European Commission

SINGLE-IMPACT FICHE
COVER AND CATCH CROPS

IMPACT: CARBON SEQUESTRATION

Data extracted in January 2022
Fiche created in February 2024

Note to the reader: This fiche summarises the effects of Cover and catch crops on CARBON SEQUESTRATION. It is based on 12 synthesis papers[1], including from 10 to 131 primary studies.

1. WEIGHT OF THE EVIDENCE

CONSISTENCY OF THE IMPACT

The effect of cover/catch crops, as compared to bare soil, on CARBON SEQUESTRATION is reported in **Table 1**.

The table below shows the number of synthesis papers with statistical tests reporting i) a significant difference between the Intervention and the Comparator, that is to say, a significant statistical effect, which can be positive or negative; or ii) a non-statistically significant difference between the Intervention and the Comparator. In addition, we include, if any, the number of synthesis papers reporting relevant results but without statistical test of the effects. Details on the quality assessment of the synthesis papers can be found in the methodology section of this WIKI.

- The effect of cover/catch crops, as compared to bare soil, on CARBON SEQUESTRATION (soil organic carbon) is overall positive. For cover crops in general and for mixed-species cover crops (applied to both arable fields and orchards), 9 results reported significant increase in soil organic carbon, versus 4 results showing no significant effects.
- More specifically, cover crops belonging to both leguminous species and non-legume species resulted in significantly increasing soil organic carbon, with 3 and 2 positive results.

Out of the 12 selected synthesis papers, 11 included studies conducted in Europe (see **Table 2**).

Table 1: Summary of effects. Number of synthesis papers reporting positive, negative or non-statistically significant effects on environmental and climate impacts. The number of synthesis papers reporting relevant results but without statistical test of the effects are also provided. When not all the synthesis papers reporting an effect are of high quality, the number of synthesis papers with a quality score of at least 50% is indicated in parentheses. The reference numbers of the synthesis papers reporting each of the effects are provided in **Table 3**. Some synthesis papers may report effects for more than one impact or more than one effect for the same impact.

				Statistically tested			Non-statistically tested
Impact	Metric	Intervention	Comparator	Significantly positive	Significantly negative	Non-significant	
Increase carbon sequestration	SOC	Cover crops	Bare soil	9	0	4	1
		Legume cover crops	Bare soil	3	0	0	0
		Non-legume cover crops	Bare soil	2	0	0	0

QUALITY OF THE SYNTHESIS PAPERS

The quality of each synthesis paper was assessed based on 16 criteria regarding three main aspects: 1) the literature search strategy and primary studies selection; 2) the statistical analysis conducted; and 3) the evaluation of potential bias. We assessed whether authors addressed and reported these criteria. Then, a quality score was calculated as the percentage of these 16 criteria properly addressed and reported in each synthesis paper. Details on quality criteria can be found in the methodology section of this WIKI.

2. IMPACTS

The main characteristics and results of the 12 synthesis papers are reported in **Table 2** with the terminology used in those papers, while **Table 3** shows the reference numbers of the synthesis papers reporting for each of the results shown in **Table 1**. Comprehensive information about the results reported in each synthesis paper, in particular about the modulation of effects by factors related to soil, climate and management practices, are provided in the **summaries of the synthesis papers** available in this WIKI.

Table 2: Main characteristics of the synthesis papers reporting effects on carbon sequestration. The references are ordered chronologically with the most recent publication date first.

Reference number	Population	Scale	Num. papers	Intervention	Comparator	Metric	Conclusion	Quality score
Ref1	Organic farming systems	Global. Most research occurred in the United States (N = 7), Spain (N	36	Organic farming systems using cover crops	Organic farming systems not using	Soil organic carbon	Organic farming systems cover	81%

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[1] Synthesis research papers include either meta-analysis or systematic reviews with quantitative results. Details can be found in the methodology section of the WIKI.

