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Changes in soil phosphorus forms through time in perennial versus annual agroecosystems

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ABSTRACT

We compared inorganic and organic P fractions to a soil depth of 92 cm in two long-term Classical Experiments at Rothamsted Research in the U.K. The predominant soil-forming factor that differentiated the sites was vegetation type. The Broadbalk plots feature annual wheat and have been in continuous production since 1843, while the Park Grass plots feature perennial grassland vegetation that has been hayed every year since 1856. To evaluate the long-term effects of annual versus perennial vegetation on soil P forms, we carried out Hedley P fractionations and microbial biomass-P fumigation-extraction analyses on soils from fertilized and unfertilized treatments of both experiments. In both P-fertilized and unfertilized soils we found an inverse relationship between pool sizes of actively cycling Po (0.5 M bicarbonate + 0.1 M NaOH fractions) and recalcitrant Pi (hot conc. HCl + final digest fractions) with Po dominant in the perennial hay meadow and recalcitrant Pi dominant in the annual wheat. Microbial biomass-P in the surface horizons of fertilized and unfertilized perennial hay meadow was an order of magnitude greater than in annual wheat. To investigate how P fractions changed through time we conducted Hedley P fractionations on archived soils sampled from Broadbalk wheat in 1893, and Park Grass hay meadow in 1876. Since 1893, unfertilized Broadbalk soils experienced almost no change in P fractions in the surface 23 cm, but substantial depletion in labile and recalcitrant Pi and Po in deeper strata. The Park Grass perennial vegetation showed greater depletion of surface soil fractions over time. When fertilized for over 100 years, almost all P fractions in the surface 23 cm were enriched in both crop types, but below 70 cm, only the active Po pool in Park Grass showed a substantial increase under fertilization. Even when fertilized, low available or occluded Pi fractions in both annual and perennial systems were substantially depleted below 70 cm. Our findings suggest that herbaceous perennials maintain a greater proportion of native or fertilizer-P in relatively available organic forms compared to annual wheat. By reducing the fraction of P held in recalcitrant forms, P fertilizer requirements could be reduced

1. Introduction

Annual crops grown largely in monocultures occupy approximately 85% of harvested area globally (Monfreda et al., 2008). There is increasing interest in how the development of perennial crops could deliver a wide range of ecosystem services relative to annual counterparts (Jordan et al., 2007; Glover et al., 2010a). Herbaceous perennial biofuel and forage crops have been shown to maintain very low rates of soil erosion and high efficiencies of soil water and nutrient uptake (Randall et al., 1997; Jordan et al., 2007). The greater proliferation and activities of roots in time and space clearly account for some of the improved ecosystem functions measured under perennials. However, research belowground, comparing microbial dynamics and other aspects of soil ecology is beginning to reveal a far more complex set of differences underlying soil–plant interactions in perennial and annual crop species (Glover et al., 2010b; Culman et al., 2010).

Ecologists have long recognized the regulating role that the element phosphorus has on aquatic and terrestrial ecosystems (Schindler, 1977; Cole and Heil, 1981; Schindler et al., 2008). In part its notable role among rock-derived nutrients is due to its low natural abundance in the lithosphere relative to requirements by vascular plants (Vitousek et al., 2010). Its low availability can also be attributed to its complex chemical behavior in soils where it commonly becomes bound or immobilized for short as well as long durations in a wide range of inorganic and organic compounds (Turner et al., 2007; Syers et al., 2008). The total and relative amounts of these compounds that are found in a soil is to a large extent driven by the interaction of Jenny's five soil forming factors (Jenny, 1941): parent material, topography, organisms, climate, and time since primary or secondary succession began (Crews et al., 1995; Wardle et al., 2004; Selmants and Hart, 2010). Pioneering

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plant species in early ecosystem development are thought to rely to a large extent on limited pools of labile inorganic P (Pi) as the pools of organic P (Po) just begin to aggrade (Wardle et al., 2004; Turner et al., 2007). But with time, the vegetation shifts reliance to cycling organic forms of soil P until late in soil development, the reliance on Po is close to complete (Crews et al., 1995; Turner et al., 2007).

In contrast to native ecosystems, modern agricultural crops rely primarily on inorganic forms of P, much of which is added as fertilizer, to balance intentional and unintentional P losses from soils (Mattingly, 1975; Syers et al., 2008). Early work to understand how to re-supply stocks of labile soil P using first acidified bones, and then apatite ores was carried out by John Lawes and Joseph Gilbert at Rothamsed Research Station in the mid 19th century. This work, which in some respects field-tested Liebig's law of the minimum (Liebig 1840), laid the groundwork for widespread adoption of "open" agroecosystems involving applications of inorganic fertilizer to balance intentional phosphorus exports in food and unintentional exports in erosion and leaching. While largely successful at balancing P exports, there is increasing recognition that the phosphorus ores that we have come to rely on (easily obtainable, high quality, affordable) are being depleted rapidly and permanently (Liu et al., 2008; Cordell et al., 2009; Gilbert, 2009).

