Supplementary Materials

Roadmap for valuing soil ecosystem services to inform multi-level decision-making in agriculture

1. Measured soil organic carbon content in study region

In Table S1 we present the data used to derive the average SOC content and its variation across arable fields in the study region (GSS). The average of 1.7 %SOC is based on around 90,000 field measurements covering 33% of the arable area. These measurements were performed by the largest agricultural extension service provider in the region, The Rural Economy and Agricultural Societies [1]. Although the measurements have not been based on a statistical sample, their sheer number and comprehensive coverage of all yield-survey districts within the region (at least 20% of the area in each district was covered) imply that they are representative of soils in the region.

Table S1. Areas of annual crops and average SOC content by yield-survey districts in the study region in 2016.

Yield-survey district	Arable land	Area annual crops [1]	Area where SOC measured [2]		%SOC	Normal yield winter wheat
	ha	%	ha	%	Ave.	kg ha^{-1}
1121	45 648	80 %	19 638	43 %	1.75	7 996
1123	35 639	77 %	7 420	21 %	1.97	6 910
1211	44 679	86 %	16 385	37 %	1.44	8 452
1212	30 481	77 %	8 531	28 %	1.65	7 488
1214	36 614	88 %	13 168	36 %	1.52	7 999
1216	50 108	87 %	19 669	39 %	1.82	7 746
1222	26 127	71 %	5 145	20 %	1.81	6 845
Total study region	269 295	82 %	89 957	33 %	1.71	7 740
				SD	0.18	594

Sources: 1) Swedish Board of Agriculture's Integrated Administration and Control System [2] and 2) Based on soil organic matter measurements taken by The Rural Economy and Agricultural Societies [1].

2. Estimation of production function coefficients

Coefficients of the generic production functions used in the empirical study are provided in Table S2. The coefficients for winter wheat and winter rapeseed were taken from previously published estimations, whereas the coefficients for spring barley (Table S3) and sugar beet (Table S4) were estimated in this study using data from the same five long-term experimental field studies run by the Swedish University of Agricultural Sciences in the region [3].

Table S2. Estimated coefficients of production functions.

Parameter	W.wheat[1]	S.barley[2]	W.rapeseed[3]	Sugar beet[2]
Intercept	-2021.99	-232.532	-4875.27	-25485.1
N	40.42	56.98408	10.51	161.7389
N^2	-0.11781	-0.26395	-0.03	-0.24038
C	6077.9	3207.824	6051	58116.47
C^2	-951.3	-580.417	-954.872	-8387.69
N*C	-4.17	-5.49744	0	-25.9008

Sources: 1) Winter wheat [4]; 2) Spring barley according to Table S3 and sugar beet Table S4; 3) Winter rapeseed [5] (Table 1).

Table S3. Estimation results for the spring barley production function.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Intercept	n/a	1080.977	-1.24963	0.2121
N	56.98408	4.536537	12.56114	0.0000
N^2	-0.26395	0.037165	-7.10201	0.0000
C	3207.824	913.8079	3.510392	0.0005
C^2	-580.417	171.7462	-3.3795	0.0008
N*C	-5.49744	1.481956	-3.70959	0.0002
R-squared	0.97	Prob(F-statistic)	0	

Table S4. Estimation results for sugar beet production function.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Intercept	n/a	14260.62	-4.371586	0.00000
N	161.7389	25.68252	6.297626	0.00000
N^2	-0.240376	0.087503	-2.747055	0.00630
C	58116.47	12346.38	4.707166	0.00000
C^2	-8387.692	2315.149	-3.62296	0.00030
N*C	-25.90081	8.083537	-3.204143	0.00150
R-squared	0.95	Prob(F-statistic)	0	

The production functions are plotted in in Figure S1 for the average SOC content in the region of 1.7 %SOC (the Today curve) and for an assumed 20% relative increase and relative decrease in SOC content to illustrate the sensitivity of the crop yield to changes in supporting ecosystem services.

The estimated production functions are plotted in Figure S1 to show the possible yields given current SOC content (1.71% from Table S1) for increasing N fertilizer rates; and those for scenarios with a Higher and Lower SOC content assuming that SOC content increases or decreases respectively, at an annual rate of 1% relative to the previous year's content (which over 20 years would result in a total change of plus or minus 22% relative to the current content respectively). According to these functions the yield of spring barley is relatively insensitive to changes in soil ecosystem services as indicated by changes in %SOC, compared to the other three crops. This is consistent with our expectations since spring barley can be grown on poorer soils, whereas particularly winter rapeseed and sugar beet are only grown on the most productive soils in Sweden.