Reference number	Population	Scale	Num. papers	Intervention	Comparator	Metric	Conclusion	Quality score
		= 6), India (N = 5), and Germany (N = 5).			cover crops	concentration	cropping did not show a mean effect different from zero (+0.136; CI -0.004/0.277, n=8), as compared to organic farming systems not using cover crops.	
Ref2	fruit tree species (apple, citrus, grape, jujube, kiwi fruit, peach, pear, plum)	Global	116	Ground cover (including cultivated green manure, sod cultivation, natural, vegetation, grass, and cover crop)	Clean tillage management	Soil organic matter	Cover crops (both legume and non-legume) significantly increase soil organic matter.	69%
Ref4	Annual and perennial cropping systems	Global. Most publications (n = 27) were from the United States, followed by Italy (n = 4), Denmark (n = 3), and others in North America, Europe, and Oceania (n = 6).	40	Cover crops	No cover crop	Soil organic carbon stock (within 30 cm depth)	Across the entire data set, cover crops demonstrated a strong, positive effect on SOC stock from 0 to 30 cm.	88%
Ref11	Arable fields cultivated with corn, soybean, wheat, other monoculture, corn-soybean rotation, corn-wheat-soybean rotation, and other rotations of more than two cash crops	Global. Tropical, arid, temperate, and snowy climates.	131	Cover crops	No cover crop	Soil organic carbon stocks to a depth of 0.3 m	Cover cropping caused a 15.5% increase in SOC (95% confidence interval of 13.8%–17.3%) in near-surface soils (i.e., ≤30 cm depth).	75%
Ref13	Tree crops (Orchards, vineyards) in the Mediterranean area. The fruit tree crops used for the study were mostly grapevines (Vitis vinifera L.) at 36% of the sample size, olive trees (Olea europaea L.) at 34% of the sample size, almond trees (Prunus dulcis (Mill.) D.A. Webb) at 15% of the sample size and citrus trees (Citrus x sinensis Osbeck, Citrus x limon (L.) Osbeck) at 7% of the sample size. We also used other fruit trees, such as avocado (Persea americana Mill.), carob (Ceratonia siliqua L.), peach (Prunus persica (L.) Stokes), chestnut (Castanea sativa Mill.) and walnut (Juglans regia L.), representing 8% of the total dataset.	Global (mediterranean climates)	46	Permanent intercropping (PC) (45%) and annual intercropping (AC) (55%). Permanent intercropping refers to the maintenance of a permanent cover crop in the alleys, such as aromatics (Thymus sp, Lavandula sp, Salvia sp, Rosmarinus sp, Brachypodium sp, Asparagus sp or natural grass), while annual intercropping means the presence of cover crops in the alleys that are annually harvested or incorporated into the soil.	Mono-cropping in orchards. Mono-cropping indicates the presence of the tree crop alone with no other vegetation cover in the alleys (bare soil).	1) Soil organic carbon stock; 2) Soil carbon sequestration rates	Both annual and permanent intercropping (cover crops with tree crops) were associated with a significant increase in SOC stocks (Mg /ha) compared to mono-cropping. Results on SOC sequestration rates (Mg /ha /year) were not statistically significant.	81%
Ref15	Vineyards	Global. The majority of studies (39 out of 50) were conducted in countries of the European Union. The largest number of studies was from Spain (n = 17), followed by Italy (n = 11), France (n = 10), the USA (n = 5), South Africa (n = 4), and Australia (n = 1), Germany (n = 1) and Turkey (n = 1).	50	Cover crops	No cover crop	Soil organic carbon stocks to a depth of 0.3 m	Cover crops were associated with a positive SOC stock change, SOC change rate in time and annual SOC sequestration rate, relative to conventional management.	94%
Ref16	Croplands excluding orchards and pastures	Global	64	Cover crops	no cover crop (fallow) . all other aspects of management held constant like in the intervention.	Soil organic carbon stock	On average, cover crops represented an effective approach for significantly increasing SOC content (6%).	75%
Ref20	Mediterranean agro-ecosystems	Mediterranean agroecosystems	10	Cover crops	No cover crops	Soil organic carbon	The sample size for mulching, cover cropping, and organic weed management was less than eight and no statistical analysis was carried out. Therefore, the result was set as 'uncertain'.	62%
Ref22	Arable crops	Global (including EU)	48	Cover crops (legume/non-legume; incorporated/surface/removed)	Bare soil with the same treatments than in the intervention	Soil organic carbon	Cover crops increased SOC by 15% compared to no cover crop. Incorporation of cover crop residue into the soil increased SOC, while having no effect on SOC with residue removal.	69%
Ref24	Arable crops in Mediterranean area	Global (Mediterranean climate). The authors analysed data from 57 publications that included data from 326 experiments and 1062 comparisons (Table 2): 26 publications from a wider review of Mediterranean farming practices (Shackelford et al., 2017) and 31 publications from our new searches (see File S3 for a list of	57	Winter cover crops (legumes, non legumes, mixtures).	Bare soil	Soil organic matter (including soil organic carbon)	In plots with cover crops as green manure there was more carbon stored in soil organic matter (+8%), compared to control plots with bare soils or winter fallows and no fertilization.	88%

