Conflicting demands of land use, soil biodiversity and the sustainable delivery of ecosystem goods and services in Europe

Farmers' costs of supplying soil ecosystem services in diverse EU regions

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Mark Brady[1], Katarina Hedlund[2], RongGang Cong[3], Lia Hemerik[4] and Stefan Hotes[5]

[1] AgriFood Economics Centre, Department of Economics, Swedish University of Agricultural Sciences (SLU), Box 730, S-220 07 Lund, Sweden.

[2] Department of Biology, Lund University, S-223 62 Lund, Sweden.

[3] Centre for Environmental and Climate Research (CEC), Lund University, S-223 62 Lund, Sweden.

[4] Biometris, Department of Mathematical and Statistical Methods, P.O. Box 100, 6700 AC Wageningen, The Netherlands.

[5] Department of Animal Ecology, Justus-Liebig-University, D-35392 Giessen, Germany.

Abstract

The quest to simultaneously increase food production and reduce agriculture’s contribution to environmental change is high on the global agenda. Considering the effects of changes in the stock of soil natural capital on agricultural production—both in terms of maximum attainable yield and resource use efficiency—is proposed as a way forward. We evaluate the impact of intensive agriculture on the economic value of soil natural capital in some of the world’s most productive arable regions. Soil organic carbon (SOC) serves as a proxy for the stock of soil capital. Production functions are estimated to determine the joint effect of SOC concentration and artificial fertilizer input on crop yield. Current intensive farming practices degrade soil natural capital resulting in lower maximum yield and increasing fertilizer input needed to produce an extra unit of food. Devoting resources to conservation of soil natural capital is a potential strategy for achieving future food security and mitigating global environmental change.

1 Introduction

Natural capital is receiving increasing attention as both a concept and framework for valuing the natural resources that are critical to economic development and, ultimately, life on Earth (Dasgupta 2010; Kareiva, Tallis et al. 2011). Soil natural capital—which we define as the power of a soil to generate sustained flows of ecosystem services—is an essential input to agriculture (Daily 1997; Dominati, Patterson et al. 2010). The most obvious service provided by soil capital in arable systems is crop yield, which in turn is supported by services such as carbon and nutrient cycling, water holding capacity, soil fertility, etc. (Barrios 2007). Other services of indirect but vital importance to human well-being include: carbon sequestration, water quality and flow regulation, regional climate and air quality regulation, and infectious disease mediation (Foley, DeFries et al. 2005; Brussaard, de Ruiter et al. 2007).

Given the prodigious increase in global food production over the past 50 years one may question whether soil natural capital is at risk, at least in the industrialized world. Soil capital degradation, particularly in the form of erosion, is a prioritized problem in developing countries where the rural poor cannot afford to purchase substitutes for ecosystem services (e.g. artificial fertilizers), but rely directly on these for their livelihood (Adhikari and Nadella 2011). Yield increases in industrialized countries have, on the other hand, been driven by increasing use of technology; new breeds of high yielding crops, and substantial inputs of artificial fertilizers and chemicals (Matson, Parton et al. 1997). Soil degradation brought about by *intensive* practices occurs more insidiously through the loss of soil biodiversity and associated soil organic matter which diminishes the soil's ability to generate ecosystem services (Altieri 1999; Swift, Izac et al. 2004; Lal 2010). More widely recognized are the environmental damage costs of intensification, particularly the pollution of water resources, loss of above-ground biodiversity and contribution to green-house gas emissions (Tilman, Fargione et al. 2001).

Table 1 illustrates how the choice of agricultural management practices affects the stock of soil organic carbon (SOC) in arable soils. Intensive practices and lack of organic amendments tend to degrade SOC. Maintaining a permanent cover of plants or incorporating substantial residues of plants and stable manure however regenerate the pool of soil carbon. Including fast growing grasses (e.g. leys or bioenergy crops) in crop rotations improves soil fertility and retention of carbon and nitrogen. Low tillage promotes organisms such as earthworms and fungi that improve soil structure.

