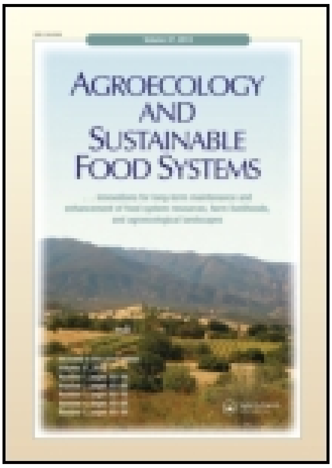

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Effects of Cultivation and Alternative Vineyard Management Practices on Soil Carbon Storage in Diverse Mediterranean Landscapes: A Review of the Literature

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Managing carbon storage at the landscape level through emission reduction and carbon sequestration is emerging as a viable local response to atmospheric carbon loading from anthropogenic activities. The conversion of uncultivated land uses and land covers (LULCs) to arable or perennial cropping systems is widely recognized as resulting in significant decomposition of soil organic carbon (SOC). Minimizing conversion and advocating alternative management of these cultivated land uses have been identified as having the potential to minimize this loss and potentially sequester atmospheric carbon. However, effective landscape management requires a more rigorous understanding to inform local decision-making. This review of published studies within diverse Mediterranean landscapes found that cultivated areas contained roughly half of the SOC of uncultivated LULCs, with vineyards often containing the lowest observed SOC levels in a landscape. Mitigation through alternative management can result in higher SOC levels than conventional management, but the latter is likely to be a fraction of the C loss from initial cultivation. However, the majority of relevant studies relied on shallow standardized sampling depths and other protocols that have been demonstrated to lead to miscalculations of existing SOC stocks. Novel sampling techniques and emerging research opportunities have the potential

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to revolutionize our understanding of this question and support scientifically sound carbon-based landscape management.

KEYWORDS soil carbon, vineyard management, grassland conversion, climate change

INTRODUCTION

Understanding carbon dynamics within anthropogenic landscapes is critical for identifying practical local means of sequestering carbon and/or reducing emissions to mitigate atmospheric loading. Within managed terrestrial systems, rapid human-induced changes in local landscape carbon storage come primarily as a result of a) the conversion of one type of land use/land cover (LULC) to another, and through b) alternative management practices within a single LULC (Guo and Gifford 2002; Stockmann et al. 2013). While changes also result from global processes such as climatic changes associated with atmospheric carbon levels, these local issues in land management are an opportunity for land managers to take the initiative and use an understanding of the carbon cycle to inform their management decisions. Landscape-level management of carbon might address both of these approaches, such as through the reforestation of degraded agricultural fields or the increased amendment with organic materials within cultivated fields. However, identifying appropriate carbon management at the landscape level requires reliably estimating the implications of LULC change and alternative management practices on landscape carbon storage. Given recent paradigm shifts and revelations in our understanding of the carbon cycle, particularly with regards to soil organic carbon (SOC), it is not clear that such information is sufficiently available to meet this increasing demand (Schmidt et al. 2011; Stockmann et al. 2013).

This literature review investigates the effects of LULC conversions and alternative management practices on soil carbon storage within diverse Mediterranean agricultural landscapes, with a special focus on the establishment and management of vineyards. Vineyards and viticulture constitute a culturally and economically important sector of agricultural production in Mediterranean climates around the world. The growth of the global wine trade in recent decades has encouraged the planting of uncultivated areas, such as grasslands, forest, pasture, and the shrubby and sparsely forested vegetation that dominates unmanaged areas under Mediterranean climates. Unlike with most annual crops, vineyards can be established on hillsides and in marginal soils, and this extensification is identified as a threat to watersheds and native ecosystems and has raised fears of increased carbon emission through the disturbance of uncultivated soils (Carlisle et al. 2010). As of 2013, California alone had 570,000 acres of wine grape production, a 4.5% increase from 2012, with much of this coming through conversion of grasslands (Climate Action Reserve 2012; California Department of Food and Agriculture 2014). In addition, vineyards and orchards can be managed through a broad range of practices and recent evidence appears to show a strong influence of certain management practices on soil carbon levels in vineyards (Carlisle et al. 2010).

The impact of LULC conversions and management practices on soil carbon storage has recently been identified as a specific topic of interest by land managers and agricultural scientists working in diverse Mediterranean landscapes (Aguilera et al. 2013; Seddaiu et al. 2013). However, these studies point out the need for more research to better inform carbon-based management. One recent white paper, which was independently published by both the Verified Carbon Standard (2012) and the American Carbon Registry (2013), suggests that land managers conduct carbon balance equations that involve detailed local quantification of attributes that are simply not known, such as the "carbon stock of belowground crop biomass for Participant Field *p* in the baseline scenario in year *y*." The more pragmatic authors of a 2010 summary on greenhouse gas emissions for the California Sustainable Winegrowing Alliance suggest estimates based on the combination of global carbon models and sequestration rates and a California-specific model that focused almost exclusively on aboveground carbon dynamics (Carlisle et al. 2010). Given some of the unique characteristics of Mediterranean landscapes, which typically contain low fertility soils adapted to low rainfall and low nutrient input, and the growing recognition of the importance of soil organic carbon in the global carbon cycles, this more practical recommendation may also be inappropriate.

This review takes a different approach, which is to search the literature for information that might be immediately available to land managers looking to understand how their management decisions might influence landscape carbon storage within their region of focus. The results are summarized and interpreted in light of recent insights and paradigm shifts within the scientific understanding of soil organic carbon. The goal is to identify general trends of the direction, magnitude, and variability of the effects of LULC conversions on soil carbon storage across Mediterranean landscapes and as a result of alternative management within vineyards. Specific quantifications of these trends will be offered if they are found to be generally reliable, and this review will conclude with recommendations for both specific further research and immediate pragmatic interpretation of what is currently known.

Soil Carbon and Response to Management

Analysis of terrestrial carbon dynamics historically often focused on aboveground carbon, and sequestration models were proposed as recently as 2006 that were based on yield and crop residue management rather than soil management and belowground carbon dynamics (Kroodsma and Field 2006). However, belowground carbon storage is often several times that of the adjacent aboveground carbon pool and, while more stable can also be very sensitive to changes in the local environment and surface management (Lal 2004). In agricultural soils this carbon is found primarily but not exclusively within organic compounds, with inorganic carbonates typically occurring at high levels only in alkaline soils, which are less frequently cultivated. The SOC pool, which globally is estimated to be four larger than the terrestrial aboveground carbon pool, has therefore become the focus of carbon-based assessment and management of diverse agricultural landscapes (Stockmann et al. 2013).

