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YSSP Report

Young Scientists Summer Program

Soil carbon sequestration following agricultural land abandonment in the EU

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Abstract

Agricultural land abandonment (ALA) is a prominent land use change throughout the European Union (EU) with several notable implications for soil and ecosystem restoration. In particular, the cessation of certain agricultural practices (e.g., tillage and biomass removal) often induces an increase in soil organic carbon (SOC) and can potentially support land-based climate change mitigation efforts. However, large uncertainties on the variability of post-abandonment soil carbon sequestration (SCS) rates and the absolute storage potentials across the EU hinders the development of dedicated policies leveraging the restoration benefits of both intentional (i.e., managed restoration and direct conversions) and unintentional ALA. We collected and synthesized SOC stock changes following ALA derived from field sites in EU member states using published chronosequence/paired plot data. In doing so, we determined how rates of soil carbon accumulation during ecological succession differ in space and time. We found a slow, but significant, rate of SOC stock increase across the EU-27 member states of 1.14% yr^{-1} ($p < 0.0001$), with an average relative change of +34% and an average time since abandonment/conversion of 33 years in the dataset (n=706). These results provide some clarity to previous regional debates on the positive/negative/neutral SCS potential of post-agricultural soils, which have likely been confounded by other key factors. SOC responses were negatively correlated with initial SOC stock, indicating a soil carbon saturation effect, and negatively correlated with soil depth. Climatic conditions have both positive and negative effects on SOC response, with an ideal temperature and precipitation window for SCS of around 13 to <17 °C and 450 to <1000 mm yr^{-1}. Biogeographical regions with climatic conditions typically outside these ranges exhibited lower relative rates of SOC stock accumulation and even losses (e.g., alpine, continental). Both past land use (cropland vs. pasture) and post-abandonment/conversion land management strategy employed (natural vs. assisted) produced divergent responses in SOC change, implying that croplands managed through natural succession would show the greatest SOC accrual while pastures that are actively converted (e.g., afforestation) would result in the lowest increases in SOC, or even losses. This variability in post-abandonment/conversion SOC dynamics must be considered in sustainable land use planning that strives to incorporate the positive ecological and climate change mitigation implications of ALA, taking into account site-specific conditions and past and present land management. Our results help inform EU ecosystem restoration policies and land management strategies on the potential soil carbon benefits, costs, and challenges of ALA.

Introduction

Agricultural land abandonment (ALA) is a prominent global land use change. But despite its ubiquity across agricultural regions (Campbell et al., 2008; Li and Li, 2017), it is relatively difficult to accurately measure and monitor at large geographic scales, which can lead to large uncertainties (Yin et al., 2020). This is due to both its differing definitions as a land use change and its rather ephemeral nature as a land use classification, often undergoing recultivation after short periods (e.g., implying shifting agriculture or unreported and unclear fallowing practices) (Benjamin et al., 2007; Heinimann et al., 2017). The lack of incentives and/or interest to report genuine ALA also produces poorly informed land use inventories and mapping efforts in under-resourced regions. In the European Union however, efforts to monitor, measure, and map ALA have achieved a comparatively higher level of success due to the incorporation of multiple sources of predictive variables and model parameters (e.g., LUISA modelling platform, see Lavalle et al., 2020). By 2030, more than 5.6 Mha is predicted to be abandoned in the EU and the UK, or 3.6% of total agricultural land (Perpiña Castillo et al., 2021).

In non-degraded agricultural landscapes, the cessation of intensive agricultural practices typically results in the spontaneous recovery of ecosystem properties towards pre-agricultural levels (Cramer et al., 2008a). Ecosystem health indicators for vegetation, soil, and animals can all improve from the ensuing ecological succession following ALA. These trajectories depend significantly on site-specific conditions (e.g., the level of degradation, the suitability for restoration, and the level of biodiversity one would find there naturally compared to the level of biodiversity maintained by the active agroecosystem before ALA) (Beilin et al., 2014; Plieninger et al., 2014; Queiroz et al., 2014). Although conventional agricultural is known to continuously deplete soil carbon (Carlson et al., 2017; Lal, 2013), one of the most important benefits of the natural recovery of post-agricultural soils is the accumulation of soil carbon stocks (Deng et al., 2014; Laganière et al., 2010; Wertebach et al., 2017).

Indeed, soil organic carbon, the largest terrestrial carbon pool that can be effectively influenced by human efforts, represents an enormous carbon sink for climate change mitigation efforts. Therefore, the ability of post-agricultural soils to reabsorb carbon until, presumably, reaching pre-agricultural levels has received increasing attention (Bell et al., 2020). Unfortunately, there remains several uncertainties surrounding ALA's potential as a climate change mitigation tool via soil carbon sequestration at a global, continental, and regional scale, despite notable instances in history of large-scale sequestration (e.g., following the collapse of the former Soviet Union (Kuemmerle et al., 2011; Schierhorn et al., 2013; Wertebach et al., 2017), or even following the mass die-off of pre-colonial South America (Koch et al., 2019). Not all landscapes accumulate carbon at the same intensity (i.e., amount of stock increase) and speeds (i.e., rate of stock increase) following ALA (Breuer et al., 2006; Hoogmoed et al., 2012; Nadal-Romero et al., 2016), and under specific conditions some can even lose soil carbon (Martinez-Duro et al., 2010; Segura et al., 2020).

