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ORIGINAL RESEARCH ARTICLE

Soil, vine, climate change; the challenge of predicting soil carbon changes and greenhouse gas emissions in vineyards and is the 4 per 1000 goal realistic?

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ABSTRACT

The evaluation of the current and future impact of climate change on viticulture requires an integrated view on a complex interacting system within the soil-plant-atmospheric continuum under continuous change. Aside of the globally observed increase in temperature in almost all viticulture regions for at least four decades, we observe several clear trends at the regional level in the ratio of precipitation to potential evapotranspiration. Additionally the recently published 6th assessment report of the IPCC (The physical science basis) shows case-dependent further expected shifts in climate patterns which will have substantial impacts on the way we will conduct viticulture in the decades to come.

Looking beyond climate developments, we observe rising temperatures in the upper soil layers which will have an impact on the distribution of microbial populations, the decay rate of organic matter or the storage capacity for soil organic carbon (SOC). All this influences the emission of greenhouse gases (GHGs) and the viscosity of water in the soil-plant pathway, altering the transport of water. Interactions between micro-organisms in the rhizosphere, the grapevine root system, degradation and fixation processes of SOC are complex and poorly understood but respond to environmental factors (such as increased soil temperatures), the plant material (rootstock for instance), and the cultivation system (for example bio-organic versus conventional, cover crop use versus open tillage). Increasing SOC stocks is discussed as a measure to reduce soil GHG emissions with the potential to improve the balance between GHG emissions and carbon removal from the atmosphere. Yet it is difficult to deduct the impact of climatic changes and cultivation practices on patterns of carbon storage or losses from soils. This paper presents a first attempt 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 using a medium realization run (Orlowsky *et al.*, 2008).

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 helps to achieve CO_2-neutrality but additional measures are required to make vineyards a significant C-sink.

KEYWORDS: regional climate evolution, soil temperature, water balance, soil organic carbon, greenhouse gas emissions

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. The European Union (EU) responded to the challenges implicit in such a goal by formulating the so-called "European Green Deal" (EGD) which was first published in December 2019. On 14 July 2021, the European Commission adopted a series of legislative proposals setting out how it intends to achieve climate neutrality in the EU by 2050. The package proposes to revise several pieces of EU climate legislation, including the EU Emissions Trading System, Effort Sharing Regulation, transport and land use legislation, setting out in real terms the ways in which the Commission intends to reach EU climate targets under the EGD. The main specifications for agriculture are: 1. reduce the use of pesticides by 50 % until 2030; 2. reduce fertilizer use by 20 %; 3. reduce nutrient losses by a minimum of 50 %; 4. increase the percentage of organic production to 25 % and at the same time implement the defined biodiversity strategy (European Commission, 2020).

Directly after the Paris agreement, the French Ministry of Agriculture launched the 4 per 1000 initiative to demonstrate that agriculture, and in particular soils, plays 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 (Lal, 2004; Lal, 2010a). 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 (Smith, 2012). 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 (Batjes, 1996; Oertel *et al.*, 2016; Paustian *et al.*, 2016). Thus, increasing net soil C storage by even a few percent could represent a substantial C sink potential.

Stabilizing global mean temperature at levels below 2 °C requires near-zero emissions of longer-lived GHGs such as CO_2 and N_2O by mid-century (Hong *et al.*, 2021). Agricultural production and land-use changes are currently estimated to contribute about 14.6 gigatons of CO_2-equivalent (CO_2-eq.) (including GHG emissions such as methane and nitrous oxide recalculated into CO_2 equivalents) or 25 % of total anthropogenic GHG emissions. Global fruit production contributes about 1 % of total (Hong *et al.*, 2021).

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 (Kahiluoto *et al.*, 2014). Therefore agriculture in general is putting more attention to soils and cultivation systems to reduce greenhouse gas (GHG) emissions and usage of soils as carbon storage component. 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 (i.e. Minasny *et al.*, 2017; Chenu *et al.*, 2019), 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, very much depends on soil status (degenerated soils have a higher potential, Flessa *et al.*, 2019) and thus will not provide a major offset for greenhouse gas emissions (White, 2016; White *et al.*, 2018; Baveye *et al.*, 2018; Baveye *et al.,* 2020).

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. Pellerin *et al.* (2019) 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 (White and Davidson, 2020).

