ha^{-1} of biogas raw material after the cultivation of an intercropping after main fruit in the same year.

The methane per hectare yields in this study of more than 6000 Nm^3 ha^{-1} shows in individual cases the considerable possibilities of sorghum cultivation in dry locations as e.g. at the study site in the Pannonian plain in East-Austria.

4. Conclusion

Climate change requires the growth of drought resistant energy crops as an alternative to the currently widely used maize. Sorghum offers the advantages of improved stability of biomass yield in dry areas with methane per hectare yields of more than 6000 Nm^3. This study delivers data to characterise biomass yield and silage quality of sorghum varieties by combining data on GDD with maturity levels in course of the vegetation period. The concept of correlating yields in course of the vegetation period with GDD values, which was introduced in this paper, offers the possibility to transfer our results to other sites. Variety selection and harvesting time proofed to be decisive factors for an optimised sorghum cultivation with up to 14% higher yields at optimum harvesting time. The anaerobic digestion experiments carried out in this study comprised maturity levels between 20 and 45% DM and revealed no decrease in the specific methane yield within this range indicating that the full biomass yield potential can be exploited without a decrease in methane production. The cultivation of sorghum as a summer catch crop proofed to be a promising option for biogas production especially with regard to sustainable increase in land-use efficiency.

Through an in-depth analysis of the results, it becomes clear that the cultivation of sorghum for biogas production still offers high optimization potentials with regard to varietal selection and the choice of the optimum harvesting time. Up to 50% methane per hectare yield losses can be avoided through proper varietal selection.

Future research should investigate site-specific crop rotations including additional main and catch crops, such as e.g. rye and sugar beet.

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4 Publikation 2 – Wannasek et al. 2019

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Double-cropping systems based on rye, maize and sorghum: Impact of variety and harvesting time on biomass and biogas yield

Autoren:

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ABSTRACT

Climate change affects the frequency and intensity of extreme weather, the results of which include production losses and climate-induced crop productivity fluctuations.

Double-cropping systems (DCSs) have been suggested as a way to increase biomass-production while simultaneously delivering environmental benefits. In a three-year field-test, two DCSs based on maize and sorghum as the main crop and rye as the preceding winter crop were compared with each other and compared with 2 single-cropping systems (SCSs) of maize or sorghum; there were comparisons of growth dynamics, optimal harvesting and growing time as well as biomass and methane yield. In addition, the impact of variety and harvest time on the winter rye optimal biomass yield was studied.

The experiments clearly showed the superiority of the DCS over the SCS. Within the DCS, the rye/sorghum combination achieved significantly higher biomass yields compared to those of the rye/maize combination. The highest dry matter biomass yield was achieved during year 1 at 27.5 ± 2.4 $t \cdot ha^{-1}$, during which winter rye contributed 8.3 ± 0.7 $t \cdot ha^{-1}$ and sorghum contributed 19.2 ± 1.8 $t \cdot ha^{-1}$. At the experimental location, which is influenced by a Pannonia climate (hot and dry), the rye/sorghum DCS was able to obtain average methane yields per hectare, 9,300 m^3, whereas the rye/maize combination reached 7,400 m^3. In contrast, the rye, maize and sorghum SCSs achieved methane yields of 4,800, 6,100 and 6,500 $m^3 \cdot ha^{-1}$, respectively. The study revealed that the winter rye and sorghum DCS is a promising strategy to counteract climate change and thus guarantee crop yield stability.

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Double-cropping systems based on rye, maize and sorghum: Impact of variety and harvesting time on biomass and biogas yield

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1. Introduction

Bioenergy production, in particular anaerobic digestion of crop biomass, is mostly limited to a small number of substrates such as maize, grass, rapeseed and sugar beets (Stambasky et al., 2016). At present, maize (*Zea mays L.*) is the predominant cultivated energy crop, mainly because of its high specific biomass yield per hectare and its advanced breeding progress (Graß et al., 2015). In Germany, 75% of the total biomass for bioenergy production results from maize which is normally cultivated as a single crop (Graß et al., 2013; Multerer, 2014). Outside Europe other countries, particularly China and India are intensifying the establishment of renewable energy technologies such as biogas production based on energy crops and agricultural residues (Jiang et al., 2011; Thomas et al., 2017). However, single-cropping and particular continuous maize have serious drawbacks, especially in their environmental impact.

Climate change leads to an increase in extreme weather events (heat waves, droughts, heavy precipitation, and storms), and these events represent a huge risk of crop failure.

It is essential to develop measures to adapt to these climate-change-induced events, increase biomass yield and prevent adverse environmental impacts of maize monoculture.

Sustainable biomass and bioenergy production systems should not only produce high yields but also adapt to climate change and increase resilience towards extreme weather events (Lobell et al., 2013; Semenov et al., 2014). The most promising strategy in sustainable land use and biomass production can be seen in double-cropping systems (DCSs), the cultivation of two crops on the same land parcel during

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Table 1
Characterisation of winter and summer crops cultivated during the field experiments.

Name	Species	Hybrid type	Season	Maturity tendency[1]	Variety denomination
Rye	*Secale cereale*	Simple	Winter	n/a	*Placido*
Maize	*Zea mays subsp. Mays*	Simple	Summer	Early/Medium	*Fernandez*
Sorghum	*Sorghum bicolor*	Triple-cross	Summer	Medium/Late	*Sucrosorgo 506 maxim*

[1] manufacturer specification.

Table 2
Rye varieties applied during the field experiments.

Name	Type	Hybrid type	Biomass yield[1]	Maturity tendency[1]	Variety denomination
Rye 1	*Secale cereale*	x	High	Medium/Late	*Placido*
Rye 2	*Secale cereale*	x	Medium	Early/Medium	*Bellami*
Rye 3	*Secale cereale*	x	High	Medium/Late	*Conduct*
Rye 4	*Secale cereale*	x	High	Late	*Pallazo*
Rye 5	*Secale cereale*	x	High	Late	*Guttino*

[1] manufacturer specification.

different growing seasons. As already confirmed by a few studies, double-cropping systems are able to achieve similar or even slightly higher biomass yields compared to single-cropping systems (SCSs), depending on the type of variety and crop combination (Graß et al., 2013; Tang et al., 2018). In a perennial field test it was demonstrated that the combination of rye and maize was able to achieve an average annual dry matter (DM) biomass yield of 23 t·ha^{-1}, which was significantly higher than the average yield of the single-cropped maize of 22 t·ha^{-1} (Graß et al., 2013). Several studies showed that DCS are also able to establish a temporal diversification and are able to improve land-use efficiency by increasing annual biomass yield per season while at the same time protecting the environment (Andrade et al., 2017; Fang et al., 2006; Goff et al., 2010; Martinez-Feria et al., 2016). Compared to SCSs, higher amounts of essential organic compounds remain in the soil with DCSs, which not only positively affects the soil structure but also alters and enhances herbivory efficiency and arthropod biodiversity, respectively (Dunbar et al., 2017). Furthermore, it is proven that plant diversification within the DCS has a positive impact in terms of an efficient and productive crop production cycle (Andrade et al., 2017). However, these results must be viewed in the context of their respective regional climatic conditions. Although many different maize varieties have been developed during recent decades, their sensitivity to drought has remained (Aslam et al., 2015). An increase in climate-induced fluctuations in maize biomass yields has been observed over recent decades in central Europe (Hawkins et al., 2013). In south-central and eastern European regions biomass yields of crops such as maize or wheat have significantly decreased over the past 40 years because of temperature change effects (Supit et al., 2010). In-depth analysis of climate change scenarios for crop productivity in Europe has shown a clear picture of agro-climatic condition deterioration due to increased drought stress across large parts of southern and central Europe (Olesen et al., 2011). However, in parts of southern and eastern Europe, a warmer climate allows crop cultivation to be shifted to the winter. In addition to lengthening of the growing season, crop water demand has significantly increased during the past two decades and thus a tremendous crop water deficit has occurred in large parts of southern and eastern Europe whereas a decline for north-western European regions has been observed (European Environment Agency (EEA), 2016). There is a certain risk of an increasing number of extremely unfavourable years, which might lead to higher crop yield interannual variability and constitute a challenge for proper crop management. Given these challenges, there are not only considerations regarding efficient land use but also regarding crops that can be grown under climate change conditions.

In the present study, the performance of sorghum as a potential alternative to maize and a more drought tolerant energy crop was investigated in a three-year field experiment. Two double-cropping systems based on two different C4-plants (maize and sorghum) as the main crop and rye as the preceding winter crop were compared regarding growth dynamics, optimal harvesting and growing time as well as biomass and biogas yield. During the same period, the influence of different winter rye varieties as well as harvesting time on biomass yield and ripeness degree was examined in an additional field experiment.

2. Material and methods

2.1. Crop selection

For the investigation of the optimal rye variety in terms of growth dynamics and biomass yield, five cultivars with different characteristics were selected. Both double-cropping and rye variety comparison field experiments were conducted in parallel over a 3- year period. The rye variety “Placido” was pre-selected and used as the winter crop for all of the double-cropping cultivation experiments. Maize and sorghum were selected as the main summer crops, respectively. A characterisation of the crop varieties can be found in Tables 1 and 2.

For comparison purpose already published data from sorghum single-cropping experiments from Wannesek et al. (2017) were used in the discussion. The field trials were conducted at the same site and time period but at a different plot.

2.1.1. Field site and experimental design

A three-year cultivation experiment (2008–2011; 3 seasons of 2008/2009, 2009/2010 and 2010/2011) were conducted at the experimental field site of the University of Natural Resources and Life Sciences (BOKU) Vienna in Raasdorf (East Austria, 151 m above sea level, 48° 15′ N, 16° 34′ E). The climate is characterised by an average annual rainfall of 550 mm and an annual average temperature of 9.9 °C (Central Institution for Meteorology and Geodynamics Austria, ZAMG; 48°12′N, 16° 34′E). The soil type is chernozem, a black-coloured fertile soil rich in humus, phosphorus and ammonium. The three year experiments for both the double- and single-cropping systems were conducted as randomised blocks with three replicates for each variety and plot. Each plot of sorghum and maize was further divided into 4 rows with a total size of 1.5 x 8 m and 3 x 8 m, respectively. The plot with rye was divided into 10 rows with a total size 1.2 x 8 m. The distance between the single rows was 12.0, 37.5 and 75.0 cm for rye, sorghum and maize, respectively. To eliminate boundary effects along the edges of the experimental field, a surrounding plot of 2 m was established and

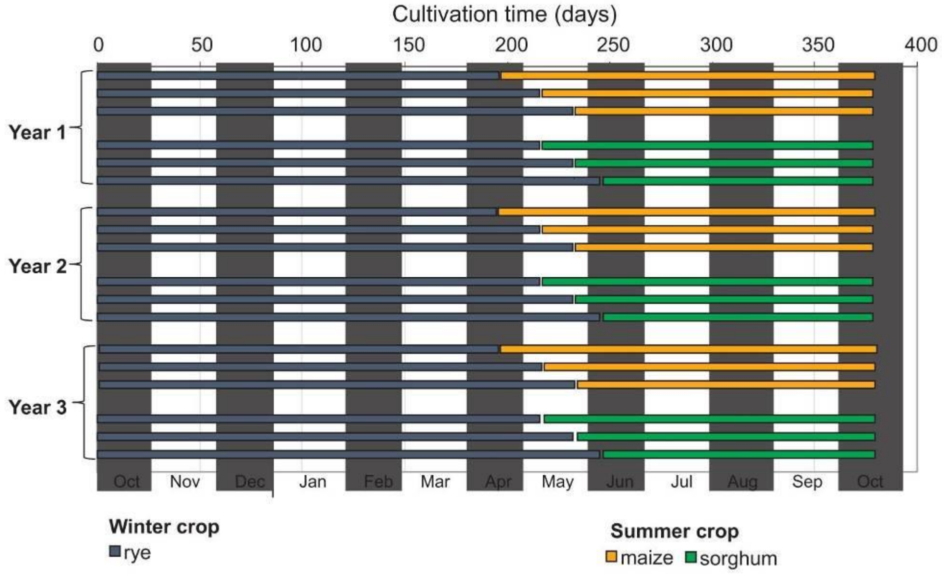

Fig. 1. Growth period of rye, maize and sorghum in the 3-year double-cropping field experiments. The bars reflect the length of the cultivation period.

was not considered for investigations. The depth of the sowing for sorghum and rye was 2.5 cm and for maize 4.0 cm, respectively. The specific sowing density for seed was set to 280 m^{-2} (rye) 22 m^{-2} (sorghum) and 7.5 m^{-2} (maize). All plots were fertilised with urea and NAC fertiliser (calcium-ammonium-nitrate with 27% N total, CaO 125%) with an annual nitrogen input of 93 kg·ha^{-1} (rye and sorghum) and 160 kg·ha^{-1} (maize).