It is apparent that any new system or policy of sustainable land management must now include a comprehensive plan for protecting and replenishing soil carbon stocks when possible (Bossio et al., 2020; Bradford et al., 2019). The ability to calculate the rates and amounts of post-agricultural SCS across large geographies is pivotal for the planning, implementation, and assessment of land management policies that wish to incorporate climate change mitigation aspects. This is made even more necessary by the fact that ALA is a continuous (i.e., both historically and presently relevant) and often unplanned land use change (LUC) that is already influencing soil carbon stocks and needs to be quantified. Therefore, the combination of robust datasets that produce region-specific rates of SCS with accurate and detailed maps of ALA in that region (i.e., the spatial body on which to apply the rates) creates the possibility to support effective and climate-smart land management policies (Vermeulen et al., 2019).

The EU-27 represents an ideal combination of data resources and land use history for an integrated, large-scale study on the soil carbon sequestration potential and implications of ALA. This is due to: the widespread historical and ongoing ALA (Lasanta et al., 2017; Levers et al., 2018; Ustaoglu and Collier, 2018); the recent political push for effective, efficient, and accessible soil carbon sequestration strategies (Montanarella and Panagos, 2021); the availability of published studies on soil properties and ALA (i.e., chronosequence data); and the detailed, robust, and up-to-date land use/cover inventory keeping that has produced high-resolution spatial projections of ALA (Perpiña Castillo et al., 2021). The continental coverage of published chronosequence and paired-plot data, in particular, allows for the quantification of total soil carbon stock changes following ALA, the determination of cluster-specific SCS rates, and the elucidation of the modulating factors on post-agricultural SCS. Despite the increasing focus on this topic in recent years, due to the complex interactions of these factors and their confounding effects, there remains much uncertainty on the direction of soil carbon response to ALA (i.e., increase, decrease, or no change), the intensity (i.e., how much change), and the duration (i.e., how long will the change last) in the various biogeographical regions of the EU.

In light of these needs and present opportunities for both research advancement and policy support, here we synthesized published chronosequence and paired-plot data from field sites within the EU-27 member states and explored the variability in SOC responses to ALA and direct conversion from agriculture to naturalized landscapes. We conducted a literature search to collate all previously synthesized data at different geographical scales with new synthesized published studies and categorized each chronosequence/paired-plot collected based on several key factors that may influence SOC stock dynamics (i.e., climate, biogeographical region, past land use, present land management). We expect a noticeable increase in SOC across the EU following abandonment/conversion, but with high variability in sequestration rates. These results are intended to provide important context on the soil carbon implications of land use change in the EU, particularly from a restoration perspective.

Methods

Literature search

Published chronosequence and paired plot studies undertaken in the EU-27 investigating the impacts of ALA (or direct land use conversions from agriculture) on grassland, shrubland, and forest succession were compiled for analysis following a literature search. While repeated measurements are the most ideal approach for determining the effects of land use change over time, chronosequences and paired plots are proven alternatives commonly employed (Breuer et al., 2006; Walker et al., 2010).

The literature search comprised of two parts. First, an initial dataset of relevant studies was established by selecting all the individual studies that included European sampling sites from the lists of references and/or databases of previously published synthesis studies on this exact or related topics (i.e., land use changes and soil properties) at any geographic scale (i.e., regional syntheses within Europe, syntheses of Europe, and global synthesis including Europe). This allowed us to collate all previously synthesized data in Europe into one combined dataset. The second stage of the literature search targeted all new and/or previously un-synthesized individual studies with relevant data. The following key terms were searched in November 2020 using ISI Web of Science with results limited to English language studies published in any year: (plough* OR till* OR crop* OR farm* OR agri* OR cultivat* OR *field OR pasture OR meadow OR grazing OR range*) AND (*forest* OR grassland OR shrubland OR natural OR secondary OR recover* OR plantation* OR conver* OR abandon* OR old* OR regenerat* OR *aside OR restor* OR succession* OR fallow OR revegetat*) AND (chronosequence OR pair*) AND (soil OR carbon). This search resulted in 4718, which were then sorted by geographic region, producing a subset of studies that had EU-27 related terms either in their title, abstract, or keywords (i.e., European country and/or geographic feature names that indicated potential sampling sites in the EU).

The list of relevant papers from these two parts of the literature search were then subjected to inclusion/exclusion criteria for data extraction. For an individual study to be included, the time since abandonment/conversion (years) and the SOC or soil organic matter (SOM) concentration or stock (various units) of the mineral soil at any depth of each chronosequence stage and paired plot must have been provided. Each chronosequence and paired plot must have featured one agricultural control field (i.e., actively cultivated, representing 0 years since abandonment/conversion). The following secondary criteria were either extracted from the studies themselves, provided by authors upon request, or determined through other online sources: sampling site coordinates (LAT/LONG), mean annual precipitation (mm), mean annual temperature (°C), past land use (cropland, pasture), post-ALA/conversion land management system (natural, assisted), and biogeographical region as per the European Environment Agency (Figure 1). Studies were excluded if they were in locations outside the EU-27 or if they failed to provide a means to determine any of the previously outlined criteria.