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 (see review by Longbottom and Petrie, 2015). In most cases C storage in above-ground biomass were found to be substantial (Williams and Smith, 1991; Brunori *et al.*, 2016; Scandellari *et al.*, 2016) with storage capacity below ground being highly variable depending on soil and root respiration rates (Franck *et al.*, 2011; Scandellari *et al.*, 2016) 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 (Novara *et al.*, 2020) to C-gain (Nistor *et al.*, 2018; Novara *et al.*, 2020; Marín-Matrínez *et al.*, 2021). The Minasny *et al.* (2017) study on the 4 per 1000 initiative identified vineyards and orchards in France as areas with a high SOC sequestration potential. In agreement, Pellerin *et al.* (2019) 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.* (2021) 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). The effects on SOC of the same amendment differed between climate zones and decreased with the duration of the experiment.

Based on the difficulties and uncertainties in estimating SOC and the potential effects of climate change and soil cultivation, the present study had three objectives. (1) Use an established soil carbon and CO_2-emission model and compare the results to measured values of SOC over time. (2) 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. (3) Use output data from a climate simulation model to predict future changes in SOC if the two cultivation practices are permanently retained.

MATERIALS AND METHODS

1. Vineyard description

The vineyard chosen for SOC monitoring is located at Rüdesheim, Germany, 49.98 °North, and 7.91 °East and consists of an array of ancient terraces with soils ranging from loamy sand to loam to shallow stony patches primarily determined by quartzite (Löhnertz *et al.*, 2004; https://bodenviewer.hessen.de/mapapps/resources/apps/bodenviewer/index.html?lang=de).

The vineyard terraces were not cultivated for many years and re-established natural vegetation had to be removed. The terraces were planted starting in 2006 as part of a student project of Geisenheim University. In total 20 different Riesling clones were planted on 6 different rootstocks on a 1.35 m (between rows) by 1.0 m (between vines) spacing. Mechanisation of vineyard cultivation steps is not possible due to restricted access and the small structured terrace plots. The soil is covered with a permanent natural cover consisting mainly of different grass species with some legumes that slowly established. Depending on precipitation rates and thus cover crop growth, the floor is mowed between 1-3 times during the growing season. In infrequent intervals (not every year) and only when soil conditions permitted, a small inter row strip of about 20 cm was loosened with backhoes.

2. SOC determination

Every year (2008 to 2021) soil samples were taken with a Pürckhauer soil sampler in April/May randomly within and between rows and analysed for two depth layers (0-30 cm, 30-60 cm) for the main nutrient components and pH. The pH varied over time and depending on the terrace sampled between 6.7 and 7.6. Samples were collected on 5-10 different spots per terrace (depending on the size) and pooled into one sample for analyses. Between 4 and 5 terraces were sampled independently each year. Carbon and nitrogen were analysed in duplicate (300 mg) from the upper 30 cm soil samples according to the Dumas dry combustion method where the samples are burned at about 950 °C under oxygen dosage in an elementary analyser (Vario MAX CNS) being corrected for carbonate carbon following the FAO protocol on the standard operating procedure for soil total carbon (FAO, 2019). Soil bulk density was taken from Hendgen *et al*. (2020).

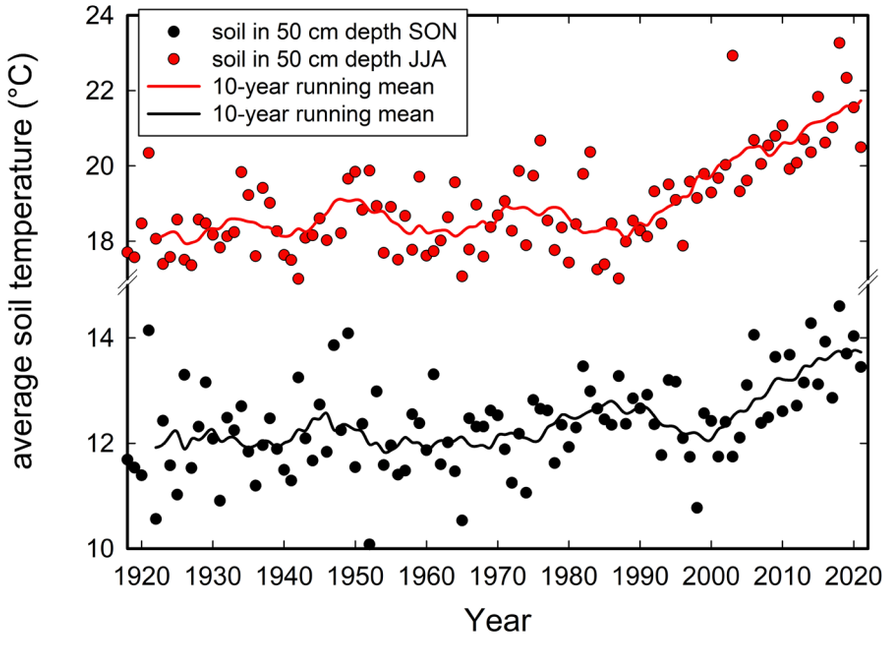


FIGURE 1. Development of soil temperature since 1919 at 50 cm depth at the Geisenheim measurement sites. Data are seasonal means for summer (June, July, August; JJA) and autumn (September, October, November; SON) from daily measurements at 2 pm. Lines show the 10-year running-mean.

