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Analyses of a long-term soil temperature record for the prediction of climate change induced soil carbon changes and greenhouse gas emissions in vineyards

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Abstract. Increasing soil organic carbon (SOC) stocks in Agriculture is discussed as a measure to reduce soil greenhouse gas (GHG) emissions with the potential to improve the balance between GHG emissions and carbon removal from the atmosphere, the so-called 4/1000 initiative. This implies that improving global SOC by 0.4% per year (4 per 1000) could largely compensate for GHG emissions. Yet it is difficult to deduct the impact of climatic change and cultivation practices on patterns of carbon storage or losses from soils specifically because changes in soil temperature are mostly not considered. Here an attempt is presented to quantify these potential impacts on SOC for a vineyard location using the RothC-model (Coleman and Jenkinson, 2005) in combination with the Geisenheim long-term (>100-year) soil temperature record and climate predictions by the STAR II-model of the Potsdam Institute of Climate Impact. It is shown that retaining pruning wood and using a full cover crop yielded a SOC increase of 16.2 t C ha^{-1} over time. However, CO_2 emissions over the simulated time span were only slightly less than C-storage in the soil. It is concluded that cover crops in vineyards help to achieve CO_2-neutrality but additional measures are required to make vineyards a significant C-sink.

1. Introduction

The Paris Agreement as a legally binding international treaty on climate change, which was adopted by 196 Parties on 12 December 2015, has at its core the aim to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius (°C) above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees °C. Directly after the Paris agreement, the French Ministry of Agriculture launched the 4 per 1000 initiative to demonstrate that agriculture, and in particular soils, play a crucial role where food security and climate change are concerned. Increasing the carbon content of soils by 0.4% or 4 per 1000 per year, could compensate for the yearly anthropogenic release of CO_2 into the atmosphere (https://www.4p1000.org).

The initiative was basically a result of preceding publications proposing the sequestration of carbon in soils as a win-win scenario to mitigate climate change [1, 2]. The initiative also referred to the potential for GHG emission reductions through wise soil management that increases SOC, tightens the soil nitrogen (N) cycle which could enhance fertility and productivity, increase soil biodiversity, reduce erosion, runoff and water pollution and contribute to buffer crop and pasture systems against the impacts of climate change [3]. General estimates assume that between 1.500 and 2.500 gigatons (1 gigaton = 1.000.000.000 tons) of carbon are stored in soils globally, more than in the atmosphere and vegetation on earth combined [4-6]. Thus, increasing net soil C storage by even a few percent could represent a substantial C sink potential.

The inclusion of soil-centric mitigation projects within GHG offset markets (i.e. verified carbon standard (2022), American carbon registry (1996-2022), EU-COWI carbon farming initiative (2021)) and new initiatives to market “low-carbon products” indicate a growing role for GHG mitigation in agriculture [7]. Therefore agriculture in general is putting more attention to soils and cultivation systems to reduce GHG emissions and usage of soils as carbon storage component.

In the recent past various funding programs on soils have been launched in different countries which can also be used to support Viticulture, such as the Emissions Reduction Fund in Australia or the Healthy Soils Program in California or the European COWI-EU farming initiative

(2021), which has recently provided an outline about methods and sampling frequency for the determination of SOC.

While many policy instruments are relevant to soil protection, soils lack a dedicated legislative framework at EU level, equivalent to those protecting water, marine environment and air. In its resolution of 28 April 2021 on soil protection, the European Parliament called on the Commission to design an EU-wide common legal framework, with full respect for the subsidiarity principle, for the protection and sustainable use of soil, addressing all major soil threats. It asked for the proposal to be accompanied by an in-depth impact assessment based on scientific data, analysing both the costs of action and non-action in terms of immediate and long-term impacts on the environment, human health, the internal market and general sustainability.

