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# At the core of the socio-ecological transition: Agroecosystem energy fluxes in Austria 1830–2010

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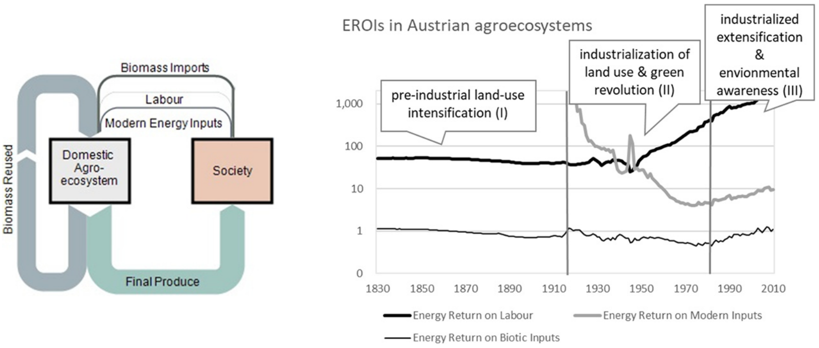
## HIGHLIGHTS

- We studied Austrian Agroecosystem Energy Returns on Investment for 1830–2010.
- Three distinct periods of land-use intensification are identified.
- Pre-industrial intensification: no modern energy inputs, EROIs slightly declined
- Industrialization: boosting modern inputs, EROIs declined except returns on labor
- Industrial extensification: less livestock, more wood, EROIs recovered

## GRAPHICAL ABSTRACT



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## ABSTRACT

Analyses of energy efficiency in biomass production offer important insights in the context of sustainable land management and biomass production. However, much of the previous research on the topic has focused on the energy efficiency of either food or energy provision. Only recently, comprehensive analyses at the total agroecosystem level have been operationalized, studying long-term change in agroecosystem energetics in the course of the socio-ecological transition. We contribute to this line of research by offering an empirical assessment of agroecosystem energetics for the case of Austria, covering the period 1830–2010 at an annual resolution. We present a quantitative assessment of energy inputs, outputs and internal energy fluxes of Austria's agroecosystem, including crop production, livestock production and forestry, as well as energy return on investment indicators. We identify three major periods: (1) "pre-industrial land-use intensification" (1830–1914) is characterized by moderate agricultural growth based on increased biomass recirculation, declining wood harvest, and, probably, slightly declining energy returns on investments. (2) From 1918 to 1985, "industrialization of land use and the green revolution" exhibits a substitution of labor by modern energy inputs, while livestock continued to rely greatly on domestic biomass. (3) "Industrialized extensification and environmental awareness" (1986–2010) features increasing energy efficiency due to declines in livestock numbers, a shift towards forestry, and a rising amount of final products from croplands at stable energy inputs. We discuss these periods in the context of changes in both ecological impacts and social metabolism, and identify trade-offs among food and bioenergy provision.

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## 1. Introduction

Biomass is an indispensable resource, both as food sustaining the endosomatic metabolism of humans, and as fuel and fiber supporting the exosomatic social metabolism (Gonzalez de Molina and Toledo, 2014; Steinberger et al., 2010). Despite persisting problems of undernourishment in some world regions, global biomass production has by and large kept pace with population growth throughout the past century (Krausmann et al., 2013) and enabled improvements in diets in many parts of the world (Kastner et al., 2012; Koning et al., 2008). The relevance of biomass as energy carrier on the other hand has declined globally since around 1950, due to increasing fossil fuel use (Fernandes et al., 2007). Future sustainable provision of biomass will face the challenge of meeting societal needs while complying with ecological constraints (Raworth, 2012). In this context, energy efficiency of biomass production plays a crucial role: Changes in energy supply are expected in the future both due to fossil fuel depletion (Mohr et al., 2015; Shafiee and Topal, 2009), and due to increasing biofuel demand for climate change mitigation purposes (IPCC, 2014). These changes pose double burdens on biomass production: not only will more biomass be needed for energy generation, but also will less fossil energy be available as input to produce biomass, i.e. the price of these inputs may increase. To understand the impact of changing energy use on biomass production, a sound understanding of energy efficiencies in biomass production is indispensable.

Energy efficiency in biomass production first attracted attention in the context of the oil price shocks in the 1970s, when the dependence of food production on fossil fuels was analyzed (Leach, 1976; Odum, 1973; Pimentel et al., 1973; Stanhill, 1974). Interest in energetic efficiencies of biomass production declined in the 1980s (Jones, 1989), but recently the topic gained attention again due to concerns over peak oil and global climate change (Arrieta et al., 2018; Hall, 2011; Pelletier et al., 2011; Pérez Neira et al., 2018). A major finding of studies on agricultural energetics was that increases in land productivity and food production in the course of the green revolution came at the expense of energetic efficiency, or declining energy returns on investments (EROIs) (Cleveland, 1995; Hatirli et al., 2005; Steinhart and Steinhart, 1974). More recent research has shown that efficiency gains in crop production have been achieved during later stages of the green revolution (Pellegrini and Fernández, 2018). However, results at the country or crop scales yield mixed results, identifying increasing efficiencies in some cases, and decreasing or stable efficiencies in others (Arizpe et al., 2011; Hamilton et al., 2013; Pracha and Volk, 2011).