The seeding time for the winter crop was set for the 29th of September for year 1 and the 5th of October for year 2 and 3. For the summer crops the date was between 18th of April and the 10th of June. Four different harvesting dates for rye and three seeding dates for each summer crop were investigated in terms of biomass yield and growth dynamics. Maize was grown after the first 3 harvesting dates (1 st, 2nd, 3rd) of the rye crop, while sorghum was grown after the last 3 (2nd, 3rd, 4th; Fig. 1). Rye harvesting occurred after 199, 220, 232 and 248 days. The summer crops were cultivated after the rye harvest. Maize was then harvested after 170, 148 and 136 days and sorghum after 148, 136 and 122 days. The seeding and harvesting dates as well as the cultivation period of the two DC systems are shown in Fig. 1.

For the rye variety comparison field experiments, the starting point was the same as described above for the DCS-winter crop. In the 1st and 3rd year four and in 2nd year five different harvesting dates were chosen. The earliest harvest occurred place after 217 days and the latest after 289 days. The other dates were distributed within this range (see Fig. 2).

For comparison purpose we use data from sorghum single-cropping experiments which were conducted at the same site at a different plot in the same time period.

2.1.2. Climatic data

Rainfall and temperature data were provided by the Central Department for Meteorology (Central Institution for Meteorology and Geodynamics Austria, ZAMG).

Rainfall and temperature were monitored during the three experimental years parallel to the vegetation period. Temperature was recorded hourly. Daily and monthly means including standard deviation were calculated.

2.2. Sampling and sample preparation

A defined size of 1 m^2 (0.37 x 2.66 m) of each variety was manually harvested. Immediately before harvest, the plant height was determined by measuring the length of all plants within the defined plot from the soil surface to the base of the tallest leaf. Harvested biomass was crushed to an average particle size of 2.5 cm using a cutting mill. A minor part was used for chemical analysis and the major part was transferred to a 2-L container, compressed and maintained for 4 weeks to produce silage. The silage was further used for the determination of the biomethane potential.

2.3. Biomethane potential (BMP) tests

BMP tests were conducted in triplicate in 1-L eudiometer batch digesters according to the guidelines VDI 4630 ("VDI 4630, 2006). The operational temperature was set to 37.5 °C. The inoculum used was taken from an AD plant digesting maize silage at a temperature of 38 °C. Before use it was transferred to a continuously stirred laboratory digester to degrade the residual biomass. To maintain the microbial culture vital, the digester was fed with maize silage every 2 weeks (internal standardisation). Silage from the crop cultivation experiments (SC rye and maize; DCS rye/maize and rye/sorghum) was mixed with 600 g of inoculum in the lab digester. For comparison purpose already published data from sorghum SC experiments was used and clearly marked. Samples were randomly taken independently from the year and the harvesting date and used for the BMP tests.

The amount of silage was calculated to obtain a mass ratio of 0.5 between organic dry matter (volatile solids) of the feedstock and the inoculum applied. The experiments were operated for 4 weeks. The amount of biogas production was periodically monitored, whereas the biogas composition (CH_4, CO_2 and H_2S) was analysed using a portable gas analyser (Dräger X-am 7000).

2.4. Chemical analysis - dry matter and volatile solids

The dry matter (DM), also known as total solids (TS), ash content and volatile solids (VS) of the harvested biomass were analysed according to standard methods DIN DEV 38 414 part 2 (DIN, 1985a) and DIN DEV 38 414 part 3 (DIN, 1985b).

2.5. Statistical analysis

The statistical analysis was conducted using the statistical software programme SAS. Data were analysed via one-way ANOVA followed by Tukey's test for post-hoc comparison. The level of significance was set

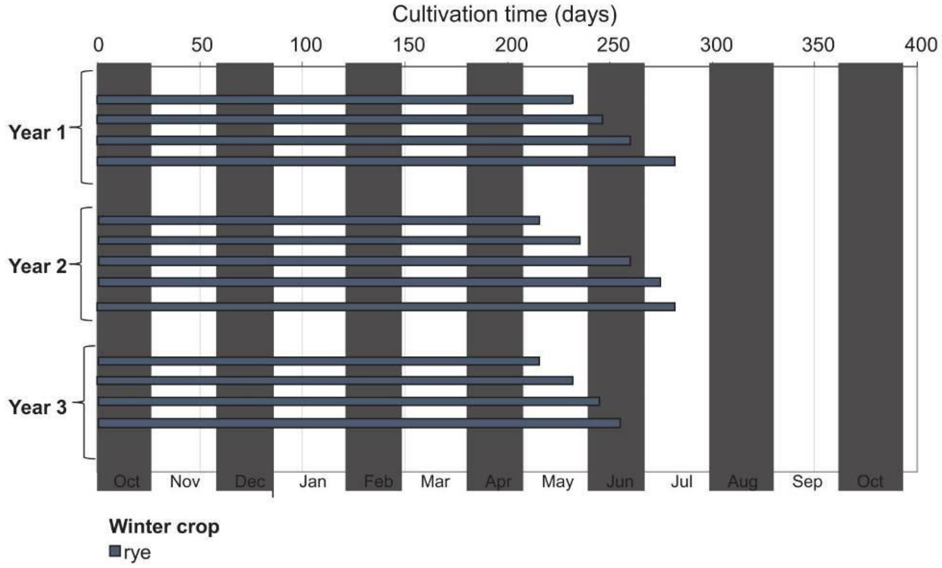

Fig. 2. Growth period of the winter crop rye in the 3-year single-cropping field experiment. The bars reflect the length of the cultivation period.

as $P < 0.05$.

2.6. Growing degree days (GDDs)

Growing degree days (GDDs) are a measure of heat accumulation to predict crop development rates such as the date that the crop will reach maturity. "Growing degree days" is a means of assigning a heat value to each day. The values are added together to give an estimate of the amount of seasonal growth that plants achieved. GDD are calculated by taking the integral of the warmth above a base temperature (Tbase). If the average daily temperature is lower than the base temperature then the GDD is zero The base temperature was set to 5, 8 and 10 °C for rye, maize and sorghum, respectively (McMaster et al., 2016; Robertson et al., 2013; White, 2003). The calculation is shown in equation 1 (modified from McMaster et al., 2016).

$$GDD = \sum_{i=1}^{n} \left(\frac{Tmaxi - Tmini}{2}\right) - Tbase;\ if\ (Tmaxi - Tmini) > Tbase$$

Tmax and Tmin are the highest and lowest hourly mean temperature during the day.

3. Results

3.1. Rainfall

Cultivation years 1 and 3 were characterised by low rainfall, particularly during the seeding period of the summer crops between April and June (< 45 mm rainfall). The total rainfall during cultivation year 3 and during year 1 was considerably lower (330 and 385 mm, respectively) compared to that of year 2 (554 mm). The cumulative rainfall distribution of all three years within the vegetation period (183 days) is shown in Fig. 3. Furthermore, the rainfall distribution 25 days before the seeding start is included, indicated as negative vegetation days. This serves to illustrate the general water supply in the soil at the beginning of the vegetation period. In the Fig. 3 there also the different sowing dates (earliest and latest) for both summer crops maize and sorghum indicated. For the latest sowing dates for both summer crops an orange and green shaded bar is applied indicating the minimum and maximum. The maximum difference between early and latest sowing was 43 and 41 days for maize and sorghum respectively.

3.2. Maize single-cropping

Maize was cultivated as a single crop at the same location and showed considerable biomass yield differences depending on the cultivation time (see Fig. 4). The span of the growth period was between 100 and 170 days. Within this span, biomass dry matter yields between 12 and 24 $t{\cdot}ha^{-1}$ were achieved.

3.3. Double-cropping culture – Comparison of 2 summer crops: Maize versus Sorghum

Two double-cropping systems based on rye as a winter crop and maize or sorghum as a summer crop were compared over a period of 3 years. The biomass dry matter yield, dry matter mass fraction, GDD and optimal range for ensiling of 2 double-cropping systems are shown in Fig. 5. The data sets shown in the Figure are consecutively numbered across the years (1–9).

The total biomass yield of the double-cropping culture rye/maize ranged between 11 and 22 $t{\cdot}ha^{-1}$. The highest biomass yield was measured during year 1 at 21.6 ± 4.6 $t{\cdot}ha^{-1}$ in which winter rye contributed 8.7 ± 0.6 $t{\cdot}ha^{-1}$and maize contributed 12.9 ± 4.2 $t{\cdot}ha^{-1}$. The total growth period comprised 368 (220 + 148) days. In terms of winter crop biomass yield, a clear and expected trend could be observed. The later the harvesting and the higher the GDDs, the higher the biomass yield ($p < 0.05$). The highest biomass yields of winter rye in the rye/maize and rye/sorghum DCSs were 10.7 ± 1.5 $t{\cdot}ha^{-1}$ at 801 GDD units and 15.0 ± 0.5 $t{\cdot}ha^{-1}$ at 985 GDD units, respectively.

In contrast, the biomass yields of both summer crops showed opposite effects, which was also expected because of reduced growing days and GDDs. Typically, the summer crop biomass yield is the highest when the winter crop cultivation period is the shortest, which is expected. However, there was one exception for maize during year 1 in which the biomass yield was the lowest (10.5 $t{\cdot}ha^{-1}$) at the highest GDDs (1,816).

Compared to those of sorghum the maize biomass yields were considerably lower and ranged between 5.1 ± 0.6 and 12.9 ± 4.2 $t{\cdot}ha^{-1}$, whereas for sorghum they were between 5.3 ± 1.0 and 19.2 ± 1.8 $t{\cdot}ha^{-1}$.

The total biomass yield of the double-cropping culture rye/sorghum ranged between 18.9 and 27.5 $t{\cdot}ha^{-1}$. The highest biomass yield was achieved during year 1 at 27.5 ± 2.4 $t{\cdot}ha^{-1}$, in which winter rye contributed 8.3 ± 0.7 $t{\cdot}ha^{-1}$ and sorghum 19.2 ± 1.8 $t{\cdot}ha^{-1}$.

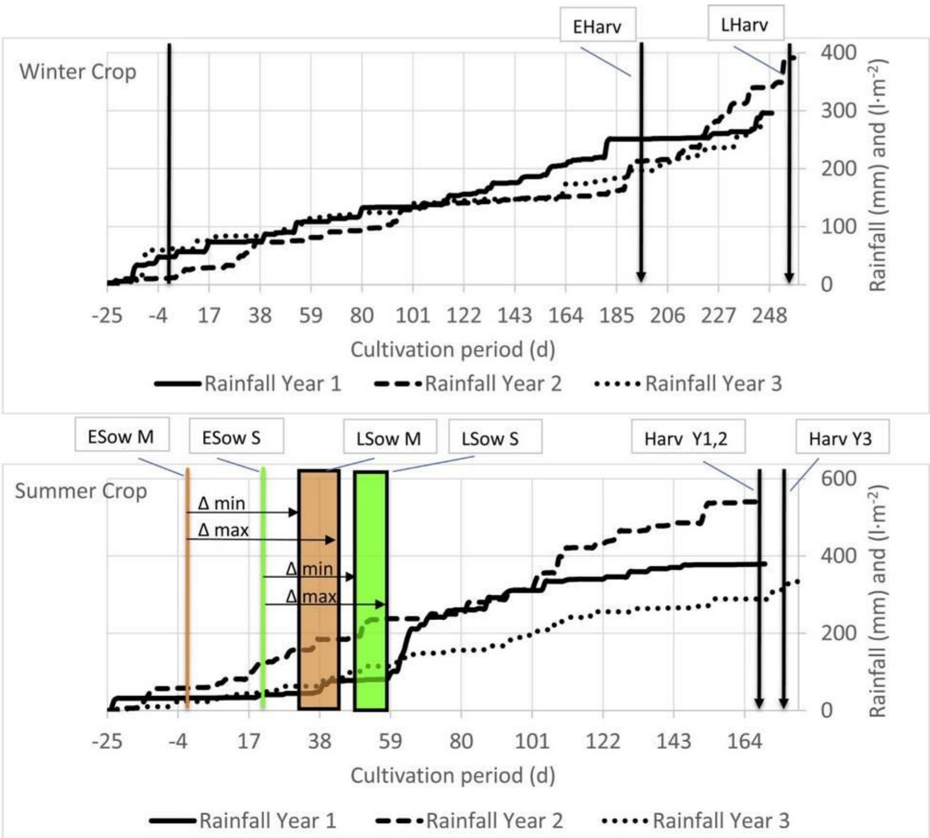

Fig. 3. Rainfall profile during cultivation period of the 3 year double-cropping field experiment. Winter crop (above) and summer crop (below). **Abbreviations:** EHarv is earliest harvest; LHarv is latest harvest; ESow M is earliest sowing Maize; ESow S is earliest sowing Sorghum; LSow M is latest sowing maize; LSow S is latest sowing sorghum; Harv Y1,2 is harvest date year 1 and 2; Harv Y3 is harvest date year 3; Δmin; Δmax is min. and max. difference between 1st and latest sowing date.