3. 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 (Löhnertz *et al.,* 2004). 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 (compare Figure 1) 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.

4. Weather data

A weather data 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). Light precipitation events (< 10 mm/day) dominate and contribute 65 % of total precipitation, whereas daily precipitation events larger than 20 mm contribute only 9 %, respectively. Mean potential evapo-transpiration (ETp) between April 1 and September 30 is on average 605 mm but has been observed to increase over the last approximately 40 years (Schultz and Hofmann, 2016).

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

The model has been developed by Coleman and Jenkinson (2005) based on several earlier versions and original data from the Rothamsted classic experiment (Jenkinson and Rayner, 1977) 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 (Riggers *et al.*, 2019; Riggers *et al.*, 2020) and also on conversion scenarios from cork oak forest to vineyards with different follow-up management systems (Francaviglia *et al.*, 2012). It has also been included in global C cycling models (i.e. King *et al.*, 1997). 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 (Schultz, 2019), although some deviations may occur (see Results and Discussion section). Due to the lack of sufficient data, likely differences in soil temperature for bare soil as compared to temperatures below cover crops (Yang *et al.*, 2021) 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 (i.e. Lopes de Gerenyu *et al.,* 2005). Additionally monthly precipitation rates and ETp values are required where care needs to be taken to apply a correction factor for the conversion of ETp values into open-pan evaporation (Coleman and Jenkinson, 2005). 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 the vineyard site and data from a literature review of Carlisle *et al.* (2010). 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 Carlisle *et al.* (2010). 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.

6. Constructing a climate change scenario

In order to estimate future changes in SOC and CO_2 emissions from the study vineyard, a data file on the required inputs previously constructed for the estimation of future changes in ETp (Schultz and Hofmann, 2016; Schultz, 2017) 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 (Orlowsky *et al.*, 2008). 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) (Jacob, 2005). This scenario is roughly equivalent to the RCP 6.0 (Representative Concentration Pathways) currently used to simulate different scenarios (see https://www.globalchange.gov/browse/multimedia/emissions-concentrations-and-temperature-projections) with an estimated CO_2-concentration of 650 ppm by 2100 (IPCC, 2021). This approach provides physical consistency of the combination of the weather variables and is in close agreement compared to the statistics of observed climatology (Orlowsky *et al.*, 2008).

RESULTS AND DISCUSSION

1. Soil temperature and precipitation observations

Figure 1 shows a 102-year time series of average summer (June, July, August, JJA) and autumn (September, October, November, SON) soil temperatures at a depth of 50 cm. Summer soil temperatures were about 6 °C warmer than autumn temperatures over most part of the last century until about 1985. After this, JJA temperatures increased faster than SON temperatures and reached average values around 22 °C today as compared to 18 °C about 40-years ago (Figure 1) and about 8 °C warmer than SON temperatures (Figure 1). When the average seasonal temperatures, adding also winter (December, January, February (DJF)), and spring (March, April, May (MAM)) of the last 22 years (2000-2021) were compared to the long-term mean (1961-1990), the increase in temperature was evident at all measurement depths and for all seasons, but most pronounced in spring and summer (Figure 2). 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 (Figure 2).

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, (Knight *et al.*, 2018), Canada, (Zhang *et al.*, 2005), China, (Zhang *et al.*, 2016; Fang *et al.*, 2019), Turkey, (Yeşilırmak, 2014), or Russia, (Reshotkin and Khudyakov, 2019; Kudeyarov *et al.*, 2009). Observed warming rates were larger in the northern, cooler regions, than in the warmer southern regions for China

