INVESTIGATION INTO CO_2 ABSORPTION OF THE MOST REPRESENTATIVE AGRICULTURAL CROPS OF THE REGION OF MURCIA

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1.-INTRODUCTION

1.1. CO_2 in Earth's Atmosphere

The phenomenon known as 'global warming' occurs when energy released by the Earth's crust is reflected and retained by certain atmospheric gases, preventing the progressive cooling of the Earth. Without the intervention of these gases, life as we know it would not be possible, as the heat released by the planet would dissipate into space resulting in extremely low temperatures on Earth. Included in such gases are carbon dioxide, nitrous oxide and methane, which are released primarily by industry, agriculture, farming and the burning of fossil fuels. The rate of industrial development on Earth means that the concentration of these gases has risen by 30% since the last century curtailing Mother Nature's attempts to restore the natural balance of concentrations of these atmospheric gases.

Of these gases, CO_2 is of particular significance, because of its effect on the Earth's climate and its permanence – it is a gas that remains active in the atmosphere for a long time. For example, of the CO_2 released into the atmosphere, over 50% will take 30 years to disappear, 30% will remain for many centuries and 20% will last for several million years (Solomon et al., 2007).

Plants have the ability to capture atmospheric CO_2, and through the process of photosynthesis, metabolise it to produce sugars and other compounds that are necessary for the plant's normal development (Fig. 1. Photosynthesis (1)). In general, it can be concluded that plants, via the process of photosynthesis, extract carbon from the atmosphere (in the form of CO_2) and convert it into biomass. On decomposition the biomass becomes part soil (in the form of humus) and part CO_2 (through respiration of micro-organisms that process the biomass (Fig. 1 (2)).

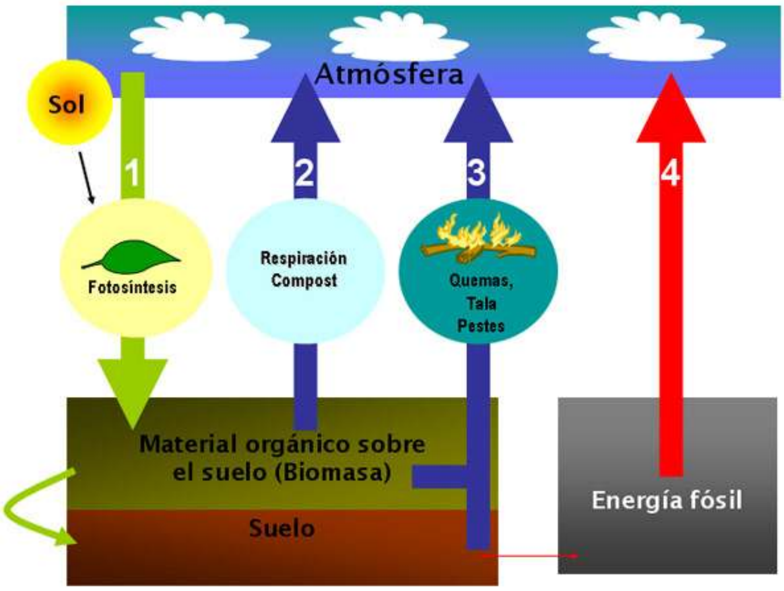

Figure 1. Carbon cycle: sources of CO_2 emissions and CO_2 sinks.

Various factors affect the amount of carbon accumulated in both plant biomass and the soil. The felling of trees and the burning of vegetable matter, such as occurs when forests are converted into farm or agricultural land, as well as logging, releases the accumulated carbon in plants and the soil (Fig. 1 (3)) and this returns to the atmosphere in the form of CO_2.

At present, an excess of CO_2 alters the natural balance of the carbon cycle as previously described, acting as a decisive influence on climatic conditions. On the one hand, CO_2 is captured from the atmosphere by plants through photosynthesis. On the other, plant respiration, the burning of fossil fuels and felling of trees for agricultural purposes increase the concentration of carbon emissions in the atmosphere, which when combined with a high rate of deforestation and insufficient attempts to replant trees, alter the balance between capture and release. Therefore, the concentration of CO_2 in the atmosphere is rising. Total CO_2 emissions from the agricultural and forestry sectors supersede those released as a consequence of the burning of fossil fuels in the transportation and energy sectors (Fig. 1 (4)).

1.2. Carbon Sinks

All systems and processes that extract and then store a gas or gases from the atmosphere are called sinks. Using their primary function, photosynthesis, plants act as carbon drainage systems. By this means, plants absorb CO_2, and offset the loss of this gas through respiration as well as that released as a result of emissions from other natural processes (decomposition of organic matter).

The absorption of CO_2 by plants constitutes an important element in the global balance of carbon (C). On a global scale it is estimated that the Earth's biosphere takes up nearly 2,000,000 tons of CO_2 per year (UNESA, 2005). This amount is a result of the small differences between the photosynthetic absorption of CO_2 and its loss through respiration, decomposition of organic matter and different types of natural disturbances. Added to this amount is the so-called net primary production in the biosphere (NPP), and it is this, which in the long term, is stored in the sink.

The CO_2 captured by plants is the result of the differences between atmospheric CO_2 absorbed during the process of photosynthesis and the CO_2 released by the atmosphere during respiration. This difference is converted into biomass and tends to fluctuate between 45 and 50% of the plant’s dry weight. Therefore, whilst CO_2 levels are high, both natural vegetation and agricultural plants act as carbon drainage systems. When this is taken into account, agriculture can become one of the most effective means in mitigating the increase of atmospheric CO_2.

The soil

To determine the amount of carbon captured by the ecosystem, the amount of stable carbon in the soil must be considered. If accumulation of carbon in the soil takes place at a slower rate than the accumulation of carbon in the biomass, then the carbon stability in the soil is greater. Therefore, the soil has a significant ability to store carbon due to the accumulation of vegetable matter during decomposition, converting it into what is called carbon humus. The pruning of trees and the shredding of their leaves can be considered as loss of crop carbon when removed from the land or burned. However, if leaf matter is left to decompose naturally, it becomes an effective way of immobilising CO_2 in the long term (Lal, 1997). In fact, after one year of plant matter accumulating on the ground, most of the carbon returns to the atmosphere in the form of CO_2. However, one-fifth to a third of this carbon stays in the soil, as either live biomass or humus (Brady and Weil, 2004).

1.3. Photosynthesis

Photosynthesis is a metabolic process fundamental to all living organisms as it involves using solar energy to biosynthesise cellular compounds. Solar energy is not just a source of energy for green plants and other photosynthetic autotrophs, but is ultimately the energy source of almost all heterotrophic organisms, through the workings of biospheric food chains. Furthermore, solar energy captured in the process of photosynthesis is the source of nearly 90% of all energy used by humans to meet their heating, electricity and energy needs, since carbon, petroleum and natural gas (fossil fuels primarily used in industry), are the products left over from the decomposition of biological matter generated millions of years ago by photosynthetic organisms.

Photosynthesis is a process that occurs in two stages (Fig. 2). The first stage is *light-dependent* (light reaction phase). This stage requires energy directly from sunlight to generate chemical energy and a reducing agent, both of which are used in the second stage. The *light-independent* stage (dark phase) occurs when the products derived from light reactions are used to form covalent carbon-carbon (C-C) bonds of carbohydrates from the CO_2 through the Calvin Cycle. This process of photosynthesis takes place in the cell's chloroplast.