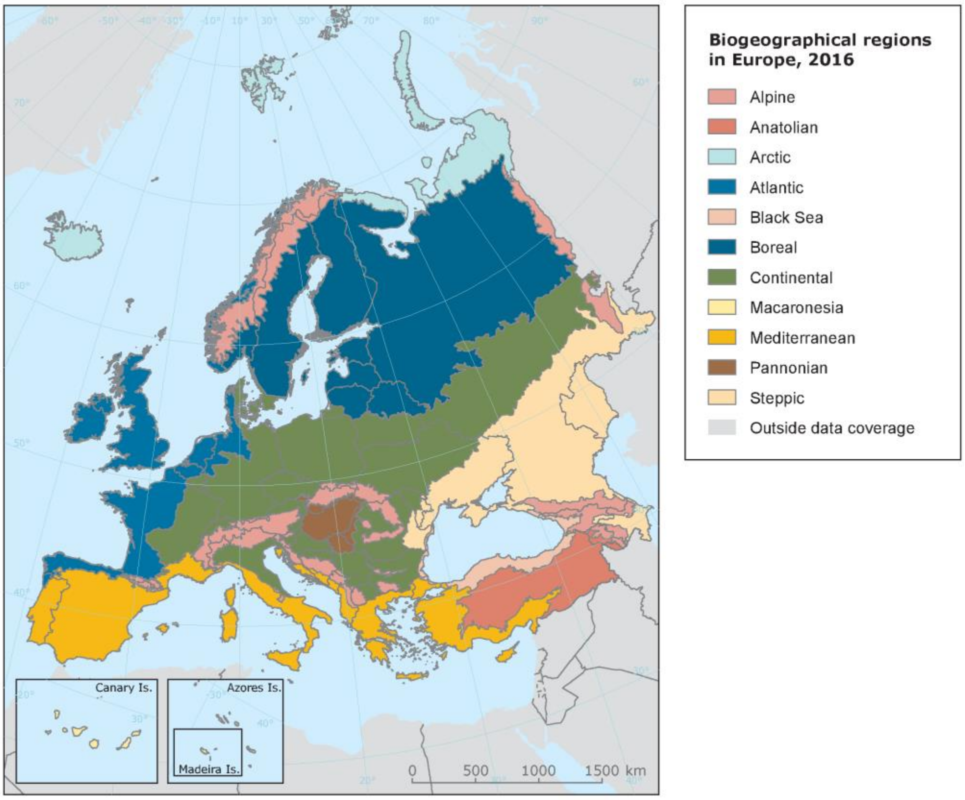

Figure 1. Biogeographical regions in Europe (EEA, 2021).

Data processing

A total of 87 published studies were identified under these criteria, ranging from 1994 to 2021 (see Supplementary Material). The final dataset featured 706 pairs of control and abandoned/converted soils throughout the EU-27, ranging in time since abandonment/conversion from 1-193 years (Figure 2).

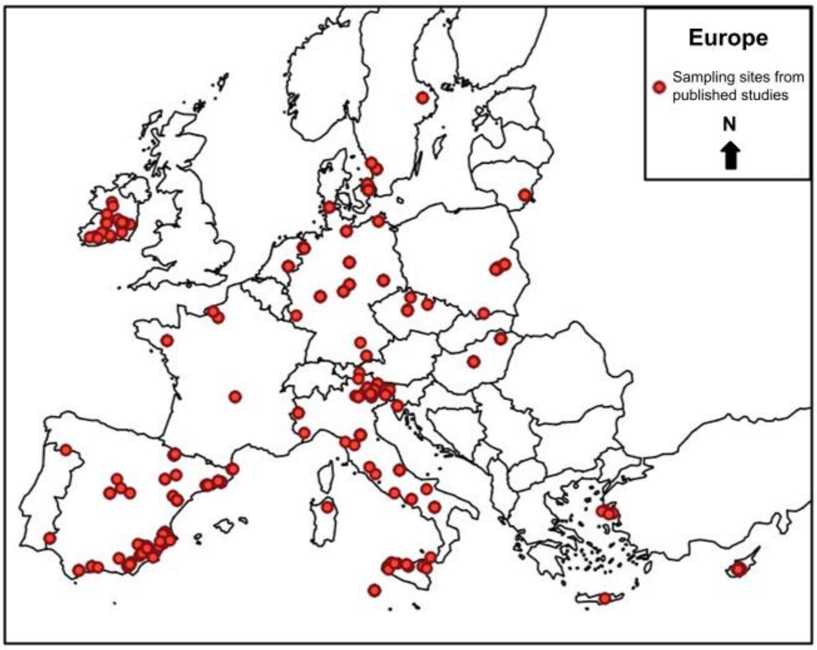

Figure 2. Map of sampling sites from the 87 published studies exclusively with EU-27 member states.