Table 1. Effect of agricultural management practices on rate of change of soil organic carbon

Management Practise	Rate of C change per year
	Degeneration
Inorganic fertilisers	-0.5%
Farm yard manure (5 ton/ha)	-0.2%
Straw addition (3 ton/ha)	-0.2%
	Regeneration
Cover crops	0.2%
Straw addition (12 ton/ha)	0.3%
Farm yard manure (35 ton/ha)	0.4%
Sewage sludge	0.9%
Miscanthus grass (bioenergy)	1.5%

In this article we evaluate the impact of intensive agricultural practices on the natural capital value of a number of highly productive arable soils across Europe. Through estimation of production functions we quantify flows of ecosystem services and evaluate how intensive agricultural practices might be affecting the natural capital *value* of soils. The explicit valuation of natural capital can be used to inform decision makers of the economic benefits of allocating scarce public resources towards conservation of soil biodiversity, but also the design of policy instruments that might be necessary to ensure the generation of ecosystem goods and services in socially desirable quantities (Daily, Polasky et al. 2009). Recognizing the value of soil natural capital in arable production systems is subsequently proposed as a way forward for meeting future challenges for agriculture.

1 Carbon: the currency of soil ecosystem services

Linking soil biodiversity to ecosystem functions and services is a challenge because soils are home to an extraordinary range of microbial and animal species (Wardle and Giller 1996; Fitter, Gilligan et al. 2005), the majority of which have never been described (Freckman, Blackburn et al. 1997). Indeed soil organisms are not just inhabitants of the soil, they are part of the soil (Hole 1981). Soil organic carbon is the basis of life for most soil organisms; it is the common currency of soil ecosystem services. For this reason SOC can serve as a proxy for the stock of soil natural capital. The strong relation between crop yield and the stock of SOC in the root zone of arable soils (Lal 2010) is attributable to soil organisms performing the biological *functions* that generate ecosystem services: nutrient cycling, nitrogen fixation, phosphorus acquisition, decomposition of organic materials, mineralization of carbon, moisture regulation, soil structure modification, pest and disease control (Barrios 2007). SOC is also correlated with other ecosystem services of relevance to agriculture including nutrient retention, water holding capacity and bio-control that can reduce reliance on chemicals (Pimentel, Acquay et al. 1992; Birch, Begg et al. 2011).

2 Production functions to predict crop yields

To quantify the impact of soil natural capital on crop yield and the need for artificial fertilizer we estimate agricultural production functions (Heady 1961). To develop and parameterize production functions we used data on the yield (kg ha^{-1}) of winter wheat (a major crop) for different levels of fertilizer application (N kg ha^{-1}) and varying stocks of soil capital (%C) from some of the world's oldest running long-term agricultural experiments; A) *Askov* in Denmark, B) *Broadbalk* at Rothamsted in the UK, C) *Bad Lauchstaedt* in Germany and D) *Scania* in Sweden (see Online Material). The resulting production functions are plotted in Fig. 1, and show the yield response of winter wheat to fertilizer N application at each site for two alternative SOC concentrations. The upper curve in each panel A-D is yield response given the highest recorded SOC concentration at each site and the bottom curve given the lowest recorded concentration, where concentration is controlled by the choice of agricultural management practices (Table 1). A quadratic function gave the best fit to the data (Table S2). In general, yield increases with fertilizer application up to the level of optimal fertilizer input, i.e. the minimum fertilizer needed to achieve the maximum yield associated with a particular level of SOC (Frank, Beattie et al. 1990). Similarly, yield increases with SOC up to the optimal level of SOC (Lal 2010). NB: the data for Askov includes a relatively narrow range of SOC concentrations, hence the relatively small differences in potential yield between the curves.

As the production functions include a measure of soil natural capital (%C), it becomes possible to determine the impact of changes in soil capital on yield and optimal fertilizer input. In particular it is possible to determine to what extent fertilizer needs to be applied to crops to compensate for declines in soil capital, and hence substitute for soil services that are reduced or lost due to degradation of soil capital (Ehrlich and Mooney 1983). This is revealed by comparing the maximum yield attainable at each site for different levels of SOC. When moving from the relevant pairs of upper to lower curves in Fig. 1 A-D the maximum yield falls by: 7% for Askov, 20% for Broadbalk, 28% for Bad Lauchstaedt and 50% for Scania; demonstrating that fertilizer can only partially substitute for services generated by soil organisms, and the necessity to increase rates of fertilizer input to achieve a particular yield at lower levels of SOC. By drawing a horizontal line corresponding to a yield of 6 t ha^{-1} in panel B) Broadbalk, it is easily seen that the lower curve demands almost 150 kg ha^{-1} fertilizer N to achieve this yield whereas the upper curve requires only 30 kg ha^{-1}.