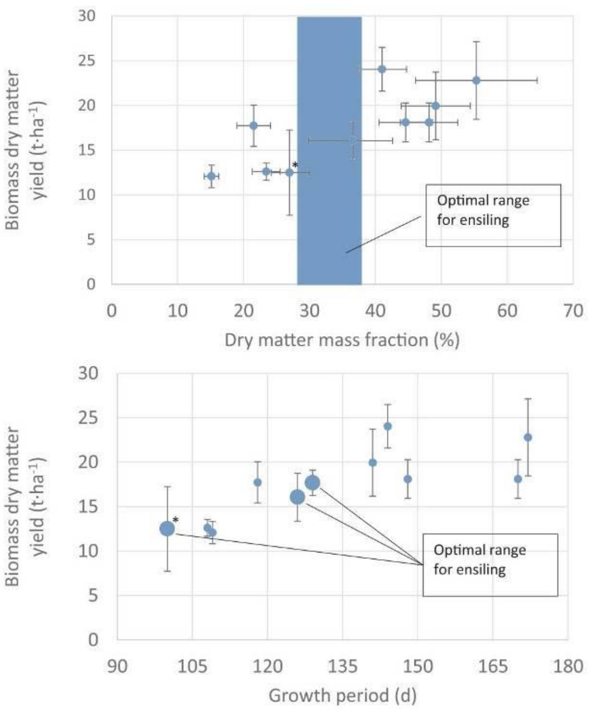

Fig. 4. Biomass yield, dry matter mass fraction and optimal range for ensiling of maize crops, cultivated in a 3-year single-cropping system. *This value was included in the optimal range for ensiling. The error bars indicate the standard deviation.

3.4. Winter rye – Impact of variety on growth dynamics

The biomass dry matter yield of all harvests within the triennial field experiment ranged between 5.5 and 18.3 t·ha^{-1} depending on the harvest date and variety. The highest yield of 18.3 ± 1.5 t·ha^{-1} was obtained by the cultivar RYE 1 during year 1 at 1,200 GDD (˜8 months). The maturity, biomass dry matter yield and harvest time of five rye cultivars as a function of GDD and specific dry matter for each cultivation year are shown in Fig. 6.

3.5. Methane yield

Biomethane potential (BMP) tests of 48 harvested and ensiled maize and 15 rye fractions with an initial range of dry matter between 17 and 43% (after harvest) were conducted. The VS/TS mass ratio was 93%. Methane yields were converted to standard conditions (273 K, 101.3 kPa). At a dry matter of 18–22% the highest methane yield on VS of 367 m^3 t^{-1} was achieved. Within a dry matter range between 23 and 27%, 28 and 33%, 34 and 39% and 40 and 43% methane yields on VS of the ensiled fractions of 337, 341, 347 and 343 m^3 t^{-1}, respectively, were achieved. If the standard deviation is considered, there is very little difference in the specific methane yields of the ensiled maize samples. The average specific methane yield on VS including all 48 maize fractions was 346 ± 27 m^3 t^{-1}. The observed methane yields of the ensiled rye biomass were within a similar range; only one with a lower dry mater (17–23%) showed a high deviation of approximately 15%. An average specific methane yield on VS including all rye fractions of 336 ± 32 m^3 t^{-1} was obtained. The specific methane yield per hectare of the investigated single and double-cropping systems at an optimal maturity level (27–35% DM) are shown in Fig. 7. The combination of rye/sorghum reached 9,300 m^3 ha^{-1}, which is significantly greater than the methane yields of rye/maize at 7,400 m^3 ha^{-1} ($p < 0.05$).

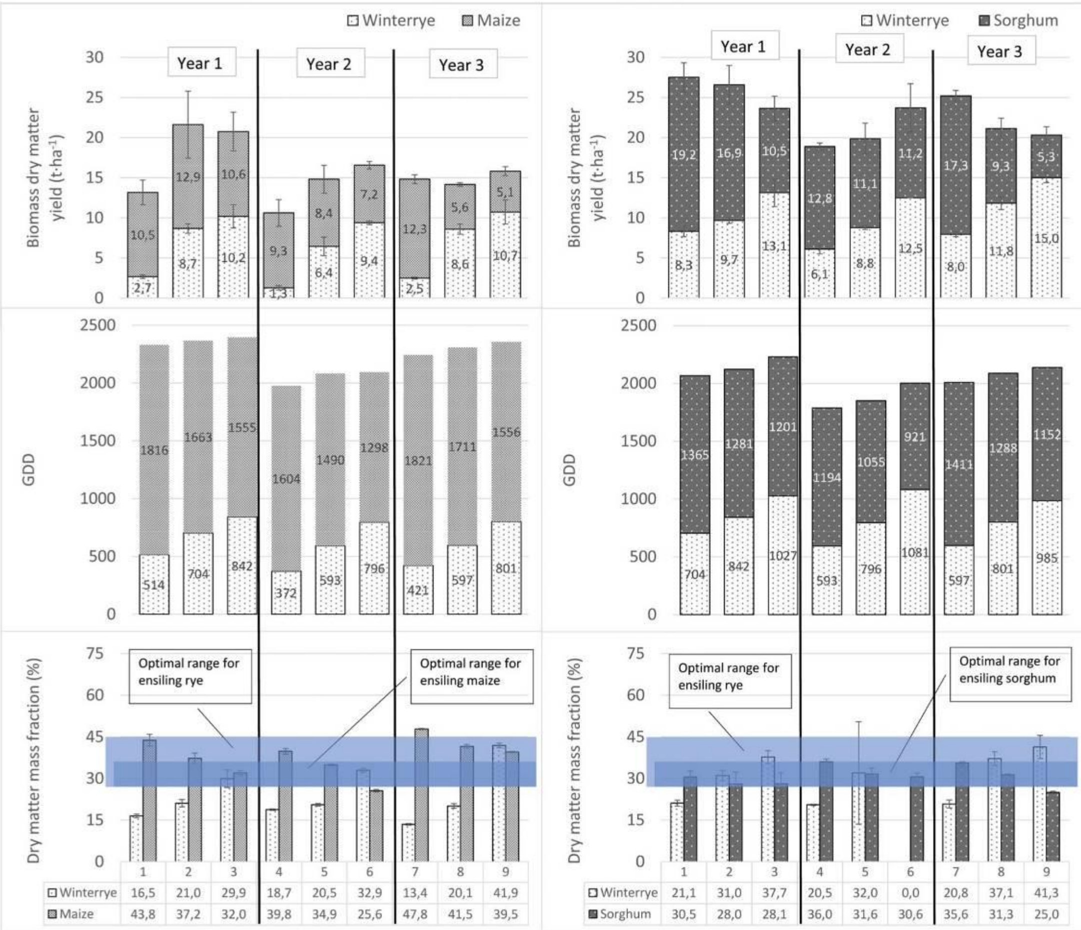

Fig. 5. Biomass dry matter yield, dry matter mass fraction, GDD and optimal range for ensiling of 2 double-cropping systems over a period of 3 years: rye/maize (left) and rye/sorghum (right).

If the outliers (upwards) are considered, then yields of both maize- and sorghum-based DCSs, of 9,800 and 10,600 $m^3 ha^{-1}$, respectively, can be achieved.

4. Discussion

In this study, two double-cropping systems based on rye/maize and rye/sorghum were compared to each other and to a maize single-cropping culture in a field experiment over a 3-year period. The influence of different harvesting and growing times on biomass yield, maturity and biogas yield was investigated. During the same period, the influence of different winter crop (rye) varieties on the aforementioned parameters was examined.

4.1. Rainfall

No constant climatic conditions were observed at the experimental site during the three year cultivation experiments. As shown in Fig. 3, during year 1 the rainfall was only 45 mm (day -25 until day 40) within a period of 2 months and was therefore considerably dryer compared to the other years. Although soil moisture content was not measured, it could be assumed that water supply during this crucial period was not as sufficient as that during years 2 and 3. In addition to the absolute amount of plant-available water, the distribution (rainfall/irrigation) within the vegetation period plays a major role in plant growth. If irrigation cannot be sufficiently guaranteed during the growing season, biomass yield will be significantly lower. The exceptions are plants with deeper root systems that are able to increase biomass yield if sufficient stored soil water is available (Young and Long, 2000).

In the present study, a maximum rainfall of 350 mm (year 3), 400 mm (year 1) and 550 mm (year 2) for the longest cultivation period (early seeding and late harvesting) of the summer crops during the respective year was measured. Although the rainfall during cultivation year 1 was very low at the beginning, no significant impact on growth performance was observed.

This fact was confirmed by Schittenhelm and Schroetter (2014), who measured the root biomass of maize and sorghum at various plant-available soil water contents (PASW) at different soil depths. The sorghum root biomass yield between a PASW of 15% (drought stress) and 80% (wet conditions) were nearly the same. In contrast, maize showed a significant reduction in root biomass of greater than 57% under drought stress conditions.

In comparison to maize, sorghum penetrates the soil to a greater depth and to higher extent (Stone et al., 2002). Under a scarcity of rainfall and dry climatic conditions, respectively, sorghum´s biomass yield superiority over maize is higher and more bound to soil water that can be captured at the site, particularly in deep soils with a high water holding capacity.

Under current climatic conditions, only the lowlands on the Pannonian Plain in e.g., east Austria and Hungary are suitable for sorghum cultivation. Climate simulation including various relevant growth parameters showed that in the near future more regions in central Europe may become a potential cultivation area for sorghum with increased biomass yields (Olesen et al., 2011; Weinwurm et al.,

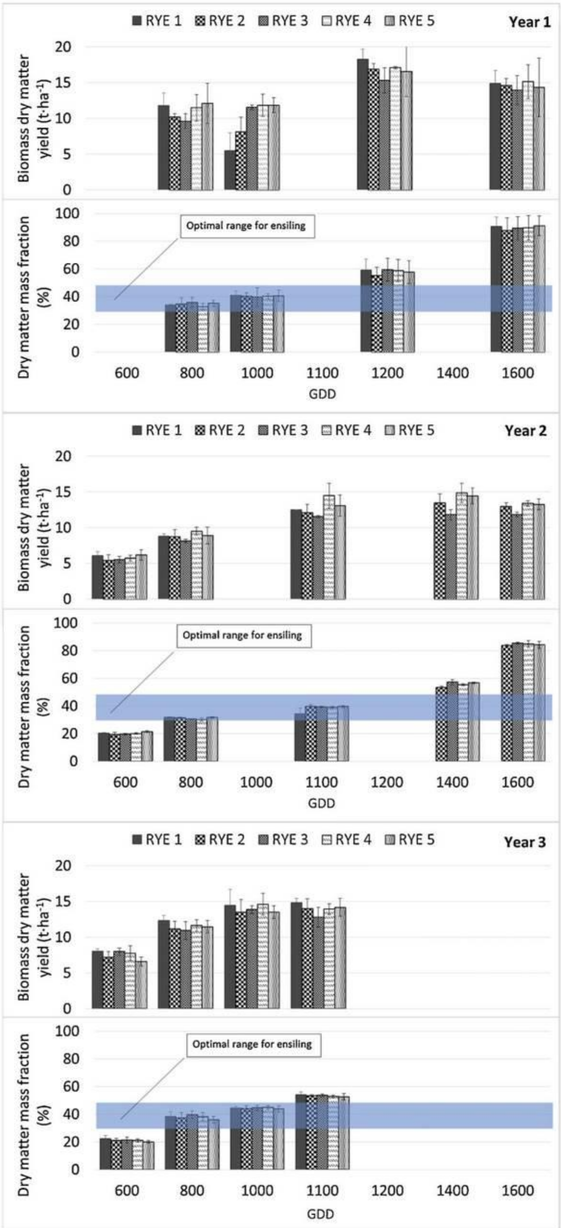

Fig. 6. Maturity, biomass dry matter yield and harvest time of five rye cultivars as a function of GDD and specific dry matter for each cultivation year.