SOC, SOM, and other key data (e.g., bulk density, pH, etc.) were extracted from tables, text, by digitizing graphs (GetData Graph Digitizer, v.2.26, Russia), or by request to the authors. There were 398 data-pairs with SOC stock already reported. When only SOM data was provided, SOC concentration values were calculated from the Van Bemmelen conversion factor following Guo and Gifford (2002). For the data-pairs with measured bulk density reported (n=115), soil carbon stocks were calculated using Eq. (1):

$$SOC_{st} = SOC_c \times BD_m \times D \tag{1}$$

where SOC_{st} is the SOC stock (Mg ha^{-1}), SOC_c is the SOC concentration (%), BD_m is the measured bulk density (g cm^{-3}), and D is the soil depth sampled (cm). Following Benites et al., (2007), when bulk density was not reported (n=193), it was estimated using the available SOC data according to the pedotransfer function of Manrique and Jones (1991) shown in Eq. (2):

$$BD_e = 1.660 - 0.318(SOC_C)^{1/2} \tag{2}$$

where BD_e is the estimated bulk density (g cm^{-3}) and SOC_c is the SOC concentration (%). The estimated BD values were used to calculate the remaining SOC stocks according to Eq. (1). To standardize the effect of time since abandonment/conversion on SOC stock between the various chronosequences and paired plots of all the studies, all SOC data points were plotted as the relative difference from their paired agricultural control SOC values, according to Eq. (3):

$$\Delta SOC_{st} = \frac{SOC_{st\_post} - SOC_{st\_pre}}{SOC_{st\_pre}} \times 100 \quad (3)$$

where ΔSOC_{st} is the relative change in SOC stock (%), SOC_{st_post} is the SOC stock after abandonment/conversion (Mg ha^{-1}), SOC_{st_pre} is the SOC stock before abandonment/conversion (Mg ha^{-1}) (i.e., the control). The relative change in SOC stock data were fit to linear regressions with 95% confidence intervals to determine the general directional responses of SOC to time since abandonment considering various climatic factors, biogeographical regions, past land uses, and management factors (assuming significance at $p < .05$ and with visualizations using Grapher (Golden Software, v.15, USA)).

Results and Discussion

SOC dynamics following abandonment/conversion from agricultural practices

Despite notable variability in responses, abandonment/conversion from agricultural practices across the EU-27 results in a slow, but significant, rate of SOC stock increase of 1.14% yr^{-1} (n=706, $p < 0.0001$) (Figure 3.a). The average relative increase amongst the data-pairs is 34%, with an average time since abandonment of 33 years. On a logarithmic scale, the positive correlation between time and SOC stock change is more noticeable, reaching a clearer direct relationship at the X,Y extremes (i.e., it converges to a 1:1 correlation at longer time scales) (Figure 3.b). These results settle some of the previous regional debates on the positive/negative/neutral SCS potential of post-agricultural soils (Bárcena et al., 2014; Bell et al., 2021), which have likely been confounded by other key factors examined here below. However, the overwhelming variability of SOC responses in the first several decades cannot be ignored and indicates the importance of the time-scale examined. Long-term land management scenarios therefore must be detailed enough to represent the factors responsible to sufficiently capture this early uncertainty in SOC responses following land use change.

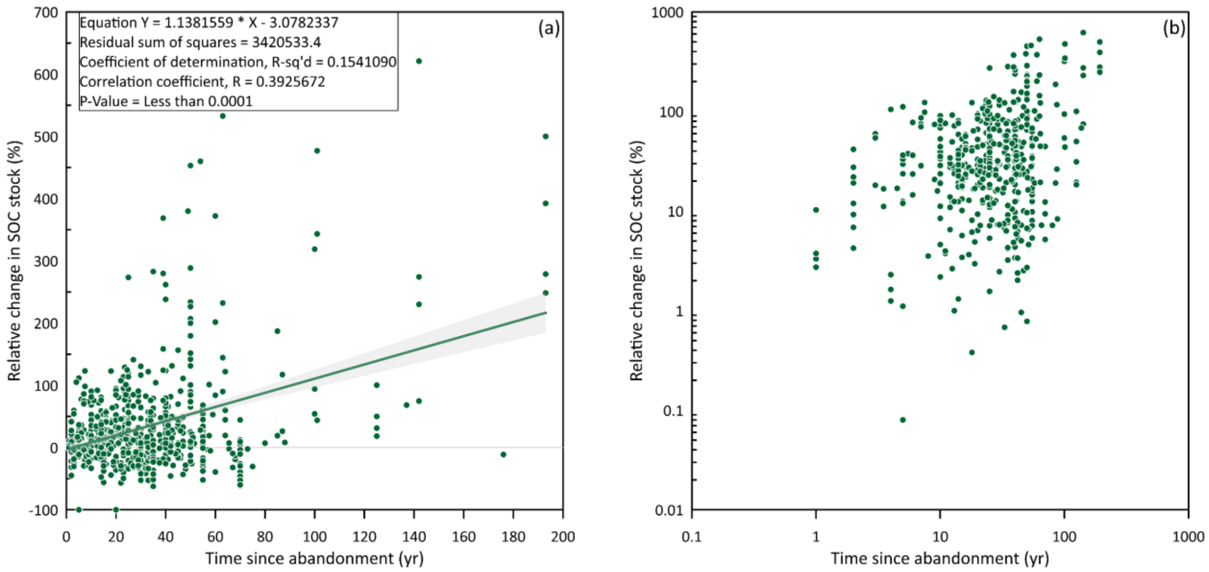

Figure 3. Relative change in SOC stock (%) over time since abandonment/conversion (yr) on a linear scale with regression results shown in the insert (a) and on a logarithmic scale (b). Shaded area represents 95% confidence interval.