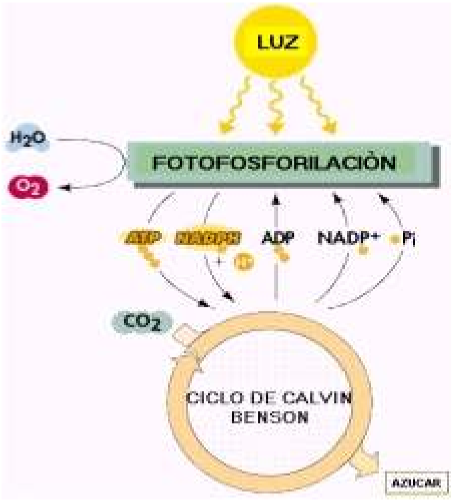

Figure 2. Diagram of photosynthesis.

In light reactions, solar energy is captured by pigments that absorb light, and, with the aid of a water molecule, convert it into chemical energy (ATP) and a reducing agent (NADPH). As a result, molecular O_2 is released. The general equation for this first stage of photosynthesis is the following:

$$\text{WATER} + \text{NADP}^+ + \text{P}_i + \text{ADP} \xrightarrow{\text{light}} \text{OXYGEN} + \text{H}^+ + \text{NADPH} + \text{ATP}$$

In the second stage of photosynthesis, the energy-rich products of the first stage, NADPH and ATP, are used as sources of energy to carry out the reduction of CO_2 and produce glucose. As a result, ADP and $NADP^+$ are produced again. The second stage of photosynthesis is summarised as follows:

$$\text{CO2} + \text{NADPH} + \text{H}^+ + \text{ATP} \longrightarrow \text{GLUCOSE} + \text{P}_i + \text{NADP}^+ + \text{ADP}$$

This reaction is carried out by conventional chemical reactions catalysed by enzymes that do not require light.

In light-independent reactions, CO_2 from the atmosphere (or from the water in aquatic/marine photosynthetic organisms) is captured and reduced with the addition of hydrogen (H^+) to form carbohydrates [(CH_2O)]. The assimilation of carbon dioxide by organic compounds is known as carbon fixation or assimilation. The energy used in the process originates from the first stage of photosynthesis. Living beings cannot make direct use of light energy. However, through a series of photosynthetic reactions, energy can be stored in the C-C bonds of carbohydrates, which are later released in the process of respiration and other metabolic processes.

Carbon fixation in C3, C4 and CAM plants

Plants have different metabolisms depending on their type of CO_2 fixation, and are classified into the categories of C-3, C-4 or CAM. The efficiency of a plant's water usage and rate of carbon fixation differs depending on the plant.

C-3 plants: These plants keep their stomata open during the day to allow fixation of CO_2, thus leading to a continual loss of water through transpiration. To avoid the risk of dehydration caused by an environmental disturbance, these plants are able to close their stomata, leading to a decrease in photosynthetic activity.

C-4 plants: Stomata are kept open during the day. These plants use intermediaries in their cells to pump CO_2, which allows the stomata to close unexpectedly, hence allowing the process of photosynthesis to continue thanks to CO_2 reserves.

CAM plants: Stomata remain open at night. Water loss through transpiration is greatly reduced. These plants also have reserves of CO_2 with which they can also close stomata without lessening their ability to photosynthesise.

The properties of C-4 and CAM plants allow them to survive in environments in which water is scarce.

Table 1. Some of the differences among C3, C4 and CAM plants.

Typical species of economic importance	*C3*	*C4*	*CAM*
	wheat, barley, pepper, fruit, rice, tomatoes	*corn, sorghum, sugar cane*	*pineapple, prickly pear*
% of flora worldwide in number of species	89%	<1%	10%
Typical habitat	Ample distribution	Warm areas and grasslands	Humid areas and tropics
First stable product from CO_2 fixation	PGA	Malate	Malate
Anatomy	Bundle sheath cells not present/without chloroplasts	Bundle sheath cells with chloroplasts (Kranz)	Succulence of cells and plant tissue
Photo respiration	Up to 40% of photosynthesis	Not detectable	Not detectable
Point of compensation for the assimilation of CO_2	40-100 $\mu l\ l^{-1}$	0-10 $\mu l\ l^{-1}$	0-10 $\mu l\ l^{-1}$
$[CO_2]$ inter cellular during daylight ($\mu l\ l^{-1}$)	200	100	10000
Frequency of stomata (Stomata mm^{-2})	40 - 300	100 - 160	1 - 8
EUA (CO_2 g fixed by kg H_2O transpired)	1 - 3	2 - 5	10 - 40
Maximum rate of growth (g m^{-2} d^{-1})	5-20	40-50	0.2
Maximum productivity (tons ha^{-1} $year^{-1}$)	10-30	60-80	Generally less than 10*

1.4. Effect of environmental stress factors on CO_2 fixation

Environmental stress factors such as salinity, desiccation, fluctuations in temperature and the reduction in solar radiation alter plant structure and metabolism, thereby affecting their growth and their role as CO_2 absorbers (Martínez-Ballesta et al., 2009). Given that they are essential for the processes of absorption and transportation of water and nutrients, such environmental factors are key variables that affect plant development. This being the case, the effect of these factors can have numerous consequences for agricultural crops, both in terms of physiological responses in the individual plant in the short-term to long-term changes in plant structure and function. Numerous studies have shown that plants, when faced with certain environmental factors, react in various ways that normally lead to water shortage (Kimball et al., 2002).

Given the severe desiccating nature of the atmosphere, controlling water loss has always been a key aspect for plant survival. On the one hand, the flow of water through a plant should be sufficient to maintain adequate nutrition and assimilation of CO_2. On the other, since assimilation and transpiration are closely linked in almost all plants, the availability of water imposes a restriction on total productivity and development (Steudle and Peterson, 1998). At the same time, to prevent desiccation of surface areas, the intake of water through the plant's roots has to compensate for the loss of water through its leaves. Given that the physiological processes are extremely sensitive to water shortage, the ability to conserve sufficient amounts of water tends to constitute the main problem in areas where the climate is warm and precipitation low.

The rise in temperatures could lead to an increase in photorespiration, which is a mechanism used to protect the process of photosynthesis, and which is not involved in CO_2 fixation (Sofo et al., 2005). The combined actions of different environmental factors (water vapour in the atmosphere and the rise in temperatures) could lead to a greater production of biomass, but only if plants receive adequate support from other essential nutrients such as nitrogen, phosphorus and potassium (human intervention could help in the provision of nitrogen to natural ecosystems since this nutrient is left over from many of our contaminating emissions when released into the environment).

It is predicted that we will see an increase in CO_2 fixation in the next 60 years due to the rise in temperatures. It is hoped that CO_2 fixation will increase 1% by every ^{o}C in areas where the average annual temperature is 30 ^{o}C and 10% in areas where the average annual temperature is 10 ^{o}C. The rate of photosynthesis will increase between 25 and 75% in C3 photosynthetic plants (those most commonly found in areas of medium and high latitudes) at double today's CO_2 concentrations. Data is less conclusive in the case of plants whose methods of photosynthesis are similar to that of C4 plants, typically those of hot areas, their response intervals ranging from 0% to an increase of 10 to 25% (UNESA, 2005).

This problem implies the need to carry out research into the effect of different environmental factors on CO_2 fixation ability and into deciphering the water and nutritional needs of agricultural crops.