Carbon enters the soil organic pool primarily through the microbial decomposition of aboveground or belowground biomass, and is primarily lost through continued decomposition leading to volatilization or through physical removal from the area of interest through surface erosion (Table 1). These processes co-occur and vary in magnitude, often seasonally, so any measurement of SOC is a static snapshot of a dynamic equilibrium reaction. Large pulsed inputs to the soil carbon pool, such as organic soil amendment in agricultural fields, are likely to have non-linear and potentially long-term effects on SOC levels (Lal 2004). While the surface horizon is an important site of carbon addition and is often immediately responsive to land use or management changes, high levels of soil organic carbon can be stored below the surface (Rumpel and Kögel-Knabner 2011). This vertical partitioning is particularly relevant in Mediterranean climates, where natural land cover types are often dominated by grasses, shrubs, and deep rooted trees, which all have the potential to move large amounts of carbon deep into the soil profile through root turnover and bulk flow of dissolved or particulate carbon within old root channels. For example, a 2000 meta-analysis found that the top 20 cm of shrubland soils worldwide contain on average only 33% of the carbon in the top meter and less than 20% of the total carbon found in the top three meters (Jobbágy and Jackson 2000). More recent studies have reinforced the importance of this "deep carbon" to the soil carbon pool and the responsiveness of subsurface carbon to surface changes, while also admitting how little is known about carbon dynamics at depth (Fontaine et al. 2007; Rumpel and Kögel-Knabner 2011). Additional recent studies have found that microbial decomposition, which drives both soil carbon dynamics, is less dependent on the intrinsic chemical complexity of organic compounds than was long thought, and more dependent on extrinsic factors that influence microbial activity and the biophysical protection of carbonaceous compounds (Schmidt et al. 2011). Important factors include soil temperature, moisture, aeration, and texture, and these site-specific characteristics interact with the chemical nature of carbon inputs to determine local SOC equilibrium levels and rates of change (Gershenson et al. 2009; Schmidt et al. 2011).

TABLE 1 Potential pathways, mechanisms, and relevant factors driving the addition to and loss of organic carbon from the soil carbon pool. "Management practices" refers to the combination of cultivation, fertilization, and irrigation practices

Pathway	Primary mechanism	Primary controlling factors
Addition of organic carbon to the soil carbon pool		
Below-ground decomposition	Microbial decomposition of roots, root exudates, and incorporated biomass	Soil and environmental characteristics; management practices; plant community and phenology
Above-ground decomposition	Microbial decomposition of surface biomass	Soil and environmental characteristics; management practices; plant community and phenology; quantity and chemical characteristics of carbonaceous amendments
Loss of organic carbon from the soil carbon pool		
SOC Decomposition	Microbial decomposition of SOC into volatile gaseous compounds (i.e. CO_2)	Soil and environmental characteristics; management practices
Erosion	Physical removal of carbon-rich topsoil from the area of interest	Soil and environmental characteristics; management practices; slope of field; surface cover

Conversion between different land use/land cover types has been found to have a strong influence on soil carbon levels, with the cultivation of previously uncultivated soils often resulting in dramatic loses of SOC (Post and Kwon 2000; Houghton and Goodale 2004). This is often considered to be primarily a result of the disturbance associated with tillage, but irrigation and nitrogen fertilization are also predicted to encourage microbial decomposition that would further reduce SOC levels (Austin et al. 2004; Lal 2004). This is recognized as an important research question in Mediterranean vineyards, where the naturally drought adapted and low fertility soils may be especially sensitive to changes in soil water and nitrogen levels (Carlisle et al. 2010). The type of cultivation is also expected to have important implications for soil carbon storage, with some researchers predicting less lose of SOC with conversion to perennial cropping systems such as vineyards, which are often minimally irrigated, fertilized, and tilled, as opposed to annual cropping systems, where such inputs and management practices are often much more intensive (Kroodsma and Field 2006; Carlisle et al. 2010). However, the increased tillage intensity in annual cropping systems also buries more surface carbon, such as crop residue, which is expected to lead to more efficient incorporation into the SOC pool than when it is left on the surface (Sanderman and Baldock 2010). In contrast, pruning residue in vineyards and orchards, for example, is typically removed from the field. In addition, annual row crops are often restricted to flatter areas, while perennial crops can be established on erosion-prone hillsides. The effect of the conversion to perennial versus annual cropping systems may therefore be highly crop, site, and management specific.

Alternative management practices within cultivated fields can have significant positive or negative effects on SOC, although even under the best circumstances the cultivated equilibrium levels are expected to be less than the pre-cultivation levels (Lal 2004; Aguilera et al. 2013). These SOC management practices can be divided into two general approaches. This first approach is to manage carbon locally within a field, and common strategies include reducing tillage intensity, seeding and incorporating cover crops as a green manure, mulching with crop residue or incorporating it into the soil, and intercropping within perennials to provide groundcover. The second approach is to amend the soil with off-site carbon, which might include fresh or composted plant or animal based products. These amendments immediately raise the carbon levels in the soil, particularly with physical incorporation, but it is often not clear to what extent this off-site carbon results in a long term increase in SOC, as much of the added biomass may be quickly volatilized. Recent studies have shown that the effect of both approaches on SOC levels can be strongly site-specific and these alternative practices have the potential to interfere with crop production, such as through increased competition for nutrients and water (Govaerts et al. 2009). This competition may be particularly relevant within vineyards, which are often water and nutrient stressed due to common Mediterranean soil and climatic conditions.

Soil organic carbon levels are often reported either as a concentration of carbon within bulk soil, typically as g C/kg soil or %C, or converted through the bulk density and sampling depth to a quantity of carbon per unit area, typically Mg C/ha. The latter unit is necessary to measure landscape carbon storage, but has some inherent shortcomings in agricultural landscapes as tillage results in a dramatic and immediate change in bulk density. This change effectively results in a new and relatively higher soil surface, such that subsequent sampling to a standardized depth does not in fact capture the same depth of soil as it would prior to tillage. There are analytic techniques that can minimize this potential error, but it remains a serious concern when comparing among cultivated and uncultivated LULCs, particularly when there isn't detailed knowledge of recent tillage events (Lee et al. 2009). Measurement of SOC levels as concentration in bulk soil avoids this problem, but it is also not immediately applicable to questions of landscape carbon storage and might be easily misinterpreted. For example, a significant increase in the surface soil does not imply a significant or even detectable overall change in the total SOC storage, and recent studies have shown that it does not even imply the direction of change (Rumpel and Kögel-Knabner 2011). This latter insight is again particularly relevant with regards to changes in tillage, which can influence both the concentration of SOC and the depth of the surface horizon. The long-held belief that no-till reliably increases SOC storage is now recognized as a result of shallow standardized depth

TABLE 2 Estimate of the percentage of SOC within the top 3 m of soil that is missed when sampling is limited to more shallow depths

Depth	Grassland	Shrubland	Forest
20	70.6	81.4	67.9
40	54.5	68.4	54.5
60	44.1	58.2	46.2
80	35.7	50.3	40.4
100	30.1	43.5	35.9
200	9.1	22.0	17.3

Adapted from Jobbágy and Jackson (2000).

sampling, and the effect of the practice appears instead to be complex and largely site-specific (Baker et al. 2007; Luo et al. 2010). Sampling of surface soil only and sampling by standardized depths are therefore both major concerns when drawing conclusions about SOC pools, and both are common in the literature through the common tendency to sample only the top 10 or 20 cm. This widespread practice, while sufficient for many agronomic concerns, is not well suited for questions of soil carbon storage (Table 2).

METHODS

This review is limited to studies since 2000, as early methods of assessing soil carbon levels are now considered less reliable, such as calculating SOC from measurements of total soil organic matter. Studies since 2000 that measure soil organic matter but not soil organic carbon were excluded, as were those that focus exclusively on SOC levels within a single LULC due to the variety of relevant factors that would make it impossible to, for example, directly compare SOC levels in a grassland in Spain against a vineyard in California. “Mediterranean” was used as a search filter for these comparative studies to ensure that all studies were in relatively similar climatic conditions. These selection criteria were relaxed for the review of vineyard management studies, as these do not necessarily include a local uncultivated LULC as reference or explicitly identify the climate zone as Mediterranean, but additional filtering was done by location to remove more temperate wine-growing regions. In this article, the analysis of alternative management practices is restricted to vineyard management, as a recent meta-analysis has addressed the broader question of conventional versus alternative management of cultivated fields but did not consider vineyard management as a unique issue (Aguilera et al. 2013). The important takeaways and shortcomings of this meta-analysis are discussed, but no attempt is made to re-analyze their data.