To achieve the maximum attainable yield at each site both SOC and fertilizer input need to be optimized; e.g. in Scania optimal fertilizer application produces 75 kg wheat kg^{-1} fertilizer N when SOC is 3.4% (top curve) but only 28 kg when it is 0.8% (bottom curve). The implication is that an optimal trade-off exists between maintaining soil capital and complementary use of artificial fertilizer; any deviation from the optimum means that too little food is being produced with too much fertilizer. It follows that future farm profits would also be less than possible. Furthermore, as artificial fertilizer causes substantial environmental impacts in both production and application these results also have implications for reducing agriculture's environmental impacts.

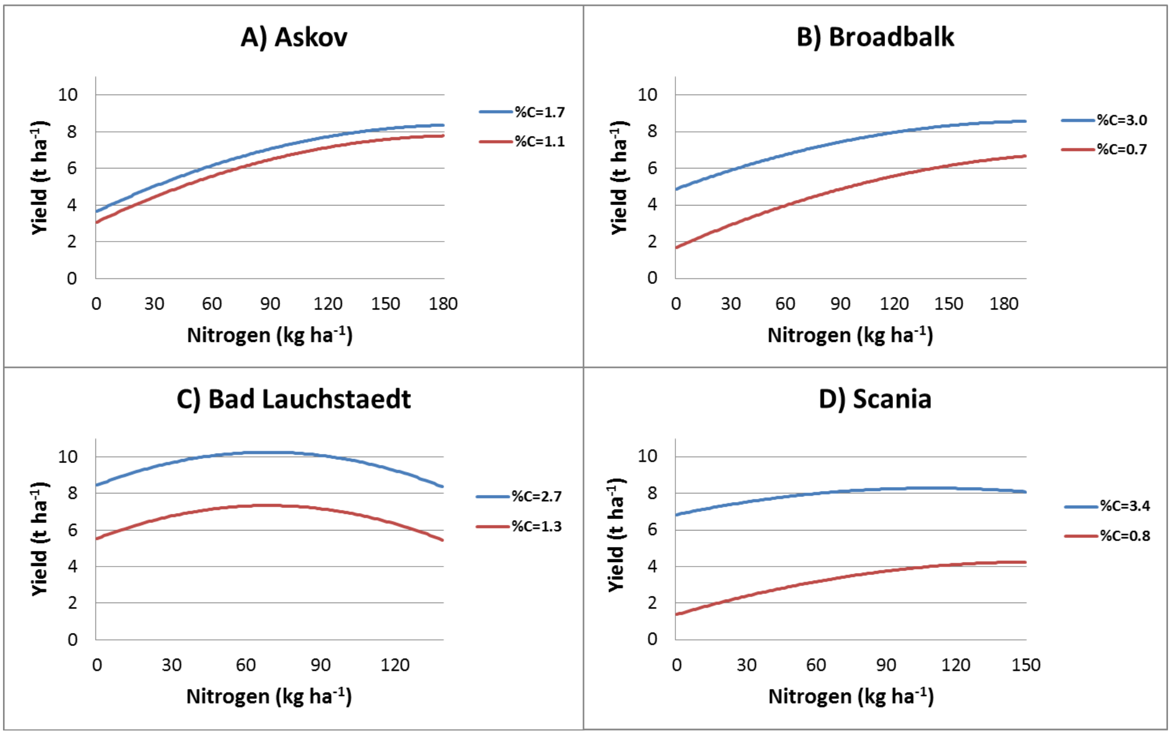

Fig. 1. Yield response of winter wheat to artificial fertilizer N application for increasing concentrations of soil organic carbon (%C) at four long-term experiment sites: A) Askov in Denmark B) Broadbalk in the UK C) Bad Lauchstaedt in Germany and D) Scania in Sweden. The top-curve in each panel is based on the highest recorded %C at each site and the bottom-curve the lowest recorded %C.

3 Investing in soil natural capital for a securer future

Two overriding challenges face agriculture in coming decades: simultaneously meeting rising food demand from a fast growing and wealthier population, and mitigating global environmental change to which agriculture is a major contributor (Godfray, Beddington et al.