1.5. Agriculture in the region of Murcia

The agriculture of the Region of Murcia plays a fairly important role in the GDP of Spain. It is one of the most lucrative farming regions in Spain and Europe due to high productivity, which is much higher than the national average. Agriculture in the Murcia region is orientated towards exportation, which suggests strong agronomic infrastructure and an efficient communications network. If we include all the indirect activities generated as a result of the farming industry, this then becomes a notable element within the context of the regional economy.

The region's excellent climate, combined with widespread adoption of eco-friendly farming practices, markedly increases the remunerative importance of this sector. The scarcity of water in the region has become a limiting factor and has led to the current situation in which the irrigation of land is dependent on underground water (which contains a large amount of saline due to overexploitation as well as the intrusion of sea water) as the Tajo-Segura inter-basin water transferral system has become insufficient to cover regional needs.

Agricultural crops of numerous varieties are the most significant products of Murcia's agricultural industry: tomatoes, lettuce, peppers, artichokes, etc., although citrus fruit (particularly lemons) and grains are also important, followed by vine fruits and other high-value orchard products, such as almonds, peaches, plums, etc.

Overall, logging has little bearing on the economy and occupies only a small area of the region. Forests are mainly located in the mountainous zones and are not needed for regional requirements. Indigenous forests have suffered from significant human incursions, so that the predominant species are now replanted pines and poplars along the riverbanks.

The adoption of good agricultural practices and sustainable farming (as in not clearing the ground, using exact quantities of fertilizer and when necessary, refraining from burning crops and relying less on ploughing) would halt the release of millions of tons of greenhouse gases. Therefore, a code of good farming practice is being established to help protect the soil, manage organic matter and soil structure, and conserve habitats, agricultural land, and permanent pasture. This change in the agronomic model could lead to a positive balance of CO_2 in farming areas. With suitable preparation and training, this sector can help mitigate the release of harmful gases through adaptation of farming techniques, promotion of eco-friendly methodology and the more efficient use of resources in farming machinery, making it ultimately more efficient all round.

Therefore, as part of this project, this study has determined the annual rate of CO_2 fixation by the agricultural crops most representative of the Region of Murcia, based on data obtained from biomass production and their concentration of carbon. Only irrigated land totalling a surface area greater than 1000 Ha was chosen. The amount of carbon fixation by individual plants was calculated only considering the annual biomass

production of the plant, allowing total carbon fixation and CO_2 concentration to be calculated.

2. MATERIALS AND METHODS

2.1. Plant and processed material

For all the varieties analysed in the carbon fixation study, only the plant or tree's annual production of biomass (both surface area (the fruit) and root), was considered (IPCC, 2003).

Crops

Tomato, pepper, watermelon, melon, lettuce and broccoli

Specimens were collected during the final stages of cultivation. Three plants from each variety were extracted manually from the soil with a spade being careful not to harm the secondary roots and were put into individual plastic bags for processing at the laboratory. The fruit, leaf, stalk and root were subsequently separated and weighed to determine the fresh weight. Specimens were then put into a laboratory hot-air oven at 70 ^{o}C until constant weight was obtained to determine dry weight. The time taken for the drying process can vary depending on the humidity and total weight of the specimen. Once the dry weight for each part of the specimen was obtained, the crops were ground using an IKA model A10 analytical laboratory grinder. A homogeneous result was obtained with particles of from 5 to 7 mm in diameter. The total amount of carbon was determined as described in the following analysis.

Photograph 1. Processing of agricultural crops.

Grains

Oats, barley and wheat

A total of 10 specimens of each variety were collected from the farm during the production stage. They were extracted manually and labelled accordingly in airtight bags until arrival at the laboratory, where they were then separated into above-ground and root parts for subsequent weighing and statistical analysis to determine the fresh weight of each plant. To determine the dry weight, the specimens were put into a hot air drying chamber at 70 ^{o}C for approximately 5 days and were then weighed on laboratory precision scales. The specimens were ground as explained in the previous section and carbon content was determined as described below.

Photograph 2. Laboratory processing of grains.

Fruit

Apricot, plum, peach, and grape

A destructive methodology was used to collect the fruit tree specimens that consisted of uprooting, by heavy machinery, three 17-year-old trees. The trees were then divided into sections (trunk, branches, and root) using a chainsaw. The leaves were then completely removed by hand along with the current year's young branches. The rest of the older trunk and branches were divided for subsequent weighing. Specimens were bagged and labelled according to parts for transferral to the laboratory. The root was processed in the same manner after being cleaned of any remaining soil and residue. This year's roots were cut and weighed. As was the case for the above ground section of the tree, a representative sample of the root was taken to the laboratory for processing.

Wooden crates with a capacity of 30 kg and a hydraulic pallet truck were used to transport the specimens from the farm to the cooperative. At the cooperative, specimens were weighed separately on industrial floor scales comprising corrugated, anti-slip, steel lifting beams, four mobile weighing platforms and a handling terminal.

The fruit specimens were taken from fruit collected at the farm. A representative sample of the fruit was taken to the laboratory in order to obtain the dry weight and the total amount of carbon in a similar process to that described previously. The total fruit crop amount was calculated from the average obtained from all the trees in the sample plot.

Photograph 3. Processing the fruit.

Citrus fruit

Lemon, orange, and mandarin

To calculate the CO_2 fixation of citrus fruits and annual quantification of CO_2, samples from 15-year-old trees were used. Extraction comprised pulling down both the above- and below- ground parts of the trees using a Caterpillar power shovel 983G (135 kW). After the trees were felled, the same shovel was used to separate the trees into three parts from which the fresh weight could be obtained. A chain saw was used to separate the branches (those which had been previously used to collect the fruit), the trunk and the roots (once any remaining soil and residue had been removed), and fresh weight was then determined using a similar procedure to that described in the previous section. The total fruit crop was calculated from the total of each tree collected in the previous crop(s) corresponding to a full year's growth.

A representative sample from each part of the tree, together with the fruit specimens, were collected to determine the dry weight at the laboratory as previously described.

The fact that leaf biomass is renewed every three years, and that total weight of the above-ground part of the plant and the root is in a 70/30 ratio with regards to the tree's total biomass, needs to be considered in order to calculate the total annual carbon fixation per tree (Morgan et al., 2006). Measurements were carried out as follows.

Photograph 4. Processing the citrus fruit.

2.2. Determining total amount of carbon

The total amount of carbon was analysed in sub-samples (around 2-3 mg PS) of leaves, stalks, fruit and roots using an NC-Thermo Finnigan 1112 EA Elemental Analyser (Thermo Finnigan-, Milan, Italy).

Photograph 5. CEBAS-CSIC Carbon Analyser.

3. RESULTS

3.1 Determining the amount of carbon and CO_2 fixation in herbaceous plants

The results of the CO_2 calculations of herbaceous plants, tomato, pepper, watermelon, melon, lettuce and broccoli are shown in tables 1 to 6.

The tables show the average values for annual biomass and CO_2 fixation based on the percentage of carbon for each section of the plant. Taking into account the annual growth of these plants, the total amount of carbon has been determined for the whole plant, keeping in mind the total production of the plant, its fruit and seeds.

