Agricultural Systems 159 (2018) 78–92

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

# A case of sustainable intensification: Stochastic farm budget optimization considering internal economic benefits of biogas production in organic agriculture

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ARTICLE INFO

*Keywords:*
Bioenergy
Anaerobic digestion
Nitrogen modelling
Risk assessment
Genetic algorithm (GA)
Monte Carlo simulation (MC)

ABSTRACT

Organic agriculture is often criticized for its lower productivity compared to conventional farming, while biogas production on organic farms is confronted with many structural constraints additionally impeding its profitability. However, integrated anaerobic digestion seems to induce multiple benefits for the respective organic farm system, such as reduced environmental impacts, improved nutrient efficiency, and stabilized or increased yields. In order to measure these effects within entire farm systems, systemic evaluation approaches are needed. Consequently, in this study we modelled twelve different livestock-keeping (LS) and stockless (noLS) organic farm prototypes comprising of arable farming, dairy cattle, grassland, and biogas production in a farm system assessment. The aim was to evaluate the impact of integrated anaerobic digestion (+ AD) on agronomic, economic, and risk aspects by applying stochastic optimization. While the absolute amount of readily available nitrogen as well as cash crop yields increase for both LS + AD and noLS + AD farm models, especially noLS farm types benefit from the novel availability of a mobile nitrogen (N) fertilizer (biogas digestate) to meet cash crop N demands. Integrated AD may increase profitability of arable farming and reduce its risk potential by displaying first order stochastic dominance. In addition, this diversification strategy may reduce the overall production risk of organic farms. By providing renewable energy as well as increasing food outputs and economic stability, the integration of AD in organic farms may serve as an example for the often postulated aim of a sustainable or eco-functional intensification of organic agricultural systems to face the challenge of productivity increases.

## 1. Introduction

A continuously growing world population (FAOSTAT, 2015) and changing patterns of consumption (Alexandratos and Bruinsma, 2012) generate both rising global energy demands (Pérez-Lombard et al., 2008) as well as increasing food needs (Godfray et al., 2010). This becomes apparent by the doubling of the world total final energy consumption in the past 40 years to approximately 9.000 million tons of oil equivalent (Mtoe) (IEA, 2014), as well as a projected increase of food needs of 70% in 2050 compared to 2007 in order to feed by then > 9 billion people (FAO, 2009; Tomlinson, 2013).

In order to meet rising energy demands, the European Union (EU) has proposed the goal of a share of renewable energies in the total energy mix of 21% by 2020 (European Commission, 2006). Consequently, many EU member states have passed legislation to increase shares of renewable energies (Haas et al., 2011; Reiche and Bechberger, 2004). Anaerobic digestion (AD) represents an important pillar of renewable energy supply, and its share has rapidly increased, e.g. in Germany over the past years (German Biogas Association, 2014) due to strong public funding under the German Renewable Energy Act (EEG, 2000) and its amendments. As a part of this development, on a smaller scale, the share of biogas production associated with organic farms has also increased substantially (Blumenstein et al., 2015).

Renewable energy production is often promoted for its potentials to mitigate negative climate effects or other environmental impacts and to substitute fossil or nuclear energy sources associated with adverse effects ($CO_2$ emission, nuclear calamities). However, particularly bioenergy production is increasingly confronted with criticism of increased GHG emissions (Searchinger et al., 2008) or unsustainable farming practices in energy crop production, causing a series of negative external effects (Matson et al., 1997; Tilman et al., 2002).

Organic agricultural (OA) systems aim for minimized external resource use and the maintenance or increase of soil fertility (Mader, 2002; Norton et al., 2009; Pacini et al., 2003). They are able to reduce negative external effects often associated with intensive production systems such as nutrient leaching or loss of biodiversity, and mitigate

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http://dx.doi.org/10.1016/j.agsy.2017.10.016
Received 1 February 2017; Received in revised form 14 September 2017; Accepted 24 October 2017

negative climate effects through reduced losses of soil organic matter as well as increased C-sequestration (Matson et al., 1997; Scialabba and Müller-Lindenlauf, 2010). Organic agricultural practices may also substantially contribute to the global need for food (Badgley et al., 2007). Recently it has been shown that the yield gap between conventional and organic production systems had been overestimated (Ponisio et al., 2015). Still, organic farming systems are often criticized for their lower productivity when increased productivity from sustainable farming practices is needed to meet world food demands (de Ponti et al., 2012; Seufert et al., 2012). In addition, it is argued that yield potentials are not yet fully exploited in OA or other low-input systems and there is a need for *sustainable* or *eco-functional intensification* of agriculture (Baulcombe et al., 2009; Niggli et al., 2008; Tilman et al., 2002).

Sustainable agricultural practices are often faced with higher production costs (Pimentel et al., 2005), and also biogas systems associated with organic farm systems face multiple restrictions, impeding their profitability. These restrictions especially concern the use of biomasses with high contents in ligno-cellulose which are less favorable for the AD process. For example, clover-grass silages require more costly equipment and result in higher operating and maintenance costs, while displaying lower biogas potentials than e.g. maize silage. For detailed explanations on structural differences of anaerobic digestion in OA compared to conventional biogas systems as well as their impact on biogas plant economics, see also Blumenstein et al. (2016).