The influence of the initial SOC stock at the time of abandonment/conversion is evident in Figure 4. The ability of post-agricultural soils with high initial SOC stocks to accrue new carbon were limited, whereas the soils with the highest relative increases in SOC stock were exclusively ones that had very low initial SOC stock (Figure 4.a). However, many soils with low initial SOC stock also had very low or even negative SOC responses to abandonment/conversion. Overall, the relationship between initial SOC stock and relative SOC increase is negative (Figure 4.b). This relationship is to be expected based on classical soil carbon saturation theory (Stewart et al., 2007), with the soils with greater initial stock presumably closer to their saturation limit and therefore with less capacity to accrue new SOC.

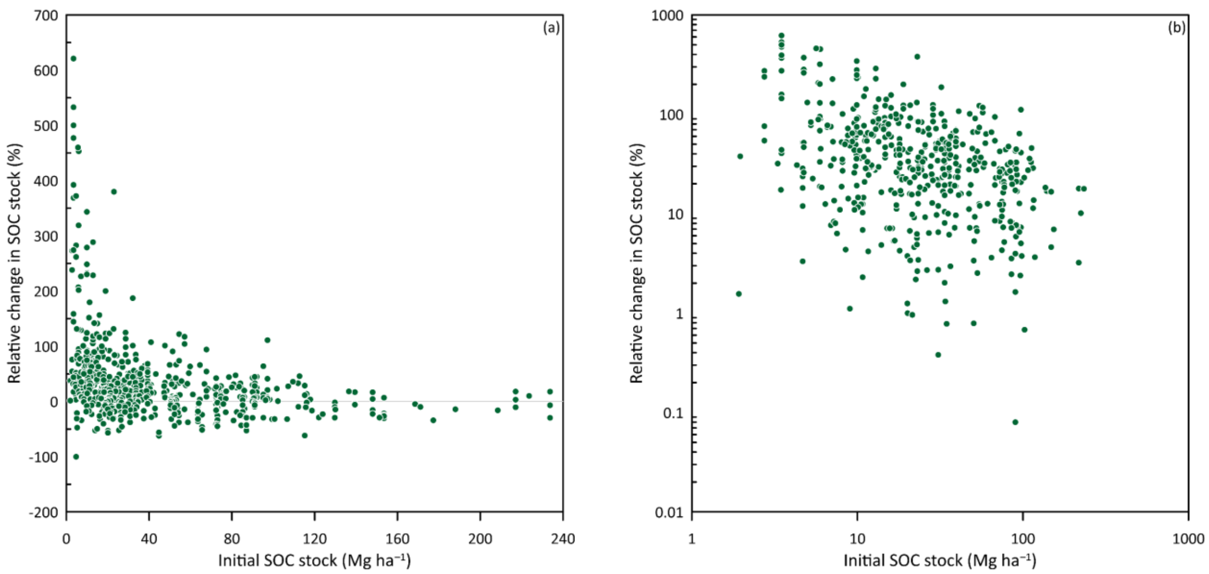

Figure 4. Relative change in SOC stock (%) against initial SOC stock (Mg ha^{-1}) on a linear scale (a) and on a logarithmic scale (b).

Amongst the different soil depth classifications examined, the relative change in SOC stock followed expected patterns (Figure 5). The highest rates of increase were found in the top-soil (<15cm), followed by the mid-soil (15-30cm). The sub-soil (>30cm) exhibited no change over time, with the potential of SOC losses after several decades.