In the tomato plants (Table 1) a greater concentration and fixation of carbon was observed than in the pepper plants (Table 2) due to a greater amount of biomass in tomato than pepper. However, when the total amount of carbon per hectare is calculated, the differences between these two plants diminish due to the pepper plant having a greater plantation density (2.2 plants m^2) than the tomato (2 plants m^2). The region currently has a great number of tomato varieties and uses different forms of cultivation. For the purposes of this study, salad tomatoes (Corvey variety) cultivated in soil were used.

Table 3 shows the CO_2 absorption rates and carbon concentration of watermelon. The values per plant are very similar to those for tomato; however, the fact that plantation density is lower also reduces the total amount of fixed carbon per hectare. When the data obtained for the watermelon is compared with that for melon (Table 4), it is clear that even though the results for carbon absorbed by the melon are much lower (approximately half), due to the watermelon's greater biomass, the total per hectare is similar as a result of greater plantation density.

Table 5 shows the difference in carbon concentration in two agriculturally significant lettuce varieties. As can be seen from the values obtained per plant, values are much higher in the Romaine variety due to its greater biomass in dry weight. However, there are no great differences between these varieties in terms of amount of carbon fixation per square metre due to the Cogollo variety having a much greater plantation range than Romaine. When calculating the total amount of carbon per hectare and year, it is important to remember that this region produces three annual harvests of these types of crops.

Table 6 shows that there are no great differences between the two different varieties of broccoli with respect to absorption efficiency of CO_2, although it is somewhat greater in the Naxos variety due to its greater biomass. As is the case with lettuce, when the amount of carbon is calculated per year and hectare, the fact that this region produces three annual harvests must be considered.

The results obtained for cauliflower (Table 7) are fairly high compared to those of the other Brassica, broccoli. These results are due primarily to its greater biomass, since plantation density is similar. Therefore, the results for carbon fixation per plant and square metre are greater.

The greatest increases in CO_2 fixation for agricultural plants can be observed in artichokes (Table 8). This result is due to its greater biomass in dry weight. Consequently, although the plantation density of artichokes is lower, it results in a greater concentration of carbon per square metre.

Table 1. *Modular values of carbon and CO_2 increase in different sections of biomass (g) in tomatoes.*

TOMATO	Fresh weight (Plant g^{-1})	Dry weight (Plant g^{-1})	Humidity %	C % (% Dry weight)	Carbon total (m g^{-2} $year^{-1}$)	Carbon total (T ha^{-1} $year^{-1}$)	PLANT TOTAL C g Plant $^{-1}$	PLANT TOTAL CO_2 g $plant^{-1}$
Root	134	22.5	83.23	38.96	17.5	0.2	8.8	32.3
Stalk	1,434	296.8	79.30	40.36	240	2.4	120	440
Leaves	866	169.7	80.40	40.99	139	1.4	69.6	255
Fruit	3,394	510.8	84.95	46.05	470.4	4.7	235.2	862
Total	**5,827**	**1,000**			**867**	**8.7**	**433**	**1,590**

Plantation density: 2 plants m^2

Table 2. *Modular values of carbon and CO_2 increase in different sections of biomass (g) in peppers.*

PEPPER	Fresh weight (Plant g^{-1})	Dry weight (Plant g^{-1})	Humidity %	C % (Dry weight %)	Carbon total (g m^{-2} $year^{-1}$)	Carbon total (T he^{-1} $year^{-1}$)	PLANT TOTAL C g $plant^{-1}$	PLANT TOTAL CO_2 g $plant^{-1}$
Root	53.4	30.3	43.23	43.15	28.8	0.3	13.1	48.0
Stalk	458	269.1	41.24	40.82	241.7	2.4	109.8	402.6
Leaves	519	305.6	41.12	31.14	209	2.1	95.2	349.1
Fruit	683	135	80.25	46.34	137.5	1.4	62.5	229.2
Total	**1,713**	**740**			**617**	**6**	**281**	**1,029**

Plantation density: 2.2 plants m^2

Table 3. *Modular values of carbon and CO_2 increase in different sections of biomass (g) in watermelon.*

WATERMELON	Fresh weight (Plant g^{-1})	Dry Weight (Plant g^{-1})	Humidity %	C % (Dry weight %)	Carbon total (g m^{-2} $year^{-1}$)	Carbon total (T he^{-1} $year^{-1}$)	PLANT TOTAL	
							C g $plant^{-1}$	CO^2 g $plant^{-1}$
Root	46.8	8.5	81.87	37.83	1.3	0.01	3.2	11.73
Stalk	2,369	285	87.99	39.29	45	0.5	112	411
Leaves	2,691	322	88.05	37.54	48	0.5	121	444
Fruit	15,989	398	97.51	42.71	68	1	170	623
Total	**21,096**	**1,013**			**162**	**1.6**	**406**	**1,489**

Plantation density: 0.4 plants m^2

Table 4. *Modular values of carbon and CO_2 increase in different sections of biomass (g) in melon.*

MELON	Fresh weight (Plant g^{-1})	Dry weight (Plant g^{-1})	Humidity %	%C (Dry weight %)	Carbon total (g m^{-2} $year^{-1}$)	Carbon total (T he^{-1} $year^{-1}$)	PLANT TOTAL	
							C g $plant^{-1}$	CO_2 g $plant^{-1}$
Root	23.6	5	80.53	39.69	2	0.02	2	7.3
Stalk	1071	134	87.47	33.62	45.1	0.5	45.1	165.4
Leaves	764	90	88.17	36.72	33	0.3	33.0	121.0
Fruit	2972	319	89.25	43.43	138.5	1.4	138.5	507.8
Total	**4,831**	**549**			**219**	**2**	**219**	**802**

Plantation density: 1 plant m^2

Table 5. *Modular values of carbon and CO_2 increase in different sections of biomass (g) in different lettuce varieties.*

COGOLLO	Fresh weight (Plant g^{-1})	Dry weight (Plant g^{-1})	Humidity %	C % (Dry weight %)	Total carbon (g m^{-2} $year^{-1}$)	Total carbon (T he^{-1} $year^{-1}$)	PLANT TOTAL C g $plant^{-1}$	PLANT TOTAL CO_2 g $plant^{-1}$
Root	56.6	12.8	77.44	39.90	229.8	2.3	5.1	18.7
Stalk	96.6	6.1	93.70	36.75	100.9	1.0	2.2	8.1
Leaves	430.2	22.3	94.81	35.08	352.5	3.5	7.8	28.6
Total	**583.4**	**41.2**			**682.7**	**6.8**	**15.1**	**55.4**
ROMAINE	**Fresh weight (Plant g^{-1})**	**Dry weight (Plant g^{-1})**	**Humidity %**	**C % (% Dry weight)**	**Carbon total (g m^{-2} $year^{-1}$)**	**Carbon total (T he^{-1} $year^{-1}$)**	**PLANT TOTAL C g $plant^{-1}$**	**PLANT TOTAL CO_2 g $plant^{-1}$**
Root	65.4	18.4	71.90	38.69	138.9	1.4	7.1	26.0
Stalk	185.2	12.6	93.17	37.91	93.1	0.9	4.8	17.6
Leaves	1121.5	65.8	94.13	35.79	459.2	4.6	23.5	86.2
Total	**1372.1**	**96.8**			**691.2**	**6.9**	**35.4**	**129.8**

Plantation density: Cogollo: 15 plants m^2. Romaine: 6.5 plants m^2

Table 6. *Modular values of carbon and CO_2 increase in different sections of biomass (g) in two varieties of broccoli.*