On 17 November 2021, the European Commission presented, as part of the EU biodiversity strategy for 2030, a new EU soil strategy [8]. The strategy, encompassing non-legislative and legislative actions, aims to bring all EU soil ecosystems in good condition by 2050. One flagship initiative announced in the strategy is a new Soil health law to address transboundary impacts of soil degradation and achieve policy coherence at EU and national level. On 5 July 2023, the Commission tabled a proposal for a directive on soil monitoring and resilience ('soil monitoring law'). In line with the soil strategy, the long-term objective of the proposed directive is to have all soils across the EU in healthy condition by 2050 which the Parliament adopted its first reading on 10 April 2024.

Pellerin *et al.* [9] have calculated the costs and benefits additional carbon storage would have for different agricultural commodities to provide a baseline for financial carbon compensation. Nevertheless, these programs have also been criticized as being ineffective [10]. Due to the uncertainty about the dimensions of the potential storage capacity in soils, several studies have attempted to quantify potential changes in C for vineyards. Depending on the environmental conditions and the cultivation practices, the estimates for C sequestration vary widely [11]. In most cases C storage in above-ground biomass were found to be substantial [12-14], with storage capacity below ground being highly variable depending on soil and root respiration rates [14, 15] and induced by differences in cultivation practices and the absence or presence of soil amendments which consequently could result in a range from net GHG emissions or C-loss [16] to C-gain [16-18].

Minasny *et al.* [19] conducted a study on the 4 per 1000 initiative and identified vineyards and orchards in France as areas with a high SOC sequestration potential. In agreement, Pellerin *et al.*[9] in a study on all soils in France also estimated the potential of vineyards for a net CO_2 extraction from the atmosphere using models developed for corn, wheat, perennial plants and permanent pastures (STICS and PaSim) to be significant. In a recent meta-analysis of data on soil amendment practices to increase SOC, Payen *et al.* [20] reported a positive effect irrespective of the amendment used but with large variations between amendments (for example prunings retained in the vineyard versus organic amendments such as manure, compost, sludge or biochar).

Some publications have actually stated that under best practice management equal or even higher sequestration rates than those implicit in the 4 per 1000 initiative may be accomplished [19, 21], whereas others have criticized the non-consideration of priming effects (addition of organic matter may at first increase decay-rates), climate induced changes in soil temperature and the equilibrium point of maximum C-storage in these studies and estimated that the C sequestration potential is much lower as strived for by the 4 per 1000 initiative and thus will not provide a major offset for greenhouse gas emissions [22-25].

Based on the difficulties and uncertainties in estimating SOC and the potential effects of climate change and soil cultivation, the present study had four objectives. (1) Analysing a long-term record on soil temperatures. (2) Use an established soil carbon and CO_2-emission model and compare the results to measured values of SOC over time. (3) Estimate the effect of already observed long-term average changes in soil temperature on SOC with two different cultivation practices, one using a permanent cover crop and one with a six month autumn-winter cover crop. (4) Use output data from a climate simulation model to predict future changes in SOC if the two cultivation practices are permanently retained.

2. Materials and Methods

2.1. Soil temperature measurements

Soil temperature measurements started in Geisenheim on the University campus (49.9836 °North, 7.9602 °East) being serviced through the German Weather Service (Deutscher Wetterdienst, DWD) on April 1st 1919 at four depths (10 cm, 20 cm, 50 cm, 100 cm), three times per day (7 am, 2 pm, 9 pm) with the exception for the 100 cm depth, which was only measured at 2 pm until January 1st 1997. From then on, it was also measured three times per day.

Starting July 1st 1947, measurements at 5 cm depth were added three times per day. The measurement field was changed three times during history. On April 1st 1936 it was moved to a vineyard location just outside the campus (49.9856 °North, 7.9563 °East), then again closer to the DWD station on August 1st 1983 (49.9866 °North, 7.9548 °East) and finally to its current position with an automatized system on December 1st 2006 (49.9859 °North, 7.9548 °East). Largest distance between sites is less than 300 m. Soil on all sites was described as deep, sandy loam to loamy with a very small stone fraction and a neutral pH [26]. Since no immediate differences in soil temperature data were noted each time the measurement location was changed, it was assumed that soil temperature values were unaffected. The observation that changes in the long-term soil temperature record occurred outside the near time-vicinity of changes in measurement sites may serve as an additional indicator for the absence of a location effect.