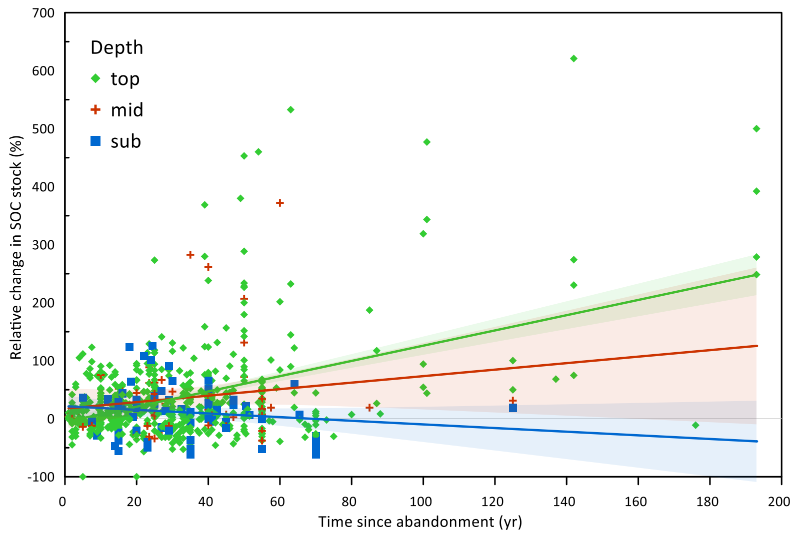

Figure 5. Relative change in SOC stock (%) over time since abandonment/conversion (yr) for different soil depths and their linear regressions. Depths include <15cm (top), 15-30cm (mid), and >30cm (sub). Shaded areas represent respective 95% confidence intervals.

Soil nutrients accumulation is known to be highest closer to the surface during ecological succession where there is comparatively more biochemical processes and exchanges occurring (Cramer et al., 2008b; Hu et al., 2018; La Mantia et al., 2013; Nadal-Romero et al., 2016). Although post-agricultural soil profiles may demonstrate a distinct legacy of tillage in having a lasting homogeneity (i.e., Sulman et al., 2020), it is also possible that the ability of new SOC to saturate deeper into the previously homogenized and SOC-depleted top/mid-soils is outpaced by the accrual of new SOC at the surface resulting in greater rates of SOC increases over time (Bell et al., 2021).

Climatic and biogeographical factors on SOC dynamics

The climatic regime present at the sampling sites had a notable influence on the rates of SOC change following abandonment/conversion from agricultural Figure 6. Similar to the results of a synthesis of natural succession post-agricultural chronosequences and paired-plots in peninsular Spain (Bell et al., 2021), the sampling sites distributed across the EU-27 were subject to an ideal temperature (Figure 6.a) and precipitation (Figure 6.b) window for post-agricultural SOC accumulation.

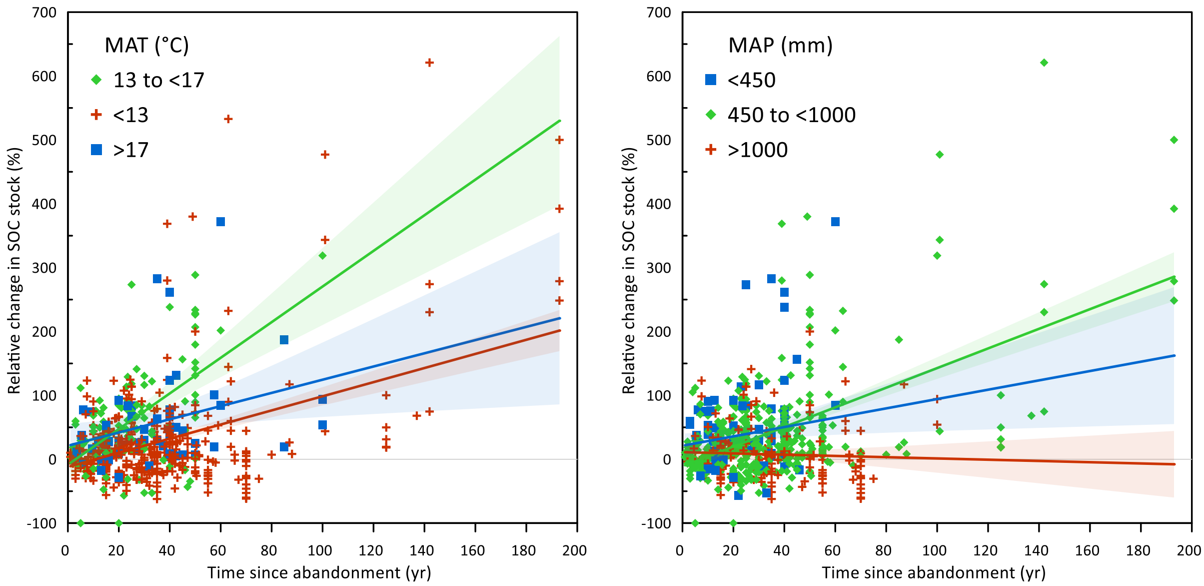

Figure 6. Relative change in SOC stock (%) over time since abandonment/conversion (yr) for mean annual temperature (MAT, °C, left panel) and mean annual precipitation (MAP, mm, right panel) and their linear regressions. Shaded areas represent respective 95% confidence intervals.

