Effect of sustainable production systems on carbon and water footprint in fruit tree orchards

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Abstract

Climate changes (mainly increased temperature and precipitation changes) will have agricultural consequences due to the interrelations between climate and soil degradation, land and water use, and landscape changes. Analysis of water and carbon resource use at a farm scale could contribute to design practices with no (or minimum) impact on the environment. Carbon footprint (CF) and water footprint (WF) are being used to indicate the impacts of the C and W use by production systems. This paper reports the effects of sustainable orchard management practices (e.g., no-tillage, retention of pruning residues, compost application, guided irrigation) on CF and WF in fruit tree orchards. Results show that CF decreases in a sustainably-managed orchard (-0.79 kg_{CO2} kg_{fruits}^{-1}) compared to locally conventional managed orchard fields (0.14 kg_{CO2} kg_{fruits}^{-1}), and is acting as a sink for carbon. The WF analysis shows that the sustainable practices contributed to the ~40% reduction of the blue water component use, associated with a corresponding increase of the green water component use. Hence, the good practices adopted may represent a local (farm scale) tool for mitigation of a global problem.

Keywords: sustainability, environmental-friendly practices, CO_2-equivalent emissions, RDI

INTRODUCTION

In the last century, the world population has quadrupled, global resource consumption and waste emissions have grown so much that the Earth is no longer able to regenerate its resources at the same speed (Haberl et al., 2007; Hoekstra, 2009). Climate change is currently seen as the most impending environmental issue and sustainability is certainly the most current solution. Recently, a new definition of "Footprint family" has been provided, as a suite of indicators to track human pressure on the planet from different angles (Galli et al., 2012). A deeper understanding of the interactions between different footprints is required in order to achieve a good environmental governance.

The two most important indicators are carbon and water footprint. The Carbon Footprint (CF) measures the total amount of GHG emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product, expressed as the mass of CO_2-equivalents (CO_2-eq) (Fang et al., 2014). The Water Footprint (WF) concept was introduced in response to the need for a consumption-based indicator of freshwater use (Hoekstra, 2003) and it is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community (Hoekstra and Chapagain, 2008). Three key water components are tracked in its calculation: the blue WF (WF_{blue}) refers to consumption of surface and ground water (irrigation water); the green WF (WF_{green}) refers to consumption of rainwater stored in the soil as soil moisture; the grey WF (WF_{grey}) refers to pollution and is defined as the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra, 2009).

Agriculture is responsible for almost 14% of equivalent CO_2 emissions and it is the largest freshwater user, accounting for 99% of the global consumptive (green plus blue) WF (IPCC, 2007; Hoekstra and Mekonnen, 2012). With increasing water scarcity, there is a growing interest in improving crop water productivity in order to meet the growing global food demand with the limited freshwater resources. The challenge is to produce more crops with less water, thus reducing the WF per unit of crop produced (Mekonnen and Hoekstra, 2014). On the other side, agriculture has a potential role in mitigating climate change by reducing the emissions of CO_2-equivalents released by farming activities and by sequestering carbon in farmland soils (Smith et al., 2007). Among the most important environmental problems of modern agricultural production systems, there is a gradual loss of soil fertility, caused from the depletion of soil organic carbon (SOC). Soil organic carbon is a very important element for soil and its increase is generally associated with improved soil tilth, improved water-holding capacity, improved storage and availability of plant nutrients, and reduced soil erosion (Marland et al., 2004).

Sustainable agriculture practices must be aimed at transforming orchard ecosystem from C source to C sink, increasing C storage and reducing the emission of carbon from soil (IPCC, 2014). This paper describes which sustainable fruit orchard management practices can be the beneficial effects on CF and WF.

Sustainable practices

Among sustainable practices in agriculture, the following have been used in this study: no-till farming; cover crops; incorporation of organic matter back into fields through retention of pruning residues and compost application; reduction of chemical fertilizers. Regarding water use in agriculture, alternative management techniques can be used in order to reduce water consumption (e.g., drip irrigation, regulated deficit irrigation, summer pruning). During the field study the sustainable managed plot (1 ha) was compared a conventionally-managed plot (involving soil tillage, burning of pruning residues, mineral fertilization, empirical irrigation).

Increasing soil organic carbon in fruit orchards

Changes in orchard management practices can result in the accumulation of SOC. For example, conversion from conventional to no-till agriculture is one of the most promising approaches for increasing SOC (Follett, 2001).

A seven-year period of changed management practices in a Mediterranean peach orchard significantly increased SOC level at the upper soil layer (0-0.1 m depth) from 1.31 to 1.78%, through a combination of increased annual C inputs (from 2.4 to 8.6 t ha^{-1}) and a lack of soil disturbance (Montanaro et al., 2012). During that period, in deeper soil layers, down to 0.4 m, SOC was improved from 0.78 to 0.89%, and litter C was increased at approx. 4.4 t ha^{-1}. That increase in SOC concentration equals approx. 55 t ha^{-1} CO_2 stored in the upper 40 cm soil layer (assuming 1.4 soil bulk density) and the litter represents additional 16.1 t ha^{-1} of CO_2. It could be argued that changes of soil management practices may have a significant ecological role by switching soil from C-source to a net C-sink at least for the upper soil layers.