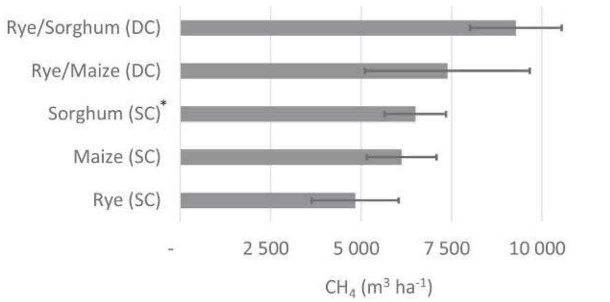

Fig. 7. Comparison of the specific methane yield of single and double cropped systems harvested at optimal maturity level. *determined in a previous study (Wannasek et al., 2017).

2014).

4.2. Maize SC

In a three-year field test of a single-cropped maize, Graß et al. (2013) measured dry matter yields of approximately 22 t·ha^{-1} when extending the growth season beyond the optimal harvesting time for ensiling. Similar findings were also reported from Schumacher et al. (2006) and Amon et al. (2007b).

In our study, at an optimal maize maturity for subsequent ensiling (dry matter content between 28 and 37%), the highest yields were 18 t·ha^{-1} after a cultivation period of 129 days. These yields are slightly smaller than those cited in the literature and must also be assessed in the context of the location (Pannonian climate: hot and dry). If the biomass dry matter content was slightly greater than the optimal ensiling quality (41% DM; 144 growing days) a biomass yield of up to 24 t·ha^{-1} was measured.

4.3. Sorghum SC

Unlike other plants, sorghum has large variety differences in biomass yield. Biomass yields achieved at this specific location (Pannonian climate: dry and hot) showed considerable higher average yields compared to those achieved in locations with regular natural rainfall (Wannasek et al., 2017). In several cultivation studies addressing various climatic regions, such as southeast China, central United States, Brazil and Europe, it was shown that sorghum is able to provide biomass yields similar to those of maize. Typical varieties investigated in long-term field tests were *sorghum bicolor* and *sorghum sudanese* (Mahmood and Honermeier, 2012; Pazderu et al., 2014; Wannasek et al., 2017).

The sorghum variety selected for the DCS in this study showed in a previous single-cropping cultivation experiment comparing different cultivars biomass dry matter yields of average 18.9 t·ha^{-1} and was one of the best performing sorghum cultivars (Wannasek et al., 2017).

4.4. Double-cropping culture – Comparison of 2 summer crops: Maize versus Sorghum

There is nearly no data available on double-cropping field tests in the literature. A recent comprehensive study was published by Graß et al. (2013) who compared various single and double-cropping systems to each other in seven different moist locations (580–820 mm of annual rainfall) in middle and northern Germany. Single-cropped maize achieved biomass yields between 22 and 24 t·ha^{-1} (28% DM) and single cropped rye 17-20 t·ha^{-1} (40% DM). In contrast, double cropped systems provided higher yields compared to those of the SCSs, particularly with consideration to diversified crop sequences in intensified DCS crop rotations (Andrade et al., 2017). The combination of rye/maize achieved yields between 23 and 26 t·ha^{-1} in which rye contributed approximately 10 t·ha^{-1} (Graß et al., 2013). Another study tested rye (*Secale cereale*) as a winter crop to cultivate pumpkin as the main summer crop and obtained a rye biomass yield of 9.9 t·ha^{-1} (Williams, 2014). A double-cropping system based on rye and maize was able to generate a total biomass yield between 13.9 and 19.3 t·ha^{-1}. Because of the low temperatures, a low average GDD value of only 383 resulted in low rye biomass yields of between 0.2 and 3.7 t·ha^{-1}. In comparison, in the location in this study, GDD values up to 1600 were achieved, and optimal values ranged between 800 and 1000.

Direct comparison of the two DC systems in our study showed that the combination of rye/sorghum achieved significantly higher total biomass yields (winter + summer crop together) than those of the rye/maize DCS ($p < 0.05$). During year 1, the highest biomass yield of 27.5 ± 2.4 t·ha^{-1} in the rye/sorghum DC system was measured. The highest total biomass yield of the rye/maize DC system was also achieved during year 1 but was significantly lower (21.6 ± 4.7 t·ha^{-1})

($p < 0.05$).

These results were the opposite of those found in the study by Graß et al. (2013). In a triennial field experiment, the combination of rye/maize achieved yields between 23 and 26 t·ha^{-1} and rye/sorghum yields between 20 and 22 t·ha^{-1}. A reason for the lower yield in this study could be the summer crop seeding date, which occurred during mid of June and thus was considerably later compared to that of our study. The contribution of rye biomass in both DCS(maize, sorghum) was approximately 10 t·ha^{-1} (Graß et al., 2013).

Comparing the cases in our study where cultivation period and thus GDD was exactly the same in both DCS, a slightly higher rye yield has been observed in the maize system. A reason could be the soil heterogeneity with a slightly better soil quality in the maize system. Considering the standard deviation most of the values are actually within the range.

Although the biomass yields range of the rye/maize system during year 1 was comparable to that of the literature, the expected trend (high GDD, highest biomass yield for summer crop) was not observed. The maize biomass yield with respect to the harvesting date showed irregular values resulting in a high standard deviation that could have been caused by an inhomogeneous water supply particularly during the first 38 days after seeding.

It is noticeable that the biomass yields during years 2 and 3 were low with total yields of approximately 15 t·ha^{-1}.

Total biomass yields of the rye/sorghum DC system during the years 2 and 3 ranged between 20 and 25 t·ha^{-1}. It is very likely that the given climatic conditions at the location (dry and hot), were the reason that sorghum had a better performance compared to that of maize.

During the experiments, it was clearly seen that sorghum could thrive above average at high temperatures with a moderate water supply. This growth behaviour was already confirmed in a comprehensive field test at exactly the same location (Wannasek et al., 2017).

The considerable difference in biomass yield is also the result of early maize cultivation and the large decrease in rye yield. Between the 1st and 2nd seeding date of maize (2nd seeding date maize = 1st seeding date sorghum), the rye yields increased by several times compared to the 2nd, 3rd or 4th seeding date of maize and sorghum.

Maize has a longer maturation period than that of sorghum. Growth occurs in both maize and rye in a predictable progression (initially slowly, then rapidly, then slowly to the maximum). This means that the larger proportion of biomass arises only after a long phase of plant development with limited increase in biomass. If this high biomass growth rate phase is interrupted by a possible earlier harvest, then large biomass amounts are not produced. This effect was observed in many cases; for instance during year 3 for sorghum the 1,411 GDDs resulted in 17.3 t·ha^{-1}, but slight decrease in GDDs (1,288) only achieved 9.3 t·ha^{-1}. Although the GDD difference is only 9%, the difference in biomass yield is nearly 50%. This shows the high growth rate during the end of the cultivation period (green rye period). During year 2, this effect was not observed, probably because of the lower temperatures and higher rainfall during year 2 compared to that during years 1 and 3. Because of this, the early seeding did not result in a higher biomass yield.

Furthermore, if there is insufficient moisture in the soil (often after harvest during spring), the field emergence may be delayed or slow, which also reduces the biomass yields later on (Du Plessis, 2003). Basically, sorghum is more suitable for later cultivation than maize because of the higher germination temperature required. Sorghum also requires a much shorter vegetation time compared to that of maize to produce comparable biomass amounts. Above all, maize has the disadvantage that it is extremely susceptible to drought stress. In the case of maize, for example, a short hot period during the growth phase irreversibly affects growth and biomass yield in most cases. This could be observed during the 3 year field test. Sorghum, however, is able to overcome this stress and regenerate itself. The main difference between maize and sorghum is that sorghum is a plant that generally grows significantly later, mainly because of its high sensitivity to early frost (Farré and Faci, 2006; Zegada-Lizarazu et al., 2012).

4.5. Winter rye – Impact of variety on growth dynamics

The biomass yields achieved in our study are fully in line with yields observed in other studies. Graß et al. (2013) reported 17-20 t·ha^{-1} (at 40% DM) for a single cropped rye grown in north/central Germany, but a 9-month cultivation period was necessary to achieve this yield. Winter rye cultivated at a location in West Austria showed a winter rye biomass yield of approximately 15 t·ha^{-1} (Amon et al., 2007a). However, apart from a few exceptions, there were very small and insignificant differences in biomass yield among the varieties (see Fig. 6).

There was a very good correlation between the time of growth/time of harvest or GDD and the biomass yield obtained ($p < 0.05$). As the GDD level increased, so did the maturity and biomass yield. The field experiments also demonstrated that in the case of high GDDs (1,600) and a long cultivation period, respectively, maturity levels of approximately 90% DM can be achieved.

However, in some cases the correlation between GDD and biomass yield was not as expected. For instance, in year 1 the biomass yield of rye 1 and 2 was higher at GDD 800 compared to GDD 1000 and the biomass yield of rye 3, 4 and 5 remained the same at GDD 800 and 1,000. This could be caused by crop bending or drought stress.

At GDD 1,600 a decrease of biomass yield was observed mainly caused by typical crumble losses at the very end of a vegetation period.

With regard to the ability for optimal ensiling, the dry matter should be within a range between 27 and 45%. Considering this, GDD values between 800 and 1,100 are sufficient to achieve optimal silage maturity. During years 1 and 3, the optimal maturity level was already and clearly achieved after 800 GDDs. These results confirmed that there is very little varietal influence on biomass yield. Furthermore, they showed that rye is very well suited as a winter crop in different double-cropping systems.

4.6. Methane yield

The obtained methane yields of both, maize (346 ± 27 m^3 t^{-1}) and rye fractions (336 ± 32 m^3 t^{-1}), in our study are in line with yields reported in the literature. In a comprehensive study investigating 12 different maize varieties at 3 different locations in Austria specific methane yields on VS between 268 and 366 m^3 t^{-1} at maturity levels from 20 to 45% DM were achieved (Amon et al., 2007b). Similar yields could be confirmed by Oslaj et al. (2010), who compared 15 different maize hybrids in Slovenia. Considerably lower methane yields on VS between 250 and 300 m^3 t^{-1} were reported by Gao et al. (2012), who tested 9 different maize varieties in China. Another study investigated the biomass yield and specific methane yield of ten different catch crop species grown in two different locations of Denmark. Among them, rye showed an average methane yield of approximately 350 m^3 t^{-1} (Molinuevo-Salces et al., 2013).

In a previous study investigating various effects on the methane yield of different varieties of sorghum grown as single crop, an average specific methane yield on VS of 338 ± 10 m^3 t^{-1} was obtained (Wannasek et al., 2017). These values were greater than the average yields, which ranged between 200 and 320 m^3 t^{-1} (Pazderu et al., 2014; Wünsch et al., 2012). One reason for the higher values could be that the focus in our study was to set the harvesting date in an optimal range of biomass dry matter content for subsequent ensiling and biogas production.

The specific methane yield per hectare of the investigated single and double-cropping systems shows that at the chosen location double-cropping systems are clearly superior to single-cropping systems. Within the studied single-culture systems, sorghum showed clear advantages over maize. Sorghum can achieve average methane yields of 6,500 m^3 ha^{-1}, while maize can achieve average values of 6,100 m^3 ha^{-}

[1] under the given climatic conditions. Rye achieved average yields of 4,800 $m^3 ha^{-1}$. Variations can sometimes produce a yield per hectare of 7,200 m^3 for both maize and sorghum and 6,000 m^3 for rye. These values, particularly for rye, are slightly greater than the yields reported in the literature. In a comprehensive study testing the impact of 25 genotypes and 3 harvest dates on the winter rye methane yield, a mean methane yield of approximately 4,400 $m^3 ha^{-1}$ was obtained. Maximum yields reached approximately 5,000 $m^3 ha^{-1}$ at a location in central Germany (Hübner et al., 2011). For maize, Gao et al. (2012) reported methane yields for individual hybrids ranging from 4,600 to 8,900 $m^3 ha^{-1}$, Amon et al. (2007b) from 6,000 to 9,000 $m^3 ha^{-1}$ and Oslaj et al. (2010) from 7,000 to 9,400 $m^3 ha^{-1}$. Oslaj et al. (2010) measured a methane content up to 60% of produced biogas in a few maize hybrids. These values clearly show the great potential and superiority of maize over other energy crops when the climatic conditions in terms of water supply and temperature input are optimal.