2010). In Fig. 2 we illustrate the potential for meeting these challenges by investing in soil natural capital, i.e. making a sacrifice today to be better off in the future. The figure shows the potential increase in flows of ecosystem services if SOC is boosted from the normal level at each site—the treatment receiving normal N fertilizer input for the region—to the optimal SOC level (Fig. 2A), i.e. that generating maximum possible profit according to our model (see mathematical results in Online Material). As can be seen this has the potential to significantly increase: yield (Fig. 2B), yield per unit artificial fertilizer (Fig. 2C) and profit (Fig. 2D). In short, more food *could* be produced per unit land and per unit fertilizer input—than is being produced today—by investing in soil capital (i.e., Fig. 2A). There exists a diversity of measures or combinations of them that could be used to do this; rotational grasses, incorporation of plant residues, stable manure or other organic amendments, cover crops and green manure or low tillage regimes (Paustian, Six et al. 2000; Dobermann and Cassman 2002; Lal, Griffin et al. 2004). Unfortunately, persisting with current intensive farming practices implies that soil natural capital will continue to be depleted and—according to our production functions—the maximum attainable yield in the future will be lower and fertilizer intensity higher than today *ceteris paribus* (because fertilizer is an imperfect substitute for soil ecosystem services).

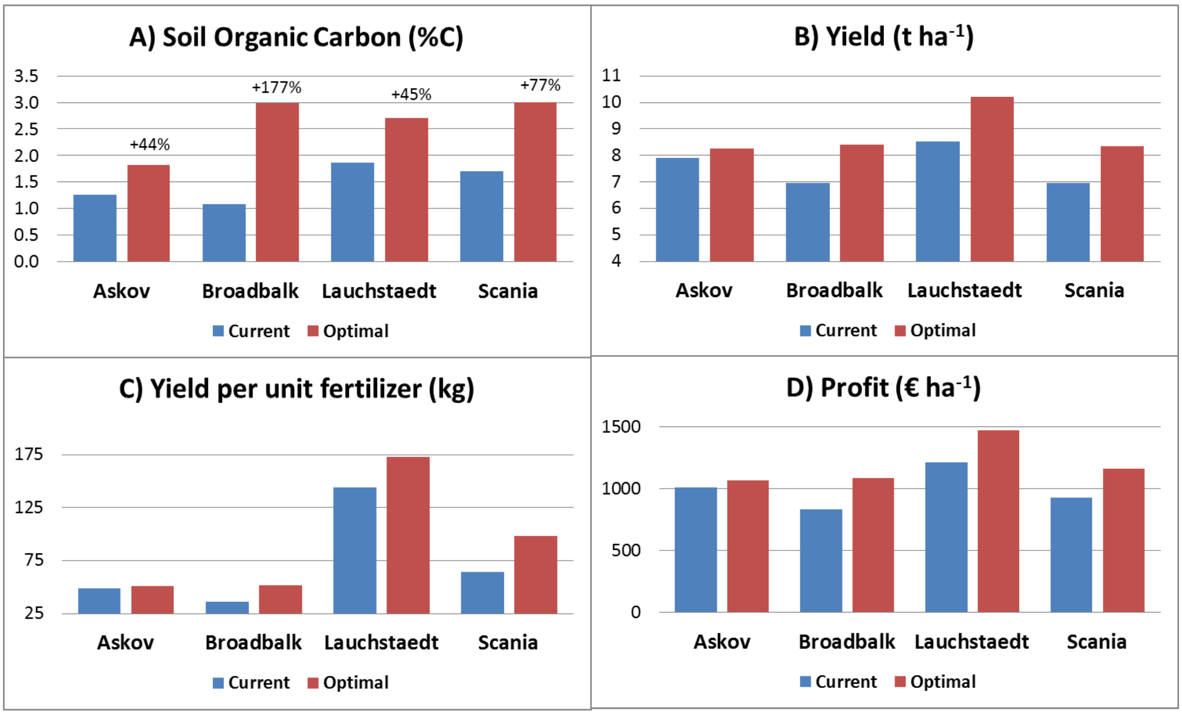

Fig. 2. Optimal increases in flows of soil ecosystem services that could be achieved by investing in soil natural capital: A) Optimal increase/investment in SOC, B) effect on hectare yield, C) effect on yield per unit fertilizer input and D) effect on hectare profit.

