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Application of partial order ranking to identify enhancement potentials for the provision of selected ecosystem services by different land use strategies

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ABSTRACT

Conventional agricultural practices have often been associated with negative externalities, such as land degradation, pollution of soil and water resources, loss of biodiversity, and decreased provision of ecosystem services (ES). In response to these negative effects, the number of indicator-based attempts to assess ES provided by land use systems has increased. However, decisions regarding the importance of the different ES are usually made subjectively. Following an objective approach through the use of a partial order ranking method, this study aimed to assess several non-provisioning ES supplied by alley cropping system (ACS) in comparison with conventional agriculture (CA). The main objective of the study was to verify the applicability of partial order ranking to an ecologically-based assessment, focusing on soil, water, and biodiversity indicators. Results from 40 hypothetical scenarios representing various site conditions of agricultural fields in Germany were calculated using the Ecosystem Services Assessment Tool for Agroforestry (ESAT-A), a toolbox designed to assess selected ES of ACS following an empirical approach. The results were ranked using partial order and were visualized by a Hasse diagram. The findings depict partial order ranking as a promising technique to support decision making in order to find priority scenarios and indicators where the provision of ES can be enhanced by establishing ACS. The minimal scenarios under CA identified with simultaneously low values of all indicators were perceived as target scenarios for establishing ACS. The values of the indicators for the current land use system need to be taken into account in order to avoid scenarios where high tradeoff was suggested. Additionally, this approach can be extended and utilized at the field level to aid farmer decisions on which land use strategy is the most suitable alternative to increase the provision of ES.

1. Introduction

Industrial agriculture has been widely acknowledged as a major contributor to global threats like climate change, land and water degradation, loss of biodiversity and ecosystem services (ES) (Foley et al., 2011; Matson et al., 1997; Tscharntke et al., 2012). Agricultural ecosystems are primarily managed to optimize provisioning ES, i.e., food, fiber, and fuel (Zhang et al., 2007), but in the production process they depend on a number of supporting and regulating ES, such as pollination, biological pest control, soil fertility, nutrient cycling and hydrological services (Power, 2010; Zhang et al., 2007). Attempts to maximize a single service often lead to a reduction in other services, also known as tradeoff (Rodríguez et al., 2006). The tradeoff between provisioning and non-provisioning ES under agricultural management has been recognized. According to Maes et al. (2012) provisioning services, i.e., crop and livestock, created tradeoffs with regulating ES, water provision and recreation on a European scale. Areas rich in agroecosystems essentially produced crops or livestock and were relatively poor in delivering other ES, while areas rich in forests or wetlands provided a wide array of ES (Maes et al., 2012). Similarly, Raudsepp-Hearne et al. (2010) reported of tradeoffs between provisioning ES on the one hand and regulating and supporting ES on the other hand, regarding tradeoff of ES bundles in Canada. In addition, the diversity of ES provision was positively correlated with regulating ES, suggesting that more multifunctional landscapes were better at providing regulating ES. However, appropriate management can ameliorate many of the negative impacts of agriculture while largely maintaining provisioning services; thus, regulating and cultural services in addition to provisioning services are supplied to human populations (Power, 2010). In this context, diversified farming systems e.g., conservation agriculture and agroforestry are better capable of delivering provisioning as well as non-provisioning ES (reviews by Kremen and Miles, 2012; Palm et al., 2014; Tsonkova et al., 2012).

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It was not until the threat of losing biodiversity and ES became imminent that their importance was globally recognized and efforts to assess ES have increased (e.g., MA, 2005). Assessments of ES, although driven by different objectives, commonly involve the use of indicators and mapping (Bastian et al., 2012, 2013; Burkhard et al., 2012; Koschke et al., 2012; Maes et al., 2012; Raudsepp-Hearne et al., 2010; Syrbe and Walz, 2012; Willemen et al., 2012). Mapping of different indicators also implies that single indicator maps are contemplated separately (e.g., Bastian et al., 2013; Maes et al., 2012; Nelson et al., 2009). A conventional solution is to assign a composite numerical score to each alternative in order to combine the information, which involves judgment, often arbitrary and controversial, about tradeoffs and substitutability among indicators (Patil and Taillie, 2004). In this context, multi-criteria decision analysis (MCDA) aimed at evaluating and choosing among alternatives based on multiple criteria is a useful tool in environmental decision making (Kiker et al., 2005). This method is also gaining importance in the study of ES. According to Fontana et al. (2013), MCDA is a suitable tool to illustrate in detail the consequences of land use change for ES provision. MCDA was applied by Karjalainen et al. (2013) to integrate ES into environmental impact assessment and Schwenk et al. (2012) to compare ES provided by different forest management alternatives.