For Sorghum, Mahmood et al. (2012) were able to achieve methane yields between 2,100 and 7,900 $m^3 ha^{-1}$. The experiments clearly showed the high influence of the sorghum variety at given climatic conditions on biomass and methane yield. This was also confirmed by Wannasek et al., 2017 who investigated the impact of climate, variety and harvesting time on crop maturity as well as biomass and methane yield. In a three-year field trial, the authors were able to achieve methane yields of 6,500 $m^3 ha^{-1}$.

However, maize methane yields might decrease to less than those of sorghum and even rye when the water supply is insufficient because of the better resistance of sorghum and rye under these conditions. A direct comparison of the two double-cropping systems also showed that in dry locations with irregular rainfall, the combination of rye/sorghum is clearly superior to rye/maize. In contrast, Graß et al. (2013) achieved 7,700 and 6,500 $m^3 ha^{-1}$, respectively, for rye/maize and rye/sorghum combinations. The winter rye biomass yields of approximately 10 $t{\cdot}ha^{-1}$ were comparable to the yields obtained in our field experiment. Because of a later seeding of the summer crops (middle June), biomass yields of approximately 16 $t{\cdot}ha^{-1}$ for maize and approximately 11 $t{\cdot}ha^{-1}$ for sorghum were obtained. In our study, the seeding time was between mid-April and mid-June and maximum DM yields of sorghum of 19.2 $t{\cdot}ha^{-1}$ (seeding on 13th May) were demonstrated. These values are exceptionally high and are mainly caused by the special climatic conditions (hot and dry) at the cultivation site, which are optimal for sorghum.

5. Conclusion

Climate change requires the growth of drought resistant energy crops as an alternative to the currently widely used maize. In a previous paper, we showed that sorghum offers the advantage of improved biomass yield stability in dry regions with methane per hectare yields of greater than 6,000 Nm^3. In this paper, we continued the investigations to research into optimum cropping strategies.

Double-cropping systems (DCSs) have proved to be able to achieve biomass yields similar or even higher to single-cropping cultivation systems (SCSs) while at the same time offering well known and confirmed additional ecological advantages. The present study achieved even higher biomass and methane per hectare yields (up to 9,300 $m^3 ha^{-1}$) with the DCS combination of rye/sorghum. This combination was superior to single-cropped sorghum, single-cropped maize and also to the DCS combination rye/maize at the same field site. After having investigated the impact of varietal selection, seeding and optimum harvesting time on sorghum biomass yield, we focused in the present study on the effect of winter rye variety selection. In contrast to sorghum, no major impact of winter rye variety on biomass yield was revealed. Maize yields in the DCS were heavily reduced by late seeding because of the short cultivation period. The present study clearly demonstrates the superiority of DCSs over SCSs in hot and dry regions. It showed the double-cropping rotation of winter rye (hardy) and sorghum (more drought resistant than maize) as a potentially promising strategy to counteract climate change and optimize crop yield stability.

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ABSTRACT

In the field of sustainable biorefinery concepts, sorghum receives increasing attention as a raw material. Main advantages of various sorghum types are fast growth as well as efficient nutrient and water utilization. When considering the competition between food and energy crop production, sorghum could be part of a sustainable solution. Through a convenient integration in a crop rotation system, sorghum could be grown as an alternative crop with good harvest results within a short vegetation period. In cooperation with a biogas plant in lower Austria, the potential of sorghum as a resource for fuel and energy production was evaluated. Field tests were carried out, and for a certain period of time, a sweet sorghum variant was incorporated into the substrate mixture of a biogas plant to monitor the process. Three concepts for grain and sweet sorghum variants were simulated in ASPEN Plus® to assess the coproduction of bioethanol and biogas in one facility and compared to the crops ethanol potential and conventional biofuel processes. The future growing conditions for this crop were evaluated on a climatologic basis for the Lower Austrian region in question. The highest harvest yields were achieved in the first year of testing, highlighting the dependency on cultivar and weather conditions. The sorghum processes could compete against the established processes, reaching up to 92 % ethanol, 107 % DDGS, 80 % methane and up to 202 % of their total energy output. Climatologic evaluation shows, that more regions in Austria will become available for sorghum cultivation due to climate change.

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Assessment of Sweet Sorghum as a Feedstock for a Dual Fuel Biorefinery Concept.

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In the field of sustainable biorefinery concepts, sorghum receives increasing attention as a raw material. Main advantages of various sorghum types are fast growth as well as efficient nutrient and water utilization. When considering the competition between food and energy crop production, sorghum could be part of a sustainable solution. Through a convenient integration in a crop rotation system, sorghum could be grown as an alternative crop with good harvest results within a short vegetation period. In cooperation with a biogas plant in lower Austria, the potential of sorghum as a resource for fuel and energy production was evaluated. Field tests were carried out, and for a certain period of time, a sweet sorghum variant was incorporated into the substrate mixture of a biogas plant to monitor the process. Three concepts for grain and sweet sorghum variants were simulated in ASPEN Plus® to assess the coproduction of bioethanol and biogas in one facility and compared to the crops ethanol potential and conventional biofuel processes. The future growing conditions for this crop were evaluated on a climatologic basis for the Lower Austrian region in question. The highest harvest yields were achieved in the first year of testing, highlighting the dependency on cultivar and weather conditions. The sorghum processes could compete against the established processes, reaching up to 92 % ethanol, 107 % DDGS, 80 % methane and up to 202 % of their total energy output. Climatologic evaluation shows, that more regions in Austria will become available for sorghum cultivation due to climate change.

1. Introduction

Sorghum is a C4 plant, therefore its water use efficiency is very good compared to other field crops (Geng 1989). An additional advantage is that sorghum roots grow very deep and therefore are able to take up water from deeper soil levels (Zegada-Lizarazu, 2012). As only 1st generation ethanol production is investigated in the course of this study, sugar or starch is needed as the main source for fermentation. In the case of sorghum both can be produced. There are variants that form free sugars that can be fermented directly to ethanol. Other variants build up grain with a high starch content which can also be fermented after a saccharification step (Rooney, 2007). Concerning the technology required for the cultivation of sorghum, existing machinery from maize cultivation can be used. The presented work was carried out in the framework of the “BiSunFuel” project, which is aimed to assess the potential for sorghum as an energy crop in Austria.

2. Materials and Methods

2.1 Field Tests

In the course of this project, planting experiments with different sorghum varieties were carried out. A special focus was laid on the opportunity of growing sorghum as a side crop. Therefore, the seeding dates were varied between May in the first year, at the beginning of June in the second year and at the end of June and beginning of July in the third year of the experiment. In the first year (2011) two sugar producing

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(Sugargraze I, SG I & Sugargraze II, SG II) and one starch producing (Chopper, C) varieties, in the second year (2012) two sugar producing varieties (Sugargraze I & Nectar, N) and in the third year (2013) two starch producing varieties (Supersol, SU & GK Emese, GKE) were examined.

2.2 Climatological Evaluation

Since the project behind this study focuses on energy and fuel production for a community in lower Austria, the harvest yield security when using sorghum as a raw material had to be assured. The following minimum climatic requirements were defined using literature research (EURALIS, 2013 and FNR, 2007) and crop modelling: soil temperature in June > 12 °C, minimum air temperature (June - September) > 4 °C and sum of degree days (June – October) > 2,500 °C. Since sorghum bicolour originates from arid subtropical climates, temperature is the limiting factor. For evaluation of potential cultivation regions the INCA dataset was used for current climate and bias corrected and localized Regional Climate Models - RCMs (Aladin, RegCM3, REMO) for future climate conditions. Eventually maps for current and future potential cultivation regions in Austria were drawn.

2.3 Biogas plant Monitoring

A local biogas plant (400 m³ biogas/h, 630 kWel) in Margarethen am Moos, Lower Austria, was monitored from early May to late July 2013. A simple flowsheet of the plant is shown in Figure 1.
Substrate feed and composition, electric consumers' power demand and operating time, the produced biomethane, biogas, and electricity were monitored in order to establish mass and energy balances.

2.4 Simulation of Sorghum Process Concepts

Process variants were developed and presented previously (Weinwurm, 2013). Different concepts were designed to accommodate the specific properties of grain and sweet sorghum cultivars. Two benchmark variants were also considered, which were considered completely independent biogas and bioethanol plants with corn silage and corn grain as feedstock, . The process variants are pictured in Figure 2. While the data for the benchmark scenario were taken from literature, the sorghum process variants were simulated with the software ASPEN Plus® V7.3.2 (Aspen Technology Inc., 2012) incorporating experimental date or, when not available, literature values. To meet project requirements, the available field area and plant scale had to be matched to the existing biogas plant. The benchmark biogas case (a) consists of the harvesting of silage maize, which is ensiled on site and used to continuously produce biogas throughout the year. The benchmark bioethanol case (b) is a conventional first generation corn ethanol process with a production capacity of 100,000 tons ethanol per year. The grain sorghum process variant (c), utilizes the "Chopper" variety, which exhibits a rather high starch content of the grains. The ensiled straw is used for biogas production, which was in all cases calculated according to VDI 4630 (2009), and the grains are dried and transported to a central ethanol plant (100,000 t/y capacity) for ethanol production. As a by-product, DDGS, which is a valuable fodder

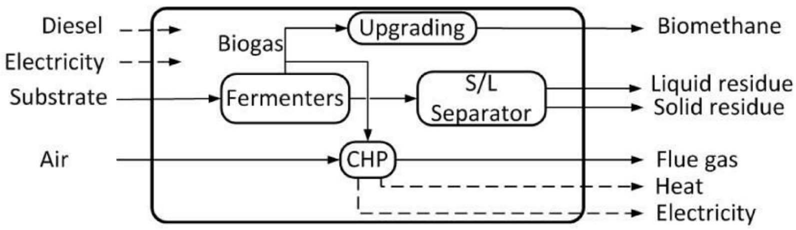

Figure 1: Flow sheet of the monitored biogas plant

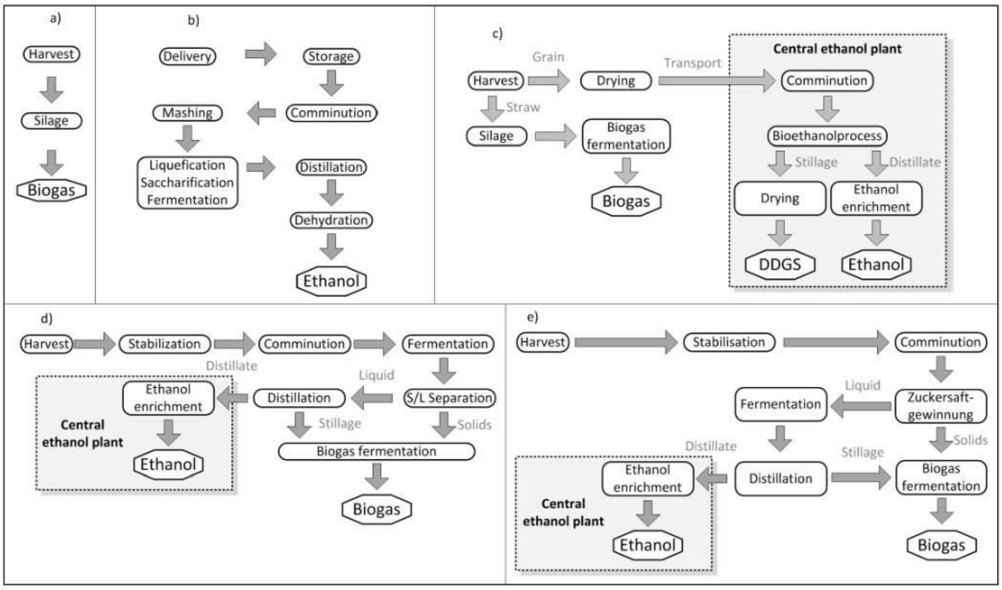

Figure 2: Evaluated process concepts: a) Benchmark Biogas variant, b) Benchmark Ethanol variant, c) Grain sorghum variant with separate grain and straw utilization, d) Sweet sorghum variant with whole plant fermentation, e) Sweet sorghum variant with separate juice fermentation

for livestock, is obtained. The concepts d) and e) were designed for use with the Sugargraze I cultivar. Sweet sorghum plants form a glucose-rich juice that can be used directly for ethanol fermentation. To prevent sugar loss through microorganisms after exposition of the juice to the environment after harvesting, the plants are stabilized by addition of formic acid to a concentration of 1 % (Schmidt et al., 1997). In process variant d), the whole plant is fed into a solid state fermenter after stabilization and size reduction. A yeast load of 4 g/kg fresh material (Rohowsky et al., 2011) and a sugar to ethanol conversion of 90.5 % is assumed (Li et al., 2013). A mainly lignocellulosic solid fraction will remain which is separated by pressing to a dry matter content of 50 %. The liquid at this stage contains about 2.8 % (by weight) of ethanol. The separated solids are washed, and the liquid fractions combined for distillation. For the last concept, the parameters of concept d) were reused, if applicable. The sugar juice is obtained in a milling process described by Dias et al. (2009) under the addition of fresh water where 96 % of the sugar is recovered. The sugar juice is fermented to ethanol (90.5 % conversion rate), distilled and purified further. The washed press cake is again used for biogas production.

