A pedometric approach to valuing the soil resource

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ABSTRACT: This paper presents an approach to valuation of the soil resource, using pedometric techniques. This value is broken down by soil functions which provide services, classified as (1) supporting; (2) production, (3) regulating; (4) cultural. For each the value can in principle be assessed quantifying the functions, enumerating and quantifying soil properties relevant to the function, and applying a quantitative model of the functions as affected by the properties. In practice this is approximated by a subset of functions and simple models. This procedure faces some complications, notably finding a common measure of value; disentangling the concepts of 'soil' and 'land'; discounting the future; and combining valuations of individual services into a common value.

1 INTRODUCTION

Soil forms the thin skin of the Earth, and is the site of all terrestrial transformations and fluxes. It forms the substrate for most activities which take place at the Earth's surface, including food production, living space and near-surface extraction. Further, it is a limited resource, which can be degraded or even destroyed. Clearly, soil is "valuable" in the common usage of the word, namely "of great price or worth", and so it should be possible to value it, i.e., perform a valuation.

Pedometrics is the application of mathematical and statistical methods to the study of the distribution and genesis of soils. It is stretching this definition to propose a "pedometric valuation"; however, from the spirit and practice of pedometrics one can extract the concepts of soil as the object of study, and quantifying under uncertainty, to justify our title. The role of pedometrics is perhaps less to value and more to quantify whatever valuation measure is chosen. Digital soil mapping, as the pedometric approach to a spatial representation of soil properties and functions, should then be a basis for pedometric valuation.

2 CONCEPTS OF VALUE AND VALUATION

In the ecological economics community "value" has a broad meaning: "the contribution of an action or object to user-specified goals, objectives or conditions" (Farber et al. 2002). This is a human-centred definition, where an attempt is made to place some measure, often expressed as financial value, on ecosystems so that systems with equal "value" have comparable effects on human well-being, as defined by humans and with their discounting of the future in favour of the present; this is the process of *valuation*. This does not imply that there is no intrinsic worth for the terrestrial ecosystem absent humans, only that this philosophical position is not operational. Spiritual, social and cultural values are presumed to be translated to a common measuring unit by assessing a willingness to pay (WTP) for the service, or willingness to accept (WTA) compensation for loss of the service (Farber et al. 2002). This view excludes value to non-humans except to the extent that humans place some value on the continued existence and well-being of non-humans or even non-biotic features of the Earth. As a philosophical position this may be debatable but as a practical position unavoidable.

Valuation of (parts of) ecosystem assets is difficult, in ways well-understood by (non-ecological) economists (Daily et al. 2000): aggregating preferences, quantifying uncertainty, and inferring value from (non-existent or distorted) market prices. Preferences for services obtained by comparing situations with or without the service can not deal with existential values. Valuation based on cost substitution, for example the value to New York City of the upstate watersheds in obviating the need for filtration plants, is only a lower bound; further, this method can not deal with services with no technological solution.

Gómez-Baggethun and Ruiz-Pérez (2011) discuss the *commodification* of ecosystem services – that is, developing markets by which identified services are traded, thereby assigning a financial value. They warn that this approach depends on the institutional setting and its ideology, and in the dominant neoliberal ideology may not be well-suited to value long-term biodiversity; similarly it does not include concepts of equity of access. A variant of this are fines for services not performed (e.g., excess nitrate to groundwater, or excess sediment delivery to a reservoir) or payments for services rendered (e.g., removing fragile soils from production as in the USA's Conservation Reserve Program). If these are based on sound empirical studies they provide a lower limit for the market value of these services.

3 SOIL AND LAND

Many efforts have been made to assign a value to land, notably as a market good or for taxation. However, the soil resource is only one component of land value. The most obvious source of a financial value for a land area is the land price in an active market. However, land prices are largely determined by location relative to other uses, markets, processing facilities, or transportation networks, and to a much lesser extent by soil characteristics. Land modifications (e.g., deep plowing, terracing, irrigation) affect land price, but these are not generally considered soil characteristics unless they are (semi-)permanent. Further, many lands are not subject to a transparent market.