The road to achieving phosphorus sustainability in agriculture will involve addressing intentional and unintentional losses from farms, as well as optimizing crop uptake of the soil P resource. Intentional loses mainly consist of the export of P in grains, fruits, meats or other plant or animal biomass that is harvested from farms and ranches. Grazing livestock on pasturelands, as well as cycling manures back to farmlands, or extracting and reusing the P from livestock and human excrement will be necessary to close the P cycle (Tweed, 2009; Elser and Bennett, 2011). Unintentional losses occur as dissolved and particulate loses in soil surface runoff as well as leaching. Work on minimum or no-till systems and cover crops illustrate the range of strategies being pursued to reduce unintentional loses. Work to improve crop P uptake efficiencies ranges from greater reliance on mycorrhizal symbioses, to genetically engineering crops to access less soluble pools of soil inorganic P (Gaxiola et al., 2011).

Perennial crops, whether for pasture, bioenergy or grain production, have the potential to address two of the three P sustainability challenges above—unintentional loses and crop uptake optimization. Maintaining perennial cover on the soil, and roots that actively take up nutrients in time and space can profoundly reduce unintentional losses (Montgomery, 2007).

It has been know for some time that cultivation reduces overall soil Po contents (Sharpley and Smith, 1983; Harrison, 1987). But only a limited amount of research to date has suggested that soils under perennial vegetation maintain greater pools of labile Po relative to less soluble pools of Pi compared to annual cropping systems (Sharpley and Smith, 1985; Daroub et al., 2001). In this paper, we explore further how the soil phosphorus pools developed under perennial crops differ from those of annual crops, and whether these differences suggest new possibilities for improved crop P uptake efficiencies. Specifically, in some of the same plots that Lawes and Gilbert first tested the role of inorganic phosphate in crop nutrition at Rothamsted, we set out to compare how forms and distribution of P had changed after more than a century of cropping annual wheat and perennial hay crops. The majority of soil P fractionation studies have focused on the upper 15–20 cm of soil (Cross and Schlesinger, 1995; Negassa and Leinweber, 2009) but here we chose to examine extant and archived soil samples to a depth of 92 cm with the expectation that important differences between perennial and annual crops may penetrate deep in the soil profile.

2. Methods

2.1. Study location selection

The Broadbalk continuous wheat and Park Grass hay meadow Classical experiments at Rothamsted Research were selected as sites for this study for two reasons. First, the close proximity of the two long term experiments afforded a unique opportunity to hold constant all but one of the five factors of soil formation described by Hans Jenny (1941) in order to compare the P economies of annual and perennial cropping systems. Essentially, the "organism" factor was varied (annual wheat and perennial hay meadow), while the factors of climate, topography, parent material and time were held largely constant.

Second, the historical continuity of land use in the Broadbalk and Park grass experiments made possible a comparison of soils that had either attained or were close to attaining equilibrium in soil organic matter (SOM) production and decomposition (Johnston et al., 2009). Indeed, both Park Grass and Broadbalk were farmed for hay and field crops, respectively, for 100+ years before the experiments were initiated. This continuity instills a good degree of confidence that SOM was in approximate equilibrium when the archived soils were sampled (see below). The SOM equilibrium of the Classical experiments was critical since our objective was to compare soil P fractions of specific crop growth forms, not soil P fractions of a transitional state between two different crop growth forms.

2.1.1. Broadbalk continuous wheat

The Broadbalk continuous wheat experiment was initiated in 1843 by Sir John Bennet Lawes and Sir Joseph Henry Gilbert specifically to study the relationship between a range of seemingly biologically important inorganic elements, including phosphorus, as well as farmyard manure on crop yields (Rothamsted Staff, 2006). Today the experiment consists of a partial factorial design of 20 nutrient addition treatments. Lime has been applied to the fields intermittently since 1950 to prevent acidity from limiting production. The Broadbalk site had been in arable cropping before the experiment began, and probably for many centuries (Rothamsted Staff, 2006). At the time of our soil sampling, Broadbalk had been planted to annual winter wheat 165 times. There were ten changes in wheat varieties over that period, but throughout the duration, all yield weights were carefully recorded, and periodic soil samples were taken and archived.

2.1.2. Park Grass perennial hay meadow

Approximately 0.5 km from Broadbalk is the Park Grass hay meadow experiment that was initiated in 1856 on a site that had previously been under grass for several centuries (Lawes and Gilbert 1880). When we sampled soils, annual aboveground net primary productivity from the experimental treatments had been measured and exported off site 153 times. As with Broadbalk, periodic soil samples were taken from the majority of treatments at Park Grass and archived. The plant community is comprised of mainly perennial grasses and forbs, with the grasses *Agrostis capillaries*, *Festuca rubra* being the most dominant. Nutrient treatments are very similar to those established at Broadbalk, but in 1903 they were divided into subplots and received different lime additions. The 98 different nutrient and lime combinations applied to Park Grass strongly influence plant diversity at the plot scale with total number of species ranging from 3 to 39 (Rothamsted Staff, 2006). Hay has been cut, weighed and removed in June or July since the experiment began. From 1856 to 1874 post harvest re-growth was typically grazed by sheep, whereas from 1875 on, a second cutting was made, weighed and removed in the fall.