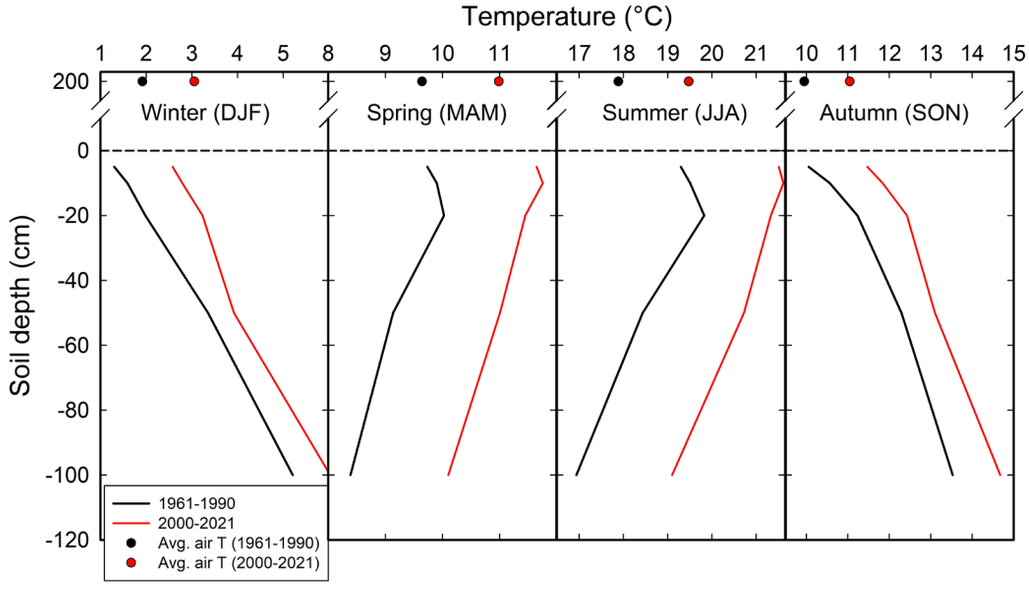


FIGURE 2. Average soil temperature profiles for winter (December, January, February; DJF), spring (March, April, May; MAM), summer (June, July, August; JJA) and autumn (September, October, November; SON) for the period 2000-2021 as compared to 1961-1990 at the Geisenheim measurement sites.
Data were compiled from daily measurements at 2 pm. Measurement depths were 5 cm, 10 cm, 20 cm, 50 cm, and 100 cm. For clarity, average air temperatures for the different seasons and different time periods are also shown.

and Russia (Zhang *et al.*, 2016; Reshotkin and Khudyakov, 2019); 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 less than in the current study (1.3 °C) but also represented a huge study area. Data from four Russian measurement series (ranging from 1950 to 1966) in different soil types and covering a latitudinal range from 46.31 °N to 65.52 °N showed a gradual warming on all sites down to a measurement depth of 320 cm (Reshotkin and Khudyakov, 2019). At 20 cm depth, the average annual soil temperature increase was between 0.21 °C-0.29 °C per decade depending on location and soil type as compared to 0.45 °C in the present study compared to the long-term mean 1961-1990. 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 (Lal, 2010b).

The stronger warming response of the soil during summer as compared to autumn (Figure 1) might be related to progressively lower soil water content of the top-soil layer during the last 40-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 (Heilman *et al.*, 1994).

Figure 3 shows the relationship of average summer soil temperature (JJA) from the dataset shown in figure 1 in relation to the average precipitation rate over the same time period. The warmest years (artificially drawn above 18 °C) include 19 of the 21 years of the current century.

However, there was no clear correlation of high temperatures with low precipitation rates. Since both temperature and moisture play a role in soil respiration and the decay rates of organic matter and thus GHG emissions from soils (Steenwerth *et al.*, 2010), considering both factors in approaches to model changes in SOC is important (Lloyd and Taylor, 1994; Zhang *et al.*, 2005; Coleman and Jenkinson, 2005). However, the importance may depend on the time of the year (Lopes de Gerenyu *et al.,* 2005) or the immediate past of a precipitation event (Carlisle *et al.*, 2006), or may depend on specific conditions of the site (Joffre *et al.*, 2003; Carlisle *et al.*, 2006). In a meta-analysis of the effects of experimental soil warming on soil respiration in different global biomes, Carey *et al.* (2016) observed a reduction in moisture in all sites, but only a weak correlation to soil respiration changes. Corneo *et al.* (2014) found no effect of warming on the diversity of microbial communities in temperate vineyard soils which might point to some adaptive responses to changes in the environment.

Anticipating yet unknown effects of increases in sub-soil temperature on organic matter degradation and mineralization, the increase in temperature may also influence the hydraulic conductance of roots and thus plant transpiration, assuming that root temperature resides close to soil temperature at the root-soil interface. This is because increasing temperatures decrease the viscosity of water, thus increasing the hydraulic conductance with potential changes in whole plant transpiration rate (Cochard *et al.*, 2000; Schultz, 2019).

