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EURAGR-25543; No. of Pages 12

ARTICLE IN PRESS

Europ. J. Agronomy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Effects of changing farm management and farm structure on energy balance and energy-use efficiency—A case study of organic and conventional farming systems in southern Germany

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ARTICLE INFO

Article history:
Received 8 January 2016
Received in revised form 3 June 2016
Accepted 6 June 2016
Available online xxx

Keywords:
Energy balance
Energy-use efficiency
Mixed farming
Arable farming
Agroforestry

ABSTRACT

Fossil energy input, energy output, and energy use- efficiency (EUE) are important indicators of the environmental effects, resource consumption and economic performance of farming systems. In this study, the energy balance (process analysis) and EUE of different organic and conventional farming systems – mixed farming, arable farming, and agroforestry (AGFS) systems – were analyzed due to their importance in Germany. The analysis was based on long-term experiments at the Scheyern Research Farm in southern Germany.

The results showed that the conversion from multi-structured organic mixed farming to a specialized organic arable farming system reduced the fossil energy input in crop production only marginally (from 5.9 to 5.5 GJ ha^{-1} yr^{-1}), but considerably decreased dry matter yield (from 5.4 to 2.5 Mg ha^{-1} yr^{-1}), energy output (from 99 to 46 GJ ha^{-1} yr^{-1}) and EUE (from 16.8 to 8.3). Improved management in the conventional arable farming system (with high-yielding varieties and better N management) reduced the energy input from 14.0 to 12.2 GJ ha^{-1} yr^{-1}, increased the energy output from 155 to 179 GJ ha^{-1} yr^{-1}, and elevated the EUE from 11.1 to 14.6. The establishment of AGFS with short rotation trees (without fertilization and pesticide use) led to the reduction of energy input.

Based on the results, we concluded that mixed farming is one of the best ways of producing food with high EUE under the conditions of organic farming. Therefore the conversion from organic mixed farming to an organic arable farming system is not recommended. Our AGFS results were from the first stage of a long-term experiment; it showed no negative effects on DM yield and energy output and positive effects on energy-use efficiency at this stage. However, further research is needed to know the long-term influence of AGFS.

1. Introduction

Modern farming systems are dependent on the input of fossil energy, which is consumed as “direct energy” (fuel and electricity used on the farm) and as “indirect energy” (energy input for the manufacture of machines, fertilizers, plant protection agents, etc.) (Hülsbergen et al., 2001). On a global scale, the input of fossil energy for the production of crops differs depending on the farming system. In some low-input arable farming systems, e.g. in large areas of Africa, the energy input of arable land is lower than 1 GJ ha^{-1}, whereas in some modern high-input farming systems in the USA and Western Europe, it can exceed 30 GJ ha^{-1} (Faidley, 1992; Pimentel, 2009). However, remarkable differences in energy input can also be found in developed countries (e.g. Germany), where examples of low-input systems (<10 GJ ha^{-1}) are extensive grassland (Haas et al., 2001) and organic arable farming (Schmid and Hülsbergen, 2015), and examples of high-input systems (>10 GJ ha^{-1}) are intensive conventional farming (Schmid and Hülsbergen, 2015), horticulture (Soode et al., 2015), and greenhouse cultivation (Soode et al., 2015).

Although agriculture produces a substantial and increasing amount of bioenergy (Dalgaard et al., 2001; Prabhakar and Elder, 2009; Börjesson and Tufvesson, 2011), it also consumes large quantities of fossil energy, which leads to the depletion of limited fossil resources. Furthermore, fossil energy input is highly related to emissions of air pollutants and greenhouse gases (i.e. CO_2 from the burning of fossil fuels) and is also an economic issue as the cost of energy is an important part of the expense of agricultural production (Erdal et al., 2007). Because nearly every step in today's production methods requires fossil energy input – from soil tillage

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http://dx.doi.org/10.1016/j.eja.2016.06.003
1161-0301/

Please cite this article in press as: Lin, H.-C., et al., Effects of changing farm management and farm structure on energy balance and energy-use efficiency—A case study of organic and conventional farming systems in southern Germany. Eur. J. Agron. (2016), http://dx.doi.org/10.1016/j.eja.2016.06.003

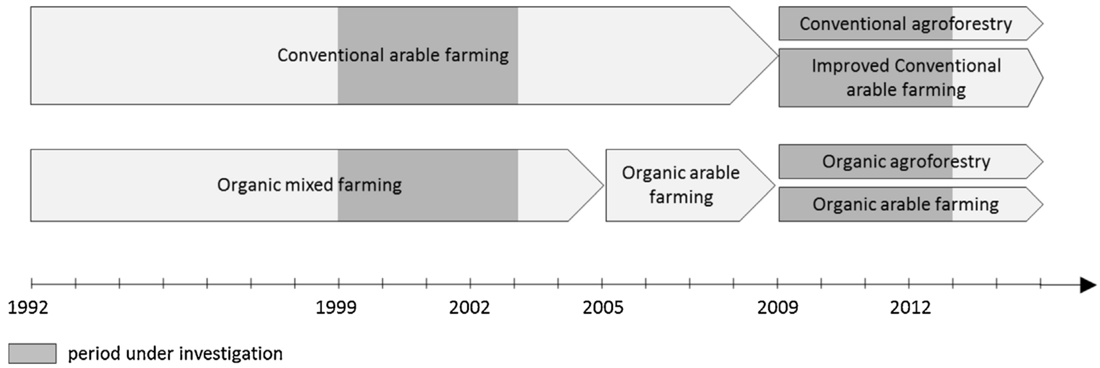

Fig. 1. The development of farming systems at Scheyern Research Farm.