Soil capital conservation (i.e. investment) decisions need to be based on how much an incremental or *marginal* change in soil capital (SOC) will influence flows of ecosystem services and, in turn, future profit. Just as the unit prices of alternative crops convey critical information for determining which crops to grow, it is the marginal value or shadow "price" of soil capital that is the key to improving natural resource decisions (Daily, Polasky et al. 2009). The appropriate decision criterion for evaluating an investment decision is to weigh the cost of the investment against the present value (PV) of the future benefits (in this case increase in profits) expected from making the investment. We calculate the PV_i of the change in future profits $(\Delta\pi_i)$ at site *i,* brought about by a marginal change in soil capital, as a perpetual annuity—since the life span of an arable soil will be indefinite if managed sustainably—such that $PV_i = \Delta\pi_i(1+\delta)/\delta$ where δ is the discount rate (e.g. Polasky, Nelson et al. 2008). Consequently the valuation of natural capital contains, unavoidably, an objective part—the change in annual profit—and a subjective part—the choice of discount factor which can be controversial, e.g. in relation to climate change (Weitzman 2007). For this reason our ensuing valuation is based on a range of discount factors—rather than a single rate that is liable to personal bias.

In Fig. 3 we present the marginal value of soil natural capital at each site (i.e. PV_i) as a box and whisker diagram spanning a range of discount factors including extremes. The box represents the most plausible range of the marginal value (i.e. using a discount factor that the majority of economist could accept) whereas the whiskers exemplify extreme assumptions: from 1.4%—the social rate of discount used in the Stern Report (Stern 2006)—to 28%; a rate based on experimental evidence from US farmers (Duquette, Higgins et al. 2012). The annual change in profit $(\Delta\pi_i)$ is based on a marginal change in SOC (i.e. a ±1% relative change in *Current SOC* concentration at each site according to Fig. 2; we assume that only relative changes in SOC are possible since the experimental data supports exponential decay/growth, Table S1). The resulting changes in annual profits being: Askov 2.32 € ha^{-1}, Broadbalk 1.36 € ha^{-1}, Lauchstaedt 5.68 € ha^{-1}, and Scania 6.06 € ha^{-1}. From Fig. 3 it is clear that although a marginal change in SOC only has a slight impact on annual profit (i.e. < 1% across all sites), the impact on the value of soil natural capital can be substantial. Just like someone saving for their retirement, a difference of some 0.5–1% in annual return will amount to little from one year to the next, but over time, will compound to make all the difference.