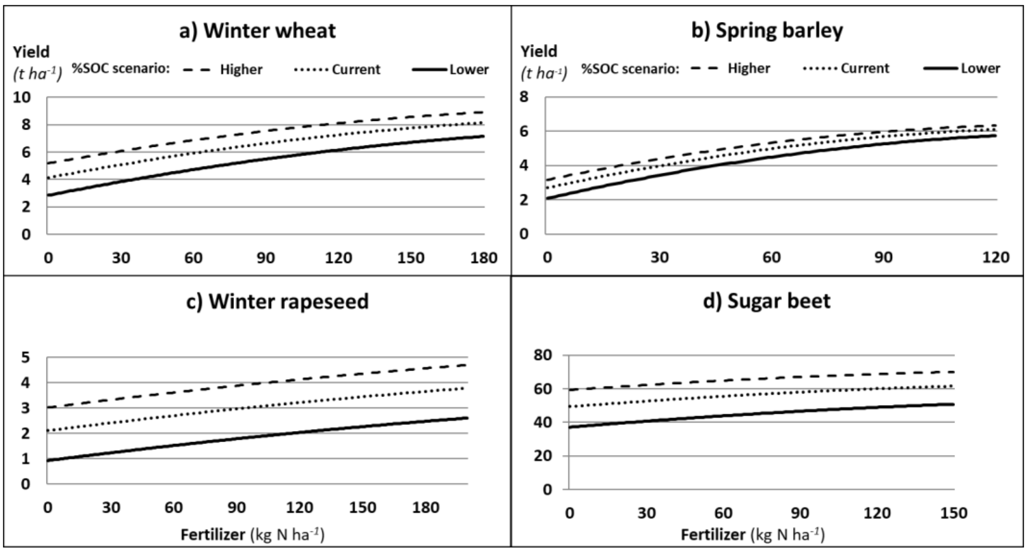

Figure 1. Plots of the production functions for the four main crops in the study region based on average current %SOC in the region and those for scenarios with Higher and Lower SOC contents: a) Winter wheat, with standard yield 7.9 t ha^{-1} and fertilizer input of 160 kg N ha^{-1}), b) Spring barley, 5.7

t ha^{-1} and 91 kg N ha^{-1}, c) Winter rapeseed, 3.6 t ha^{-1} and 172 kg N ha^{-1}, and d) Sugar beet 60 t ha^{-1} and 120 kg N ha^{-1}.

3. Derivation of parameters for calculating total C stock

To derive the parameters of the C storage function, Eq. (8) in the main text, we used data from the five long-term experimental sites used to estimate the production functions (Table S2), to calculate average values for the region (Table S5). The five LTE sites were established in the 1950s to be representative of agricultural conditions across the region and for the purpose of studying soil fertility.

Table S5. Approximation of average soil bulk density and carbon stock per ha of arable land in the study region.

	Soil Bulk Density (kg dm^{-3})				Organic C in topsoil		
	Depth (m)				C	Stones	C
LTE site	< 0.10	< 0.20	< 0.30	Ave. to 0.30	%	%	t ha^{-1}
S. Ugglarp[1]	1.51	1.49	1.48	1.49	1.92	13.5	74.4
Ekebo[2]	1.40	1.45	1.54	1.46	2.38	13.5	90.3
Fjädringslöv[2]	1.60	1.72	1.78	1.70	1.28	6.7	60.9
Orup[3]	1.52	1.57	1.50	1.53	2.44	4.0	107.5
Örja[3]	1.81	1.72	1.75	1.76	1.40	0	73.8
Average				1.59	1.88	8	81.4

Sources: Parameter values for each long-term experimental (LTE) site are from: 1) Kirchmann, et al. [6]; 2) Kirchmann, et al. [7]; and 3) Kirchmann and Eriksson [8].

Following from Eq. (8), C stock (t ha^{-1}) is calculated as follows using S.Ugglarp as an example:

$$C\_store = 0.0192 \times (1 - 0.135) \times 1.49 \times (3 \times 106) = 74{,}237 \text{ kg ha}^{-1} \text{ or } 74.2 \text{ t ha}^{-1} \quad (1)$$

where the small difference compared to Table S5 is due to rounding.

4. Economic data used to parameterize farmers' profit functions

The economic data used to parameterise the farmers' profit functions and their sources are detailed in Table S6.

Table S6. Economic data used to parameterize the farmers' profit function.

Crop	Product prices [1] (€ kg^{-1})	Cost of applying Fertilizer [2] (€ kg^{-1})	Fixed costs [3] (€ ha^{-1})
Winter wheat	0.148	1.80	64.15
Spring barley	0.114	1.81	57.40
Winter rapeseed	0.313	2.01	44.33
Sugar beet	0.063	3.82	131.48

Sources: 1) Expected market prices in 2015 [9]; 2) Based on unit costs of fertilizers (N 1.01 € kg^{-1}, P 1.87 € kg^{-1} and K 0.99 € kg^{-1}) and energy input related to yield (0.94 € per liter diesel) as a linear function of N input, and 3) based on unit prices of energy for driving machinery and costs of pesticides 64.81 € per dose ha^{-1}). For derivations of 2) and 3) see Hristov, et al. [10, Table 14]. Original values in Swedish Kronor were converted to Euro using the exchange rate of 10.40 SEK €$^{-1}$ (Sveriges riksbank. Search interest & exchange rates as at 20190204 from https://www.riksbank.se/en-gb/statistics/search-interest--exchange-rates/).

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