The time series is not continuous. Missing values comprise the periods 21st March 1945 – 1st May 1945 for the 10 and 20 cm depths and from 1st of May 1945 – 17th January 1946 for all depths except at 50 cm. Periods with missing measurement values thereafter occurred for all depth during 10 days in February 1969, 7 days in February 1977 and on several individual days between 1st January 1996 and 31st December 2006 for the measurement depth at 5 cm, 10 cm, 20 cm, and 50 cm. To estimate missing values during this time period, linear extrapolation was used between the values of the neighbouring days. Temperature measurements were conducted with standard mercury thermometers until December 1997 and with electronic resistance thermometers (Pt100) thereafter. Measurement plots were kept free of vegetation. Temperature data shown are those from the 2 pm measurements.

2.2. Weather data

A weather station is located on campus and in the past has been serviced by the DWD and the University. The climate in Geisenheim can be categorised as humid temperate. Annual precipitation is 544 mm (1981-2010) (DWD) and is approximately equally distributed throughout the year (maximum in July with 60 mm, minimum in April with 35 mm). Mean potential evapotranspiration (ETp) between April 1 and September 30 is on average 605 mm but has been observed to increase over the last approximately 40 years [27].

2.3. The Rothamsted RothC-26.3 model for the turnover of carbon in soil

The model has been developed by Coleman and Jenkinson [28] based on several earlier versions and original data from the Rothamsted classic experiment [29] and is freely available as a Windows version. The model has previously been used in studies on climate change effects on a large array of soils and climate conditions across German croplands [30, 31] and also on conversion scenarios from cork oak forest to vineyards with different follow-up management systems [32]. It has also been included in global C cycling models [33].

The model calculates the turnover of organic carbon and allows for the effects of soil type, temperature, moisture content and degree of plant cover on the turnover process. It consists of five different pools: decomposable and resistant plant material, microbial biomass, humified organic matter and inert carbon. It uses a monthly time step to calculate total organic carbon (t ha^{-1}) and CO_2-emissions (t ha^{-1}). The required climate data as input comprise monthly average air temperature (°C) with the argument that soil temperatures are not readily available and soil temperature values follow air temperature values. For the Geisenheim site this has been shown as a valid assumption [34], although some deviations may occur. Due to the lack of sufficient data, likely differences in soil temperature for bare soil as compared to temperatures below cover crops [35] were ignored and model runs were performed for all scenarios with the same set of temperature data. For the prediction of GHG emissions, soil and air temperature data have been judged equally useful [36]. Additionally monthly precipitation rates and ETp values are required. The model allows two types of simulations: "direct" that uses the known input of organic carbon to the soil to calculate SOC, and "inverse" that evaluates the input of organic carbon required to maintain the stock of SOC.

Inputs are also required on the clay content of the soil (in our case 24% was used) since this adjusts the partitioning between CO_2 evolved and the microbial biomass and humified organic matter during decomposition and the depth of the soil layer in question (25 cm). For the type of soil cultivation, it is only possible to distinguish between 100% cover crop and bare soil. The addition of plant residues per month (t C ha^{-1}) is also required. In this study, rates of 0.3 t C ha^{-1} for pruning wood in January and February and 0.15 t C ha^{-1} for March were used based on estimates from a vineyard site of the University and data from a literature review [37]. The only other additional input was on C from leaf drop in autumn, with 0.36 t C ha^{-1} for October and November estimated from spacing and canopy height and based on cited values of [37].

An estimate of the decomposability of the incoming plant material is also required. This needs to be estimated by the ratio of Decomposable Plant Material (DPM) to Resistant Plant Material (RPM). The model provides four choices since in most cases these data are not known, agricultural crops and improved grassland (DPM/RPM 1.44), unimproved grassland and scrub (DPM/RPM 0.67), and deciduous and tropical woodland (DPM/RPM 0.25). For the initial model runs in this study a ratio of 0.25 was used assuming pruning wood consists of a large amount of relatively resistant plant material.