All meta-analyses and literature reviews face the problem of trying to summarize results among diverse studies that may use widely disparate methods, which can undermine any quantitative conclusions such as average effect size. This is a particularly critical issue here given the relatively small number of studies, the broad range of sampling depths that were used, and the diversity of landscape demarcations, which may or may not include subgroupings for topography or other relevant characteristics. Results that were reported only in more complex subgroupings, such as by LULC plus soil type or topography, were collapsed through a simple averaging within LULCs of interest. This is suboptimal, but more rigorous interpretation is not possible from the published data. Due to the limited number of relevant studies, we did not filter them based on sampling methods or attempt to correct for sampling depth through the calculations in Table 2. Results that were reported only through figures were visually quantified to the best of our ability. All results were converted to %C or Mg C/ha. While some studies included years since conversion or adoption of alternative practices, we did not attempt to calculate rates of change from this information as we considered the number of studies insufficient given the diversity of relevant factors.

EFFECT OF CONVERSION TO CULTIVATED LAND USES/LAND COVERS

This literature review did not find relevant long-term experimental LULC conversion studies or reliable observational studies that sampled before and after conversion with a sufficient timespan in between. Instead, the effect of conversion must be inferred from sampling within existing patterns of LULC. This was found to primarily be done through one of three different approaches (Figure 1). The most rigorous but least generalizable are paired-site studies, where contrasting LULCs are sampled from immediately adjacent sites that share other importance characteristics such as soil type and topography. Similar to these are mosaic landscapes, where multiple LULCs occur within close proximity to each other and land characteristics and histories are well known. At the broader scale are meta-analyses of soil samples, which often re-examine hundreds or thousands of soil cores that were collected for large-scale soil surveys and were geocoded to known LULCs, soil types, and climatic zones. For the purposes of this review, these comparisons among LULCs are also reported as the implied carbon loss with conversion, which

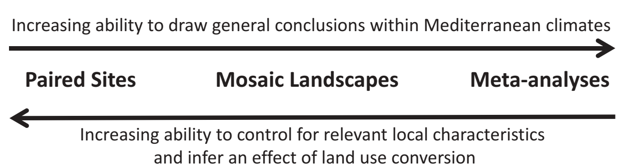

FIGURE 1 Summary of three different strategies of using existing diverse landscapes for inferring the effects of land use/land cover conversions when time-lapse studies are not available.

was calculated as percent difference relative to the uncultivated LULCs. When there are multiple potentially relevant uncultivated land cover types, this implied loss is represented as a range. All relevant studies and comparisons are summarized in Table 3.

Paired Sites

This article found five published papers that applied the paired-site approach for comparing cultivated and uncultivated fields in Mediterranean climates, all in Italy or California (USA). All of these studies, which totaled 16 unique cultivated-uncultivated paired sites, found dramatically less SOC in the cultivated fields. The average implied loss in soil carbon storage with the cultivation was 44.7% with conversion to annual cropping ($n = 5$ paired sites) and 46.7% with conversion to perennial cropping ($n = 12$). The implied loss with conversion to vineyards was 52.1% ($n = 9$) versus 30.6% with conversion to olive groves or citrus orchards ($n = 3$). One study used detailed knowledge of historical land use changes to study the conversion between perennial and annual cropping and found that the establishment of a vineyard within part of an annually cropped field resulted in a 105% increase in SOC levels after more than 30 years, while the establishment of an annual field within an old vineyard resulted in a loss of 9% of the vineyard SOC levels over the same time period (Novara et al. 2012).

One study in California's Mendocino County illustrates the variability of SOC levels within Mediterranean LULCs and the complexity of trying to correlate how the former responds with change to the latter (Williams et al. 2011). This study applied a paired-site approach within a mosaic landscape of five vineyards that were in close proximity but highly variable in terms of soil type, topography, and internal heterogeneity. Six paired sites were selected within these five vineyards where representative vineyard plots were immediately adjacent to representative uncultivated areas of "wildland." Paired soil pits were dug to a minimum of one meter at each of the six sites and the SOC concentration and bulk density was measured at 0–15, 15–45, 45–75, 75–100 intervals. The total carbon storage within each pit was found to be highly variable within wildlands, ranging from 110 to 200 and averaging 146.7 Mg C/ha and within vineyards, ranging from 30 to 100 and averaging 70.8 Mg C/ha. The difference between adjacent wildland-vineyard paired sites, interpreted here as the implied SOC loss with conversion to vineyard, ranged from 10 to 110 Mg C/ha (9.1–76.9%) with an average of 75.8 Mg C/ha (50.1%).

Mosaic Landscapes

This second approach is applied in complex landscapes where paired sites are not available, but other characteristics, such as regional climatic

TABLE 3 Summary of published articles that report SOC levels under multiple land use/land cover classes within diverse Mediterranean landscapes (average implied change in SOC is shown in bold at the bottom of the table)

			Uncultivated LULC			Cultivated LULC			Implied carbon loss with conversion		
Source	Location	Sampling depth (cm)	Description	%C	Mg C/ha	Description	%C	Mg C/ha	Difference in %C	Difference in Mg C/ha	% loss of uncultivated C
Paired sites											
Riffaldi et al. (2002)	Sicily, Italy	0–15	Grassland	2.8		Orange groves	2.6		0.2		7.1
						Winter wheat	2.1		0.7		25.0
						Vegetables	1.7		1.1		39.3
Caravaca et al. (2002)	Central Italy	0–20	Grassland (1)	2.13		Vineyard	0.32		1.81		85.0
			Grassland (2)	1.17		Olive orchard	0.85		0.32		27.4
			Grassland (3)	1.44		Sunflower	0.55		0.89		61.8
			Grassland (4)	0.87		Wheat/ sunflower	0.39		0.48		55.2
Carlisle et al. (2006)	California, USA	0–20	Oak woodland	4.63		Vineyard	2.48		2.15		46.4
Williams et al. (2011)	California, USA	0–100	Wildlands (1)		180	Vineyard (1)		70		110	61.1
			Wildlands (2)		120	Vineyard (2)		50		70	58.3
			Wildlands (3)		140	Vineyard (3)		80		60	42.9
			Wildlands (4)		200	Vineyard (4)		95		105	52.5
			Wildlands (5)		110	Vineyard (5)		100		10	9.1
			Wildlands (6)		130	Vineyard (6)		30		100	76.9
Novara et al. (2012)	Sicily, Italy	0–40	"Garrigue"		112	Vineyard		71		41	36.6
						Olive grove		53		59	52.7
						Arable land		65		47	42.0
								Cultivated	**0.96**	**66.9**	**45.8**
								Perennial	**1.12**	**69.4**	**46.3**
								Vineyards	**1.98**	**70.9**	**52.1**

(*Continued*)

TABLE 3 (Continued)