Reference number	Population	Scale	Num. papers	Intervention	Comparator	Metric	Conclusion	Quality score
		included publications and a modified PRISMA flow diagram). The data came from approximately 50 species or mixtures of cover crops, 12 food crops, and 5 countries: Italy (24 publications), the United States of America (20 publications), Spain (9 publications), France (2 publications), and Greece (2 publications).						
Ref29	Vineyards. Global dataset. About 40% of all datasets originated from irrigated vineyards, 50% were rainfed vineyards and the other studies did not provide information on the use of irrigation. Most datasets came from vineyards under Mediterranean climates (n = 100), oceanic climates (n = 56), and steppe or continental climates (n = 22; three studies included vineyards from different climates). Most studies implemented randomized block designs within one experimental vineyard (n = 113), only few studies implemented block designs in several vineyards (n = 12), whereas 56 datasets used individual vineyards as replicate. The majority of studies investigated the effects of bare soil management (mostly due to tillage, sometimes by use of herbicides or both) compared to cover crops or natural vegetation (n = 137 datasets). We investigated the effects of conventional vs. organic management in 27 studies and 17 datasets originated from other types of intensive vs. extensive vegetation management like the contrast of single to diverse cover crop species in inter-rows or mulching vs. mowing of vegetation.	Global. Major wine producing regions world-wide except Asian countries, New Zealand and Argentina	74	Cover crops or natural vegetation growth for soil cover in vineyards	Bare soil or removal of spontaneous vegetation in vineyards by herbicides use or tillage	Soil organic carbon	Carbon sequestration showed significant positive responses to natural vegetation management.	94%
Ref30	In all the experiments the commercial crops were soybean or corn and always sowed after the cover crop.	Pampas	62	Cover crops	No cover crops	Soil organic carbon	The average increase due to cover crops was around 7% of the soil carbon content in the 0–20 cm layer.	81%

Table 3: Reference numbers of the synthesis papers reporting for each of the results shown in **Table 1**.

				Statistically tested			Non-statistically tested
Impact	Metric	Intervention	Comparator	Significantly positive	Significantly negative	Non-significant	
Increase carbon sequestration	SOC	Cover crops	Bare soil	Ref4, Ref11, Ref13, Ref15, Ref16, Ref22, Ref24, Ref29 and Ref30		Ref1, Ref11, Ref13 and Ref22	Ref20
		Legume cover crops	Bare soil	Ref2, Ref11 and Ref22			
		Non-legume cover crops	Bare soil	Ref2 and Ref22			

3. FACTORS INFLUENCING THE EFFECTS ON CARBON SEQUESTRATION

Table 4: List of factors reported to significantly affect the size and/or direction of the effects on carbon sequestration, according to the synthesis papers reviewed.

