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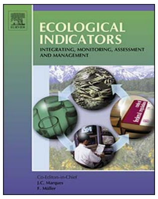

Research paper

Relationship between stoichiometry and ecosystem services: A case study of organic farming systems

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ABSTRACT

Over the past five decades, the delivery of global Ecosystem Services (ES) has diminished and this has been driven partly by anthropogenic activities. Agro-ecosystems cover almost 40% of the terrestrial surface on Earth, and have been considered as one of the most significant ecological experiments with a potential to both contribute to and mitigate global ES loss. In the present study, six different ES (food and fodder production, carbon sequestration, biological pest control, soil water storage, nitrogen regulation and soil formation) were quantified in various organic farming systems and the hypothesis that there is a link between these ES and C:N, C:O and H:O stoichiometric ratios in farming systems was experimentally tested. The results show that different ES are correlated with the stoichiometric ratios to different extents. There are significant positive linear correlations between C:N stoichiometric ratios and all measured ES in the investigated organic farming systems, while not all the ES are correlated with the C:O and H:O ratios. This study has expanded the horizons of stoichiometry by linking a fundamental chemical property of molecules with an emergent property of organic farming systems, namely their ecosystem service provision.

1. Introduction

There is compelling evidence that over the last 50 years, humans have changed ecosystems more rapidly than in any earlier period of time of human history, and the current consumption of natural resources results in global Ecosystem Service (ES) degradation (MEA, 2005). Global ES have been depleted mainly due to the anthropogenic alterations of ecosystems to meet the rapidly growing demands of food, fibre and fuel mainly provided by agro-ecosystems (Tilman et al., 2002; MEA, 2005; Pretty, 2013). Agro-ecosystems are the dominant form of land management and have been considered as the largest ecological experiment on Earth not only with a great potential to reduce ES but also to enhance them (Porter et al., 2009; FAOSTAT, 2014). Various ES have been identified, classified, and quantified in agro-ecosystems at different spatial scales including those at local (Porter et al., 2009; Ghaley et al., 2014; Fan et al., 2016), regional (Sandhu et al., 2008; Alam et al., 2014; Dominati et al., 2014), and global scales (Costanza et al., 2014; Sandhu et al., 2015). The big challenge for agro-ecosystems is to obtain a high level of food and fodder production whilst minimizing environmental damage and perhaps contributing positively to ES provision (Tilman et al., 2002). Diminishing global ES have been related to anthropogenic activities such as land-use changes, vegetation coverage and field management practices (Vitousek, 1994; Friedel, 2011; Duncker et al., 2012; Fan et al., 2016). Anthropogenic activities have also altered the fluxes of multiple chemical elements such as carbon (C), nitrogen (N), phosphorus (P), Oxygen (O), Hydrogen (H) and their ratios, or stoichiometry, within ecosystems. Stoichiometry is the study of the molecular balance in chemical substances, such as seawater – an important finding in ecological stoichiometry was the discovery of the Redfield stoichiometric ratio of 106C:16N:1P (Redfield, 1958) in planktonic biomass and that this was very close to the C:N:P ratio of marine water.

Stoichiometric ratios in ecological interactions and processes can provide fundamental insights into these systems and help to unravel biogeochemical cycling in ecosystems (Sterner and Elser, 2002). Studies show how anthropogenic activities strongly influence ecosystem functions via alteration of stoichiometry within them; Li et al. (2016) demonstrated that soil C, N, and P stocks induced by land use changes caused perturbation of an ecosystem, Bai et al. (2012) presented that long term grazing altered the stoichiometry of steppe ecosystems, resulting in altered ecosystem functions and Ptacnik et al. (2005) showed the impact on agricultural and coastal ecosystem functions as a result of

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stoichiometric changes in Mississippi River watershed and the northern Gulf of Mexico. Such alternations in ecosystem functions influenced ES. Therefore, stoichiometry can be considered as a relevant and hypothesis generating approach for management of human impact on ES. Ghaley et al. (2015) observed C:N and C:O stoichiometric ratios under three agricultural production systems (intensively managed conventional wheat system, combined food and energy (CFE) system, and old beech forest system) and presented that C:N and C:O stoichiometries have positive correlations with regulating, supporting ES, but negative relationship with provisioning ES. An alternative, but perhaps connected, explanation of these results would be that alternations of C:N, C:O ratio might change the ecosystem structure and function which, in turn affects ES. C and N are the fundamental indicators of biogeochemical cycles in ecosystems, and alterations of C:N stoichiometry in an agroecosystem might affect primary production, nutrient cycling, plant community composition and plant-herbivore interactions (Sterner and Elser, 2002; Sitters et al., 2013). The causal link and argument is that C, O, and H constitute different important organic compounds in agroecosystems and play significant roles in their metabolism. C:O and H:O ratios are associated with growth and maintenance respiration processes and these ratios capture the state of chemical oxidation or reduction in agro-ecosystem. With agro-ecosystem evolution from an annual arable system to a perennial 150 year old forest, the C:O and H:O ratio increased, indicating that carbon and hydrogen element use efficiency decreases probably because forests are more chemically reduced than an arable system. Such results can be explained when complex molecules like starch ($C_6H_{10}O_5$ = C:O and H:O is 1.2:1 and 2:1, respectively), cellulose ($C_9H_{10}O_2$ − C:O and H:O ratios is 4.5:1 and 5:1, respectively), linoleic acid ($C_{18}H_{32}O_2$ − C:O and H:O ratios is 9:1 and 16:1, respectively) are formed from the primary product of photosynthesis-glucose CH_2O (C:O and H:O ratios is 1:1 and 2:1 respectively) by metabolism and its costs via associated growth and maintenance respiration leading to the loss of two atoms of oxygen for each atom of carbon − as CO_2. Thus, as ecosystems become more 'mature' the C:O and H:O stoichiometries move in the direction of more C and H per unit O.