2.4. Constructing a climate change scenario

In order to estimate future changes in SOC and CO_2 emissions for a vineyard, a data file on the required inputs previously constructed for the estimation of future changes in ETp [27, 38] was used that also contained temperature and precipitation data. This file is based on model-outputs of a regionalized version of the STARII model of the Potsdam Institute of Climate Impact [39]. The STARII model constructed time series from 2007-2060 by resampling of observed weather data according to trend information of the Global climate model ECHAM5/OM with the A1B scenario (SRES, Special Report on Emission Scenario) [40]. This scenario is roughly equivalent to the RCP 6.0 (Representative Concentration Pathways) currently used to simulate different scenarios [41] with an estimated CO_2-concentration of 650 ppm by 2100 (https://www.globalchange.gov/browse/multimedia/emissions-concentrations-and-temperature-projections).

This approach provides physical consistency of the combination of the weather variables and is in close agreement compared to the statistics of observed climatology [39]. Additionally and as a comparison, different regionalised simulation models were used based on different climate change scenarios to simulate trends in ETp until 2100 based on Hofmann et al. [42].

3. Results and Discussion

3.1. Soil temperature observations

Figure 1 shows a 105-year time series of average summer (June, July, August, JJA) soil temperatures across the entire soil profile. Summer soil temperatures were about 6 °C warmer than autumn temperatures over most part of the last century until about 1985 (data not shown). After this, JJA temperatures increased faster than SON temperatures. Whereas exceptional warm seasons have occurred throughout the measurement period, 16 of the 20 warmest years were recorded since 2000 with some remarkable "jumps" over the past 14 years (Fig. 1).

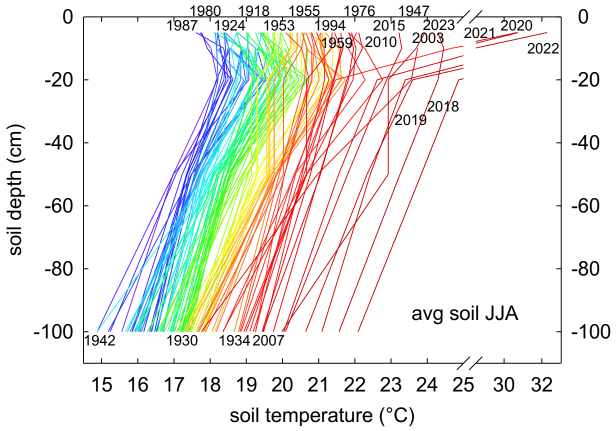

Figure 1. Development of the average soil temperature at 2pm for the summer months (JJA, June, July, August) across the soil profile over the period 1919 – 2023. Some years are indicated for orientation.

Average observed temperature increases in the soil were similar to those observed over the same time span in the air for winter and autumn, but slightly larger for the spring and summer seasons (data not shown). Long-term records on soil temperature are not very common, but increasing temperatures have been reported for different parts of the world (for example Eastern Australia, [43], Canada, [44], China, [45, 46], Turkey, [47], or Russia, [48]). Observed warming rates were larger in the northern, cooler regions, than in the warmer southern regions for China and Russia [45, 48]; however, the trend was less clear for Canada. For the whole of Canada, the annual mean soil temperature increased by 0.6 °C during the last century (1901-1995) at a depth of 20 cm, which is much less than in the current study (up to 6 °C) but also represented a huge study area.

Irrespective of the pattern and extend of the increase in soil temperatures, they are likely to have already profound effects on microbial-community characteristics, activity and thus C turn-over rates [49]. The strong warming response of the soil might be related to progressively lower soil water content of the top-soil layers during the last approximately 25-years during that particular time of the season. The less soil water, the more solar radiation is converted into sensible heat (measurable as temperature), whereas with higher soil moisture some of the incoming energy is used to vaporize water [50]. The sudden deviation of the soil temperatures to very high temperatures in recent years in upper layers is supporting this explanation while the strong warming extended down to 1m soil depth (Fig. 1).