			Uncultivated LULC			Cultivated LULC			Implied carbon loss with conversion		
Source	Location	Sampling depth (cm)	Description	%C	Mg C/ha	Description	%C	Mg C/ha	Difference in %C	Difference in Mg C/ha	% loss of uncultivated C
							Orchards		0.26	59.0	29.1
							Annual		0.79	47.0	44.6
Mosaic landscapes											
Steenwerth et al. (2002)	California, USA	0–6	Grassland (perennial)		14.8	Agriculture (irrigated)		9.4		5.5–5.4	37.2–36.5
			Grassland (annual)		14.9	Agriculture (rainfed)		8.6		6.3–6.2	42.3–41.6
Evrendilek et al. (2004)	Southern Turkey	0–20	Forest		56.5	Cropland		32.6		23.9	42.3
Le Bissonnais et al. (2007)	Southern France	0–5	Garrigue	5.2		Vineyard	0.9		4.3		82.7
Moscatelli et al. (2007)	Central Italy	0–20	Forest	1.45		Agriculture (conven-tional)	0.8		0.65–0.55		44.8–40.7
			Grassland	1.35		Agriculture (organic)	0.9		0.55–0.45		37.9–33.3
Martinez-Mena et al. (2008)	Southeast Spain	0–5	Forest	2.1		Olive Grove	1.3		0.8		38.1
Blavet et al. (2009)	Southern France	0–5	Scrubland	3.9		Vineyard (mulched)	0.8		3.1		79.5
						Vineyard (unm-ulched)	0.5		3.4		87.2
Almagro et al. (2010)	Southeast Spain	0–15	Forest		51.9	Olive grove		26.6		25.3	48.7

Marzaioli et al. (2010)	Southern Italy	0–10	Forest	8.4		Vineyard	1.3		7.1–3.3		84.5–71.7
			Shrubland	4.6		Orchard	2.6		6.0–2.0		71.4–43.5
			Pasture	8.1							
Lagomarsino et al. (2011)	Sardinia, Italy	0–20	Oak forest	2.51		Vineyard (tilled)	1.42		1.09–0.74		43.3–34.3
			Pasture	2.16		Vineyard (no–till)	1.28		1.23–0.88		49.0–40.7
Emran et al. (2012)	Northeast Spain	0–15	Oak forest	2.90		Vineyard	0.26		3.45–1.60		93.0–86.0
			Pine forest	1.86		Olive grove	1.5		2.21–0.36		59.6–19.4
			Scrubland (w/ fire)	3.06							
			Scrubland (w/o fire)	3.71							
			Pasture	3.70							
Francaviglia et al. (2012)	Sardinia, Italy	0–100, by horizon	Oak forest		50.5	Vineyard (tilled)		36.4		17.3–14.1	32.2–27.9
			Pasture		53.7	Vineyard (no–till)		37.4		16.3–13.1	30.4–25.9
Martinez-Mena et al. (2012)	Southeast Spain	0–5	Forest	2.64		Olive Grove	1		1.64		62.1
Seddaiu et al. (2013)	Sardinia, Italy	0–100, by horizon	Oak forest		50	Vineyard (tilled)		33		49–17	59.8–34.0
			Pasture (open)		82	Vineyard (no–till)		32		50–18	61.0–36.0
			Pasture (near trees)		74						
						Cultivated			**2.73–1.77**	**24.2–15.4**	**56.5–48.2**
						Perennial			**3.12–2.01**	**31.6–17.5**	**61.4–51.1**
						Vineyards			**3.38–2.47**	**33.2–16.2**	**63.9–55.1**
						Orchards			**2.66–1.2**	**25.3**	**56.0–42.4**
						Annual			**0.6–0.5**	**11.9–11.8**	**40.9–38.9**

(*Continued*)

TABLE 3 (Continued)

			Uncultivated LULC			Cultivated LULC			Implied carbon loss with conversion		
Source	Location	Sampling depth (cm)	Description	%C	Mg C/ha	Description	%C	Mg C/ha	Difference in %C	Difference in Mg C/ha	% loss of uncultivated C
Meta–analyses											
Arrouays et al. (2001)	France	0–30	Grassland		128.6	Vineyards + orchards		24.1		104.5–61.4	81.3–71.8
			Forest		85.5	Arable land		59.1		69.5–26.4	54.0–30.9
			Pasture		97.2						
Rodriquez-Murillo (2011)	Spain	Full soil profile, by horizon	Meadows		131	Vineyards		42.5		88.5–16.5	67.6–28.0
			Bushland		113	Olive groves		39.9		91.1–19.1	69.5–32.4
			Broadleaf forest		93.6	Agriculture (irrigated)		50.8		80.2–8.2	61.2–13.9
			Coniferous forest		75.8	Agriculture (rainfed)		57.6		73.4–1.4	56.0–2.4
			Pasture (intensive)		73.2						
			Pasture + broadleaf forest		59.0						
Martin et al. (2011)	France	0–30	Grasslands		75.7	Vineyards		32		43.7–38	57.7–54.3
			Forests		70	Orchards		40		35.7–30	47.2–42.9
						Annual crops		45		30.7–25	40.6–35.7
Romanya and Rovira (2011)	Spain	0–25	Grasslands	1.6		Vineyards	0.8		0.8		50
						Orchards	1.0		0.6		38
						Cereals	1.1		0.5		31.3

*Munoz–Rojas et al. (2012)	Andalusia, Spain	0–75	Scrub	49.1	Perennial	52.2	(+6.3 – +12.8)		(+12.8 – +19.5)
			Forest	47.8	Arable	58.3	(+9.2 – +10.5)		(+18.7 – +22.0)
					Cultivated		**0.63**	**68.6–25.1**	**54.5–36.0**
					Perennial		**0.7**	**72.7–64.7**	**58.7–45.3**
					Vineyards		**0.8**	**66.1–27.3**	**58.4–44.1**
					Fruit/Nut		**0.6**	**58.4–24.6**	**51.6–37.7**
					Annual		**0.5**	**63.5–53.0**	**48.6–22.8**

The original descriptions are retained when possible, but in some cases subgroups within the original literature were collapsed into more common general groupings for the table. LULCs with only periodic cultivation, such as rotational hay crops, were excluded, as were cultivated areas under long–term fallow. When appropriate, cultivated LULCs are compared against the uncultivated LULCs with the highest and the lowest SOC in the landscape to produce a range of values for the implied SOC change with conversion. The average implied changes in SOC is shown at the bottom of the table. The study with an asterisk (*) was treated as an outlier and not included in calculating these averages.

conditions, are thought to be shared among the sampled LULCs. Comparison of SOC values among LULCs in mosaic landscapes is therefore more likely than paired site studies to be influenced by factors that may in fact vary among the sampled locations, such as topography, soil type, and land use history. A common response to this potential heterogeneity is to sample broadly and make additional LULC divisions, such as between forest, shrubland, and grassland, or to make topographical categories within each LULC. While necessary, this sub-categorization makes comparison of cultivated and uncultivated areas difficult as it is not clear what, if anything, is an appropriate local reference for the cultivated areas. In general this approach might also be expected to underestimate SOC loss with conversion as the comparisons are often cultivated flat areas against uncultivated hillsides, which, all else being equal, are expected to be naturally lower in SOC than flat areas due to erosion.