Different alternatives described by multiple indicator sets can also be compared by partial order ranking (Brüggemann and Patil, 2011; Brüggemann et al., 2014; Sørensen et al., 2000). Partial order is considered to be a method that is based as far as possible on the data matrix alone (Brüggemann and Carlsen, 2011; Lerche et al., 2002); hence, its main advantage is the high degree of objectivity. The method has been applied widely in the environmental sciences, including assessing chemical pollution (Brüggemann et al., 2008) and water quality (Voyslavov et al., 2013) as well as ranking pesticides (de Loof et al., 2012), watershed health (Brüggemann and Patil, 2010) and polluted regions (Brüggemann et al., 2013). However, to our knowledge this method has not yet been applied in the context of ES assessment. The practical advantage of using partial order ranking to assess ES results from the ability to concurrently order alternatives, e.g., scenarios representing various site conditions with respect to multiple indicators based solely on their values. Thus, scenarios with minimal and maximal provision of ES can be objectively identified, which can assist decision makers in elaborating strategies to enhance ES provided by cultivated land. It was with this intention that the following assessment, including selected non-provisioning ES and land use systems, was conducted.

The aim of this study was to identify target scenarios where several non-provisioning ES could be enhanced through the establishment of agroforestry and to highlight the main influencing factors that determine the provision of ES under land use strategies.

2. Materials and methods

2.1. Assessment methodology

Before partial order ranking could be conducted, results for different land use systems and ES were to be produced. For calculating results, the Ecosystem Services Assessment Tool for Agroforestry (ESAT-A), a toolbox designed to facilitate the assessment of several ES by selected indicators, was used (Tsonkova et al., 2014). The tool requires easily accessible data as input and produces multiple indicators tied to selected non-provisioning ES related to soil, water, and biodiversity provided by conventional agriculture (CA) and a short rotation alley cropping system (ACS) (Fig. 1). ACS is a land use practice characterized by simultaneously growing conventional crops in alleys between stripes of fast growing trees. Accordingly, CA in this study is the current practice without integration of trees. The results obtained were afterwards evaluated using the method of partial order ranking via the application of selected modules of the software PyHasse, as shown in Fig. 1. The methodology is described below.

2.2. ESAT-A

2.2.1. Input

The required input data are related to descriptions of soil and climate, i.e., soil texture [-], soil organic carbon [%], precipitation [mm year^{-1}], temperature [°C], as well as the field management, e.g., crop rotation length of 20 years, fast growing tree species, rotation length of trees [year], yield [t ha^{-1} year^{-1}], and trees proportion [%] (Fig. 1). Dominati et al. (2010) distinguish between inherent soil properties derived from soil formation and manageable soil properties derived from active soil management. Inherent soil properties typically include slope, depth, and texture and cannot be readily changed without significant modification of the soil, while manageable soil properties typically include mineral nitrogen, organic matter content, or macroporosity (Dominati et al., 2010). Extending this distinction to include all site and management parameters that are required as input in Fig. 1, the influence of inherent properties and management can be accentuated.

Spatial data regarding soil texture, slope angle, soil organic carbon, groundwater level, precipitation, temperature and wind speed were derived from an official soil map of Germany (BGR, 2007), the German weather service (long-term average 1971–2000) and a digital elevation model of Germany. These data were used to devise scenarios representing plausible conditions for German agricultural lands. Raster maps with 1 km^2 grid cells were generated using the Conversion Tool in ArcMap10®. These maps were subsequently analyzed using the Spatial Analyst Tool in ArcMap10® to form regions with analogous characteristics. Forty scenarios covering typical site characteristics in Germany were used to calculate results for CA and ACS with 20% poplar trees (scenarios 1–40 and 41–80, respectively) (Table 1). The soil quality index, which is a measure of soil productivity in Germany, was used to differentiate between crop rotations at low, medium and high soil quality with increasing crop yield. A detailed overview of the input data is presented in Appendix S1.

2.2.2. Output

The output indicators were linked to the related ES as shown in Fig. 1. The indicator calculations were based on established algorithms and methods, i.e., carbon stock in soil was calculated according to Batjes (1996) and the effect of land management according to the method of humus balancing (VDLUFA, 2004); nutrient use efficiency (NUE) for nitrogen and phosphorus was assessed according to Adegbidi et al. (2001); erosion by water according to Schwertmann et al. (1989), erosion by wind according to Müller and Waldeck (2011); seepage rate according to Wessolek et al. (2004); nitrate concentration and phosphorus loss according to Feldwisch et al. (1998); plant diversity according to Marks et al. (1992); and plant protection products (PPP) were assessed according to their application over the total management period.

Each indicator was normalized to [0,1]-scale by $qn_i(x) = (q_i(x) - q_i min)/(q_i max - q_i min)$, $q_i min$ and $q_i max$ being the minimum and maximum values with respect to the indicators, defined in Tsonkova et al. (2014). Since it is desired to have the indicator value for erosion by water, erosion by wind, nitrate concentration, phosphorus loss, and PPP approaching the minimum value, the values of these indicators were reversed, so that the normalized value of 1 constantly indicated high provision. Accordingly, the outcome of ESAT-A, a normalized value between 0 and 1 indicating low to high provision of ES for each land use system and each