Since both temperature and moisture play a role in soil respiration and the decay rates of organic matter and thus GHG emissions from soils [51], considering both factors in approaches to model changes in SOC is important [28, 44].

In a meta-analysis of the effects of experimental soil warming on soil respiration in different global biomes, a reduction in moisture in all sites was observed [51], but only a weak correlation to soil respiration changes. Similarly, no effect of warming on the diversity of microbial communities in temperate vineyard soils was found [52] which might point to some adaptive responses to changes in the environment.

3.2. Simulated SOC changes using the RothC-26.3 model

The RothC-model was tested on measured SOC data over a period of 14 years (2008-2021) after re-cultivation and planting [34] on a plot with 100% surface area under a natural cover crop. Measured SOC values were highly variable but increased from 2010 on, which the model was capable of tracing when run in a complete vegetation cover mode and with the parameters listed as inputs (pruning wood and leaf mass, see Materials and Methods). When the model was run with the same input conditions but with bare soil (tillage mode) from April to September, simulated SOC decreased slowly. Open soil or tillage has been shown to decrease SOC under conditions of no or low C-input from other sources in many crops including vineyards [11, 20, 54, 55].

3.3. Simulations of climate change effects

In order to simulate climate change effects on SOC, ETp is needed as an input.

3.3.1. ETp

Figure 2 shows the development in average annual ETp over the period 1957 to 2023 as compared to the simulation with several regionalized climate change models for a RCP 4.5 scenario and the STAR II model for a RCP 6.0 scenario. The observed increase in ETp is stronger than the simulated RCP 4.5 scenarios irrespective of the model. The STAR II model based on a RCP 6.0 scenario mimicked the development reasonably well (Fig. 2). Nevertheless, showing individual ETp values for the five most recent years, 2018-2023, indicates that the trend in the increase of ETp may actually accelerate and develop beyond RCP 6.0. This trend is mainly based on changes in vapour pressure deficit of the air (VPD). As compared to the beginning of measurements (1930) average daily VPD has increased 63% in summer (JJA) and 44% in autumn (SON) (data not shown). In the absence of any clear pattern on precipitation changes [34], increasing VPD and thus altered ETp is the most likely candidate causing stronger soil surface drying.

3.3.2. SOC and CO_2-emissions

In order to quantify the effects of already observed changes in soil temperature on SOC development and CO_2-emissions, the difference of the seasonal values at a depth of 20cm and the other seasons (DJF, December, January, February; MAM, March, April, May; SON, September, October, November) for the time span 2000-2021 as compared to 1961-1990 (DJF + 1.25 °C; MAM + 1.42 °C; JJA+1.51 °C; SON+1.19 °C) were added to the input data to run the model over the time span from 2009 to 2021 (Fig. 3 adapted from [34]).

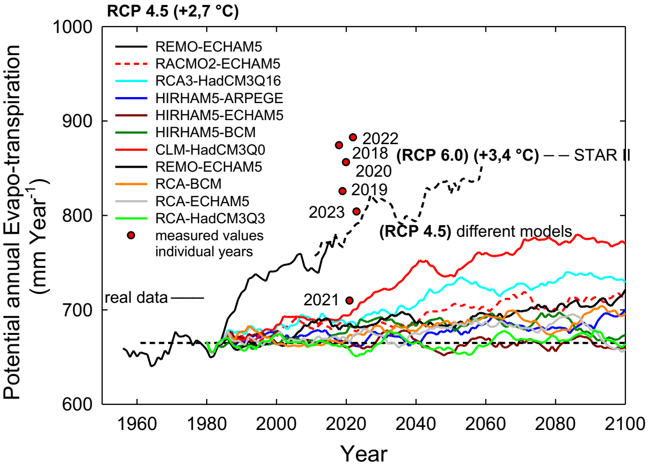

Figure 2. Annual reference evapo-transpiration, ETp, of 10 climate simulations for the weather station Geisenheim (Rheingau, Germany). Coloured lines show 11-year running means for individual model runs. The period 1957 – 2017 shows 10 year-running means for observed ETp data. Subsequent years 2018-2023 are shown as individual measurement points. STAR II RCP 6.0 simulation for the same station is shown as dashed line starting in 2011. The graphic is a modified and updated version from [42].