Factor	Reference number
Cash crop	Ref11
Climatic conditions	Ref16
Cover crop biomass production	Ref4
Cover crop residue management	Ref22
Cover crop type	Ref22

Factor	Reference number
Crop residue retention	Ref16
Growing window	Ref4
No factor reported	Ref24
Pedo-climatic zone	Ref4
Rotation type	Ref4
Soil depth	Ref11 and Ref16
Soil pH	Ref16
Soil texture	Ref4 and Ref11
Tillage	Ref4
Time scale	Ref16

4. KNOWLEDGE GAPS

Table 5: Knowledge gap(s) reported by the authors of the synthesis papers included in this review.

Ref Num	Gap
Ref4	The limited number of observations within certain categories of growing window, climate, cover crop species diversity, and functional type reduces the generalizability of our findings. Cover crop growing window as a key management predictor of soil C stock response demonstrates promise, but there are too few observations in the autumn and continuous cover categories to robustly evaluate mechanisms that contribute to higher SOC in these systems. In general, most publications provided poor descriptions of cover crop management. While we could usually ascertain data about the type of cover crop species or functional group planted, numerous studies omitted data about termination date and termination method. Other sparse data included soil characteristics like bulk density, soil texture, and pH. A little more than one-half of our data set measured aboveground cover crop biomass production, and even fewer measured cover crop C:N ratio. Better data reporting and measurements can reduce knowledge gaps and uncertainty around optimal cover crop management for improved selection of cover crop species, planting, and termination dates. This knowledge can help to improve cover crop establishment across growing conditions and maximize biomass cover to increase soil C and provide other environmental co-benefits
Ref11	Most existing comparisons reported soil carbon concentration (i.e., SOC%) changes without reporting soil bulk density (BD). Since BD is necessary to calculate SOC stocks, we had to estimate BD for many instances based on correlations developed using reported values (Fig. A5). As this process added additional uncertainty to the dataset, we recommend that soil carbon stock and BD should be reported in the future studies. Likewise, it is important that studies report SD values whenever possible. Substantially fewer data were available for the subsurface layers (>30 cm) compared with the surface layers (≤30 cm). Our results suggested that CCs may not change SOC concentrations in subsurface soil layers; however, this conclusion may be due to the small sample size (only 38 experiments from 7 studies and only 5 experiments from 3 studies have standard deviation information). Because of this uncertainty, future experiments should strive to include samples from subsurface layers, which should help evaluate subsoil benefits of CCs in the future. Comparisons collected in this study covered a wide time period (1960–2014) and included samples from various depths and sampling increments. We did not attempt to account for any sampling differences in this study. In addition, most comparisons were reported after less than 5 years of data collection, even though CC effects on SOC are often not detectable in the first few years after establishment, due to high spatial field variability or soil heterogeneity. Future CC experiments should continue to collect data for mid- (e.g., 5–10 years) and long-term (e.g., >10 years) periods to the extent possible. Longer-term data are particularly important to understand maximum sequestration potentials in soils. The ~0.1–~1 Mg ha–1 yr–1 carbon sequestration rates found in this study
Ref15	Some sources of uncertainty in our study were due to the fact that our methodology used an approach based on fixed depth to calculate SOC stocks. Bulk density, which was used with SOC concentration and sampling depth to estimate SOC stocks, was only provided in a few studies (30%). Pedotransfer functions (Equation (2) and (3)) were, thus, used to estimate this parameter from the SOC concentration reported in the studies. However, there is high uncertainty in the prediction of bulk density using these functions, since specific management practices may affect differently bulk density within a given land use.
Ref16	The authors did not calculate SOC sequestration rates for cover crops due to the lack of some ancillary information (e.g., bulk density).
Ref24	Effects of cover crops on pollinators, natural enemies, and other forms of biodiversity have only rarely been studied in Mediterranean climates.