The positive rates of relative SOC stock change were greatest at mean annual temperatures between 13 and 17 degrees Celsius and at precipitations between 450 and 1000 mm per year. The apparent limiting effect of precipitation levels above 1000 mm per year have been reported across the Mediterranean and are likely the result of precipitation induced N leaching, decreases in aggregate protected SOC, and increases in less protected particulate SOM fractions (Alberti et al., 2011; Gabarrón-Galeote et al., 2015; Guidi et al., 2014; Navas et al., 2012). At the global scale, precipitation and SOC accumulation during ecological succession generally correlate negatively (Jackson et al., 2002), although dry conditions found in semi-arid climates (e.g., <450 mm yr^{-1}) can also limit net primary productivity (NPP) and therefore limit organic matter inputs that promote SOC accumulation (Bonet, 2004; Gabarrón-Galeote et al., 2015; Robledano-Aymerich et al., 2014). For grasslands on previously managed pastures, SOC also correlates positively with temperature and negatively with precipitation (Kämpf et al., 2016; La Mantia et al., 2013; Pellis et al., 2019). As a partial function of climatic conditions, the European biogeographical regions also display a wide variety of rates of change for SOC stock following abandonment/conversion Figure 7. These biogeographical regions are based on biota, unlike biomes, and emphasize endemic and/or spatially distinct and limited taxa and communities (Morrone, 2018).

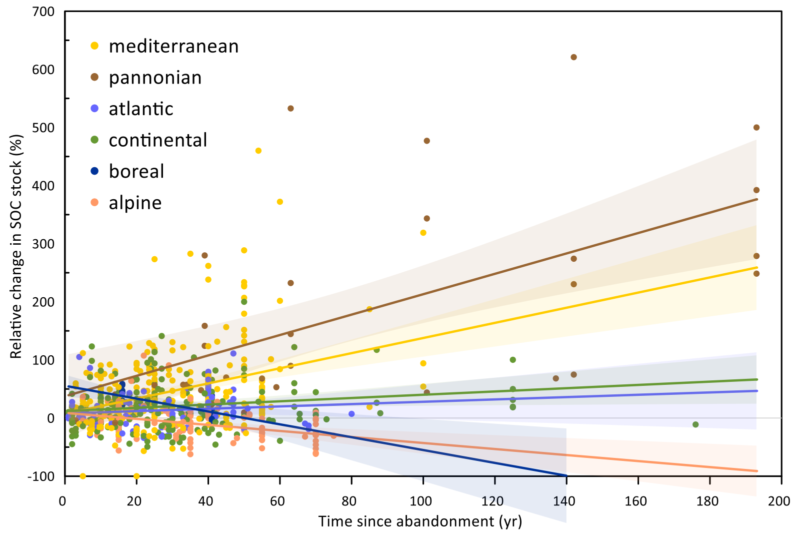

Figure 7. Relative change in SOC stock (%) over time since abandonment/conversion (yr) for the biogeographical regions in Europe and their linear regressions. Shaded areas represent respective 95% confidence intervals.

Some of the highest relative rates of SOC stock increase were from soils withing the Mediterranean biogeographical region (n=280, 1.3% yr^{-1}, p < 0.0001), likely attributed to the higher relative contribution of new organic matter production and inputs post-abandonment/conversion compared to the lower significance of such additions in landscapes with greater NPP (i.e., more temperate zones). In other words, the act of ALA/conversion can have a much more dramatic impact on Mediterranean agroecosystems in terms of SOM than in other regions (Bell et al., 2021). In accordance with this, we see a much lower relative rate of SOC stock increase in Continental soils (n=198, 0.28% yr^{-1}, p < 0.05), and even a negative rate (i.e., steady SOC loss) in soils within Alpine regions (n=94, -0.52% yr^{-1}, p < 0.0005), as the site conditions increasingly differ from Mediterranean.

Land use and management factors on SOC dynamics

Aside from abiotic factors across the EU influencing SOC response to ALA, such as climate and topography, human driven factors play a very significant role especially at smaller spatial scales (i.e., the plot or landscape). In this study, we explored the influence of past land use classification, namely cropland and pasture, and post-abandonment/conversion land management systems, whether natural succession or assisted restoration. Sites that were croplands before abandonment/conversion had a notably greater relative rate of SOC increase over time (n=543, 1.37% yr^{-1}, p < 0.0001) than sites that were previously used as pastures (n=156, -0.3% yr^{-1}, p < n.s) (Figure 8).

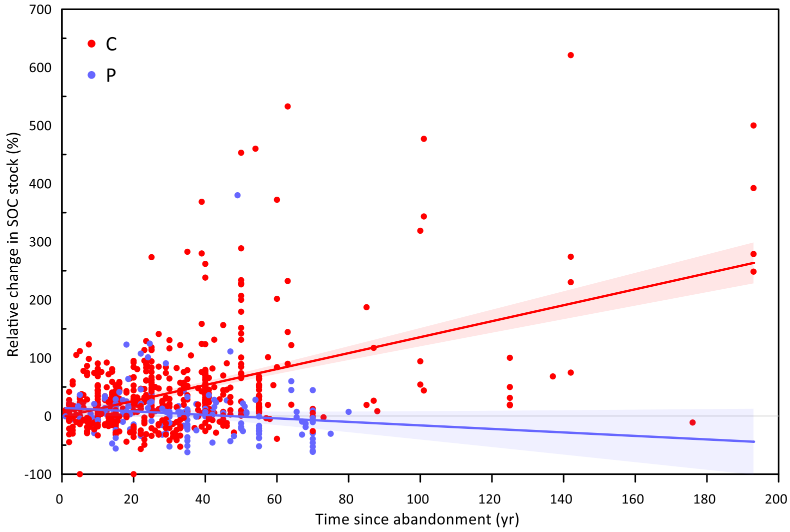

Figure 8. Relative change in SOC stock (%) over time since abandonment/conversion (yr) for post-agricultural sites that were croplands (C) or pastures (P), and their linear regressions. Shaded areas represent respective 95% confidence intervals.