The effects of differences in cultivation practices remained much larger than the effects induced by changes in temperature. With cover crop, SOC build-up was reduced by only about 1 t C ha^{-1} with additional SOC losses in the partly bare soil version of the same order of magnitude (Fig. 3A). Changes in CO_2-emission rates were inverse to those in C-storage (Fig. 3B). Accumulated CO_2-emissions over 13 years were nearly twice as high in the partly bare soil treatment as with a complete cover crop irrespective of the soil temperature effect (Fig. 3B). Differences in soil temperature of bare as compared to covered soil (not considered in this study) may have modified these values.

Yang *et al.* [35] in a study comparing soil temperature below various clover mixtures to bare soil in a humid clay soil in Canada found no differences in average temperature at soil depths between 15 to 60 cm between August and May over two consecutive seasons. However, season-specific differences were apparent with below cover crop temperature being cooler in spring (up to 3 °C at 15 cm, and 1.8 °C at 60 cm depth) and warmer in winter (not quantified over longer periods) [35]. Since temperature response of decay rates or organic matter are non-linear in the Roth-C model [28], these differences need to be incorporated in future studies.

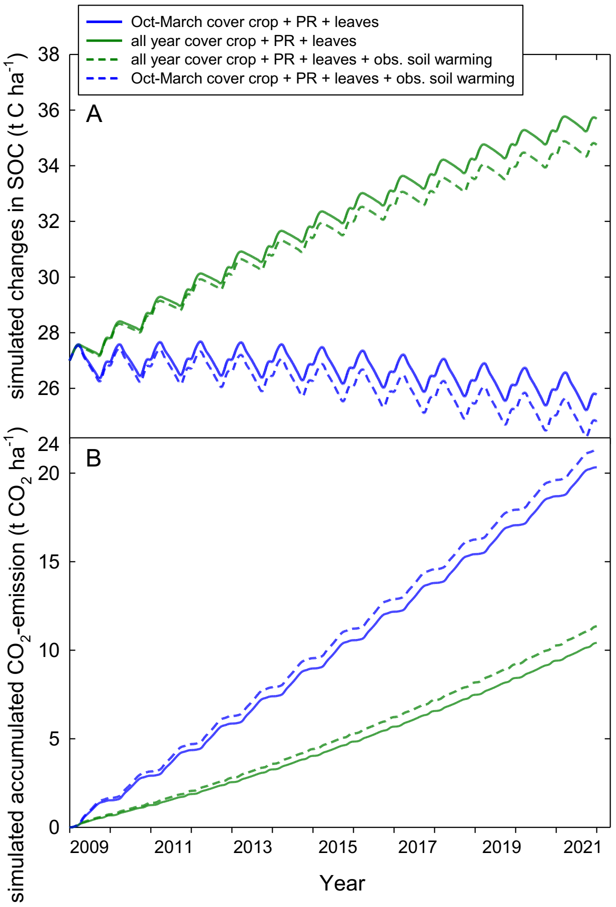

Figure 3. Simulated changes in SOC values (A) and concomitant CO_2-emissions (B) for a vineyard with full cover crop throughout the year and part time cover crop (October to March) using the RothC-model. Simulations were based on real climate data for that particular period (continuous lines) and a second run adding the observed temperature changes for 2000-2021 as compared to 1961-1990 at a depth of 20 cm (from [34]).