The overall picture that emerges from 14 studies within mosaic landscapes again shows dramatically lower SOC levels in cultivated fields compared to the surrounding uncultivated areas, presumably as a result of the conversion to cultivated LULC classes. Perennially cropped fields were found to have on average 64.1% less carbon than the uncultivated LULC with the highest SOC in the landscape, and 52.1% less than the uncultivated LULC with the lowest SOC levels in the landscape (12 comparisons in 10 studies). This implied loss in SOC with cultivation was again found to be greater for conversion to vineyards (maximum 70.7%, minimum 59.1%, 7 comparisons) than to other orchard crops (maximum 55.5%, minimum 42.3%, 5 comparisons). The comparison of annually cropped fields against uncultivated LULCs was only found in five comparisons within three studies, with the implied loss of SOC with cultivation averaging a maximum of 43.4% and a minimum of 37.3%.

These studies of mosaic landscapes illustrate many of the complications that can arise from alternative methods, particularly with sampling depth and LULC classification. A single mosaic landscape in Sardinia that contained oak forest, fields under pasture/hay rotation (5:1 years), and vineyards was the focus of three apparently independent studies. The first of these to be published used a standard sampling depth of 20 cm and the results imply that the conversion from oak forest to pasture resulted in 13.9% loss of SOC that spiked to 43.8% loss during the one year of cultivation to grow hay (Lagomarsino et al. 2011). This suggests both a very rapid loss of SOC with cultivation and a rapid recovery during the subsequent five years as pasture. However, the second study sampled the soil profile in each LULC and found that when total SOC storage estimates were corrected for the depth, SOC concentration, and bulk density of the top soil horizon, the hay fields contained the highest SOC in the landscape at 57.5 Mg C/ha (Francaviglia et al. 2012). The explanation given for this was that periodic cultivation of pasture/hay fields resulted in thicker carbon-rich surface horizons that were

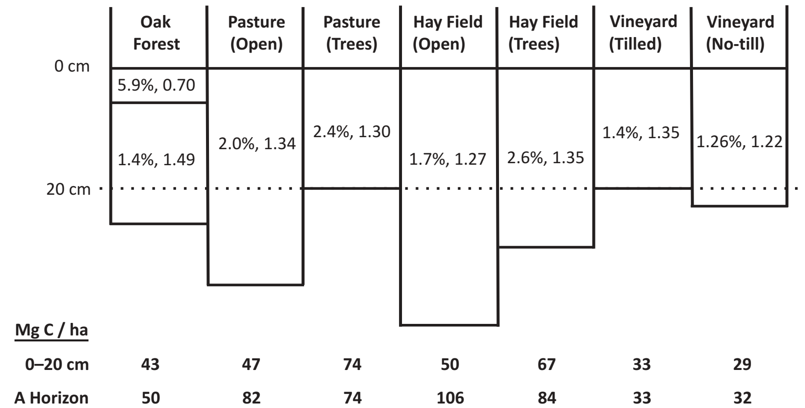

FIGURE 2 Conceptual diagram of SOC concentration, horizon depth, and bulk density (kg/dm^3) for surface soil under seven land use/land cover categories in Sardinia, Italy, as measured in Seddaiu et al. (2013). "Pasture" is in a 5:1 year rotation with "hay fields," which were presumably recently tilled but only in the "open" areas. The areas marked as "trees" were presumed by the authors to have never been tilled. The common "0 cm" level may be deceptive here, as difference in bulk density and thickness with tillage treatments may come as a relative increase in the level of the soil surface. The dotted line indicates the portion of the soil that would be sampled with a standardized sampling depth of 20 cm as opposed to by horizon depth. The associated estimates of carbon storage from each method are given at the bottom of the figure, where the "0–20" estimate is calculated as the fraction of the total storage that falls in the top 20 cm assuming homogeneous SOC concentrations within each horizon.

not adequately measured with the 0–20 cm sampling method. The most recent study found similar results within this mosaic landscape, and also observed thicker surface horizons in the open areas within pastures and hay fields that received periodic tillage as opposed to the portions of these same fields where solitary oak trees prevented cultivation of the immediately surrounding soil (Figure 2; Seddaiu et al. 2013). All three of these studies found that conversion of oak forest to vineyards resulted in an implied SOC loss of more than 30%, making it by far the LULC with the least carbon storage within this landscape.

Meta-Analyses of Soil Surveys

The third approach to estimating the effects of LULC conversions on SOC storage is to conduct meta-analyses of hundreds or thousands of soil samples that were part of large-scale soil surveys, and to correlate the SOC results with maps of land use, soil types, climate, and other relevant spatial information. This approach lacks the resolution of the earlier methods and shares many of the concerns found of the analysis of mosaic landscapes, but the spatial scale of these meta-analyses supports general inference of the effect of conversion.

Only five meta-analyses of SOC were found in the literature and they were focused only on France (2) and Spain (2), with an addition meta-analysis restricted to Southern Spain. The four country-wide studies all found dramatically lower SOC values under cultivated areas than uncultivated areas, and in all direct comparisons vineyards were found to have greater implied SOC loses than orchards and both were greater than annual cropland (Table 3). These conclusions are in agreement with the general trends found in the paired-site and mosaic landscape studies, but surprisingly, the meta-analysis restricted to Southern Spain shows a radically different trend, with SOC levels being higher in both perennial and annual cropland than in uncultivated forest or scrubland. The reasons for this are unclear, but may be attributed to LULCs in this region being strongly correlated with patterns of topography or parent material that might be naturally low in SOC.

The two meta-analyses from France represent alternative ways to conduct large-scale estimates of SOC stocks. The 2001 study combined data from multiple pre-existing forest, agricultural, and rangeland soil surveys, which used different sampling protocols and analytic methods, including fixed depth versus horizon-based sampling and carbon stock estimates through associated bulk density measurement versus those that were not. The analysis was restricted to the top 30 cm to try to correct for some of these difference, although it is not clear how the authors interpreted the surveys that sampled as 0–20 cm and 20–40 cm. These georeferenced soil samples were then classified within seven LULC classes, which included "arable land," "vineyards, fruit trees, and olives," and what the authors called "complex cultivation practices" and 17 soil types. This LULC + Soil Type classification makes it difficult to infer the general effect of cultivation, but vineyards and perennial crops had the lowest carbon stocks in all soil types except for one, in which it was virtually identical to SOC stocks under annual crops (Arrouays et al. 2001).

The 2011 meta-analysis within France interpreted SOC stocks from a 1974 soil survey that used a spatial sampling design and standardized sampling method. In this survey, a 16-×-16 km grid was drawn over France and at the center of each cell 25 soil samples where taken by auger to 30 cm and bulked, with a single representative pit dug to measure local bulk density at fixed depth intervals. The SOC stock was then calculated for the 0-30 cm soil layer within each cell using a single laboratory protocol. Land use and land cover was classified hierarchically into 7 primary, 22 secondary, and 41 tertiary classes, which allowed for multiple interpretations of the correlation of SOC stocks with LULC. The median SOC storage under vineyards (32 Mg C/ha) was higher only than uncultivated coastal areas (24.2), and dramatically less than other LULC types such as orchards (∼40), annual crops (∼45), forest (70), and grasslands (75.7). The highest observed SOC storage under vineyards was also lower than the highest observations under orchards and annual crops, with the latter showing both broader variability and a large number of outliers with high SOC stocks (Martin et al. 2011).