3. Results

3.1 Field Tests

The experiment in the first year showed that the sorghum variety "Chopper", which is a grain variant, would be the most promising option for ethanol production. The sugar forming varieties showed similar biomass yields but the lower sugar content leads to a lower ethanol yield. In the second year of the experiment, the seeding date was moved to the 15th of June. Due to slow growth at the beginning of the vegetation period, the maximum yields were about 60 % of those from the first year. As the starch variety showed the highest potential in the first year, it was decided to investigate two starch varieties with two seeding dates in the third year of the experiment. The first seeding date was the 25th of June and the second was the 6th of July. As the summer in 2013 was extraordinary dry and hot, yields remained very low. The analysis of the grain showed that there was no yield that would have been relevant for ethanol production. The harvest yields are shown in Figure 3.

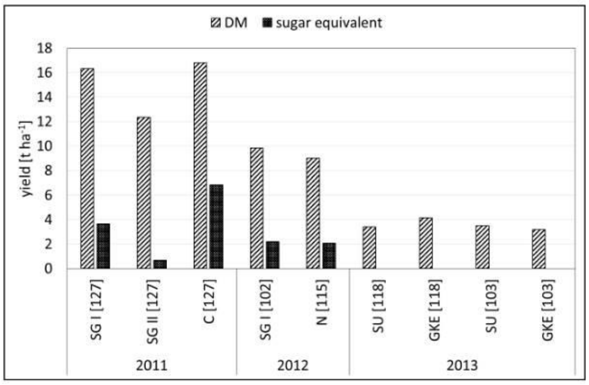

Figure 3: Dry matter (DM) and sugar yields for the sugar forming sorghum varieties Sugargraze I (SG I), Sugargraze II (SGII), and Nectar (N), and the starch forming varieties Chopper (C), Supersol (SU) and GK Emese (GKE). Vegetation days are indicated in brackets

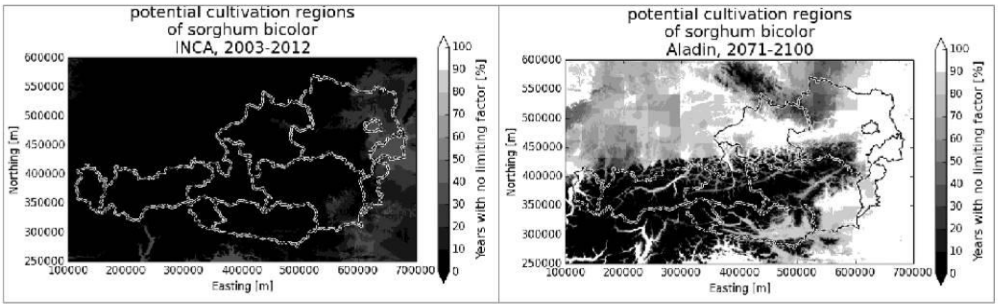

Figure 4: Potential cultivation regions (light shading) under current climatic conditions (INCA-dataset, 2003 – 2012) (left) and by end of the century (Aladin RCM, 2071 – 2100) (right)

3.2 Potential cultivation regions

Under current climatic conditions, only the flatlands in east most Austria and around Lake Constance are suitable for cultivation of sorghum bicolor in most years. The most critical factor is the high vulnerability to temperatures below 4 °C. However, due to climate change, more low regions become potential sites for cultivating sorghum bicolor as can be seen in Figure 4.

3.3 Biogas plant Monitoring

The mass balance was based on the data for substrate input, biomethane output and biogas flow to the CHP unit. No measurement of the flue gas could be established, so the CHP unit was taken out of the mass balance. Lacking a flow measurement of the fermentation residue, we estimated the residue via the experimentally determined biogas potential, and therefore the consumed volatile solids (data not shown) to close the balance. All streams were averaged and considered constant over the monitoring period. The substrate consisted of grass (4.3 % of the total VS (volatile solids)) input, sorghum (30.7 %), beet greens (5.3 %), green rye (7.1 %), alfalfa (5.5 %), corn straw (36.6 %), horse manure (6.1 %), and liquid manure (4.6 %). Measurements and estimates resulted in the Balance in Table 1. The difference between Input and Output of 56.6 kg/h equals 2.3 % of the biomass input. It includes gas losses, moisture in the flue gas, all other losses, as well as measuring and rounding errors.

Table 1: Biogas plant mass balance

	Substrate	Biogas to CHP	Biomethane	Residue	Sum	Difference
Input (kg/h)	2,425.5				2,425.5	
Output (kg/h)		353.5	1.2	2,014.3	2,369.0	56.5

Table 2: Process yields and gains

	Benchmark processes		Sorghum processes		
	Bioethanol	Biogas	GS	SS-WPF	SS-SJF
Specific yields					
Ethanol (kg/t TS)	377.91		317.07	97.22	93.83
CH4 (kg/t TS)		240.93	206.32	168.88	172.66
DDGS (kg/t TS)	373.26		362.97		
Total Energy (kWh/kg TS)	2.82	3.35	2.57	3.07	3.10
Total annual yields					
Ethanol (t/y)	702.00		648.72	332.64	321.04
CH4 (t/y)		959.17	297.92	577.85	590.78
DDGS (t/y)	693.36		742.64		
Total Energy (GWh/y)	5.24	13.32	8.98	10.51	10.60

GS: Grain Sorghum process, SS-WPF: Sweet Sorghum – Whole plant fermentation, SS-SJF: Sweet Sorghum – Separate Juice Fermentation

3.4 Simulation of Sorghum Process Concepts

Preliminary simulation results have been previously presented (Weinwurm, 2013). Since then, the simulation the concepts has been completed, and a number of assumptions had to be adjusted. The specific product yields (kg product per ton dry input) of methane, pure ethanol and dry DDGS and total annual yields were calculated. Energy yields were also calculated based on the lower heating value of the produced ethanol and methane. All calculated yields are shown in Table 2.

For the benchmark bioethanol plant, average harvest yields for Lower Austria were assumed (Bader and Kriesel, 2012). Ethanol and DDGS yields were taken from Friedl (2012). The biomethane yield was assumed to be 240.9 kg/t TS, in the middle of the range reported by Englert et al. (2009). As can be seen in Table 2, the specific ethanol yield with GS is lower than with the benchmark process (84 % of the benchmark value) and the methane yield is also somewhat lower (86 %), while the specific DDGS yield in GS was calculated to be 97 % of the benchmark yield.GS is quite competitive due to the coproduction of bioethanol and biogas which combined yield roughly 77 % of the specific energy output of the benchmark biogas process. The specific ethanol, methane and energy yields from the sweet sorghum variants only reach up to 26 %, 72 % and 93 % with the SS-SJF process. In terms of total annual production, the GS process can partially compete with the classic processes. Ethanol production reaches about 92 % and DDGS production reaches 107 % of the benchmark maximum, but is still outperformed by the benchmark biogas process with a combined energy output of 67 % of the benchmark value. The sweet sorghum processes reach up to 80 % of the benchmark biogas, and 202 % of the benchmark ethanol process' energy output. Theuretzbacher et al. (2012) presented the ethanol potential for several crops which was compared to the simulated yearly production from the available field area (Figure 5). Utilizing the sweet sorghum variety SG I, the simulated sweet sorghum processes yielded 80 % of the plants ethanol potential (410.4 t/y). The GS process seems to be highly efficient, reaching 97 % of the potential ethanol production.

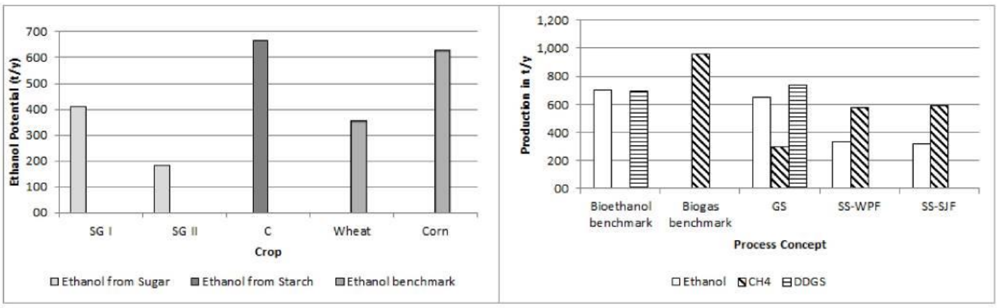

Figure 5: Annual ethanol potential of different crops (left) and simulated product gains (right)

4. Conclusions

The results show that sweet sorghum could be utilized in small scale, decentralized plants to provide fuel and energy in an ethanol and biogas coproduction plant. Grain sorghum straw could be a viable option to produce some biogas locally, and use the efficiency of a central bioethanol production site for the sorghum grains. It is interesting, that all proposed concepts yield a higher combined Energy than the established benchmark ethanol process which may be a result of omitted data in the sources. It was shown that both cultivar and climate strongly affect sorghum as a viable future option for decentralized energy supply.

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6 Zusammenfassung, Gesamtdiskussion und Ausblick

Die Notwendigkeit nachhaltig intensivierter und ökonomisch erfolgreicher Fruchtfolgesysteme ist für die Biogasproduktion und den steigenden Bedarf an anaerob vergärbarer, nachwachsender Biomasse weiterhin von zunehmendem Interesse. Vermehrter Bedarf an ökologisch produzierter Pflanzenbiomasse ergibt sich künftig zudem aus dem Einsatz in Bioraffinerien. Die Intensivierung der Biomasseproduktion in Form nachwachsender Rohstoffe aus landwirtschaftlichen Fruchtfolgesystemen muss in jedem Fall den Voraussetzungen der Nachhaltigkeit entsprechen. Auch die jüngsten Ansprüche an Fruchtfolgen aus dem fortschreitenden Klimawandel sind dabei unbedingt zu berücksichtigen und bedürfen angepasster und ertragsstabiler Lösungen. Durch die in Produktionszonen für nachwachsende Rohstoffe meist vorherrschende Flächenknappheit muss die Flächenintensivierung nicht nur nachhaltig sein, sondern es darf auch keine weitere Flächenausdehnung auf futter- und lebensmittelproduzierende Ackerflächen erfolgen.

In den hier durchgeführten Untersuchungen konnten, auf der Suche nach Fruchtfolgesysteme die den oben genannten Anforderungen entsprechen, offene Fragen zur Sortenwahl, zum Anbauzeitpunkt, zum Erntezeitpunkt, zum Ertragsverhalten und zum Reifeverhalten quantitativ und qualitativ beantwortet werden.