The recent interest in energy efficiency of biomass production has not only addressed food, but even more so the production of biofuels. The major question here was “do biofuels provide significantly more energy than they require for production and processing?”. The answer to this question is usually yes, though energy returns are much lower than for fossil fuels (Farrell, 2006; Hammerschlag, 2006). According to a review by Solomon (2010), EROI values presented in different studies range between 1.1 and 1.65 for corn ethanol and 4.4 to 11 for cellulosic ethanol, with the exception of a study by Pimentel and Patzek (2005) who arrive at much less optimistic estimates. Differences in these results show the limited comparability of different assessments, owing to methodological and conceptual challenges in agroecosystem energy accounting related to system boundary choices (Atlason and Unnthorsson, 2014; Giampietro et al., 1992; Murphy et al., 2011).

So far, most research has focused on the energetic efficiency of biomass production for either food or energy provision. In order to explore the fundamental interrelations of energy efficiency and biomass provision for both food and energy, a more comprehensive approach is required. At the level of regional agroecosystems, a recent methodological proposal (Galán et al., 2016; Tello et al., 2016) enables to study long time periods in order to trace shifts from biotic to fossil energy carriers and their effects on land-use intensification strategies, i.e. the socio-ecological transition (Fischer-Kowalski and Haberl, 2007). A number of regional long-term case studies have applied this method (Cunfer et al., 2018; Gingrich et al., 2018b; Parcerisas and Dupras, 2018; Marco et al., 2018). They displayed that the shift towards fully industrialized agriculture was accompanied by both increasing external energy inputs and stable internal energy fluxes within the regional agroecosystem, mainly feed and litter (Gingrich et al., 2018a).

Comprehensive national-scale assessments of agroecosystem energy efficiency change have been conducted only for the cases of Spain (Guzmán et al., 2018) and, with a different accounting framework, France (Harchaoui and Chatzimpiros, 2018). Here we present a new national-scale assessment of agroecosystem energetics for the case of Austria over a 180-year period (1830–2010), covering the transition from a traditional organic to an industrialized land-use system of a Central European country. We advance agroecosystem energy accounting to trace the effects of both agricultural modernization and shifts in biomass production on agroecosystem energetics. Three periods of major land-use intensification strategies are identified and discussed against changes in ecosystem pressures and shifts in social metabolism, making use of extensive existing literature on Austria (e.g., Krausmann, 2001; Gingrich et al., 2016). Conclusions are drawn for future sustainable food and energy provision.

## 2. Methods, data and case study

### 2.1. Agroecosystem energy flows and their socio-ecological context

This study adopts the approach of socio-ecological metabolism and investigates biophysical exchange processes between society and the environment, as well as associated changes in environmental pressures (Gonzalez de Molina and Toledo, 2014; Haberl et al., 2006). The empirical core of this study is an analysis of annual national agroecosystem energy flows for the case of Austria in the period from 1830 to 2010. We quantify inputs to, outputs from and recycling fluxes within the national agroecosystem, defining the agroecosystem as the sum of all biomass production processes, i.e. crops, livestock products and wood. For the total agroecosystem we assess biomass reused within the agroecosystem and external (societal) energy inputs (Galán et al., 2016; Tello et al., 2016). The inputs to the agroecosystem are disaggregated into biomass, labor and modern energy inputs (Fig. 1a). In addition to this analysis of the agroecosystem as a whole, we decompose it into its three major components agricultural land, livestock and forest (Gingrich et al., 2018b), and quantify the amount of energy exchanged between them (Fig. 1b). By disaggregating different types of inputs and outputs, and changes in fluxes among the compartments of the agroecosystem, we are able to identify different intensification strategies through time.

Based on the different kinds of inputs displayed in Fig. 1a, we establish three energy efficiency indicators, or Energy Return on Investment (EROI) ratios:

$$\text{Energy Return on Modern Inputs (EROMI)} = \frac{\text{Final Produce}}{\text{Modern Energy Inputs}} = \frac{\text{Final Produce}}{(\text{Fuels} + \text{Fertilizers} + \text{Electricity})} \quad (1)$$

$$\text{Energy Return on Labor Inputs (EROLI)} = \frac{\text{Final Produce}}{\text{Labor Inputs}} \quad (2)$$

$$\text{Energy Return on Biotic Inputs (EROBI)} = \frac{\text{Final Produce}}{\text{Biotic Inputs}} = \frac{\text{Final Produce}}{(\text{Biomass Reused} + \text{Biomass Imports})} \quad (3)$$

EROMI (Eq. (1)) divides final produce (crops, wood, and livestock products; see definition below) by modern energy inputs from fuels and machinery use, fertilizer and electricity. This indicator is similar to that of studies on the fossil-fuel dependence of agriculture