Most importantly, a land transaction only takes into account benefits to the purchaser, and many ecological services provided by a land area influence a much wider area and therefore beneficiaries. These may be partly reflected in land-use laws (e.g., zoning, agricultural districts) or tax policy (conservation credits, penalties for excess pollution) – the commodification of ecological services mentioned above – but again, the value of the soil resource in this can not be disentangled from land.

Soil is intimately linked with the atmosphere (climate) and hydrosphere. The definition of soil here accepts the concept of USDA Soil Taxonomy that counts soil moisture and temperature regimes as soil characteristics, and thus included in the concept of soil value.

4 SOIL SERVICES AND FUNCTIONS

Soil is a key component of all terrestrial ecosystems, so when discussing how to value soils it makes sense to begin with definitions from the ecological economics community. A key concept is *ecosystem functions*: "the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly" (de Groot 2002); these goods and services are called *ecosystem services*. As with any service, these have a value, and much effort has been spent trying to quantify this (Farber et al. 2002). Ecosystem functions were categorized by de Groot (2002) as *regulation*, *habitat*, *production* and *information* functions; these are valued in three ways: ecological values (based on sustainability), socio-cultural values (based on equity and cultural perceptions), and economic values (based on efficiency and cost-effectiveness) (de Groot 2002, Fig. 1). Specializing to soil, Haygarth and Ritz (2009) identify 18 services provided by UK soils, each with a corresponding function,divided into four groups: (1) *supporting* (primary production, soil formation, nutrient cycling), (2) *provisioning* (refugia, water storage, food supply, biodiversity, raw materials, platform), (3) *regulating* (water, gas, climate, erosion), and (4) *cultural* (recreation, cognitive, cultural). Dominati et al. (2010) present a less comprehensive grouping of soil services: (1) food and biomass production; (2) environmental services such as nutrient cycling, storage, filtering, and transformation of pollutants; (3) biological habitat for soil organisms, maintaining their gene pool; (4) a non-renewable source of raw materials; (5) cultural heritage; and (6) the substrate for man-made structures.

The soil resource is *natural capital* (Dominati et al. 2010): an investment (by nature or previous human activities) which can return benefits indefinitely. This complicates valuation, because "indefinitely" is not a concept in classical economics.

When valuing an activity undertaken on a specific parcel, any effect (positive or negative) outside the immediate parcel and time is called an *externality*; these are notoriously difficult to value even for fairly direct effects such as nitrates, phosphates or zoonoses in drinking water, let alone long-term effects on natural capital. The soil as such does not cause externalities, it is the land use on a soil. The value of soil comes from minimizing negative externalities (e.g., fixing P to avoid eutrophication) or maximizing positive ones (e.g., as a C sink).

5 TOWARDS A PEDOMETRIC VALUATION OF THE SOIL RESOURCE

The value of soil can in principle be assessed by enumerating and quantifying the various service-providing soil functions, enumerating and quantifying soil properties, and applying some quantitative model of the functions as affected by the properties. Some of these are fairly easy to quantify, others essentially impossible with current knowledge and concepts. This task is divided according to the grouping of services by Haygarth and Ritz (2009).

5.1 *Supporting*

The supporting service of biomass production is largely valued through the provisioning service (see below) of food, fibre, timber and other renewable products, or through the regulatory services (see below). Nutrient cycling is also assessed as a regulatory service. Soil formation is slow relative to current needs; this service is assessed by preventing degradation and soil loss beyond equilibrium; this is also considered in regulatory services.

An important supporting service is the value of avoiding thresholds ("tipping points", due to the non-linearity of degradation processes) where the soil resource is (within human time frames) irreversibly damaged to the point where it no longer functions to supply a service. Some soils are more resistant and/or resilient, and hence are more valuable in this sense.

5.2 *Provisioning*

The most-studied valuation is for the provisioning food supply service. The well-established techniques of economic land evaluation (Rossiter 1995) can be applied: (1) describe various land utilization types (LUT), which include management; (2) compute the costs and benefits on a land evaluation unit (LEU), wherein some LEU will have sub-optimal land qualities (LQ) matching the LUT's land use requirements (LUR), leading to higher costs, lower benefits or both. Net present value (NPV) is used to discount the future, although this is only effective for short-term discounting of e.g., investments. To restrict the land evaluation to soil, non-soil factors of production (labour, machinery, transport) can be standardized to an optimum within the soil's agroecological zone. LUTs must be feasible in the socioeconomic and political context, although they do not have to be the current land use. If the context changes, the value of the soil as a factor of production would also change, so the valuation would have to be re-done with a new set of LUT. The value of several LUTs can be aggregated as an average or a maximum; the standard deviation or other measure of spread can be used as a measure of flexibility. This approach is only applicable to sustainable LUTs, i.e., those that do not substantially change the soil resource, as required by the FAO Framework.