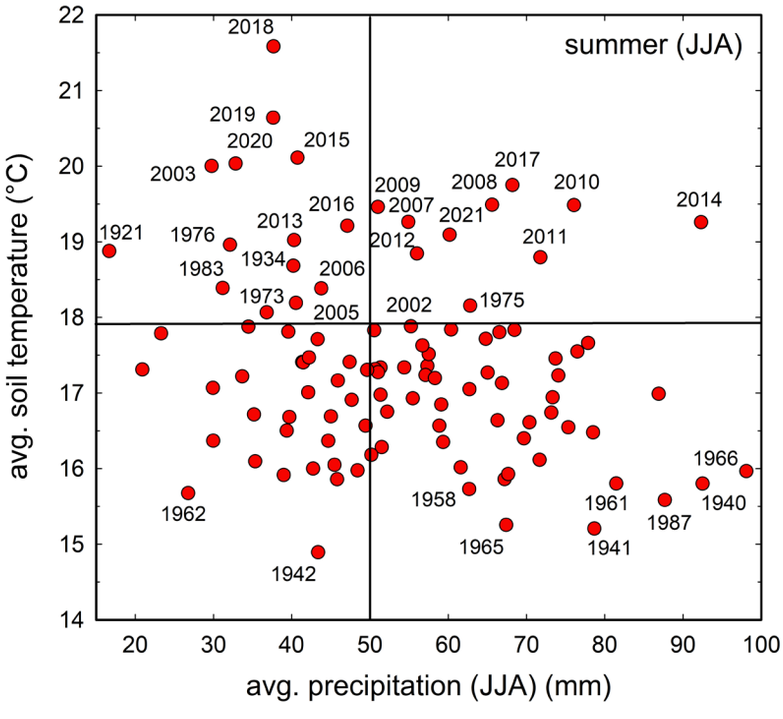


FIGURE 3. Relationship of average soil temperature in summer (June, July, August; JJA) to summer precipitation rates over the period 1919 – 2021. The lines were drawn artificially to roughly distinguish between warm and cool and dry and moist summer seasons. Exceptional years are marked.

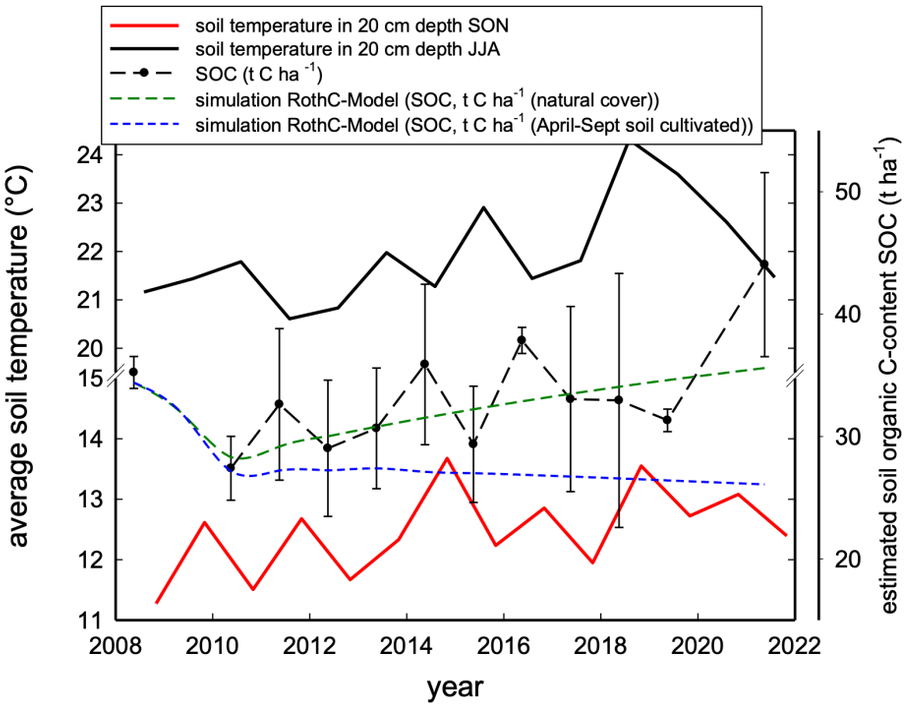


FIGURE 4. Measured SOC values in an experimental vineyard on terraces since 2008. Data are mean values ± SD from 4-5 terraces. The year 2008 was the post-planting year when soil was manually kept mostly free of vegetation. Since 2009 a natural cover crop was left to develop achieving 100 % cover by 2010. Dashed lines represent runs with the RothC-model (soil organic carbon (t ha^{-1})). The green line shows a simulation with open soil in 2008-2009 and 100 % cover thereafter. The blue line shows a simulation with open soil in 2008-2009, a cover crop from October to March and open soil for the remaining year. Yearly input of carbon through pruning wood and leaves were equal for both treatments. Continuous lines show soil temperatures (bare soil) from the Geisenheim site for summer (June, July, August; JJA) and autumn (September, October, November; SON).