Die Gesamterträge der Fruchtfolgesysteme spielen hinsichtlich monetärer Anforderungen an die Biomasseproduktion beziehungsweise notwendiger Methanhektarerträge der hervorgebrachten Biomasse eine wesentliche Rolle. Eine Antwort darauf geben die detaillierten Ergebnisse und Strategien hinsichtlich Ernte-/Anbauzeitpunktoptimierung, Gasertragstests sowie Ergebnisse zu sorten- und pflanzenartspezifischem Reifeverhalten. Auch der Gesamtertrag von Zweikultursystemen hinsichtlich des jährlichen Methanhektarertrages konnte aus den durchgeführten Untersuchungen in Abhängigkeit der am Versuchsstandort vorherrschenden Niederschläge und Wachstumsgradtage ermittelt werden.

In den in beiden Studien durchgeführten Feldversuchen über jeweils 3 Vegetationsperioden wurden im Einkulturversuch 5 Sorten Sorghum zu unterschiedlichen Erntezeitpunkten, eine

Biomassesorte Mais als Hauptfrucht zu unterschiedlichen Erntezeitpunkten sowie 5 Roggensorten zu unterschiedlichen Erntezeitpunkten untersucht.

In Zweikulturfruchtfolgen wurde Mais mit der Winterzwischenfrucht Roggen sowie Sorghum ebenfalls mit der Winterzwischenfrucht Roggen über 3 Vegetationsperioden an 3-4 unterschiedlichen Anbau-/Erntezeitpunkten untersucht.

Niederschlag

Die **Ergebnisse und Analysen der Klimadaten** zeigen die Ausgangslage an Niederschlägen von 350 bis 550 mm Niederschlag pro Vegetationsjahr. Trockenstressresistenz ist eine immer wichtigere positive Eigenschaft für Kulturpflanzen, die in niederschlagsarmen Regionen angebaut werden. Während der Versuche über 3 Vegetationsjahre hinweg konnten sehr unterschiedliche Wetterbedingungen zwischen den Jahren und auch zwischen den Monaten innerhalb einzelner Vegetationsperioden festgestellt werden. Die positiven Auswirkungen der Anpassungsfähigkeit von Sorghum an Trockenperioden wurden hierbei beobachtet. Negative Auswirkungen der Trockenperioden auf die Ertragsbildung konnten in wesentlich stärkerem Umfang bei Mais im Vergleich zu Sorghum verzeichnet werden. Die besser ausgeprägte Fähigkeit von Sorghum gegenüber Mais des Überdauerns von niederschlagsarmen Zeiten wurde in der Studie von Schittenhelm and Schroetter (2014) bestätigt. Trockene Vegetationsphasen beispielsweise über den Zeitraum von 2 Monaten von April bis Juni, mit einem Niederschlag von 45mm wurden in gegenständlichen Feldversuchszeiträumen anhand der Wetterdaten festgestellt, welche erhebliche Trockenstressbedingungen deutlich machen. Abgeleitet davon ergab sich speziell unter vorherrschenden Wetterbedingungen am Versuchsstandort die Erwartungshaltung der Vorzüge einer Sorghum/Roggen-Zweikulturfruchtfolge gegenüber einer Fruchtfolge mit Mais.

Wachstumsgradtage

Als gute Möglichkeit zur **Standardisierung des Vegetationsverlaufes** wurde die **Methodik** der **Wachstumsgradtage** in den Versuchen implementiert. Aus den **Temperaturdaten** wurden als Vergleichsbasis Wachstumsgradtage generiert und anstatt der Vegetationstage herangezogen. In den statistischen Tests konnten hierbei signifikantere Ergebnisse beobachtet werden im Vergleich zu denselben Tests mit Vegetationstagen. Zur Berechnung der Wachstumsgradtage [Growing Degree Days – GDD] sämtlicher Zeitpunkte wurde folgende Formel verwendet:

$$GDD = \sum_{i=1}^{n} \left(\frac{Tmax_i + Tmin_i}{2}\right) - Tbase;\ if\ \left(\frac{Tmax_i + Tmin_i}{2}\right) > Tbase$$

Tmax and **Tmin** are the highest and lowest hourly mean temperature during the day.

Tbase is the specific base growth temperature for the respective crop.

Wachstumsgradtage / Growing Degree Days [GDD] Berechnungsformel

Ein weiterer positiver Aspekt der Wachstumsgradtage ist die standortübergreifende Aussagekraft, anhand der an jeweiligen anderen Standorten verfügbaren Wachstumsgradtage in der Vegetationsphase. Das Ertrags- und Reifeverhalten kann anhand der mittels GDD dargestellten Versuchsergebnisse für dieselben Kulturpflanzen und Sorten auch für andere Standorte gut abgeschätzt werden.

Sorghum im Einkultur-Sortenversuch

In einer Reihe von Studien (Schittenhelm and Schroetter, 2014; Young and Long, 2000) wird Sorghum als eine an Trockenperioden angepasste Pflanze bestätigt, unabhängig von der jeweiligen Sorte. Ein tiefwurzelndes Verhalten begünstigt im Fall von Sorghum die Anpassungsfähigkeit an längere niederschlagsarme Perioden. Im Einkulturversuch der 5 Sorghum-Sorten über 3 Jahre konnten erhebliche Ertragsunterschiede zwischen den Sorten festgestellt werden. Der Maximalertrag wurde von einigen Sorten bereits sehr früh, zum 2. Erntezeitpunkt, erreicht und von anderen Sorten erst zum 4. oder 5. Erntetermin. Zumeist korreliert eine frühere Abreife mit etwas geringeren Erträgen. Explizit verzeichneten die frühreifen ertragsstarken Ernten etwa 15% geringere Erträge als die ertragsstarken späteren Erntezeitpunkte. Aus diesen Ergebnissen mittels GDD standardisiert kann eine gute Bewertung der Sorten für die Anwendung an unterschiedlichen Standorten und die Sorteneignung zur Zwischen- oder Hauptfruchtnutzung abgeleitet werden. Die züchterisch noch nicht so weit entwickelte Pflanze Sorghum brachte, verglichen mit gängigen landwirtschaftlichen Kulturpflanzen wie Mais und Roggen, in der Untersuchung zum Ertragsverhalten hinsichtlich Sorteneinfluss stark differierende Ergebnisse. Unter den ausgewählten Sorten unterschieden sich die Maximalerträge im jeweils selben Vegetationsjahr um bis zu 50%. Dies stellt die Wichtigkeit der angepassten Sortenwahl für eine Ertragsmaximierung in der Biomasseproduktion mit Sorghum dar. Die höchsten Erträge der 3 untersuchten spätreifen Sorten aus gegenständlicher Studie lagen im Durchschnitt bei 18.9 t ha^{-1}. Die untersuchten Erträge konnten in vergleichbarer Höhe in anderen Studien (Herrmann et al., 2012; Mahmood et al., 2012; Pacuta et al., 2014), bestätigt werden.

Im Kontext des Klimawandels und der damit gepaarten Mehrung extremer Wetterereignisse sowie Temperaturanstiege geht man in einer Reihe von Simulationen und Studien davon aus, Anbaugebiete von Sorghum in Ein- und Zweikulturfruchtfolgen in Österreich sowie Mitteleuropa künftig deutlich ausgeweitet zu sehen. Es wird erwartet, dass die Vorzüge der C4-Pflanze Sorghum (Ertragsentwicklung, Trockenresistenz, Tiefwurzler) in künftigen Fruchtfolgen für Biomasseproduktion guten Anklang finden werden (Weinwurm et al., 2014; Olesen et al., 2011).

Hinsichtlich des Reifeverhaltens gaben die Sorghum-Sortenversuche im Einkultursystem über 3 Jahre ebenfalls guten Aufschluss für die qualitative Eignung zur Lagerfähigkeit und der Mindestanforderung von Vegetationsdauer und Wachstumsgradtage für jeweilige Sorten. In vorliegenden Untersuchungen konnten an den Versuchsernteterminen Trockensubstanzgehalte [TS] von 15% (98d) bis 51% (170d) gemessen werden. Eine konservierende Lagerung durch Silierung sollte im Reifespektrum von 27-35% TS erfolgen (Amon et al., 2007a; Steinhöfel et al., 2006). Der optimale Erntezeitpunkt wurde daher innerhalb dieses Reifespektrums festgesetzt. Ein zu geringer Trockensubstanzgehalt würde in Lagerverlusten (bis zu 10%) resultieren, ein zu hoher Trockensubstanzgehalt würde den Konservierungsprozess der Silierung behindern oder sogar unterbinden (Herrmann et al., 2009; Hermann et al., 2011). In den Sortenversuchen mit Sorghum konnte gut gezeigt werden, wie schnell der optimale Erntezeitpunkt, abhängig von der jeweiligen Sorghum-Sorte, erreicht werden konnte. Der optimale Erntezeitpunkt wurde sowohl durch das Erreichen des silierfähigen Reifegrades (27-35% TS) als auch den ermittelten Höchstertrag innerhalb des optimalen Reifezeitfensters definiert. Bei einer der 5 Sorghum-Sorten, jene mit frühem Reifezeitpunkt, konnte in den Versuchen das Erreichen des optimalen Erntespektrums [27-35% TS] bereits nach rund 1100 Wachstumsgradtagen beziehungsweise 113 Vegetationstagen beobachtet werden. Diese Erkenntnis lässt sehr gut auf die Möglichkeit zur Nutzung frühreifer Sorghum-Sorten in nachhaltigen Zweikulturfruchtfolgen beziehungsweise als Sommer-Zwischenfrucht schließen.

Die höchsten Erträge der spätreifen Sorten traten erwartungsgemäß vermehrt am oberen Ende des optimalen Reifespektrums, bei 35% TS und darüber, auf. Der höchste Biomasseertragswert im Einkultursystem mit Sorghum wurde mit 20.67 t TM ha^{-1} gemessen.

Die Messungen der spezifischen Methanausbeute für Proben innerhalb des Reifespektrums von 27-35% Trockensubstanz ergaben einen durchschnittlichen Wert von 338.0 m^3 t^{-1}. Eine signifikante Änderung der spezifischen Methanausbeute in der Abhängigkeit des Reifegrades konnte in jenem Reifespektrum nicht festgestellt werden. Die Methanhektarerträge, die aus den Analysen und Messungen generiert werden konnten, ergaben für die ertragsreichsten Sorten über die drei Versuchsjahre 5500 – 6500 m^3 ha^{-1}, was einen wesentlichen Erfolgs- und Entscheidungsfaktor für Biomasseproduzenten und Biogasanlagenbetreiber darstellt. Die am schnellsten abreifende und dadurch als Sommerzwischenfrucht jedenfalls prädestinierte Sorghumsorte erreichte über die 3 Jahre hinweg nennenswerte Erträge von 3700 – 4630 m^3 ha^{-1} in einem vergleichsweise kurzen Vegetationszeitraum.

Die Ergebnisse aus den 5 Sorten-Versuchen mit Sorghum konnten daher wesentliche Ertragsgrößen und einen Einfluss der GDD auf das unterschiedliche Abreifeverhalten der Sorten zeigen. Weiters wird die Eignung von Sorghum zur ökonomisch vielversprechenden Biomasseproduktion für Biogasnutzung sowie zur möglichen Anwendbarkeit in nachhaltigen Zweikultursystemen unter vergleichsweise trockenen Standortbedingungen gezeigt.

Wie die Studie Weinwurm et al. (2014) zeigt, eignet sich Sorghum im Speziellen auch für den Einsatz in zukunftsweisenden Bioraffineriekonzepten.

Maisertrag

Der in **Einkulturversuchen als Hauptfrucht** ebenfalls ermittelte Ertrag von **Mais** als Vergleichsbasis ergab in vorliegender Studie innerhalb des Reifegrades 27-35% maximale Trockenmasseerträge [TM] von 18 t ha^{-1}. Diese liegen etwas unter jenen Erträgen vergleichbarer anderer Studien, welche jedoch zumeist an Standorten mit höheren Niederschlägen und besserer Wasserversorgung durchgeführt wurden (Graß et al., 2013; Schumacher et al., 2006; Amon et al. 2007b).