Another approach to valuation of the provisioning service is a parametric soil index, such as the Storie Index and its derivatives or the German "Bodenbonitierung" (soil valuation) system. These combine soil characteristics related to productivity of an indicator crop grown under common technology, to provide a fair basis for taxation or land exchange. This assumes that the land user will or could adopt this implicitly-defined production system. The pedometric approach here is a multivariate function of yield of an indicator crop, under a defined production system, as affected by soil characteristics, including soil climate. This yield is often expressed as a proportion of a maximum, which is valued by its net financial benefit.

Soil as a mineable resource can be valued by the market price, net of production costs, of the extracted material. The future is completely discounted, as the resource is destroyed. If the mined area is restored to some productive use, that value is added. For example, a mined area can be a good substrate for structures, or a site for waste storage.

The value of a particular soil as a platform for structures can be assessed by the avoided cost of the same construction on less suitable soils.

5.3 *Regulating*

Environmental services from soils are valued with the same techniques as other ecological services (Farber et al. 2002). This is quite contentious; pedometrics does not judge the proper measure, but rather provides the numbers required once a measure is chosen. For example, the filtering and purification of land applications sewage sludge could be assessed by models of leaching and transformations. The value of the land application is the value of avoidance of other treatment methods, and the value of groundwater of a given quality.

5.4 *Cultural*

The relative value of a soil for recreation (sports grounds, public parks) can be assessed by land evaluation techniques: comparing the soil-related costs (e.g., need for drainage) and benefits (e.g., number of days a sports field can be used). Cognitive (e.g., pleasure in landscapes) and cultural (e.g., historical record) must be translated to a measure that can be compared with other values. This may be possible if more financially-attractive alternative soil uses are prevented at some direct cost (e.g., tax advantages for conservation).

Another cultural value, not explicit in the framework of Haygarth and Ritz (2009), is the preservation of the soil resource for future use. Since conventional economics discounts the future, certainly the far future (when unanticipated services must be provided by the soil) can not be valued financially. Still, society recognizes this value, for example in policies to protect prime farmland from development, or to protect rare natural areas. Immediate financial compensation can be given for removing some land use possibilities (e.g., preventing a land owner from draining a swamp, which would be productive cropland). Here the pedometric approach to valuing the (avoided) production service (above) applies.

5.5 *Scale and viewpoint*

A major complication is the socio-political unit by which soil services are valued. Regulating water quality in New York City watersheds has a high value for all recipients of this water, yet a negative value for a dairy farmer whose production is curtailed by restrictions on manure spreading, and who draws water from an on-farm well rather than a reservoir. In this example the political power of the metropolis prevails, perhaps with compensation to the farmer.

5.6 *A single value?*

A given soil can provide multiple services synchronically (at the same time) – for example, food production and environmental services – or diachronically (over time) – for example, waste disposal followed by revegetation followed by recreation. Further, a given soil may be suited to various incompatible services (e.g., food production, housing, waste disposal) which can not be realized at the same time, and some of which preclude future alternate uses. The "highest" value could be presented, but this must also take into account the scarcity of the resource against the demand for a given use. This becomes a spatial optimization problem. For example, in an area with limited wetlands which provide essential environmental services, a given Histosol is more valuable than if these are abundant.

6 THE ROLE OF DIGITAL SOIL MAPPING

The first role of DSM is as an upgrade to traditional soil mapping of soil types distributed on the landscape and represented as polygons with a linked attribute database; these then serve as land evaluation units. DSM can provide better geometry and more objective landscape segmentation and characterization.

Another role of DSM is producing fine-scale inputs of soil characteristics to distributed models of soil functions that assess (parts of) environmental services, for example, N transformations (outgassing, leaching) or erosion (sedimentation, loss of organic matter and nutrients). Pedotransfer functions are important here, the classic example being soil hydraulic properties inferred from directly-mapped soil characteristics such as particle-size distribution and organic matter concentration.

