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A new detailed map of total phosphorus stocks in Australian soil

Raphael A. Viscarra Rossel, Elisabeth N. Bui *

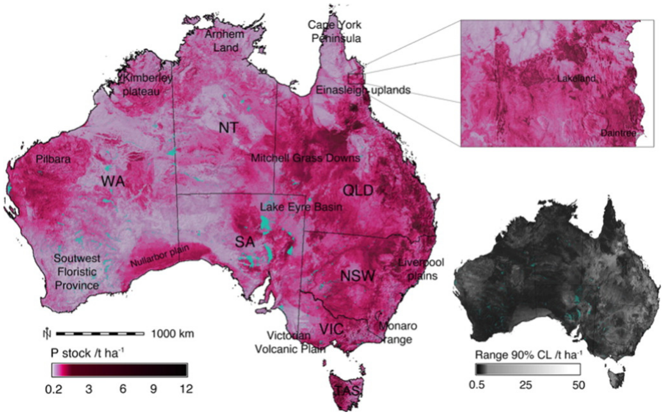
CSIRO Land and Water, PO Box 1666, Canberra, Australian Capital Territory 2601, Australia

HIGHLIGHTS

- We model and map total soil phosphorus stocks over Australia.
- Statistical uncertainty is reported.
- Spatial pattern of total soil phosphorus reflects lithology and weathering.
- Basalt-derived soils have the largest total soil phosphorus stocks.
- Lake Eyre Basin has a surprisingly high level of soil phosphorus.

GRAPHICAL ABSTRACT

Map of soil P stocks in the 0–30 cm layer across Australia and its uncertainty presented as the 90% confidence limits of the predictions. The inset shows the detail achieved by the fine spatial resolution (90 × 90 m pixels) mapping. Lakes are shown in blue. The map can be downloaded from https://data.csiro.au/dap/



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ABSTRACT

Accurate data are needed to effectively monitor environmental condition, and develop sound policies to plan for the future. Globally, current estimates of soil total phosphorus (P) stocks are very uncertain because they are derived from sparse data, with large gaps over many areas of the Earth. Here, we derive spatially explicit estimates, and their uncertainty, of the distribution and stock of total P in Australian soil. Data from several sources were harmonized to produce the most comprehensive inventory of total P in soil of the continent. They were used to produce fine spatial resolution continental maps of total P in six depth layers by combining the bootstrap, a decision tree with piecewise regression on environmental variables and geostatistical modelling of residuals. Values of percent total P were predicted at the nodes of a 3-arcsecond (approximately 90 m) grid and mapped together with their uncertainties. We combined these predictions with those for bulk density and mapped the total soil P stock in the 0–30 cm layer over the whole of Australia. The average amount of P in Australian topsoil is estimated to be 0.98 t ha^{-1} with 90% confidence limits of 0.2 and 4.2 t ha^{-1}. The total stock of P in the 0–30 cm layer of soil for the continent is 0.91 Gt with 90% confidence limits of 0.19 and 3.9 Gt. The estimates are the most reliable approximation of the stock of total P in Australian soil to date. They could help improve ecological models, guide the formulation of policy around food and water security, biodiversity and conservation, inform future sampling for inventory, guide the design of monitoring networks, and provide a benchmark against which to assess the impact of changes in land cover, land use and management and climate on soil P stocks and water quality in Australia.

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* Corresponding author.
E-mail address: elisabeth.bui@csiro.au (E.N. Bui).

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1. Introduction

Phosphorus (P) is essential for all living organisms; it is present in all living cells (nucleic acids, adenosine triphosphate (ATP), and phospholipids that form cell membranes), and animal bones. “P is the master element” that regulates the other biogeochemical cycles (Redfield, 1958). It is ecologically significant and underpins our ability to produce food (Vitousek et al., 2010). Replenishing the fertility of soil that has been stripped of its P and other vital nutrients is a primary requirement for increasing food production and reducing global food insecurity (Cordell et al., 2009).

Its source is almost entirely geological, from rocks and volcanic ash, and all life depends on its release during weathering and soil formation. During pedogenesis, the rock-bound P pool decreases and P enters soil, plant, microbial, and aqueous pools, where it is incorporated into organic compounds. Eolian accession (Chadwick et al., 1999) and tectonic uplift and erosion (Porder et al., 2007) replenish soil P in places. During long-term ecosystem development, the biological P pool grows at the expense of the mineral one and eventually microbes become the largest biological pool of P in soil (Turner et al., 2013). Over long periods (~10^6 years), levels of mineral P can decrease drastically so that primary productivity and plant biomass decrease causing ecosystem retrogression (Wardle et al., 2004; Zemunik et al., 2015). That is, as soil ages the biological P pool in ecosystems becomes limiting and plants and saprotrophic organisms compete for P (Turner et al., 2013). In the southern hemisphere, where landscapes have been exposed to weathering and leaching for millions of years without being rejuvenated by glaciation, large expanses of soils contain small concentrations of total P (Hopper, 2009). For example, most Australian soil contains little P and variations are primarily due to different lithologies.