2. Measured and simulated SOC changes using the RothC-26.3 model

Figure 4 shows a comparison of measured SOC in the experimental vineyard and a prediction of total organic carbon (t ha^{-1}) with the RothC-model. As the starting point, SOC values from the post-planting year were taken when the soil was kept free of vegetation (2008). Since 2010, a natural cover crop was established. Soil temperature data for the summer and autumn seasons from the Geisenheim measurement site are also shown. Due to planting and partly cultivating the soil (removal of natural vegetation which had established during the fallow period), SOC values dropped by about 15-20 % from 2008 to 2010 (Figure 4) but recovered thereafter. This response is typical for land-use changes in general (Arrouays *et al.*, 2002) but SOC losses can be more severe (i.e. Flessa *et al.*, 2019; 30-40 %) and usually persist for longer periods of time. They also depend on the type of vegetation converted and the persisting climatic conditions (West and Post, 2002). The change in soil organic carbon described for the examined vineyard in Rüdesheim, Germany, is much different (only surface vegetation removed, no deep-ploughing before planting) from those observed when natural oak vegetation was cleared and vineyards planted in California with an estimated C loss of 33 t ha^{-1} over a period of 30-32 years (Carlisle *et al.*, 2006) or in the simulation study with the RothC-model from cork oak forest to vineyard (with deep ploughing to 40 cm) with a loss of 13.1-14.1 t C ha^{-1} (25-27 % of initial value) depending on subsequent management (Francaviglia *et al.*, 2012). Measured SOC values show a highly variable but slow increase 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). The variation in SOC content seemed to be related to soil temperature because SOC was lower following seasons with warmer temperatures and *vice versa* (Figure 4). When the model was run with the same input conditions but with bare soil (tillage mode) from April to September, simulated SOC decreased slowly, thus did not match the observed development. 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 (Longbottom and Petrie, 2015; Wolff *et al.*, 2018; Tezza *et al.*, 2019; Payen *et al.*, 2021). The rate of increase in SOC (about 0.75 t C ha^{-1} y^{-1}) (Figure 4) observed in the trial is comparable to the rates with similar treatments (crushed prunings and cover crop) in the review of literature conducted by Longbottom and Petrie (2015), such as Morlat and Jacquet (2003) and Morlat and Chaussod (2008) with a range of 0.5 t C ha^{-1} $y^{-1}$to about 0.69 t C ha^{-1} y^{-1}. Reasons for the natural-cover induced increase in SOC are diverse: roots and above-ground biomass (i.e. litter, pruning wood) enrich organic pools in soil, and soil and root respiration can

lower oxygen concentration in the soil which slows down mineralisation.

3. Simulations of climate change effects

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 20 cm shown in Figure 2 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 (Figure 5). 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 (Figure 5A).

Changes in CO_2-emission rates were inverse to those in C-storage (Figure 5B). 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 (Figure 5B). Differences in soil temperature of bare as compared to covered soil (not considered in this study) may have modified these values. Yang *et al.* (2021) 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