BROCCOLI-PARTHENON	Fresh weight (Plant g^{-1})	Dry weight (Plant g^{-1})	Humidity %	C % (Dry weight %)	Carbon total ($g\ m^{-2}\ year^{-1}$)	Carbon total ($T\ he^{-1}\ year^{-1}$)	PLANT TOTAL C $g\ plant^{-1}$	PLANT TOTAL CO_2 $g\ plant^{-1}$
Root	228.5	42.9	81.23	41.48	186.8	1.9	17.8	65.3
Stalk	600.9	63.0	89.52	41.50	274.5	2.7	26.1	95.7
Leaves	103.9	11.0	89.41	42.04	48.6	0.5	4.6	16.9
Inflorescence	207.4	22.2	89.57	43.98	101.8	0.5	9.7	32.5
Total	**1140.7**	**139.1**			**611.75**	**6.1**	**58.2**	**210.4**
BROCCOLI-NAXOS	**Fresh weight (Plant g^{-1})**	**Dry weight (Plant g^{-1})**	**Humidity %**	**C % (% Dry weight)**	**Carbon total ($g\ m^{-2}\ year^{-1}$)**	**Carbon total ($T\ he^{-1}\ year^{-1}$)**	**PLANT TOTAL C $g\ plant^{-1}$**	**PLANT TOTAL CO_2 $g\ plant^{-1}$**
Root	196.5	43.9	77.66	39.35	181.4	1.8	17.3	63.4
Stalk	848.5	101.7	88.01	40.00	427.1	4.3	40.7	149.2
Leaves	51.4	6.4	87.55	41.81	27.9	0.3	2.7	9.9
Inflorescence	186.5	19.9	88.55	44.21	96.0	0.5	4.4	16.1
Total	**1182.7**	**161.9**			**682.4**	**6.8**	**65.0**	**238.7**

Plantation density: 3.5 plants m^2

Table 7. *Modular values of carbon and CO_2 increase in different sections of biomass (g) in cauliflower.*

CAULIFLOWER	Fresh weight (g plant^{-1})	Dry weight (g plant^{-1})	Humidity %	C % (% Dry weight)	Carbon total (g m^{-2} year^{-1})	Carbon total (T he^{-1} year^{-1})	PLANT TOTAL g C Plant^{-1}	g CO_2 Plant^{-1}
Root	83.75	20.7	75.31	38.19	83.0	0.8	7.9	29.0
Stalk	235.35	24.1	89.76	36.27	97.2	1.0	8.7	31.9
Leaves	1,246.50	118.9	90.46	38.40	479.4	4.80	45.70	167.60
Inflorescence	801.00	74.5	90.69	41.77	326.7	3.3	31.1	114.0
Total	**2,366.60**	**238.2**			**986**	**9.9**	**93.4**	**342.5**

Plantation density: 3.5 plants m^2

Table 8. *Modular values of carbon and CO_2 increase in different sections of biomass (g) in artichoke.*

ARTICHOKE	Fresh weight (g plant^{-1})	Dry weight (g plant^{-1})	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} year^{-1})	Carbon total (T he^{-1} year^{-1})	PLANT TOTAL g C Plant^{-1}	g CO_2 Plant^{-1}
Root	827	277.5	66.5	42.20	82	0.8	117.1	429.4
Stalk	1281	397.5	69.0	39.00	108.5	1.1	155	568.3
Leaves	2281	439	80.7	39.15	120.3	1.2	171.6	629.2
Inflorescence	598	146	75.7	42.33	43.2	0.4	61.8	226.6
Total	**4987**	**1260**			**354**	**3.5**	**506**	**1,854**

Plantation density: 0.7 plants m^2

3.2 Calculation of CO_2 absorption and carbon content in grains

In tables 9, 10 and 11 the total amount of annually absorbed carbon in grams per plant is shown along with the sections of the biomass in oats, barley and wheat, as well as the total amount of CO_2 absorbed by these grains. As the tables show, the three grain varieties do not exhibit any great differences in the various absorption levels per plant. However, if we estimate the CO_2 fixation amount per square metre, the values are somewhat lower for barley, due to its lower plantation density.

Table 9. *Annual values of CO_2 absorption and assimilated carbon in oats.*

OATS	Fresh weight (g $Plant^{-1}$)	Dry weight (g $Plant^{-1}$)	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} $year^{-1}$)	Carbon total (T he^{-1} $year^{-1}$)	PLANT TOTAL g C $plant^{-1}$	g CO_2 $plant^{-1}$
Root	4.7	0.4	91.03	34.21	17.5	0.2	0.1	0.37
Surface part	18.5	6.7	63.89	42.02	360.4	3.6	2.8	10.27
Total	**23.1**	**7.1**			**378**	**3.8**	**3.0**	**10.63**

Plantation density: 128 plants m^2

Table 10. *Annual values of CO_2 absorption and assimilated carbon in barley.*

BARLEY	Fresh weight (g $Plant^{-1}$)	Dry weight (g $Plant^{-1}$)	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} $year^{-1}$)	Carbon total (T he^{-1} $year^{-1}$)	PLANT TOTAL g C $plant^{-1}$	g CO_2 $plant^{-1}$
Root	2.1	0.9	53.63	27.65	24.9	0.2	0.2	0.7
Surface part	61.8	7.9	87.29	42.73	300	3.0	3	12.3
Total	**63.9**	**8.8**			**325**	**3.2**	**3.6**	**13.0**

Plantation density: 100 plants m^2

Table 11. *Annual values of CO_2 absorption and assimilated carbon in wheat.*

WHEAT	Fresh weight (g $Plant^{-1}$)	Dry weight (g $Plant^{-1}$)	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} $year^{-1}$)	Carbon total (T he^{-1} $year^{-1}$)	PLANT TOTAL g C $plant^{-1}$	g CO_2 $plant^{-1}$
Root	1.5	0.7	49.80	26.54	23.2	0.2	0.2	0.7
Surface part	16.8	6.7	60.23	42.26	354	3.5	2.8	10.3
Total	**18.3**	**7.4**			**377.2**	**3.8**	**3.0**	**11.0**

Plantation density: 125 plants m^2

3.3. Calculation of total carbon and CO_2 fixation in fruit trees

The results of the calculations of CO_2 in apricot, plum, peach, nectarine, grape, lemon, orange and mandarin trees are shown in tables 12 to 16.

The tables record the average total values for biomass and CO_2 fixation in percentage of carbon for each section of the plant. The total amount of carbon of the whole plant is calculated taking into account the annual production of fruit and the plant's annual growth rate.

Table 12 contains data on the analysis of the apricot tree, in which a greater concentration of carbon and CO_2 fixation per tree was found than in the other fruit trees analysed. However, it is important to consider that the density of apricot plantation is half that of the other fruit trees. The peach tree exhibited higher results per square metre (Table 14). In fact, if we consider only the content of carbon and CO_2 fixation per square metre, the apricot would be the species with the lowest values, followed by the plum (Table 13). The highest values are seen in the peach and nectarine (Tables 14 and 15). The plum tree has the lowest dry weight (biomass) of the four analysed, which would indicate a greater capacity to fix CO_2 and accumulate carbon.

The data obtained for grapes (Table 16) shows that in spite of having approximately half the dry weight of nectarine, these two plants have similar values for carbon accumulation per square metre. On the other hand, when the results for carbon accumulation and CO_2 fixation are compared per vine with the data obtained from the fruit trees, much lower values are exhibited (up to 75% lower if we compare it with the apricot tree).