Historically, farmers around the world have relied on natural soil P to grow food, however increased famine and soil degradation have led to a search for mineable sources of P fertilizers, including P rock and guano. Over the last half century, the widespread use of fertilizers contributed to increased crop yields and to reducing hunger. Whilst Australian agricultural soil is naturally P-deficient, we have agricultural export commodities that need significant amounts of P to maintain production. But mineable resources of P globally are limited and the notion of ‘peak P’ and its socio-political consequences are receiving increasing attention (Elser and Bennett, 2011; Obersteiner et al., 2013).

After fertilizer is applied, P (and nitrogen (N)) unused by biota can enter streams and promote eutrophication of receiving water bodies (Conley et al., 2009), although algal blooms in Australia also occur naturally when P adsorbed on sediments is re-mobilized (Donnelly et al., 1997). Phosphorus is a stable element, which binds readily with soil minerals. It is mainly lost from the soil by erosion when P laden soil particles are eroded by wind or water. Phosphorus and N pollution from gully erosion and agricultural runoff is a major threat to the long-term health of the Great Barrier Reef and its fringing lagoons (Mallela et al., 2013).

In Australia, where plant communities have evolved in relatively P-poor soil, excess P from agricultural fertilizers can also impact native terrestrial biodiversity. Recruitment from seeds of native species diminishes in soil with greater P concentrations (Specht, 1963; Heddle and Specht, 1975) and this promotes invasion by exotic plant species (e.g. Morgan, 1998; Fisher et al., 2006). Landscape restoration trials that tried to re-establish native vegetation have sometimes failed because of excessive amounts of residual soil P (and N) from fertilization in agriculture (e.g. Prober and Wiehl, 2012).

Knowing the spatial distribution of soil P is important because it enables the evaluation of ecosystem and agricultural productivity, environmental quality, and the management of biodiversity. Here we present a new map of total soil P stock, in the 0–30 cm layer, over Australia and briefly describe the data-driven spatial modelling used to produce it. The new map and that of its uncertainty, is more detailed (3-arcsecond or approximately 90-m grid resolution) and more reliable than previous ones (Fig. 1). We evaluate the spatial variability in soil P stock across Australian landscapes and derive estimates of the mean and total stock and their uncertainties for Australia, its states and territories. We also evaluate the contribution of environmental predictors used in the modelling, which are proxies for the factors of soil formation and discuss our results with respect to other datasets that were not used in the modelling, namely the Australian soil orders (Isbell, 2002), major vegetation groups in the National Vegetation Information System (NVIS) (Department of the Environment and Water Resources, 2007) and land use (ABARES, 2010), and how they reflect the variability in soil P stock.

2. Materials and methods

2.1. Total P inventory

The total P data came from a national collation of soil data made by the Soil and Landscape Grid of Australia project (Grundy et al., in press). The dataset contains site data that were held in government agencies of the Australian states and territories and CSIRO, and spectroscopic estimates of total P made with the national soil visible–near infrared database (Viscarra Rossel and Webster, 2011) on soil samples collected for the National Geochemical Survey of Australia (NGSA) (de Caritat and Cooper, 2011). The site data comprised soil that was collected mostly from agricultural regions, and analysed using primarily X-ray fluorescence but also other methods, between 1970 and 2013. At each NGSA site, samples were collected and bulked to produce two specimens from within two depth layers, 0–10 cm and 60–80 cm (de Caritat and Cooper, 2011). The spectroscopic measurements were made on the fine earth fraction (<2 mm) of these samples, and we used data from 1315 sites.

The combined dataset represents soil from all states and continental territories of Australia, all soil orders present in the Australian Soil Classification (Isbell, 2002), all climatic and bioregions, and all classes of land use (ABARES, 2010).

2.2. Three-dimensional spatial modelling of total P and its uncertainty

The methods used for the three-dimensional spatial modelling of soil attributes at six depth layers, 0–5, 5–15, 15–30, 30–60, 60–100 and 100–200 cm, are described in Viscarra Rossel et al. (in press). The maps conform to the specifications of the *GlobalSoilMap* project (Arrouays et al., 2014) and are Australia's contribution to that project (Grundy et al., in press). Below we provide only a summary, describing the mapping of total soil P and its uncertainty.

Phosphorus in soil varies with depth and is the outcome of climatic, biotic, and landscape processes interacting over time on parent material. Some of these environmental factors are easier to observe and measure than the soil itself, so that these data can serve as surrogates from which to predict soil P. For example, remote sensors can measure and record reflectance and emissions from vegetation and soil, a digital elevation model can be used to provide topographic representations of the landscape, derive terrain attributes, and drainage structure. Thus, a model was set up for total soil P using the machine-learning algorithm Cubist (Quinlan, 1992), at the sites and depths for which there were data. To account for the covariation of the soil data within the profile, data from the centre point of each of the six standard layers were used as a dependent continuous variable in the model. Thus, the model could be used to predict elsewhere in Australia in the lateral and vertical dimensions. The environmental variables used as predictors are listed in Table S1 (Supplementary material).

Cubist partitions the response data into subsets within which their characteristics are similar with respect to the predictors. A series of rules derived using *if* and *else* defines the partitions, and these rules are arranged in a hierarchy. A condition may be a simple one based on one predictor or, more often, it comprises several. If a condition is

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