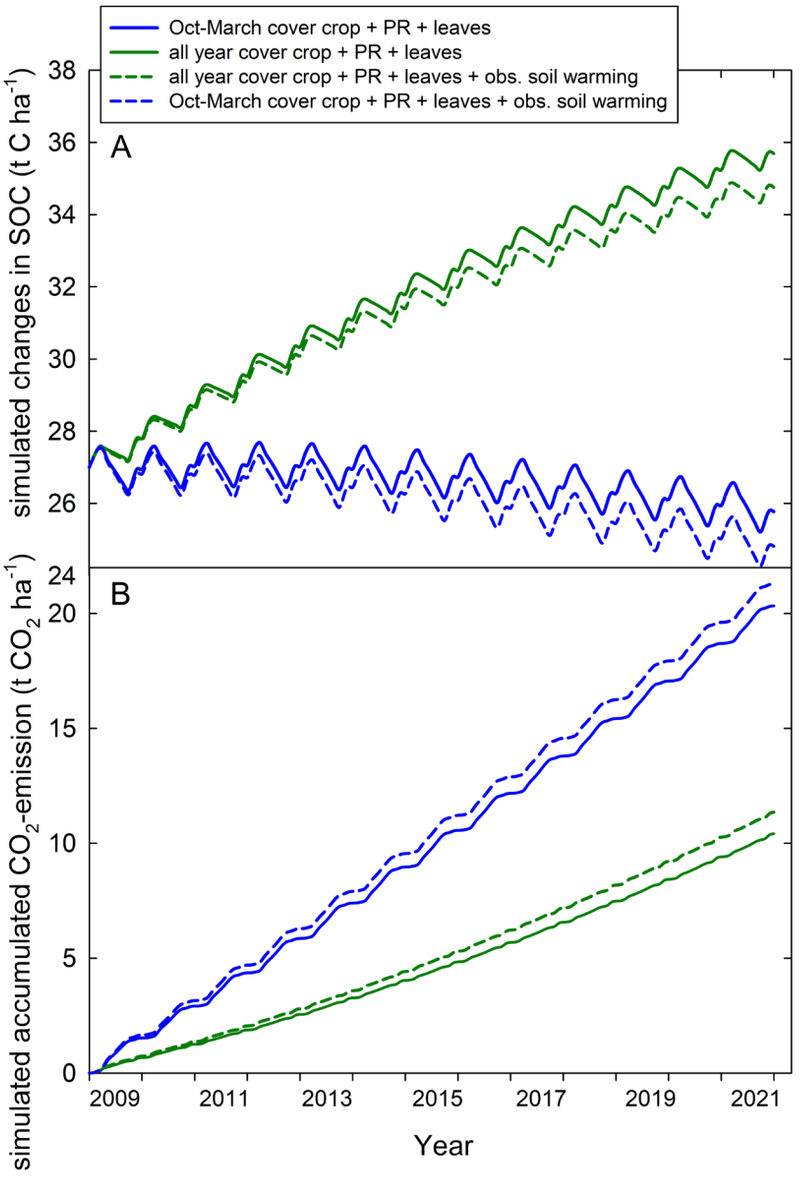


FIGURE 5. Simulated changes in SOC values (A) and concomitant CO_2-emissions (B) for a vineyard with full cover crop throughout the year and part time cover crop (October to March) using the RothC-model. Simulations were based on real climate data for that particular period (continuous lines) and a second run adding the observed temperature changes for the four seasons 2000-2021 as compared to 1961-1990 (see Figure 2) at a depth of 20 cm.

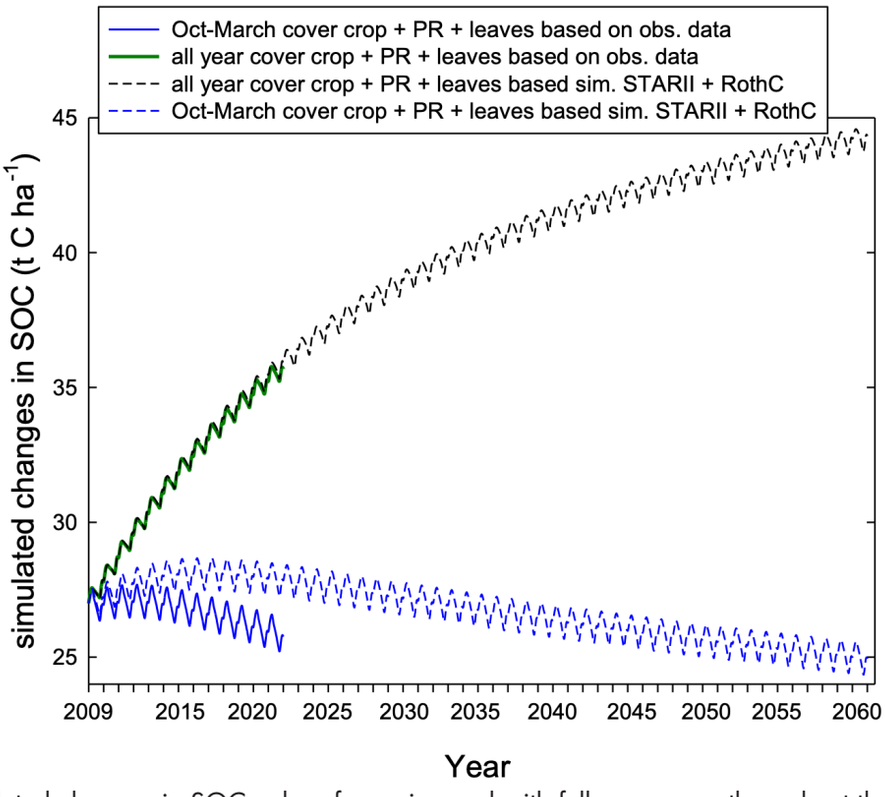


FIGURE 6. Simulated changes in SOC values for a vineyard with full cover crop throughout the year and part time cover crop (October to March) from 2009 until 2060 combining the RothC-model with a STAR II model prediction of air temperature, rainfall and ETp based on an A1B/RCP 6.0 scenario (dashed lines). Continuous lines represent simulations based on real climate data as input between 2009 and 2021.