There is a large body of research that discusses the stoichiometric ratios in forest, grassland systems, but there is little study presenting the C:N, C:O and H:O stoichiometries in agricultural systems. Although the results of Ghaley et al. (2015) demonstrated an empirical link between ES and carbon stoichiometry, these findings were general and these results were only based on a small data set (three production systems). The relationship between stoichiometry and each individual ES in his study has not been elucidated. Therefore, further studies are needed to test these relationships.

Over the last 30 years, the number of organic farms, the organic land area, the market trade of organic food and the amount of research funding of organic farming have continuously increased globally (Reganold and Wachter, 2016). The organic area of the EU-28 accounted for 25 percent of the world's organic area, and the retail sales of the EU-28 contributed to 36 percent of the world retail sales in 2015 (Willer and Lernoud, 2017). Denmark has a long tradition of supporting organic products and has the highest organic share of the market in the world (DST, 2015; Willer and Lernoud, 2017). Although organic farming plays an increasingly more important role in EU and Danish agroecosystems, only a few of the studies quantify the ES in organic farming systems (Sandhu et al., 2008; Porter et al., 2009; Fan et al., 2016).

The objectives of this study are, using organic farming systems as a case to 1) quantify the different ES in various organic farming systems with different crop types and management practices; 2) measure the C:N, C:O and H:O stoichiometries in these organic farming systems; 3) explore the relationship between C:N, C:O and H:O stoichiometries and each individual ES. The following hypotheses are proposed: 1) different organic farming systems have different C:N, C:O and H:O stoichiometries and provide different quantities of ES and 2) organic farming systems with high C:N, C:O and O:H stoichiometries have higher ES provisions.

2. Materials and methods

2.1. Study sites

In order to achieve the objectives, twenty eight organic farming systems in Denmark distributed on Zealand and Jutland including in 1) five organic winter rye fields in Lejre (55°36′N, 12°01′) with different conversion years, 2) fifteen experimental fields comprised of four types of crops (winter wheat, spring barley, ryegrass, and oats) in Taastrup (55°40′N, 12°18′E), and 3) ten ryegrass experimental field plots in Foulum (9°34′E, 56°29′N) were investigated to assess their ES and C:N, C:O and H:O stoichiometric ratios.

2.1.1. Winter rye fields in lejre

The five winter rye fields were selected based on an overview of all organic farms in Denmark. These five fields were selected to provide the widest range of years since conversion to organic farming but having the same climatic conditions as well as soil type. Four organic winter rye fields were converted in 1956, 1999, 2004 and 2013, referred to as 56, 15, 10, 1 year old winter rye, respectively. The four organic winter rye fields were managed by three farmers who are neighbours in Lejre. Thus, the field management practices were similar between these fields as they have the same agricultural consultant. More information on these fields can be found in Table 1. One conventional winter rye field was included as a control.

2.1.2. Organic fields in taastrup

Twelve experimental fields located in Taastrup, managed by University of Copenhagen, converted to organic farming in 1999 were investigated. These twelve fields grew four types of cereal crops (spring barley, ryegrass mixed with clover, spring oat, and winter wheat) with three different field management treatments. These three treatments were 1) harvested the grain and removed the straw from the fields (referred as no input) 2) harvested the grain and incorporated the straw into soil (referred as straw incorporation) and 3) not only harvested the grain and incorporated the straw into soil, but also applied additional animal manure to cereal crops (referred as straw +manure). Spring barley, oat and winter wheat received 90, 20 and 150 kg N ha^{-1} in pig or cattle slurry every year. More information about these fields can be found in Table 1.

2.1.3. Organic grass production systems in foulum

Ten organic grass production systems located at Foulumgaard, managed by Aarhus University were converted to organic fields in 1987 when a mixed six-year rotation replaced cereal cropping (Eriksen et al., 2004). In 2011/2012, three plots in the mixed six year rotation fields (undersown barley −four years of ryegrass clover-barley) were prepared with three nitrogen levels (0, 100, and 200) by applying cattle slurry. Half cattle slurry was injected into the soil in April, and another half was applied following a grass harvest in late May. Thus, in 2015 (the sampling year), the 1–3 year-old grasslands with three nitrogen treatments were established. These plots were referred to as 1 year old ryegrass clover, 2 year old ryegrass clover, and three year old ryegrass clover, and referred nitrogen as N0, N100 and N200. Furthermore, permanent grassland (22-year old) cultivated with perennial ryegrass and clover adjacent to the organic grassland was taken as reference. No animals were grazed in permanent grassland and grass has been mowed four times per year since 2011, more information can be found in Table 1.

2.2. Field sampling

In order to monitor ES and measure their stoichiometries in all the

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