A promising option to address the challenges of lower productivity in organic agriculture or unfavorable profitability of biogas production associated with organic farms may be a holistic perspective on the entire organic farm system including integrated biogas production. Various research results indicate positive implications of integrated biogas production, e.g. on the efficiency of nutrient availability of the associated organic farming system (see Section 1.2 of this paper). Therefore, by integrating AD and OA systems the productivity of the whole farming system may be enhanced. In addition to increased food output this might also include economic advantages for the associated farm. Integrated AD in OA might therefore be able to not only stabilize its financial performance as part of a diversification strategy often applied in OA (Zander, 2008), but also serve both goals of an enhanced productivity (food output) of organic farming systems as well as contribute to the growing needs for renewable energy.

Organic farming systems are often diverse and particularly pursue a holistic view on nutrient cycles and subsystem interactions. Therefore, rather than solely analyzing isolated problems, economic evaluations should incorporate a more integrated approach, too. Hence, in order to assess complex agro-ecological systems such as e.g. integrated OA biogas systems, it appears reasonable to consider the expected systemic effects based on a system analysis of on-farm material and nutrient fluxes as well as a detailed economic evaluation of these effects.

### 1.1. Research objectives

Several studies describe models and tools that target the generation of crop rotations based on agronomic aspects including nitrogen fluxes, such as ROTOR (Bachinger and Zander, 2007), ROTAT (Dogliotti et al., 2003), REPRO (Küstermann et al., 2010) or ECOSIM (Möller, 1995). Partially, these models also integrate the assessment of basic economic key figures. Other studies optimize crop rotations with the goal of maximizing the economic output by applying linear programming (LP) (Acs et al., 2007; Karpenstein-Machan et al., 2013). Further sources analyze the N utilization in crop rotations using LP (Hengsdijk and Ittersum, 2003) or apply network flow models to optimize crop rotations (Detlefsen and Jensen, 2007). However, to our knowledge there is no study optimizing the economic output of entire organic farm systems, including not only arable farming but also grassland farming, animal husbandry and anaerobic digestion, based on the modelling of internal nitrogen fluxes. Therefore, we aim at integrating a truly systemic view on the whole farm system which is often not considered in detailed analyses of singular subsystems of farms. In addition, we implemented a – to our knowledge - new approach combining an agronomic model with integrated computational optimization as well as risk assessment (stochastic optimization) to optimize both agronomic and economic outputs. Furthermore, we included specifications inherent to organic farm systems such as agronomic restrictions for the planning of crop rotations or the integrated cultivation of legumes to facilitate $N_2$ fixation.

In summary, the overall aim of this paper is to display the effects of integrated AD on nutrient (nitrogen) management as well as their implications on farm systems economics (AD system economics from Blumenstein et al., 2016 complete the farm system evaluation). Subsequently, the model outcomes are compared with other research to test their validity.

### 1.2. Agronomic implications of integrated AD for organic farm systems

Economic effects of AD integration are based on agronomic implications within adjacent OA farm systems. Providing the foundation for model assumptions and subsequent economic evaluation in the paper at hand, a comprehensive overview of agronomic effects including their quantification (wherever stated in the literature) of integrated anaerobic digestion on farm systems is given (Table 1).

Integrating biogas production into organic farming has the potential to induce multiple positive agronomic effects that may enhance the economic outcome of the associated organic farm system (Siegmeier et al., 2015). These effects become especially obvious by an increased nitrogen efficiency. For example, lower mean stable and storage N emissions can be expected for digested slurry compared to undigested slurry/solid manure (Wendland et al., 2012; KTBL, 2010). In addition, a changed composition of N fractions in the digested slurry towards more readily available $NH_4$-N gives reason to expect higher cash crop yields and higher product qualities through increased grain protein contents (Amon et al., 2006; Möller et al., 2008a; Stinner et al., 2008). Furthermore, harvest and digestion of clover-grass grown for $N_2$ fixation in organic crop rotations instead of mulching can lead to a better spatio-temporal allocation of nitrogen, allowing for an improved synchronization of N supply and crop N demand, especially in stockless farm systems, where mobile fertilizers are rare (Möller and Müller, 2012). Furthermore, by removing the clover-grass biomass from the field instead of mulching, $N_2$ fixation of legumes increases (Möller, 2009; Stinner et al., 2008) whereas N losses through $N_2O$ emissions are considerably reduced (Helmert et al., 2003; Möller and Stinner, 2009). Also, a significantly reduced weed infestation potential with diminished cultivation costs can be expected through the digestion of animal excrements and herbal biomasses that reduces weed germination capacity by up to 100% (Allan et al., 2003; Engeli et al., 1993; Šarapatka et al., 1993; Westerman et al., 2012a, 2012b). As the nitrogen efficiency increases, changes in the crop rotation may become feasible with the integration of a higher porportion of N-affine crops (Möller et al., 2008a) that typically generate higher market prices. No clear picture of positive or adverse effects on soil organic matter, plant health or soil life can be drawn from the literature due to inconsistent research results. Carbon supply may be either in- or decreased by anaerobic digestion (Möller, 2009; Möller et al., 2008a; Stinner et al., 2008). Earthworm populations and soil microbes might be affected, but not necessarily in a negative way (Ernst et al., 2008; Frøseth et al., 2014; Johansen et al., 2013). And the increased N availability can lead to crop lodging or increased infestation with N-affine weeds (Möller, 2009; Möller et al., 2008a; Stinner et al., 2008).

For a more detailed analysis of AD systems integrated into organic farm systems, displaying the various agronomic effects and further system implications, see also Siegmeier et al. (2015).