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) (Yang *et al.*, 2021). Since temperature response of decay rates or organic matter are non-linear in the Roth-C model (Coleman and Jenkinson, 2005), these differences need to be incorporated in future studies.

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 (Figure 6). 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 (Poeplau *et al.,* 2011). Morlat & Chaussod (2008) 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}, Figure 6). The concurrent accumulated CO_2 emission rates reveal the dilemma in devising the correct strategy for soil management. Overall CO_2 emissions (59 t CO_2 ha^{-1} = 16.1 t C ha^{-1} cover crop treatment) over the simulated time span were only slightly less than C-storage in the soil (18 t C ha^{-1}) in the permanent cover crop treatment (Figure 7) and the difference between storage capacity and emission rates would need to be "over" compensated in the storage of C in permanent vine structures in order to make vineyards a significant C-sink instead of a source. As with SOC development, CO_2 emissions from observed weather data input as compared to STAR II predictions were very similar, with deviations to higher values for the input of real weather data for the part time tillage treatment (Figure 7). The C-balance of this treatment over the 61 year time span was strongly negative. SOC losses and CO_2-emissions combined accounted for 23.4 t C ha^{-1} lost until 2060.

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 (i.e. Wan *et al.*, 2011; Riggers *et al*. 2019, Riggers *et al.*, 2020) 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.* (2011) 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 %

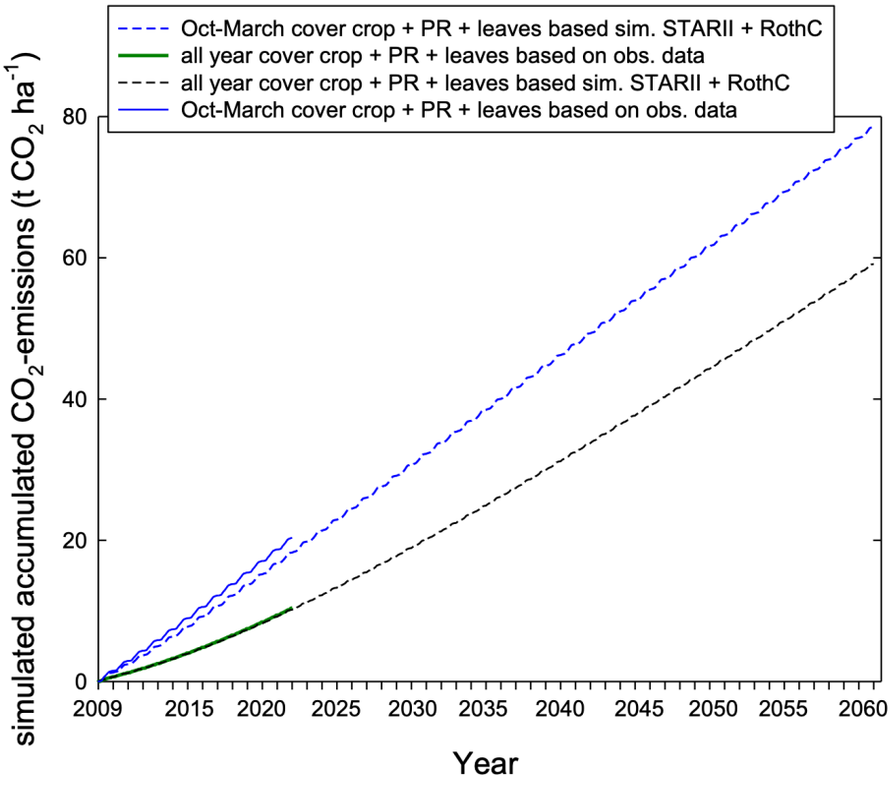


FIGURE 7. Simulated changes in CO2-emissions for a vineyard with full cover crop throughout the year and part time cover crop (October to March) from 2009 until 2060 combining the RothC-model with a STAR II model prediction of air temperature, rainfall and ETp based on an A1B/RCP 6.0 scenario (dashed lines). Continuous lines represent simulations based on real climate data as input between 2009 and 2021.

(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} (Figure 6). 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) (Flessa *et al.*, 2019). 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.* (2021) 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 (Riggers *et al.*, 2021).

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 (Francaviglia *et al.*, 2012; Muñoz-Rojas *et al.*, 2015). 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 (Francaviglia *et al.*, 2012). Muñoz-Rojas *et al.* (2015), 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, 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 (Celette *et al.*, 2008; Longbottom and Petrie, 2015). Wolff et al. (2018) 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.* (2019) 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 the review of Longbottom and Petrie (2015). Wolff *et al.* (2018) 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 (Marin-Martinez *et al.*, 2021; Longbottom and Petrie, 2015; Payen *et al.*, 2021), 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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