and sowing, to fertilizing, crop protection, harvesting and the transport of agricultural products – fossil energy input is also a measure of the production intensity. In addition, energy input is the basis for a classification of high-input and low-input farming systems; it describes the degree of human intervention in agroecosystems in a simple way (Hülsbergen and Schmid, 2015). The energy input is also an indirect indicator reflecting the pressure of farm management on biodiversity and habitats: it negatively correlates to the amount of species on agricultural land (Herzog et al., 2013). Energy input, energy balance, and energy-use efficiency have been used as sustainability indicators for agriculture (Valtýniová and Křen, 2011; Altieri and Nicholls, 2012; Roy and Chan, 2012; Gaudino et al., 2014). The complex interactions between fossil energy input, crop yield, productivity and energy-use efficiency in plant production and the environment mean the study of agricultural energy balances is very important.

Numerous studies have analyzed the energy balance and energy-use efficiency of different organic and conventional farming systems (Sartori et al., 2005; Küstermann et al., 2008; Gelfand et al., 2010; Gomiero et al., 2011; Astier et al., 2014; Gaudino et al., 2014). The fossil energy input per hectare in conventional farming systems is higher compared to the input in organic farming systems as a result of the use of mineral nitrogen and synthetic chemical pesticides (Gomiero et al., 2011). However, if we consider the different yield level of organic and conventional systems and the energy input per unit of agricultural product, it is still unclear which system is more energy efficient (Gomiero et al., 2008, 2011). Furthermore, it is not enough to compare organic and conventional farming systems in general if we want to understand energy balances of farming systems. Management factors that influence the energy balance (e.g. farm structure such as crop rotation and livestock density (Schmid and Hülsbergen, 2015), production intensity such as input of mineral N and pesticides (Hülsbergen et al., 2002; Deike et al., 2008)) and new technologies, which can lead to a reduction of agricultural energy input and a higher energy-use efficiency (e.g. new machinery and precision farming (Gupta and Seth, 2007), high-yielding varieties (Parry and Hawkesford, 2010)), should be included.

At present, there are different trends with regards to changing farm structures and management in Germany and Western Europe: (1) the conversion from multi-structured organic mixed farming to specialized organic arable farming systems, partly associated with a reduction in crop diversity (Best, 2008; Konstantinidis, 2012; Vockinger, 2013; Hülsbergen and Rahmann, 2013; KTBL, 2015); (2) improved management in conventional arable farming systems e.g. new machinery, precision farming and high-yielding crop varieties (Hall and Dorai, 2010); and (3) the establishment of agroforestry systems (AGFS) for combined food and bioenergy production in both conventional and organic systems (Johann-Heinrich von Thünen-Institut, 2012; Smith et al., 2012; Nerlich et al., 2013). Agroforestry systems are multifunctional land use systems with trees incorporated into agricultural crop and/or animal production. The interaction between woody and non-woody components benefits these systems economically, ecologically, environmentally and socially (Reynolds et al., 2007; Jose, 2009), such as improving biodiversity conservation, air and water quality, and carbon sequestration (Jose, 2009). It has also been claimed to increase EUE of the systems (Smith et al., 2012). These changes will affect the farming (production) intensity, yield performance and energy-use efficiency of European agriculture in the long term but so far have not been studied thoroughly.

The Scheyern Research Farm in southern Germany enables the analysis and comparison of the energy balance and energy-use efficiency of different organic and conventional farming systems within one experimental farm and thus under comparable soil and climate conditions, using a unique long-term data set (Fig. 1).

This article analyzed data collected from Scheyern Research Farm from (1) 1999–2002, when an organic mixed farming system and a conventional arable farming system were running; the results of this period have been reported by Küstermann et al. (2008), and (2) 2009–2012, when the farming systems were converted to organic and conventional arable farming and agroforestry systems. The period 2009–2012 is also the first stage of a 20-year long-term agroforestry experiment. The effects of the change from organic mixed farming to organic arable farming and organic agroforestry, as well as from conventional arable farming to conventional agroforestry, can therefore be analyzed within Scheyern Research Farm.

The aim of this study is to quantify the effects of changing farm structure and farm management on energy balance and energy-use efficiency in different farming systems. To achieve this, this study (1) adapts the energetic process analysis method, which is used for energy balancing in arable and mixed farming systems by Küstermann et al. (2008), to agroforestry systems and (2) uses the data from Scheyern Research Farm to analyze and discuss the energy balance and energy-use efficiency of the change in the conventional and organic farming systems. The primary goal is to find ways of improving agricultural energy-use efficiency in a sustainable manner.

2. Methodology

2.1. Experimental site

Scheyern Research Farm is located in southern Germany, 40 km north of Munich (48°30.0′N, 11°20.7′E), 445–498 m above sea level in a hilly landscape. The soil type is characterized as loamy to sandy cambisols derived from tertiary sediments partly covered by loess (Schröder et al., 2002). The average annual precipitation and temperature are 887 mm and 8.3 °C, respectively (Deutscher Wetterdienst, 2012). No irrigation is used.

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