Table 12. *Total CO_2 accumulated annually per tree, per section of biomass in apricot .*

APRICOT	Fresh weight (g tree^{-1})	Dry weight (g tree^{-1})	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} year^{-1})	Carbon total (T he^{-1} year^{-1})	TREE TOTAL g C tree^{-1}	TREE TOTAL g CO_2 tree^{-1}
Root	25,217	15,130	40.00	43.04	132.8	1.3	6,512	23,870
Branches	10,185	6,057	40.53	46.74	57.8	0.6	2,831	10,381
Leaves	12,081	5,074	58.00	45.13	46.7	0.5	2,290	8,396
Fruit	125,000	18,588	85.13	64.5	174.3	1.7	8,545	31,331
Trunk	10,297	6,134	40.53	46.74	58.5	0.6	2,867	10,512
Total	**182,780**	**50,983**			**470.1**	**4.7**	**23,045**	**84,498**

Plantation density: 0.0204 trees m^2

Table 13. *Total CO_2 accumulated annually per tree, per section of biomass in plum.*

PLUM	Fresh weight (g Tree^{-1})	Dry weight (g Tree^{-1})	Humidity %	% C (% Dry weight)	Total carbon (g m^{-2} year^{-1})	Total carbon (T he^{-1} year^{-1})	TREE TOTAL g C tree^{-1}	TREE TOTAL g CO_2 tree^{-1}
Root	12,600	7,840	37.78	48.21	215.0	2.2	3,780	13,859
Branches	2,882	1,487	48.40	47.09	39.9	0.4	700	2,568
Leaves	1,737	722	58.43	42.41	17.5	0.2	306	1,123
Fruit	75,000	10,583	85.89	49.38	297.9	3.0	5,226	19,161
Trunk	4,792	2,355	50.86	47.09	63	1	1,109	4,066
Total	**97,011**	**22,987**			**633.3**	**6.3**	**11,121**	**40,777**

Plantation density: 0.057 trees m^2

Table 14. *Total CO_2 accumulated annually per tree, per section of biomass in peach.*

PEACH	Fresh weight (g Tree^{-1})	Dry weight (g Tree^{-1})	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} year^{-1})	Carbon total (T he^{-1} year^{-1})	TREE TOTAL g C tree^{-1}	TREE TOTAL g CO_2 tree^{-1}
Root	15,308	9,832	35.77	48.02	268.9	2.7	4,721	17,312
Branches	4,200	2,259	46.22	45.56	58.9	0.6	1,029	3,773
Leaves	11,700	5,005	57.22	44.13	125.9	1.3	2,209	8,099
Fruit	78,000	8,182	89.51	46.84	218.5	2.2	3,833	14,053
Trunk	7,273	3,911	46.22	45.56	101.6	1.0	1782	6,534
Total	**116,481**	**25,122**			**773.8**	**7.7**	**13,574**	**49,771**

Plantation density: 0.057 trees m^2

Table 15. *Total CO_2 accumulated annually per tree, per section of biomass in nectarine.*

NECTARINE	Fresh weight (g Tree^{-1})	Dry weight (g Tree^{-1})	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} year^{-1})	Carbon total (T he^{-1} year^{-1})	TREE TOTAL g C tree^{-1}	TREE TOTAL g CO_2 tree^{-1}
Root	13,308	8,548	35.77	48.02	234.0	2.3	4,105	15,052
Branches	3,200	1,721	46.22	45.56	41.9	0.4	784	2,875
Leaves	9,700	4,150	57.22	44.13	52	0.5	1,831	6,714
Fruit	75,000	9,608	87.19	49.01	299.2	3	4,709	17,266
Trunk	5,273	2,836	46.22	45.56	80	0.8	1,292	4,738
Total	**106,481**	**26,862**			**739.8**	**7**	**12,721**	**46,644**

Plantation density: 0.057 trees m^2

Table 16. *Annual amounts of CO_2 absorption and assimilated carbon in grape.*

GRAPE	Fresh weight (g Tree^{-1})	Dry weight (g Tree^{-1})	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} year^{-1})	Carbon total (T he^{-1} year^{-1})	TREE TOTAL g C tree^{-1}	g CO_2 tree^{-1}
Root	6,242	2,788	55.33	44.98	103	1.0	1,254	4,599
Branches	3,615	1,387	61.62	45.89	52.2	0.5	637	2,335
Leaves	5,187	1,737	66.58	46.18	65.8	0.7	802	2,941
Fruit	47,500	6,992	85.28	47.17	270.4	2.7	3,298	12,093
Trunk	1,624	800	50.74	45.89	30	0	367	1,347
Total	**64,168**	**13,704**			**521.4**	**5.2**	**6,358**	**23,315**

Plantation density: 0.082 plants m^2

3.4 Determination of CO_2 in citrus plants

In each table corresponding to the citrus fruits (Tables 17-19) the total in tonnes according to variety and section of biomass are shown, as well as the total annual amount of assimilated CO_2 per tree.

The results for lemon (Table 17) were the highest, not only when compared to the rest of the citrus plants, but also when compared to the rest of the orchard crops. In this case, lemon shows higher levels of fixation and accumulation as much per tree (due to its having the greatest biomass) as per square metre. In general, it seems that lemon has the greatest capacity for CO_2 fixation. The orange (Table 18) shows much lower values than lemon but similar when a general comparison is made with the other fruit trees, whilst mandarin showed the lowest amounts (Table 19).

Table 17. *Annual CO_2 absorption amounts and assimilated carbon in lemon trees.*

LEMON	Fresh weight (g Tree^{-1})	Dry weight (g Tree^{-1})	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} year^{-1})	Carbon total (T he^{-1} year^{-1})	TREE TOTAL g C tree^{-1}	g CO_2 tree^{-1}
Root	26,833	13,953	48.00	43.87	174.9	1.7	6,121	22,446
Branches	17,000	8,898	47.66	44.23	112.4	1.1	3,935	14,430
Leaves+stalk	36,667	15,576	57.52	43.30	192.7	1.9	6,744	24,729
Fruit	200,000	26,540	86.73	42.51	322.3	3.2	11,282	41,368
Trunk	4,330	2,266	47.66	44.23	28.6	0.3	1,080	3,960
Total	**284,830**	**67,233**			**831**	**8.3**	**29,163**	**106,933**

Plantation density: 0.028 trees m^2

Table 18. *Annual CO_2 absorption amounts and assimilated carbon in orange trees.*

ORANGE	Fresh weight (g Tree^{-1})	Dry weight (g Tree^{-1})	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} year^{-1})	Carbon total (T he^{-1} year^{-1})	TREE TOTAL g C tree^{-1}	g CO_2 tree^{-1}
Root	7,555	2,420	67.97	44.13	44.8	0.4	1,068	3,916
Branches	6,217	3,362	45.93	44.13	62.3	0.6	1,483	5,439
Leaves+stalk	8,893	3,945	55.64	40.80	67.6	0.7	1,610	5,902
Fruit	100,000	20,568	82.86	41.90	362.0	3.6	8,618	31,599
Trunk	2,845	1,538	45.93	44.13	28.5	0.3	679	2,489
Total	**133,510**	**31,833**			**565.2**	**5.6**	**13,458**	**49,345**