EFFECT OF ALTERNATIVE MANAGEMENT WITHIN CULTIVATED FIELDS

A 2013 meta-analysis of soil carbon management studies within Mediterranean cropping systems found that alternative practices had the potential to increase SOC levels compared to conventional management. This trend was observed to be highest within horticultural production, where the alternative practices on average increased the SOC levels by as much as 48% over the conventional comparisons. Cereal and perennial crops showed an average response of 15% and 25%, respectively. However, when broken down to specific practices, the primary finding of this meta-analysis was that practices that added large amounts of off-site carbon to the soil resulted in higher amounts of soil carbon. In contrast, the manipulation of local carbon had mixed results, with cover cropping resulting in an average of only 10% increase over conventional management and no-till increasing SOC in horticultural crops by 18.2% but reducing it in woody perennials by 22.5%. The combination of off-site carbon amendment and local carbon management produced the best results within the agronomically viable options, with an average increase of 49.2% over conventional management (Aguilera et al. 2013). This increase through combined management amounted to 1.11 Mg C/ha per year, but there was no mention that this rate must surely plateau over time as the soil carbon pool reaches a new equilibrium point (Stewart et al. 2007). Without this context, it is unclear how this rate might compare to the estimates of carbon lost through the initial cultivation of previously uncultivated LULCs, which in a single mosaic landscape ranged from 10 to 110 Mg C/ha with conversion to vineyards (Williams et al. 2011). Most strikingly, this meta-analysis found that alternative management practices increased SOC levels by, on average, 51.6% over conventional management in controlled experimental studies, but only by 11.4% in on-farm observational trials, which corresponds to sequestration rates of 1.28 and 0.31 Mg C/ha per year. This meta-analysis shows that while it is possible to increase SOC levels in cropped fields through alternative management, this increase may be relatively minor in the larger landscape context. As most of these studies use a shallow sampling depth (average of 25.7cm) and measure SOC levels as a concentration, these results cannot be directly compared to carbon storage of uncultivated LULC. In addition, with only five studies of management within woody perennial species and no further distinction made among perennial crop types, additional analysis is necessary to draw conclusions and management recommendations for vineyards.

Seven papers were found that sampled among commercial vineyards that were applying alternative management strategies under real-world agronomic constraints (Table 4). Seven of the 14 comparisons within these papers compared management of local carbon through no-till intercropping (5) or mulching with pruning (2), two compared known amendments with

TABLE 4 Summary of published articles that measured SOC levels within existing vineyards under conventional and alternative management practices (average implied change in SOC is shown in bold at the bottom of the table)

				Conventional		Alternative		Implied C gain with alternative	
Source	Location	Sampling depth	Carbon source	Description	%C (Mg C/ha)	Description	%C (Mg C/ha)	Difference in %C (Mg C/ha)	% gain of conventional C
Besnard et al. (2001)	Champagne, France	0–10	Local	Pruning residue is removed and no carbonaceous soil amendment is used	1.5	Mulched with pruning residue	2.6	1.1	73.3
			Off-site		1.5	Mulched with oak bark	5.2	3.7	246.7
			Off-site		1.5	Mulched with urban compost	2.9	1.4	93.3
Probst et al. (2007)	Eastern France	0–10	Local + off-site	Not Biodynamic certified	3.1	Biodynamic	3	−0.1	−3.0
Blavet et al. (2009)	Southern France	0–5	Local	Pruning residue is removed	0.5	Pruning residue is incorporated	0.8	0.3	60.0
Okur et al. (2009)	Western Turkey	0–20	Local + off-site	Not organically certified	0.75	Organic	0.78	0.03	4.0
Coll et al. (2011)	Southern France	0–15	Local + off-site	Not organically certified	1.02	Organic (7 years)	1.08	0.06	5.9
						Organic (11 years)	1.24	0.22	21.6

						Organic (17 years)	1.35	0.33	32.4
Lagomarsino et al. (2011)	Sardinia, Italy	0–20	Local	Tilled	1.42	No-till	1.28	−0.14	−9.9
Francaviglia et al. (2012)	Sardinia, Italy	Surface horizon	Local	Tilled	(36.4)	No-till	(37.4)	(1.0)	−2.8
Virto et al. (2012)	Northeast Spain	0–5	Local	Tilled	0.92	Intercropped w/ grass (1 year)	1.57	0.65	70.7
						Intercropped w/ grass (5 year)	1.25	0.33	35.9
		5–15			0.89	Intercropped w/ grass (1 year)	1.11	0.22	24.7
						Intercropped w/ grass (5 year)	1.00	0.11	12.4
		15–30			0.88	Intercropped w/ grass (1 year)	0.93	0.05	5.7
						Intercropped w/ grass (5 year)	0.94	0.06	6.8
Seddaiu et al. (2013)	Sardinia, Italy	Surface horizon	Local	Tilled	(33)	No-till	(32)	(–1)	−3.2
						Observational studies		**0.52**	**37.8**

off-site carbon, and five did not describe specific management practices but compared conventional vineyards against those that were managed as organic or biodynamic. Of these, the first group of studies found only minor and mixed results from no-till intercropping but more dramatic increases with the mulching or incorporation of pruning residue; the second group found large increases in SOC among the vineyards that had received heavy carbon-rich amendments; and the third found SOC levels to be generally higher within active organic or biodynamic vineyards than analogous conventional vineyards, but the difference was variable even within the same study and region. The average response to alternative management among the observational studies was an increase of +0.52% C with highly variable sampling depths, which was on average an increase of 37.8% over the conventional management (Table 4).

Eleven experimental studies were found that studied management of local carbon through intercropping with groundcover species (19 comparisons), cover cropping that is seeded then incorporated as green manure (4), and mulching with crop residue from pruning (1) (Table 5). All of these studies found SOC levels to increase with the alternative management, for an average change of +0.36% C and an average of 61% increase over the conventionally managed comparison. This was found to be significant in many of the comparisons, but often only at the soil surface. As these practices are expected to reduce erosion as compared to conventional tillage or soil kept bare through herbicide application, the observed increases in SOC could come through sequestration of atmospheric carbon or by reduced losses of existing SOC through erosion (Table 5).

Six experimental studies were found that totaled 19 comparisons of vineyard plots amended with off-site carbonaceous materials against those that were not. All of these comparisons found an increase in SOC levels following amendment by an average of +0.67% C, a 68% increase over unamended soil. However the type and quantity of material used varied tremendously and the difference was again often only significant in the top 5 or 10 cm of the soil. While the increase in carbon in amended soils might include some that is sequestered from the atmosphere or maintained through reduced erosion, it is likely that much of the observed increase in vineyard SOC levels is simply residual off-site organic carbon that had been transplanted into the vineyard soil pool (Table 5).