Using a RCP 6.0 equivalent scenario with the STAR II model for the two cultivation practices to predict SOC changes from 2009 up to 2060 for the permanent cover crop showed very good agreement between the simulation based on real data input (2009 until 2021) and the one based on the STAR II predictions (Fig. 4). SOC values approached an equilibrium stage towards the end of the simulation period with a total gain in SOC of 18 t C ha^{-1} over a 61 year period (average 0.3 t C ha^{-1} y^{-1}). Estimates show that it will take between 20 and 200 years for a soil to reach a new equilibrium depending on the initial conditions and the treatments applied [56]. Morlat and Chaussod [57] have demonstrated how SOC is affected in vineyards when different amendments were used in a long-term study (30 years). Irrespective of the treatment, a plateau of maximum SOC was reached after about 22 years despite continuous addition of external C indicating the finite storage capacity of soils.

For the partly open soil (tillage) scenario, simulations based on the real weather data showed a much faster decrease in SOC stock, than the one predicted by the STAR II scenario. Nevertheless, keeping the soil part of the season bare will inevitably lead to C-losses, albeit small over the time span considered (-2 t C ha^{-1}, Fig. 3). The concurrent accumulated CO_2 emission rates reveal the dilemma in devising the correct strategy for soil management. The C-balance of this treatment over the 61 year time span was strongly negative (Fig. 4). SOC losses and CO_2-emissions combined accounted for 23.4 t C ha^{-1} lost until 2060 (data not shown) [34].

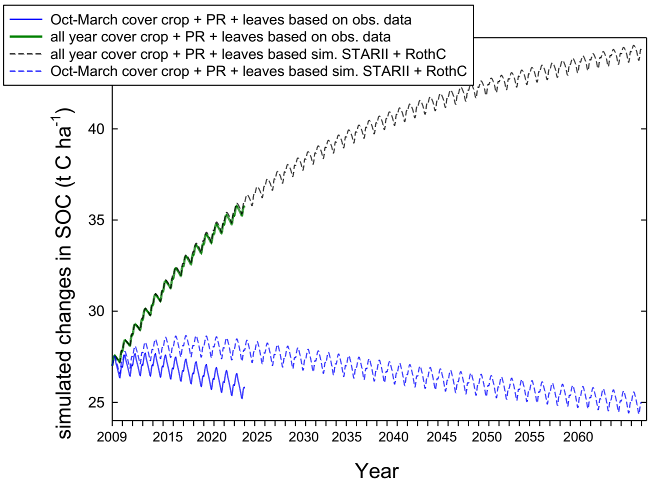

Figure 4. Simulated changes in SOC values for a vineyard with full cover crop throughout the year and part time cover crop (October to March) from 2009 until 2060 combining the RothC-model with a STAR II model prediction of air temperature, rainfall and ETp based on an A1B/RCP 6.0 scenario (dashed lines). Continuous lines represent simulations based on real climate data as input between 2009 and 202 (from [34]).

Running the RothC-model with the two different cultivation practices, showed the importance on SOC development in a climate change scenario. Previous uses of Roth-C for the estimation of SOC have mostly shown substantial decreases [30, 31, 58] over time. To evaluate these results, it is necessary to take the base conditions under consideration. For example, in the study by Wan *et al.* [58] for 626 original grids (50 x 50 km) on agricultural soils across China, using A2 and B2 climate change scenarios, SOC losses by 2050 were estimated to be 12% in northern China (A2) and 7.7% (A2) and 4.5% (B2), respectively, in southern China. For the stronger warming scenario, this resulted on average in a SOC decrease of 6.8 t C ha^{-1} compared to the baseline values of the 1980s. In these simulations, the pre-conditions were no addition of manure or crop residuals and open tillage. As a comparison, the part-time tillage simulation with some crop residues added of the present study resulted in a loss of 5.5% by 2050, thus an accumulated SOC loss of 1.5 t C ha^{-1} (Fig. 4).