Pastures are expected to have greater initial SOC stocks than croplands at the time of abandonment/conversion, resulting in a lower or negative relative changes in SOC stock as indicated in Figure 4. Croplands, on the other hand, may receive more intensive agricultural practices than pastures, including significant biomass removal and regular tillage, which depletes SOC stocks and allows for greater positive relative changes in SOC stock following the cessation of these practices (i.e., abandonment/conversion) (García et al., 2007). Although there is variation among cropland types, with cereal cultivation receiving SOM friendly management practices akin to pastures (e.g., manure application, stubble grazing, seed fallowing) compared to woody croplands that receive poor SOM management practices (e.g., pruned branch losses), croplands as a whole are generally under more SOM degrading management systems than pastures and meadows (Navas et al., 2012; Ruecker et al., 1998). Similar to past land use, the influence of post-abandonment/conversion management systems also produced divergent SOC responses in our dataset (Figure 9).

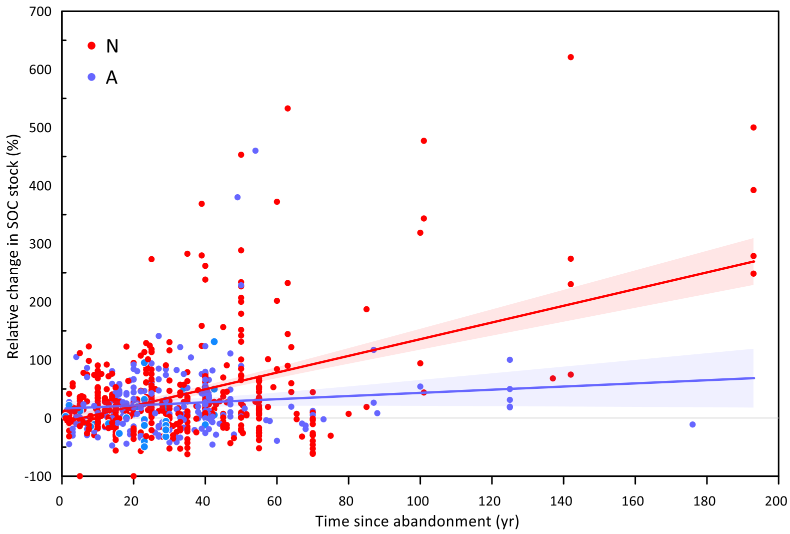

Figure 9. Relative change in SOC stock (%) over time since abandonment/conversion (yr) for post-agricultural sites that were managed through natural succession (N) or assisted restoration (A), and their linear regressions. Shaded areas represent respective 95% confidence intervals.

Sites that were abandoned from agriculture and left to undergo spontaneous ecological succession exhibited a greater rate of relative change in SOC stock (n=460, 1.47% yr^{-1}, $p < 0.0001$) compared to sites that were actively restored or converted to new vegetation land covers (n=208, 0.27% yr^{-1}, $p <$ n.s.). The potential of each management approach for SOC accrual certainly depends on conditions at the site of abandonment/conversion. For example, in the Mediterranean biogeographical region the long land use history involving intensive agricultural often requires specific forms of active restoration to overcome stalled vegetation recovery that natural succession may lead to (Garcia-Franco et al., 2014; Ruiz-Navarro et al., 2009; Segura et al., 2020, 2016).

Conclusions

The widespread historical and ongoing agricultural land abandonment across the EU-27 has resulted in slow, but steady increases in soil organic carbon stocks at an overall rate of 1.14% yr^{-1}. However, large variabilities in rates are apparent, with some post-agricultural landscapes losing SOC stock over time. In general, sites with low initial stock had greater potential for SOC accumulation while sites with high initial stock are presumably closer to SOC saturation and unlikely to exhibit large relative increases post-abandonment/conversion. Climatic conditions certainly influence the likelihood of an abandoned/converted agro-landscape to accumulate SOC, with the ideal mean annual temperature window being around 13 to <17 °C, and 450 to <1000 mm yr^{-1} for precipitation. Biogeographical regions with climatic conditions typically outside these ranges exhibited lower relative rates of SOC stock accumulation and even losses (e.g., alpine, continental). Both past land use (cropland vs. pasture) and post-abandonment/conversion land management strategy employed (natural vs. assisted) produced divergent responses in SOC change, implying that croplands managed through natural succession would show the greatest SOC accrual while pastures that are actively converted (e.g., afforestation) would result in the lowest increases in SOC, or even losses. This variability in post-abandonment/conversion SOC dynamics must be considered in sustainable land use planning that strives to incorporate the ecological and climate change mitigation benefits of agricultural land abandonment, taking into account site-specific conditions and past and present land management histories.

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Supplementary Material: List of papers synthesized

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