CONCLUSIONS, IMPLICATIONS, AND DIRECTIONS FOR FUTURE RESEARCH

The clear trend throughout the literature on soil organic carbon storage in Mediterranean landscapes is that conversion to cultivated LULCs leads to dramatic losses of SOC. Conversion to perennial cropping was found to

TABLE 5 Summary of published articles that measured SOC levels through experimental manipulation of vineyard management practices. Statistically significant differences are indicated with an asterisk and the average implied changes in SOC is shown at the bottom of the table

				Conventional		Alternative		Implied C gain with alternative	
Source	Location	Sampling depth	Carbon source	Description	%C	Description	%C	Difference in %C	% gain of conventional C
Blavet et al. (2006)	Southern France	0–5	Local – intercropping	Tilled	1.6	No-till, seeded w/ rye/fescue	1.5	−0.1	−6.25
Lejon et al. (2007)	Burgundy France	0–20	Local – intercropping	Tilled (Site 1)	0.98	No till, seeded w grass	1.18	0.2*	20.4
						No till, seeded w/ clover	1.71	0.73*	74.7
						No till, seeded w/ fescue	1.26	0.28*	28.6
			Local – pruning residue	Tilled, residue is removed (Site 2)	0.55	Tilled, residue is incorporated	0.77	0.22*	40.9
Smith et al. (2008),	California, USA	0–30	Local – intercropping	Tilled	1.10	No till, seeded w/ rye	1.55	0.45*	40.9
Steenwerth and Belina (2008)						No till, seeded w/ fescue	1.40	0.30*	27.2
Celette et al. (2009)	Southern France	0–100	Local – intercropping	No till, soil is kept bare with herbicide	0.61	No till, seeded w/ barley	0.58	−0.03	−4.9
						No till, seeded w/ fescue	0.56	−0.05	−8.2
		0–30			0.86	No till, seeded w/ barley	0.84	−0.02	−2.3
						No till, seeded w/ fescue	0.84	−0.02	−2.3

(*Continued*)

TABLE 5 (Continued)

				Conventional		Alternative		Implied C gain with alternative	
Source	Location	Sampling depth	Carbon source	Description	%C	Description	%C	Difference in %C	% gain of conventional C
Okur et al. (2009)	Western Turkey	0–20	Local – cover cropping	Tilled, natural regeneration	0.8	Tilled, oat/vetch cover crop	0.9	0.1	12.5
Marquez et al. (2010)	Central Spain	Not given	Local – intercropping	Tilled, natural regeneration	0.98	No till, seeded w/ brachypodium	1.05	0.07	7.1
						No till, seeded w/ rye	1.04	0.06	6.1
Adams (2011)	California, USA	0–10	Local – cover cropping	Tilled, natural regeneration	0.6	Tilled, grass/clover cover crop	0.61	0.01	1.7
Bartoli and Dousset (2011)	Eastern France	0–5	Local – cover cropping	Tilled, natural regeneration	1.39	Tilled, clover cover crop	2.56	1.17*	84.2
						Tilled, fescue cover crop	3.24	1.85*	133.0
Peregrina et al. (2012)	Northern Spain	0–45	Local – intercropping	Tilled	0.60	No till w/ natural vegetation	0.73	0.13*	20.0
López-Piñeiro et al. (2013)	Southwest Spain	0–10	Local – intercropping	Tilled	0.17	No till w/ natural vegetation	1.37	1.20*	705.9
Ruiz-Colmer et al. (2013)	Central Spain	0–10	Local – intercropping	Tilled	0.59	No till, seeded w/ rye	0.91	0.32*	54.2
						No till, seeded w/ grass	0.91	0.32*	54.2
Blavet et al. (2006)	Southern France	0–5	Off-site	Unamended	1.7	Mulched with straw	1.6	−0.1	−6.25

Lejon et al. (2007)	Burgundy, France	0–20	Off-site	Unamended (1)	0.98	Straw	1.22	0.24*	24.5
						Conifer bark	1.63	0.65*	66.3
						Conifer compost	1.71	0.73*	74.5
				Unamended (2)	0.55	Farmyard manure (high)	0.98	0.43*	78.2
						Farmyard manure (low)	1.07	0.52*	94.5
						Mushroom compost (high)	0.94	0.39*	70.9
						Mushroom compost (low)	1.36	0.81*	147.3
Okur et al. (200)9	Western Turkey	0–20	Off–site	Unamended	0.8	Manure (high) + oat/vetch cover crop	0.98	0.18*	22.5
						Manure (low) + oat/vetch cover crop	0.96	0.16*	20
Bartoli et al. (2011)	Eastern France	0–5	Off–site	Unamended	1.39	Conifer bark	2.65	1.26*	90.6
						Conifer compost	2.29	0.9	64.7
						Straw	1.71	0.32	23
Mugnai et al. (2012)	Central Italy	0–30	Off–site	Unamended	2.18	Compost (w/o NPK)	5.26	3.08	141.3
						Compost (w/ NPK)	2.75	0.57	26.1
Peregrina et al. (2012)	Northern Spain	0–25	Off–site	Unamended	0.65	Fresh spent mushroom substrate (high)	1.22	0.57*	87.7
						Fresh spent mushroom substrate (low)	0.94	0.29*	44.6

(*Continued*)

TABLE 5 (Continued)

				Conventional		Alternative		Implied C gain with alternative	
Source	Location	Sampling depth	Carbon source	Description	%C	Description	%C	Difference in %C	% gain of conventional C
						Composted spent mushroom substrate (high)	1.6	0.95*	146.1
						Composted spent mushroom substrate (low)	0.92	0.27*	41.5
						Experimental studies		**0.49**	**65.0**
						Local carbon management		**0.33**	**63.4**
						Cover cropping + pruning residue		**0.67**	**54.5**
						Intercropping		**0.24**	**66.2**
						Off-site carbon amendment		**0.65**	**66.9**

have on average a greater implied carbon loss than conversion to annual cropping, with vineyards often having the lowest observed SOC levels within diverse agricultural landscapes. These conclusions may in fact underestimate the carbon lost with conversion, as the current uncultivated sites used for comparison are more likely to be on marginal soils that are naturally low in soil organic carbon. Due to this and the nearly ubiquitous shallow sampling depth used by these studies, the quantification of these trends as presented in Table 3 should not be considered a reliable predictor of potential carbon loss with future conversion. Instead, while the broader trends appear to be nearly universal to Mediterranean landscapes, quantification should be done locally in an attempt to capture site-specific characteristics and local carbon dynamics.

While a return to uncultivated LULCs might be an appropriate land management practice to sequester carbon in some circumstances, there is increasing interest in how to improve soil carbon stocks in actively cultivated fields through alternative management practices. Observational and experimental studies show that there is potential to have higher SOC levels in vineyards under alternative management, at least in the surface soil, but it is unclear to what extent this increase would be sequestration of atmospheric carbon as opposed to improved local retention of existing SOC or the addition of carbon from off-site sources. While potentially effective, these alternative practices should not be expected to compensate for the carbon lost with initial establishment of vineyards in previously uncultivated soils. Due to the relatively small number of studies and the wide variety of sampling depths, topography, and other factors that are known to be relevant to SOC dynamics, the summary statistics presented in Tables 4 and 5 should be applied with caution to specific landscapes to quantitatively estimate changes in SOC levels with alternative management. In general, the observed trends should guide management decisions only until more locally adapted estimates can be made.

Improved Soil Sampling

Perhaps the most striking shortcoming in our current understanding of SOC dynamics is a result of the tendency to use shallow standardized sampling depths. This practice is largely a result of the difficulty of sampling to greater depths and may also be in part a holdover from agronomic soil testing of nutrient levels for shallow rooted crops. An improvement can be seen in some recent papers that incorporate the depth of the surface horizon in the calculation of SOC stocks (Francaviglia et al. 2012; Seddaiu et al. 2013). However, this approach still has the potential to miss deeper carbon and can become more arbitrary when horizons are not clear. The traditional alternative to shallow surface sampling is to dig soil pits, but less intensive alternatives have recently been developed and are now available to soil scientists and other interested researchers. These techniques commonly involved soil augers or corers that are powered by small engines or hydraulic systems, and these alternatives give an operator the necessary power to remove compact soil at depth while still retaining the precision to remove soil between desired depths intervals (Rau et al. 2011). These improved sampling techniques can inform three-dimensional soil maps that allow for more accurate calculation of soil carbon stocks and support representative rather than randomized soil sampling.