Plantation density: 0.042 trees m^2

Table 19. *Annual CO_2 absorption amounts and assimilated carbon in mandarin trees.*

MANDARIN	Fresh weight (g $Tree^{-1}$)	Dry weight (g $Tree^{-1}$)	Humidity %	% C (% Dry weight)	Carbon total (g m^{-2} $year^{-1}$)	Carbon total (T he^{-1} $year^{-1}$)	TREE TOTAL g C $tree^{-1}$	g CO_2 $tree^{-1}$
Root	2,858	957	66.52	44.98	17.9	0.2	430.5	1578.5
Branches	1,050	632	39.78	44.98	11.8	0.1	284.4	1042.8
Leaves+stalk	4,667	2,239	52.02	40.57	37.8	0.4	908.4	3330.8
Fruit	80,000	15,496	80.63	43.50	280.8	2.8	6740.8	24716.3
Trunk	435	262	39.78	44.98	5	0.05	118	432
Total	**89,010**	**19,587**			**353**	**3.5**	**8,482**	**31,101**

Plantation density: 0.042 trees m^2

In summary, figures 3 and 4 show comparisons between the annual fixation of the different citrus crops per square metre (m^2 in Figure 1) and per tree/plant (Figure 2). In figure 2, trees have been separated from other crops due to their different scale. The data show that 50% of crops (both arboreal and horticultural) fix more than 500 grams of carbon per square metre. In other words, more than 1800 grams of CO_2 per square metre.

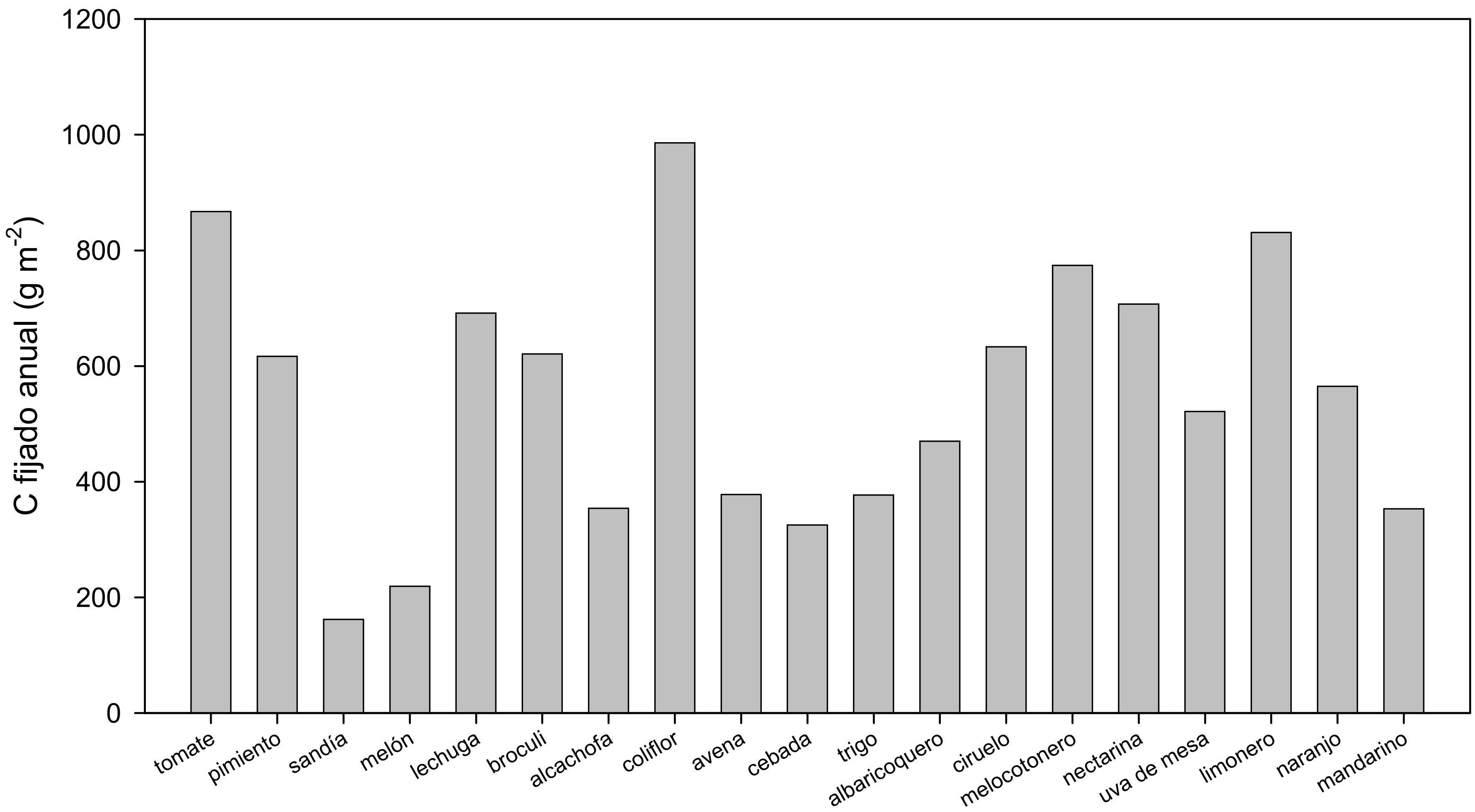

Figure 3. Total annual carbon fixation per crop expressed per square metre (m^2).