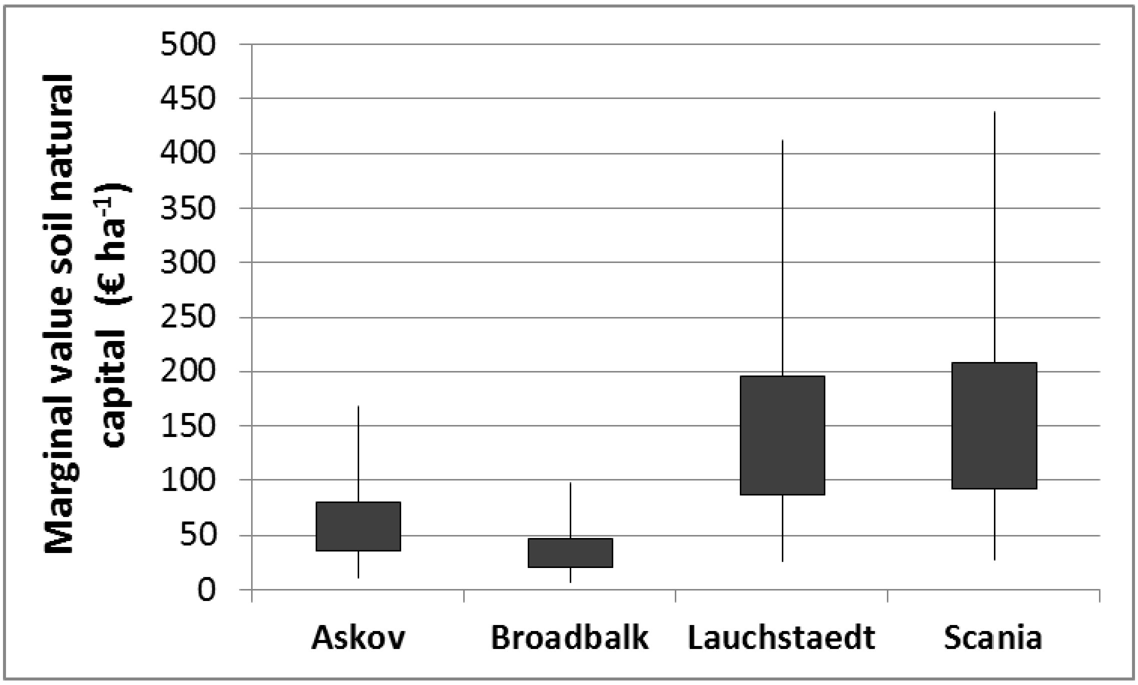

Fig. 3. The marginal (economic) value of soil natural capital at the four long-term experiment sites. Boxes represent the most plausible range of the value based on the discount rate ranging from 3% (box top) to 7% (box bottom), whilst whiskers represent extremes of the discount rate: 1.4% (whisker top) to 28% (whisker bottom).

A striking aspect of Fig. 3 is the divergence in value between regions; the marginal value of soil capital at Lauchstaedt and Scania is 3 to 4 times higher than that at Askov and Broadbalk. This is because a 1% change in SOC generates a relatively small absolute change in SOC at the latter sites (*Current SOC* shown in Fig. 2A is relatively low), and hence generates relatively smaller changes in annual profits which reduces the compounding affect over time.

An important question in the face of uncertainty is whether the value of soil natural capital is affected by *expectations* about future prices (e.g. sharply increasing energy or food prices). To determine this we calculated the elasticity of the marginal value of soil capital with respect to changes in the prices of wheat and fertilizer. We find that a relative increase of 1% in the expected price of wheat leads to a 0.66–0.76% increase in the value of soil capital depending on the site (a result that is independent of the discount rate). In the case of fertilizer, a 1% relative increase in price results in the natural capital value increasing by 0.03–0.31%. Consequently, expectations about rising prices in the future increases the value of soil natural capital; implying that more soil capital should be conserved (i.e. invested in) than if simply considering today's prices.

4 Why farmers aren't conserving soil capital

One explanation for farmers' failure to conserve soil capital is high discount rates (e.g., Jaffe and Stavins 1994). Another is that the annual effects of depleting soil capital are so small that farmers might not be aware of these changes (especially in light of the stochastic nature of harvests due to weather variation and technical developments in yields); and hence there might be an information problem. However, more to the point, if they did have this information could we expect the rational farmer to change their soil management practices in any case? Returning to Fig. 3 the value implied by the top of each box reflects a fairly standard social rate of discount (3%) whereas the value implied by the bottom of each box reflects, more truly, farmers' private rates of discount (7%). Farmers like all individuals tend to be myopic due to i) finite life expectancy and ii) impatience, preferring a benefit now than in the future (Pigou 1932). As such, a wedge occurs between society's valuation of soil natural capital and that of farmers who, consequently, are likely to be overexploiting it from society's perspective. Under such circumstances corrective policy action needs to be considered as market forces alone will encourage overexploitation of soils to the detriment of future generations (Fisher and Krutilla 1975).

5 Meeting the challenges facing agriculture

We could not agree more with Tilman et al. (Tilman, Fargione et al. 2001) that significant scientific advances and regulatory, technological, and policy changes are needed to control the environmental impacts of agriculture. Our results indicate that restoring soil natural capital provides an additional strategy for meeting this challenge whilst simultaneously increasing food production potential. Moreover, investing in soil natural capital would avoid placing all our eggs in one "technological" basket; have faith, but tie your camel first. The back side is that we are faced with the dilemma of sacrificing some yield today (i.e. the cost of investing in soil capital) in order to produce more in the future. As our unique valuation of soil natural capital so plainly demonstrates, this value alone is not likely to provide farmers with sufficient incentive to conserve soil capital at levels that are desirable from society's perspective. Such an investment would, however, not only improve the ecological sustainability of agriculture but also the incomes of future generations of farmers (Fig. 2D). In this article we have shown that the risks of degrading soil natural capital could be substantial. The rational question that comes to bear is: How much soil capital should we conserve or invest in for future generations? Responsible management demands consideration of the answer.

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