Landscape Carbon Models

The common current approach to correlating SOC stocks with land use/land cover conversions and alternative management practices is to measure SOC storage under different conditions or treatments. However, this sampling strategy may not capture the full heterogeneity in the landscape and the corresponding variation and distribution of values within each LULC or management practice. In addition, the goal from a land manager's perspective is to build predictive models that allow for reasonable inference of carbon stocks and response dynamics across diverse landscapes. This requires estimating both how SOC levels respond to the interaction of LULC type, topography, climate, and other landscape characteristics, and how these levels might change over time, particularly in the context of global climatic changes. Much more research is clearly needed, but some authors are already working on this next step and have begun to build such models of carbon stocks in diverse landscapes. Three recent efforts in particular deserve special mention within Mediterranean landscapes as they demonstrate early efforts to model SOC dynamics over space and time.

The previously discussed study in Mendocino County combined the SOC measurements from the 12 paired soil pits and an additional 32 soils pits at representative vineyard and wildland sites with high resolution spatial mapping to calculate total belowground carbon stocks within each managed ranch (Williams et al. 2011). This approach modeled the interaction of soil type, LULC, topography, and other potentially relevant factors, and found that within each ranch the wildland areas contained on average only 16% more SOC than vineyards rather than the 100% that was found through the paired site approach. This difference may be due to the likely preference for establishing vineyards in fertile—and relatively carbon rich—areas, such that the remaining wildlands are now found in naturally lower carbon soils. The integrated model-based approach used in this study, which also measured aboveground carbon stocks, offers a relatively rare example of quantifying total carbon storage within a spatially bounded area, which could soon be used to estimate carbon stocks and associated carbon credit for property owners.

The 1974 soil survey of France that was the basis of Martin et al. (2011) was repeated between 2000 and 2009 using a similar sampling protocol, and the spatially explicit results were the foundation of a model of SOC storage that incorporated climate, soil type, land use, and management practices (Meersman, Martin, De Ritter, et al. 2012; Meersman, Martin, Lacarce, et al. 2012). This modeling approach allowed for estimates to be made at a 250 m resolution across France and for an average SOC stock to be calculated for each LULC type that takes into account variation in other relevant factors, rather than simply as a direct mean of all observations within a predefined category. This approach calculated that throughout France, vineyards and orchards had SOC levels on average one third that of forests and grasslands and dramatically less than annual croplands (Table 6). The reinterpretation of the soil data as a model allows for site-specific estimates to be made that take into account local soil and climatic characteristics and to estimate the local effect of LULC conversion under different landscapes characteristics through the modeling equivalent of a paired-site approach.

One of the three published studies of the mosaic landscape in Sardania, Italy used the observed SOC measurements and known land use histories to apply the Rothamsted Carbon Model for this mosaic landscape to generate 90 year projections given alternative global emission and local climatic scenarios (Francaviglia et al. 2012). These simulations estimated increases in SOC in all LULCs with little or no active cultivation (oak forest, pasture/hay, semi-natural fallow areas) but dramatic continued declines within both tilled and untilled vineyards (Table 7). This study found that in 2007 the tilled vineyards, the LULC with the lowest soil carbon stocks, contained 66.5% of the carbon found in pasture, the LULC with the highest observed stocks, but on average the model predicted that this difference will increase and in 90 years the same vineyards will contain only 42.1% of the SOC stored in pastures.

TABLE 6 Average SOC stocks within multiple LULCs in France as estimated by a landscape carbon model the integrates climate, soil type, land use, and management practices on soil carbon storage, based on 2,000+ soil samples

		Implied carbon loss with conversion	
LULC type	Average SOC stock (Mg C/ha)	Mg C/ha	% loss of uncultivated C
Forest	94.1	N/A	N/A
Grassland	85.8	N/A	N/A
Cropland	55.7	38.4–30.1	40.8–35.1
Vineyard/orchard	32.7	61.4–53.1	65.2–61.9

Adapted from Meersman, Martin, De Ridder, et al. (2012).

TABLE 7 Estimates SOC stocks in 2097 within multiple LULCs in a region Sardinia, Italy, under two scenarios of atmospheric carbon levels and two scenarios of local weather implications, as modeled through the Rothamsted Carbon Model and based on sampling in 2007 (the "former vineyards" had gone out of production in 1977)

		High global CO_2 emissions		Low global CO_2 emissions		
	2007 Baseline	Climate Model A	Climate Model B	Climate Model A	Climate Model B	Average predicted 2097 SOC storage
Tilled vineyards	36.3	−13.6	−13.6	−13.6	−13.3	22.8
No–till vineyards	37.5	−8.5	−8.3	−8.5	−9.5	28.8
Hay fields	54.6	4.7	3.3	2.8	3.7	58.2
Pasture	52.5	2.3	2.4	2.6	2.9	55.1
Former vineyards	44.5	3.9	4.2	3.8	4.3	48.6
Oak forest	50.5	1.6	1.6	1.7	2.1	52.3

Adapted from Francaviglia et al. (2012).

Targeted Surveys of Diverse Landscapes and Vineyards

The most rapid and cost-effective means of furthering our understanding of how SOC stocks respond to changes in land use/land cover and specific management practices is likely to be conducting targeted soil surveys within diverse landscapes and existing managed areas. Past studies of mosaic landscapes have attempted to control for potential heterogeneity by sampling strictly within simple predefined categories, such as LULC or LULC + Topography. Future surveys, however, could support a more model-based interpretation if the sampling design were to explicitly capture the range of all potentially relevant characteristics and measure them locally whenever possible. Such characteristics would include soil type and horizon depths, land use history and time since conversion, management practices, and climatic conditions. A similar modeling approach was applied to interpret the most recent soil survey of France, but these studies use a gridded sampling scheme that may not be appropriate to capture the full range of potentially relevant variables when applied for finer spatial resolution studies (Meersman, Martin, De Ritter, et al. 2012; Meersman, Martin, Lacarce, et al. 2012). Such a targeted soil survey could be particularly useful for understanding the effects of alternative management within vineyards, which can vary widely in the scale and intensity of both initial cultivation and subsequent management.

Life-Cycle Analysis of Specific Alternative Practices

As more land comes under cultivation every year, leaving less uncultivated soil behind to convert in the future, there will continue to be increasing interest in studying the effect of alternative practices. However, before alternative management practices can be strongly recommended and rewarded as mitigating atmospheric loading of the carbon cycle, the broader implications of these production practices need to be understood. Some recent studies of alternative vineyard management do document differences in wine quality or grape yield, with one study observing an average decline of 40% with alternative management (Celette et al. 2009; Ripoche et al. 2011; Ruiz-Colmenero et al. 2011). However, an integrated life-cycle analysis is often entirely lacking, which would place these gains in the context of agronomic concerns and potential changes in greenhouse gas emissions with alternative practices. The California Sustainable Winegrowers Alliance recently summarized the literature on these emissions and put forth a strategic research plan, so more integrated analyses may be forthcoming (Carlisle et al. 2010).

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