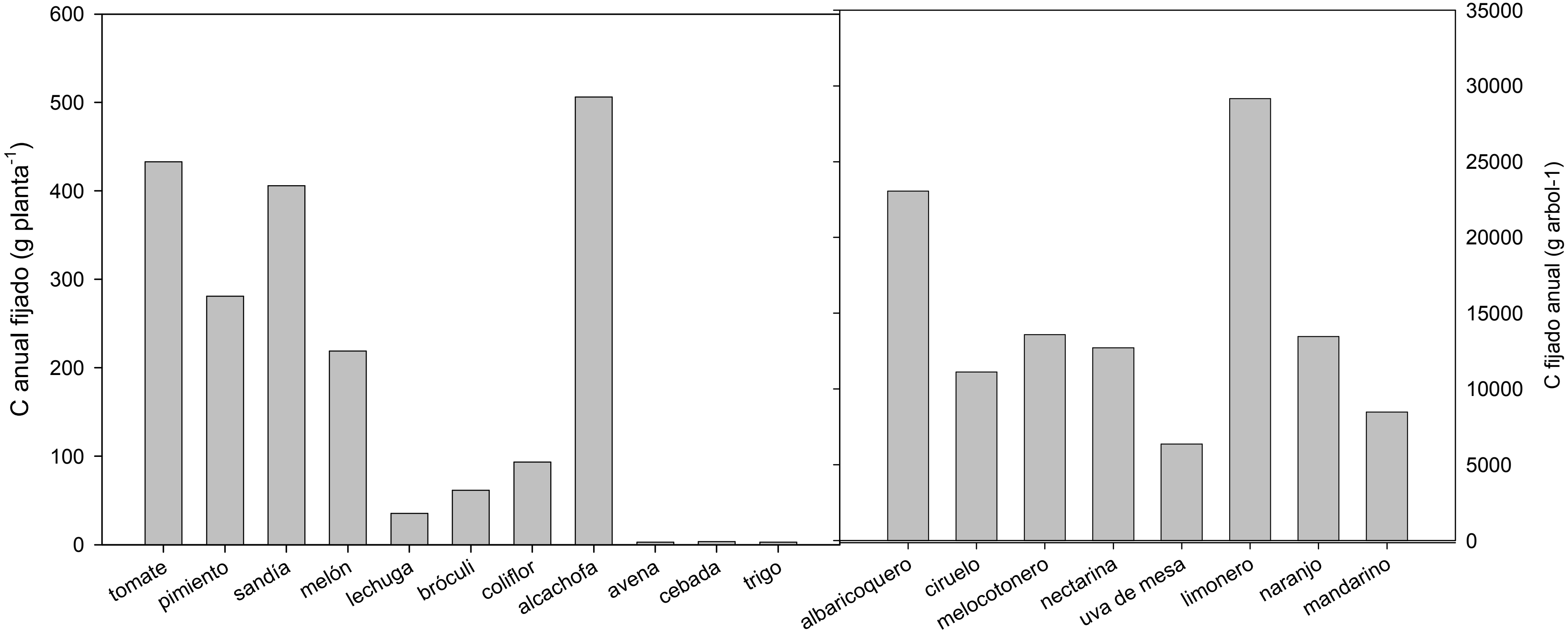

Figure 4. Total annual carbon fixation per crop (per plant and tree).

4. DISCUSSION

The data shown in this study has been obtained from agricultural crops from the Region of Murcia. Specimens were collected from different areas of the region where the crop species is most representative. Therefore, even though growth and variables will be different in other regions, this study reflects the general pattern in this area.

This study focuses on the CO_2 fixation ability per plant in order to compare the results among different agricultural crops. However, for a more in-depth study of the total values obtained, results per hectare combined with knowledge of plantation density need to be taken into account.

In general, of the data obtained in this work, we can affirm that of the agricultural crops analysed, artichoke is the most efficient in terms of CO_2 fixation, followed by tomato and watermelon (Figure 1). However, when results per square metre are analysed, cauliflower is the most efficient crop and artichoke then becomes one of the least efficient together with watermelon and melon. When grain varieties are analysed per individual plant they are found to be very efficient in CO_2 fixation, superseding all values obtained for agricultural plants. However, when analysed per square metre, results drop significantly to much lower amounts.

Among the fruit trees analysed, peach and nectarine are the most efficient fixers of CO_2 per square metre cultivated, followed by plum, and, lastly, apricot. Although apricot shows the best CO_2 fixation per tree, its efficiency is reduced because its plantation range (7m x 7m) is much greater than that of the other fruit trees (3.5m x 5m). On the other hand, if we take into account that the relation of kg of carbon to kg of dry matter is very similar for all varieties, this indicates that, aside from plantation density, the natural growth ability of these species is a factor that affects CO_2 fixation per plant. For example, the plum tree is cultivated with the same size plantation density as the peach and nectarine trees. However, CO_2 fixation capacity is reduced when compared to the other varieties due to its slower growth.

Of all the orchard crop species analysed in this study, the lemon shows the greatest ability to fix CO_2 both per square metre and per tree. In this case, the most relevant factor for CO_2 fixation is the lemon tree's abundant natural growth, which it maintains throughout its lifecycle, resulting in leafier trees with greater surface foliage, therefore giving it a greater ability to fix CO_2. In modern agriculture, orange and mandarin are cultivated much less intensively than lemon. However, in spite of their lower plantation range, their ability to fix CO_2 is much lower than lemon, peach and nectarine, which have a lower dry weight than orange. In this case, the curtailing factor for the CO_2 fixation of orange trees is plantation density.

Lastly, grape cultivation shows more than acceptable CO_2 absorption rates as compared to those obtained for the rest of the species, especially considering that it has the lowest biomass. In this case, CO_2 fixation is benefited by a high plantation density (3.5m x 3.5m).

An important factor to consider is the quantity of waste matter obtained from each crop and the use made of it. For example, plant material obtained from tree pruning could lead to a soil carbon fixation rate of between 20 and 35% of carbon concentrate in one year on decomposition (Brady and Weil, 2004). Such a practice will improve soil conditions and reduce CO_2 emissions into the atmosphere, as the burning of waste and crop matter is not only a destructive act that generates CO_2 but also ruins the soil due to, amongst other factors, the elimination of small insects and micro-organisms in the outer layers of the soil (Blanco-Roldan and Cuevas, 2002). Furthermore, the potential to use this by-product as raw material from which to generate renewable energy sources like, for example, bio-diesel should be kept in mind. If we combine waste from pruning with that generated from the handling and/or conversion of fruit and vegetable products in industry (skin, pulp, stones and seeds) we can obtain a significant quantity that can then be converted to bio-fuel, aromas, animal feed and/or water, either for irrigation purposes or as purified water (Biodisol.com, 2009). All these by-products will increase the ecological efficiency of crops and lead the way towards completely sustainable agriculture.

The type of fertilizer used for each crop also needs to be considered. The massive use of chemical fertilizers in the farming industry has increased concern over matters such as decline in soil fertility and the increase in greenhouse gas emissions. The draining of soil nutrients is a result of the increase in pressure on agricultural land giving rise to a greater outward flow of non-replenished nutrients (Wopereis et al., 2006). This is why organic farming methods are needed to ensure that intensive farming does not endanger sustainable use of the soil. However, small producers are reluctant to use organic matter and compost due to the uncertainty of their benefits and efficiency. In fact, a disadvantage of organic farming is that yields are normally lower compared to those obtained by conventional farming methods (Mäder et al., 2002; Dumas et al., 2003) because organic fertilizers provide nutrients more slowly than mineral fertilizers and do not distribute nutrients as equally (Båth, 2000; Kirchmann et al., 2002; Gunnarsson, 2003). Therefore, crops cultivated with organic fertilizers normally grow more slowly when compared with plants cultivated with more easily available mineral fertilisers (Robertson et al., 2000). Whilst it has not been conclusively shown that organic products are more nutritive than conventional products (Winter, 2006) it has been observed that organic fertilisers lead to a reduction in greenhouse gases (Matson et al., 1990). Agricultural fertilisers can be considered the most significant anthropogenic source of N_2O, contributing to 70% of greenhouse gases (Bouwman 1994; Watson et al., 1992).

The results of this study also suggest possible political inroads that need to be taken if atmospheric CO_2 fixation is to increase. Firstly, crops must be cultivated over a broader range in areas where forest cover is scarce. And secondly, a greater water investment will result in an increase in agricultural biomass. In this respect, the semi-desert climate of much of the Region of Murcia leads to high incidences of evapor-transpiration and as a result a greater demand for water (Cubasch et al., 2001).

5. CONCLUSION

As can be inferred from this study, we depend on plants to counteract the effects of global warming. Therefore, the solution to climate change necessarily depends on conserving as much crop land as possible. We should optimise the carbon fixation capacity of plants by adopting the best agronomic practices and utilisation of crop by-products. Furthermore, the powerful ability of plants to adapt, which has allowed them to weather huge changes for millions of years, should be used as a basis for scientific study to allow us to evaluate the state of our agricultural industry for future climatic scenarios.

Therefore, the results of this study highlight the need to provide our region's agricultural industry with greater water sources that will ensure an increase in agricultural biomass and therefore a greater atmospheric fixture of CO_2. Furthermore, we need to commit to reusing organic by-products for energy sources, fertilisers and even water, taking advantage of moisture remaining in the organs and tissues of the plant that are not used.

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