Mehrkultursysteme Sorghum/Roggen & Mais/Roggen

Vielversprechende Ergebnisse konnten aus den **Fruchtfolgen im Mehrkultursystem Sorghum/Roggen sowie Mais/Roggen festgestellt** werden. Während in vergleichbaren Studien (Graß et al., 2013) an Standorten mit höheren Niederschlägen (580-820 mm/a) das Mehrkultursystem mit Mais/Roggen eine Überlegenheit in der Ertragsentwicklung gegenüber Sorghum/Roggen zeigte, ergab sich in den Feldversuchen am Versuchsstandort unserer Studien, Groß-Enzersdorf, ein gegenteiliges Bild. Die grundsätzlichen Vorzüge in den Gesamterträgen neben den ökologischen Vorteilen von Zweikultursystemen gegenüber Einkultursystemen ohne Winter-/Sommerzwischenfrucht konnten von Andrade et al. (2017) festgestellt und bestätigt werden. In unseren Versuchen wurden am Versuchsstandort Groß-Enzersdorf in Niederösterreich (330-554 mm NS/Jahr) **27,5 t TM ha^{-1} im Zweikultursystem Sorghum/Roggen erreicht,** wobei die Höchsterträge im selben Zeitraum und am selben Standort für **Mais/Roggen-Zweikultursystem 21,6 t TM ha^{-1}** ergaben. Dies lässt deutlich auf die bereits beschriebenen Vorzüge in der Anpassungsfähigkeit der C4-Pflanze Sorghum an niederschlagslimitierte Standortbedingungen schließen.

Hinsichtlich der ökologisch positiven Aspekte der Zweikultursysteme und des damit verbundenen Sommer- und Winterzwischenfruchtanbaues sowie des guten Biomasseproduktionsvermögens von Sorghum an warmen und trockenen Standorten im Sommer, stellt die untersuchte Fruchtfolge im Kontext des Klimawandels eine vielversprechende Möglichkeit dar.

<u>Roggenertrag</u>

Von den oben genannten Gesamterträgen beliefen sich die **Roggenerträge im Zweikultursystem** auf den geringeren Ertragsanteil von 8-9 t TM ha^{-1}. Als Winterzwischenfrucht in den kalten Monaten des Jahres hatte Roggen die wesentlich längere Vegetationsdauer im Zweikultursystem von zumeist knapp 9 Monaten. Die ebenfalls in den Feldversuchen der Studien durchgeführten Sortenversuche mit Roggen über 3 Vegetationsperioden zeigten, dass der Sorteneinfluss hier einen wesentlich geringeren Einfluss der Roggen-Sorte auf die Ertragsentwicklung und das Reifeverhalten hat.

<u>Methanertrag</u>

Um die Darstellung auf die für Biogasanalgenbetreiber essenziellen Ergebnisse auszuweiten, konnten die **spezifischen Methanerträge der geernteten Proben** mittels Gasertragstest

gemessen werden. Aus den Analysen der geernteten Biomasseproben wurden die durchschnittlichen Methanerträge, bezogen auf organische Trockensubstanz [oTS], für Roggen in Höhe von 336 m^3 t^{-1}, für Mais in Höhe von 346 m^3 t^{-1} sowie jene für Sorghum in Höhe von 338 m^3 t^{-1} bestimmt. Im Vergleich mit Literaturdaten konnte festgestellt werden, dass die ermittelten Gaserträge von Mais und Roggen ähnlich wie die aus vergleichbaren Feldversuchsstudien ausfallen (Amon et al., 2007b; Oslaj et al. 2010). Für Sorghum wiesen die Messungen der spezifischen Gasausbeuten höhere Werte im Vergleich zu ähnlichen Untersuchungen und vergleichbaren Studien auf (Pazderu et al., 2014; Wünsch et al., 2012).
9.300 m^3 ha^{-1} erreichten **die Methanhektarerträge** beim Multiplizieren von Gasertrags- und Flächenertragsergebnisse im Feldversuch des Zweikultursystems Sorghum/Roggen. Am vergleichsweise trockenen Versuchsstandort, welcher eine repräsentative Grundlage für verbreitete und weiter zunehmende Feldparameter im Kontext des Klimawandels darstellt, erreichte die Zweikulturfruchtfolge Mais/Roggen signifikant geringere Methanhektarerträge von 7400 m^3 ha^{-1}. Die Überlegenheit der Sorghum-Zweikulturfruchtfolge mit Roggen ist auch hier nochmals klar ersichtlich.

Für Biomasseproduzenten und Anlagenbetreiber in niederschlagsarmen Anbauregionen stellen die untersuchten Fruchtfolgen und gezeigten Ergebnisse nicht nur auf Grund der absoluten Höchsterträge mit Sorghum vielversprechende Möglichkeiten dar. Auch die Ertragsstabilität und das verminderte Risiko an Ernteausfällen ist mit Sorghum wesentlich besser und somit ertragssicherer für die Biomasseproduzenten, Landwirte und Biogasanlagenbetreiber.

Ausblick

Weitere Potenziale könnten künftig durch fortschreitende Pflanzenzüchtung, vor allem bei der noch vergleichsweise wenig verbreiteten Nutzpflanze Sorghum, hinsichtlich der Ertragsfähigkeit sowie der Klima- und Standortanpassung ausgeschöpft werden.

Die Vorzüge der Mehrkulturfruchtfolge mit Sorghum/Roggen gegenüber jener mit Mais/Roggen wie am Beispiel unserer Feldversuche im pannonischen Klima, könnten in Zukunft zu einer wesentlich breiteren Anwendung von Sorghum in der Biomasseproduktion beitragen.

Es ist davon auszugehen, dass das gezeigte Kultursystem mit Sorghum im Vergleich zu Mais im Kontext des weiter voranschreitenden Klimawandels einen steigenden Bedarf verzeichnen wird, und immer mehr einen Beitrag zur ökologischen Flächenintensivierung in nachhaltig gestalteten Fruchtfolgen für Biomasseproduktion leistet.

Auch die gute Eignung von Sorghum zur stofflichen Verwertung in Bioraffinerien, wird einen wesentlichen Beitrag zu einer nachhaltigen Zukunft in biobasierten Industrieprozessen (biogene Chemikalien-, Wert- und Werkstofferzeugung) liefern und helfen den Einsatz fossiler Ausgangsstoffe zu reduzieren.

Eine Zukunft der Produktion von Energie aus 100% nachhaltigen und erneuerbaren Ressourcen kann nicht als Aufgabe einer einzelnen Technologie gesehen werden. Vielmehr gilt es, Möglichkeiten wie hier dargestellt mit einer Reihe weiterer nachhaltiger Formen ökologischer Energiegewinnung zu kombinieren, und so den Weg in eine klimaneutrale Zukunft zu schaffen.

Nur unter Optimierung sämtlicher uns zur Verfügung stehender erneuerbarer Energieformen im Mix des künftig erneuerbaren Gesamtenergieaufkommens können wir in absehbarer Zeit den Weg zum Ausstieg aus der Verbrennung fossiler und CO_2-anreichernder Energieformen beschreiten.

Auch die nachhaltige Biomasseproduktion aus dem Energiepflanzenbau sowie die Biogastechnologie werden einen wesentlichen Beitrag als Facette im zukünftigen Gesamtenergiemix leisten.

7 Schlussfolgerung

Die Notwendigkeit alternativer Kulturpflanzen und Fruchtfolgen mit guter Anpassungsfähigkeit an Standorte geringen Jahresniederschlages ergibt sich aus stetig voranschreitendem Klimawandel und der Klimaerwärmung. Genau diese Ertragsstabilität konnte in vorliegenden Studien anhand der Kulturpflanze Sorghum demonstriert werden, einen zukunftsweisenden und gangbaren Lösungsweg darzustellen.

6.000 Nm^3 Methan pro Hektar in Einkultursystemen und bis zu 9.300 Nm^3 Methan pro Hektar und Jahr im Mehrkultursystem gemeinsam mit Roggen lassen sich unter Einsatz von Sorghum am Beispiel des untersuchten Standortes im pannonischen Klima produzieren. Die Studien liefern charakteristische Daten zu Reifeverhalten in Abhängigkeit der Vegetationsperiode sowie der Sortenwahl, optimalen Erntezeitpunkt sowie Ertragsentwicklung der Biomasse. Diese Daten stellen wichtige Grundlagen für Entscheidungen seitens Anlagenbetreibern, und generell für die Bildung von Biomasseproduktionsstrategien dar.

Mit dem Einsatz und der Standardisierung anhand von Wachstumsgradtagen (Growing-Degree-Days, GDD) wird eine standortübergreifende Abschätzung von Ertragsentwicklung und Abreifeverhalten unter Einbezug der Klimadaten des zu beurteilenden Standortes möglich. Eine Optimierung der generellen Fruchtfolge- und Anbaustrategie für die Biomasseproduktion zur Biogasnutzung lässt sich aus den Ergebnissen gut ableiten. Wie die Studien zeigen, lassen sich unter Einbezug gegenständlicher Erkenntnisse bei der Wahl des optimalen Erntezeitpunktes bis zu 14% höhere Methanhektarerträge erreichen. Ebenfalls konnte klar gezeigt werden, dass im Spektrum des optimalen Erntezeitpunktes zwischen 27 und 35% TS Gehalt keine signifikante Abnahme der spezifischen Methanausbeute mit zunehmender Reife stattfindet. Die Überlegenheit von Sorghum/Roggen-Zweikultursystemen gegenüber von Mais/Roggen hinsichtlich der maximal zu erreichenden Gesamterträgen auf untersuchtem, vergleichsweise niederschlagsarmem Standort, stellt eine wichtige Erkenntnis für Biomasseproduzenten in ähnlichen Anbaugebieten dar.

Ein Optimierungspotenzial ergibt sich aus den Sorteneinflüssen bei Sorghum, welche lediglich durch Sortenwahl zu sonst selben Bedingungen Ertragsunterschiede von bis zu 50% zeigten. Sorghum in nachhaltigen Zweikulturfruchtfolgen erwies sich als vielversprechende Variante in der zu erzielenden Notwendigkeit der nachhaltigen Steigerung der Flächeneffizienz in Anbaugebieten für Biomasseproduktion. Künftige Forschung sollte weiterhin auf integrierte und nachhaltige Fruchtfolgesystem mit weiteren Kulturpflanzen wie Rüben, Sonnenblumen und vielen anderen Kulturen abzielen. Züchterische Weiterentwicklung der Kulturpflanze Sorghum stellt ein noch auszuschöpfendes Potenzial dar.

Vorliegende Ergebnisse können in ihrer Gesamtheit zu einer vielversprechenden Strategie im Beitrag zur Bekämpfung des Klimawandels mitwirken, und die Ertragsstabilität in der Biomasseproduktion zur Biogasnutzung erhöhen.

8 Conclusion

The need for alternative crops and crop rotations with good adaptability to locations with low annual precipitation results from constantly increasing climate change and global warming. Exactly this yield stability could be demonstrated in the present studies on the basis of the cultivated plant Sorghum.

6,000 Nm^3 of methane per hectare in single-cropping systems (SCS) and up to 9,300 Nm^3 of methane per hectare each year in double-cropping systems (DCSs) using rye and sorghum could be produced for example on the field trial site in the Pannonian climate.

The present work provides characteristic data on maturity levels in course of the vegetation period as well as the variety influence on yield, optimal harvest time and biomass yield development. This data is an important basis for decisions by plant operators and in general for biomass production strategies.

With the use of growth-degree days (GDD), a cross-location estimation of yield development and maturity is possible, taking into account the climatic data of the sites to be assessed.

An optimization of crop rotation and cultivation strategy for biomass production used in biogas plants can be derived from the results. Variety selection and harvesting time proofed to be decisive factors for an optimized sorghum cultivation with up to 14% higher yields in methane per hectare at optimum harvesting time.

The anaerobic digestion experiments carried out in this study comprised maturity levels between 20 and 45% DM and revealed no decrease in the specific methane yield within this range indicating that the full biomass yield potential can be exploited without a decrease in methane production. The field trials achieved even higher biomass and methane per hectare yields (up to 9,300m^3 ha^{-1}) with the DCS combination of rye/sorghum. This combination was

superior to single-cropped sorghum, single-cropped maize and to the DCS combination rye/maize at the same field site.

Through an in-depth analysis of the results, it becomes clear that the cultivation of sorghum for biogas production still offers high optimization potentials regarding varietal selection and the choice of the optimum harvesting time. Up to 50% methane per hectare yield losses can be avoided through proper varietal selection.

Sorghum in sustainable two crop rotations proved to be a promising option in the need to achieve a sustainable increase in land use efficiency in biomass production areas. Future research should continue to target integrated and sustainable crop rotation with other crops such as sugar beet, sunflower and many others.

In addition, expansion of the crop yields and progress in biomass quality could be achieved with breeding efforts which shows another potential that can still be exploited.

Overall, these results may contribute to a promising strategy in climate change mitigation and increased yield stability in biomass production for biogas use.

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