Soils with high levels of SOC have a greater capacity for water and nutrient storage, promoting high levels of healthy microbial activity, contributing to impart resilience to the effects of climatic extremes such as drought or high rainfall events. Elevation of soil C input (e.g., compost) had favourable effects on fruit yield, effectively replacing mineral fertilisers in the nutrient management of commercial fruit tree orchards through associated increases in organic matter and total N, P and K (Baldi et al., 2010). Montanaro et al. (2012) documented that improvement of soil macronutrients reservoirs (via increasing carbon input) enhances crop yields. That is, a 30% increased yield was recorded in a sustainably-managed peach orchard receiving 4.2 t ha^{-1} y^{-1} C input (mainly crop residue retentions and compost additions). The increased yield helps also to reduce WF per unit of product, because of the increased use efficiency.

Carbon footprint

During the last century, C loss from cultivated soils has in part been indicated for the observed trend for global warming (IPCC, 2007). Carbon economy at an orchard scale is mainly driven by the capture *VS* emissions trade-off. Although measurement of C sequestered is relatively easily accessible (through increased tree biomass and SOC analysis), determinations of CO_2 soil emission remain problematic, mainly because specific equipment is required. However, CO_2 emissions must be taken into account if the accuracy of estimates of orchard C budget are to be improved.

Orchards are very important ecosystems, for their potential role in sequestering C from the atmosphere through the C storage in the living organs of trees. A significant amount of sequestered CO_2 is distributed in permanent structures, in the root system, leaves, pruning materials and fruit (Figure 1). Fruit is the principal component, accounting for almost 32% of the total CO_2 fixed in the tree structure (Figure 1). In a study conducted in Southern Italy, the CFs of two peach orchards managed differently (under conventional or sustainable practices) have been analysed taking into account the following components: inputs including cover crops, leaves, roots turnover, yield and pruning material and compost (only for sustainable), permanent structures, soil respiration, fertilization, farm operations and pruning residues burned (Figure 2). CO_2 emissions from soil depends on soil moisture, degree of soil aeration, microbial biomass, root density and quantity of organic matter. The CF of the peach orchard under sustainable management resulted in emissions of -0.79 kg_{CO2} kg_{fruits}^{-1} compared to 0.14 kg_{CO2} kg_{fruits}^{-1} under conventional management practices, considering an annual average yield (seven years) of 23.2±2.03 and 17.9±2.35 t ha^{-1}, respectively. Results reported in Figure 2 show that different management practices can transform an orchard from a C source (under conventional management practices) to a C sink (under sustainable management practices). This is mainly because of the increase of C input through cover crops, pruning retention and compost application. Pruning materials may count as carbon loss from the orchard system, if removed from the grove, but if left to decompose naturally, they represent an efficient means of long-term CO_2 immobilisation (Lal, 1997).

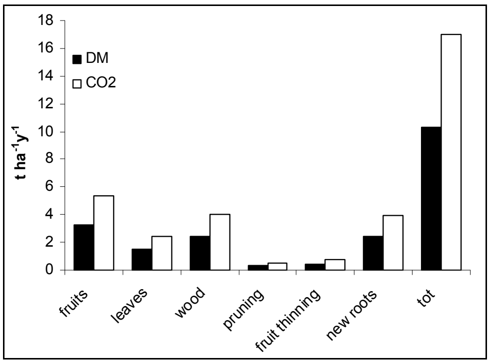

Figure 1. Dry matter and respective CO_2 value contained in peach plants (cultivar Springcrest/GF677, 500 trees ha^{-1}).

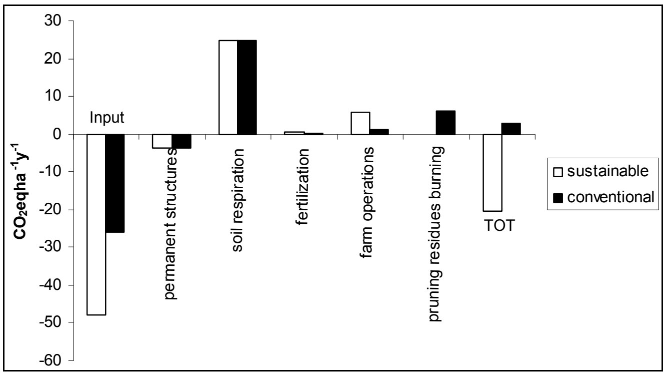

Figure 2. CO_2 fluxes (t ha^{-1} y^{-1}) comparison in a peach orchard managed with conventional and sustainable agricultural practices. Input includes: cover crops, leaves, roots turnover, yield and pruning material and compost (only for sustainable).

This study reveals that changed soil management practices, with low pressure on soil, have the potential to positively influence several aspects of environmental quality, increasing the amount of carbon in soil and, thus, reducing CO_2 emissions in the atmosphere.