7 EXAMPLE

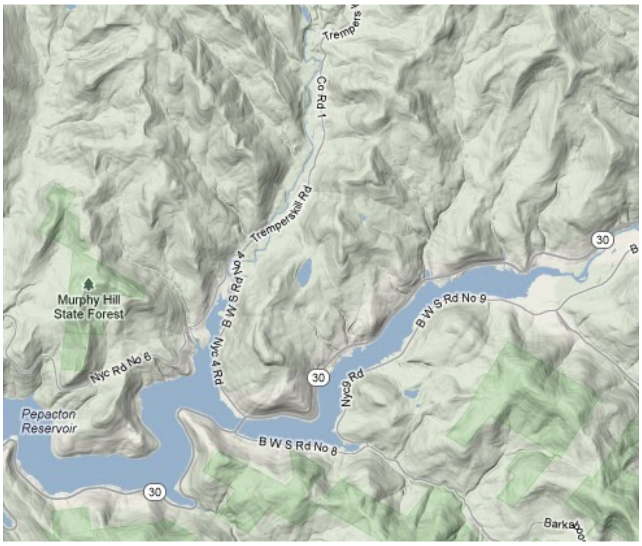
As an illustration of the approach, consider the value of soil in the western Catskill Mountains, New York State, USA. This area is well-known for its management plan, which was developed as an alternative to the construction of filtration system for New York City's water supply (Pires 2004). The principal *provisioning* service is maize silage, hay, and pasture for intensive dairy farming in narrow valleys and some upland inholdings upstream of the large drinking water reservoirs (e.g., Pepacton). Large areas of steep mountainsides are covered with virgin or second-growth forest, which are locally logged. The principal *regulating* service is controlling the quantity and quality of water that enters the reservoirs, either directly from hillside surface or throughflow, or via streams feeding the river branches upstream of the reservoirs. A *cultural* service is supporting the rural lifestyle and attractive countryside; indeed this is why the provisioning services are tolerated. The *supporting* services here are implicit, underlying the provisioning and regulating services.

Much of the forest is state-owned and managed as wilderness or wild areas, which provide an important recreational resource for the metropolitan population. The reservoirs also are used for recreational fishing. Although primarily cultural services, these do have a direct economic value to rural communities.

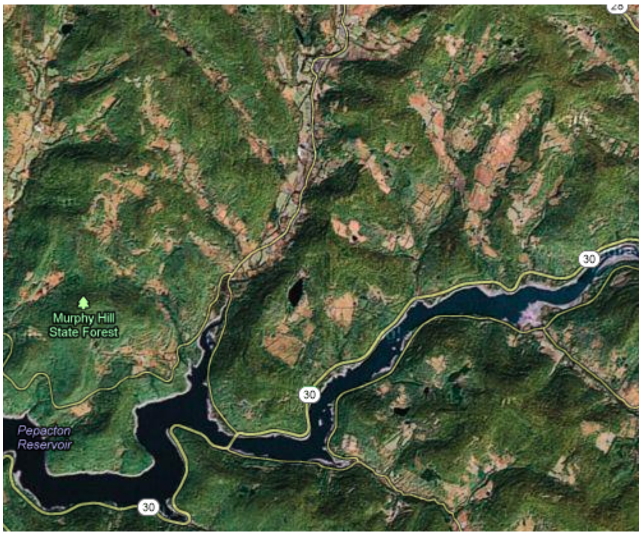
Soil functions supporting the provisioning service are nutrient supply and storage capacity, and functions affecting the water balance. Soil functions supporting the regulating service are infiltration/runoff partitioning, residence time of deep drainage and throughflow, P sorption, and N transformations. In the pedometric approach, these must all be assessed by models.