Estimates for the development of SOC in German croplands are actually on the same order of magnitude (-0.59 t C ha^{-1} over the next 30 years) [59]. Running the RothC and other models in inverse mode, thus estimating what would be necessary to add in terms of organic carbon in order to maintain current stocks, Riggers *et al.* [31] estimated between 1.3 t C ha^{-1} and 2.3 t C ha^{-1} depending on the climate change scenario for the same croplands (991 sites) by 2099. To achieve the goals of the 4 per 1000 initiative, organic carbon additions in the order of +5.5 t C ha^{-1} to 7.1 t C ha^{-1} would be required [31].

In cases when the RothC-model or a further refined version (CarboSOIL) were used for the simulation of SOC developments in vineyards with different cultivation practices in the Mediterranean (Sardinia, Italy), different outcomes were predicted [32, 60].

Comparing a grassed vineyard (drip irrigated) with pruning residues remaining in the vineyard to a 40 cm deep tilled vineyard with pruning wood removed, earlier predictions showed a decrease in SOC stock for both treatments in the range of 8.3-9.5% (grassed vineyard) and 13.3-13.6% (tilled vineyard) of initial stock (36.3-37.5 t C ha^{-1}) over 90 years irrespective of the climate scenario (A2 or B2) and climate model used after a previous conversion from a cork forest [32]. Muñoz-Rojas *et al.* [60], for the same sites simulated slight increases in SOC in the soil layer 0-25 cm (0.2-1% by 2050), but a slight decrease (0.2-0.5%) in the tilled and grassed (0.4-1%) vineyard in the soil layer between 25 and 50 cm.

In the present study retaining pruning wood and using a full cover crop yielded a SOC increase of 16.2 t C ha^{-1}, thus an average increase of 0.32 t C ha^{-1} y^{-1} by 2050 slowly approaching an equilibrium stage. Keeping the soil bare for the April to September period yielded C-losses. If all model assumptions are correct and without consideration of the concomitant CO_2-emissions and an original SOC content of 27 t C ha^{-1}, the 4 per 1000 goal would be met on first sight. Considering CO_2-emissions, which proceed more or less linearly over the time span studied (see also Fig. 3), the net gain in the system C falls short of the 4 per 1000 goal. Thus, depending on the soil type and the cultivation practices the question on the real potential of vineyard soils as C-sink remains open.

Additionally, the use of cover crops may be critical when water resources are scarce [11, 61]. Wolff *et al.* [54] in a detailed study on the effects of soil management on the global warming potential (including GHG emissions from fuel for management) in a Californian vineyard found that the environmentally best treatment (net negative global warming potential) had a 32% reduced yield as compared to the treatment with a positive global warming potential, probably due to increased water deficit by the permanent cover crop.

Pellerin *et al.* [9] estimated the C-sink potential for French vineyards. They concluded that a permanent cover crop (2/3 cover) should be applicable on about 150.000 ha vineyards which would lead to an additional sequestration of 246 kg C ha^{-1} y^{-1} (tot. of 36.900 tons C y^{-1}) and a part-time cover crop (winter) could be used on 410.000 ha and would sequester about 159 kg C ha^{-1} y^{-1} (tot. of 65.190 tons C y^{-1}). Despite the fact that their study did not include possible effects of climate change and could only give a rough average across many different regions with vastly different conditions, the results are in line with the simulations presented in the present study or data such as those presented in a review [11]. Wolff *et al.* [54] also found comparable C-storage values in the soil of 306 kg C ha^{-1} y^{-1} in the least invasive minimum tillage and cover crop treatment and only 47 kg C ha^{-1} y^{-1} in the treatment with 2 tillage and one mulch passes.

The model also offers the possibility to add different forms of organic carbon and calculate the response of SOC and GHG emissions. This feature has so far not been used but should be extended in order to increase the efforts to determine best practice scenarios for regions and individual vineyards for the future. Since many amendment practices have a positive effect on SOC and can reduce GHG emissions [11, 22], this feature needs to be considered for a wide range of vineyard situations across different climatic regions in order to evaluate if a 4 per 1000 goal is realistic and for what time span.

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