Water footprint

To reduce the impact of agriculture's WF is necessary to increase the efficiency of irrigation system, the Water Use Efficiency (WUE) and the soil water storage capacity. Strategies aimed to improve rainwater recharge in soils by using specific soil management techniques (e.g., cover crops) in order to reduce the blue component, should be applied (Dichio et al., 2004). Furthermore, optimal irrigation system design is worthwhile to save water during the early years after planting (especially for early ripening ccultivars) and improve plant water use efficiency (Dichio et al., 2007). The use of water saving techniques in fruit-growing is crucial due to increasingly limited water availability. The regulated deficit irrigation technique (RDI) is an irrigation management method that allows reducing irrigation volumes at selected phenological stages. The reduction in water supply is applicable at the phenological stages less sensitive to water deficit without affecting yield and quality (Dichio et al., 2004).

Postharvest is defined as the less sensitive period for peach trees to water deficit. In this period it is possible to reduce irrigation without a negative effect on peach growth and yield, as foreseen by the deficit irrigation strategies (Dichio et al., 2007). WF_{blue} was calculated in a sustainable managed peach orchard (220 L kg_{fruits}^{-1}) and in a conventional one (380 L kg_{fruits}^{-1}), with an annual yield (average of six years) of 23.2 and 17.9 t ha^{-1}, respectively. These results reveal that environmental-friendly management practices reduce the water consumption (Dichio et al., 2011).

Furthermore, canopy management (e.g., summer pruning) can also affect WF. In fact, with a partial reduction of leaf area through summer pruning, in a peach orchard it is possible to reduce water demand at about -24 L d^{-1} $tree^{-1}$, which is about 750-1000 m^3 ha^{-1} (Dichio et al., 2011).

Improving soil C content may be beneficial also for irrigation management, because of some effects on soil hydrological properties (e.g., soil porosity, soil water infiltration rate and retention, soil structural stability) (Bhogal et al., 2009). The increase of annual C input under sustainable practices has beneficial effects on soil water holding capacity (WHC) (at 2 m depth) of a sustainable managed olive orchard (4,250 m^3 ha^{-1}) compared to a conventional one (2,934 m^3 ha^{-1}). Furthermore, the soil water infiltration rate measured in a sustainable olive orchard (i.e., non-tilled, pruning materials retention and cover crops) was about 10-fold of that of a conventional grove (i.e., tilled, removal of pruning materials), allowing a greater water reservoir of 1,000 m^3 ha^{-1} (1 m depth) compared with conventional plot at the end of winter time (Palese et al., 2009).

Soil microbial communities

Quantitative and qualitative response of soil microbial communities to alternative agricultural management systems often helps to identify sustainable agricultural practices aimed at improving orchard production (Sofo et al., 2010b). Sustainable orchards showed a higher total number of bacteria and microbial complexity, with a more genetic, functional and metabolic diversity of soil microorganisms (Sofo et al., 2010a, 2013). Recently, the effect of sustainable agricultural management systems has been evaluated for genetic, functional, and metabolic diversity of soil microbial communities by using a combination of culture-dependent and independent methods (Sofo et al., 2010a, b, 2013). Microorganisms involved in N cycle were investigated because N is the most important nutrient influencing vegetative growth and yield quality and quantity in trees (Fernandez-Escobar et al., 2006). In an olive orchard under sustainable management, the number of bacteria (Azotobacter, ammonifying and proteolytic bacteria) in the soil beneath drippers (i.e., wetted soil) was significantly higher than that along inter-row (dry soil) (Table1).

Table 1. Amount of Ammonifying, Azotobacter and Proteolytic bacteria in soil sampled along the row under the emitter (WET) and at the inter-row (DRY) position. Adapted from Sofo et al. (2010b).

	CFU g^{-1} dry soil	
	Wet	Dry
Ammonifying bacteria	6.10E+08	2.00E-07
Azotobacter	3.75E+08	1.15E+08
Proteolytic bacteria	1.20E+08	9.40E+06

In a peach orchard there was a significantly higher number of cultivable bacteria from sustainable management than the conventional management (1.13E+07 vs. 1.06E+07 $\log_{10}$ CFU g^{-1} dry soil) (Sofo et al., 2010a). In addition, a 12 years of sustainable management practices in an olive orchard increased the bacterial and fungal amount in soil [Fungi: 21.4 (sustainable) vs. 2.9 (conventional) CFU*10^4 g^{-1} dry soil; Bacteria: 35.6 (sustainable) vs. 10.0 (conventional) CFU*10^6 g^{-1} dry soil)] (Sofo et al., 2013). The positive effects of minimum tillage and organic carbon input on soil bacteria are due to increased soil aeration, cooler and wetter conditions, temperature and moisture buffering capacity of the soil, as well as higher carbon content in surface soil (Brady and Weil, 2008).

CONCLUSIONS

This study highlights the beneficial effects of sustainable orchard management practices to preserve the environment, as approaches to climate change mitigation. In particular, restoration of organic soil, through compost addition, pruning retention and cover crops, improves chemical and microbiological fertility of the soil and increases the soil water holding capacity, reducing the blue water footprint. Changes in orchard management aimed to implement C sequestration and reduce CO_2 emission help the orchard system to act as a sink for carbon.

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