An important example is the regulation of P-carrying runoff. In this area, saturation excess runoff has been identified as the major contribution to overland flow which carries P from manure applications, as well as spring flushes in second-growth forested areas, to streams; a smaller contribution is from deep drainage and baseflow over the fairly shallow bedrock or fragipans under hillside soils (Mehta et al. 2004). A Soil Moisture Routing model (SMR) has been developed to simulate these flows from variable source areas (VSA), which are dynamically-determined contributing areas. Thus a VSA is not a fixed soil or management unit, but rather an area determined by a separate model. The SMR model conceptualizes soil as layers with vertical and lateral flow, possibly with restricting layers (fragipans and bedrock) that impede free drainage and thus retard infiltration into episaturated soils. Five soil properties are used by the model: soil depth, porosity, field capacity, wilting point, and saturated hydraulic conductivity. These five properties are produced by DSM techniques, on the required grid size, determined by the sensitivity of the SMR model output (P to streams) to grid size, although in the study of Mehta et al. (2004) these were derived from soil type polygons (SSURGO) and associated attribute tables rather than by DSM. The four hydraulic properties are generally produced by pedotransfer functions from DSM-derived soil properties (§6). These may also be dynamic, depending on season and management.

The key point for soil valuation is that the different soils in the region function differently, and so have differential value. The absolute value for the best soil (i.e., providing the highest-quality service) can be approximated by considering the scenario where that soil is absent, i.e., reduced to bare rock. In that case all soil services are removed. The value of the production service on this soil is thus the financial benefit of the production system.



(a) Terrain



(b) Land cover

Figure 1: A portion of the western Catskills, near the Pepacton Reservoir. Source: Google Maps.

A representative area (Figure 1) near Andes in Delaware County, NY was selected to illustrate these calculations, here only conceptually. The published soil survey (Seifried and Havens 2006) describes the soils and presents extensive tables of relative soil services (e.g., productivity ratings, suitability for engineering works) based on expert judgement. For the production function, maize silage was chosen as an indicator crop because of the dominance of the dairy industry in the area. The most productive soil is the Barbour series (coarse-loamy over sandy or sandy-skeletal, mixed, active, mesic Fluvaquentic Dystrudepts) which occurs on the narrow floodplains of Tremper Kill, a tributary to the Pepacton reservoir. This soil has a standardized silage yield of 50 T ha^{-1}, roughly equivalent to 22 T ha^{-1}milk when "processed" through dairy cows. Although net milk prices vary widely, a profit of \$ 40 T^{-1} milk results in \$ 880 ha^{-1} value. By contrast, the Wellsboro series (coarse-loamy, mixed, active, mesic Typic Fragiudept) which occurs on the lower slopes of adjacent hillsides, has a standardized yield from 31 – 36 T ha^{-1}, depending on slope phase; i.e., its productive value is about 60% of the Barbour series. Shallow and stony soils, e.g., the Halcott series (Loamy-skeletal, mixed, active, frigid Lithic Dystrudepts) have no production function for this indicator crop. These sorts of calculations can easily be made more sophisticated and extended to all soil types.

Some soils also support production forests; these are rated by a per-species site index and projected timber volume; for example northern red oak (*Quercus rubra*) Wellsboro of and Halcott soils have site indices of 78 and 55, corresponding to about 4 m^3 ha^{-1} and 2.8 m^3 ha^{-1} timber, respectively; at 2011 reported stumpage prices this is about \$580 and \$410 ha^{-1} return to land. These values must be discounted by the rotation length of 60–80 years and then normalized to a per-year basis for comparison with annual crops.

The primary regulating service in this area (avoiding reservoir pollution) is distributed over the landscape, i.e., the contributing area to a reservoir. Conceptually, the permitted concentration of the pollutant (e.g., P) in reservoir water is converted to an amount, and then divided by contributing area. Soils that per unit area retain or degrade the pollutant at this amount are satisfactorily fulfilling their portion of the regulating service; above or below this amount have a negative or positive economic value determined by the cost (or avoidance) of filtering the water delivered from that area. However, in this area there is no filtration, and the goal is to avoid building an extremely expensive system. Thus the value is in staying below a threshold.

8 FINAL REMARKS

The approach outlined in this paper needs to be expanded and further specified. It is fairly easy to identify the various benefits humans and the ecosystem derive from soils on the landscape. However, placing a single value on a given soil area is not simple. The principal challenges are: (1) disentangling the values of soil and land; (2) valuing regulating services; (3) quantifying regulating services with models; (4) apportioning the contributions of spatially-distributed soil areas to a concentrated externality (e.g., reservoir pollution) with distributed models; (5) quantifying cultural services; (6) accounting for value of the soil resource into the indefinite future; (7) combining valuations of individual services into a common value.

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