5. SYNTHESIS PAPERS INCLUDED IN THE REVIEW

Table 6: List of synthesis papers included in this review. More details can be found in the summaries of the meta-analyses.

Ref Num	Author(s)	Year	Title	Journal	DOI
Ref1	Crystal-Ornelas, R; Thapa, R; Tully, KL	2021	Soil organic carbon is affected by organic amendments, conservation tillage, and cover cropping in organic farming systems: A meta-analysis	Agriculture, Ecosystems & Environment 312, 107356	10.1016/j.agee.2021.107356
Ref2	Fang, LF; Shi, XJ; Zhang, Y; Yang, YH; Zhang, XL; Wang, XZ; Zhang, YT	2021	The effects of ground cover management on fruit yield and quality: a meta-analysis	ARCHIVES OF AGRONOMY AND SOIL SCIENCE	10.1080/03650340.2021.1937607
Ref4	McClelland, SC; Paustian, K; Schipanski, ME	2021	Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis	Ecological applications, 31, 3, e02278	10.1002/eap.2278
Ref11	Jian, Jinshi; Du, Xuan; Reiter, Mark S.; Stewart, Ryan D.	2020	A meta-analysis of global cropland soil carbon changes due to cover cropping	Soil Biol. Biochem. 143, 107735	10.1016/j.soilbio.2020.107735
Ref13	Morugan-Coronado, A; Linares, C; Gomez-Lopez, MD; Faz, A; Zornoza, R	2020	The impact of intercropping, tillage and fertilizer type on soil and crop yield in fruit orchards under Mediterranean conditions: A meta-analysis of field studies	Agric. Syst. 178, 102736	10.1016/j.agsy.2019.102736
Ref15	Payen FT, Sykes A, Aitkenhead M, Alexander P, Moran D,	2020	Soil organic carbon sequestration rates in vineyard agroecosystems	J. Clean. Prod. Elsevier	10.1016/j.jclepro.2020.125736

Ref Num	Author(s)	Year	Title	Journal	DOI
	MacLeod M.		under different soil management practices: A meta-analysis	125736	
Ref16	Bai, XX; Huang, YW; Ren, W; Coyne, M; Jacinthe, PA; Tao, B; Hui, DF; Yang, J; Matocha, C	2019	Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis	Global Change Biology, 25, 2591-2606	10.1111/gcb.14658
Ref20	Lee, H; Lautenbach, S; Nieto, APG; Bondeau, A; Cramer, W; Geijzendorffer, IR	2019	The impact of conservation farming practices on Mediterranean agro-ecosystem services provisioning-a meta-analysis	REG ENVIRON CHANGE	10.1007/s10113-018-1447-y
Ref22	Muhammad, I., Sainju, U.M., Zhao, F., (...), Fu, X., Wang, J.	2019	Regulation of soil CO2 and N2O emissions by cover crops: A meta-analysis	Soil and Tillage Research 192, pp. 103-112	10.1016/j.still.2019.04.020
Ref24	Shackelford, GE; Kelsey, R; Dicks, LV	2019	Effects of cover crops on multiple ecosystem services: Ten meta-analyses of data from arable farmland in California and the Mediterranean	LAND USE POLICY, 88, 104204.	10.1016/j.landusepol.2019.104204
Ref29	Winter, S; Bauer, T; Strauss, P; Kratschmer, S; Paredes, D; Popescu, D; Landa, B; Guzman, G; Gomez, JA; Guernion, M; Zaller, JG; Batary, P	2018	Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: A meta-analysis	J APPL ECOL	10.1111/1365-2664.13124
Ref30	Alvarez, Roberto; Steinbach, Haydee S.; De Paepe, Josefina L.	2017	Cover crop effects on soils and subsequent crops in the pampas: A meta-analysis	Soil and Tillage Research 170, 53-65	10.1016/j.still.2017.03.005