Connecting the Water and Carbon Cycles for the Generation of Food Security and Ecosystem Services

SHIVAAN BURKE*[a] AND RAUL PONCÉ-HERNANDEZ[b]

** Corresponding author, Email:-* shivaanmburke@trentu.ca

a). Applied Modelling and Quantitative Methods Graduate Program, Trent University
b). GEORESLAR Laboratory, Environmental and Resource Science and Department of Geography, Trent University

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Abstract

Water scarcity and food insecurity are pervasive issues in the developing world and are also intrinsically linked to one another. Through the connection of the water cycle and the carbon cycle this study illustrates that synergistic benefits can be realized by small scale farmers through the implementation of waste water irrigated agroforestry. The WaNuLCAS model is employed using La Huerta agroforestry site in Texcoco, South Central Mexico, as the basis for parameterization. The results of model simulations depicting scenarios of water scarcity and waste water irrigation clearly show that the addition of waste water greatly increases the agroforestry system's generation of crop yields, above - and below-ground biomass, soil organic matter and carbon storage potential. This increase in carbon sequestration by the system translates into better local food security, diversified household income through payments for ecosystem services and contributes to the mitigation of global climate change.

Keywords: *agroforestry; wastewater irrigation; carbon sequestration; water scarcity; food security; ecosystem services*

Introduction

Water scarcity remains one of the primary driving forces behind poverty, especially in the developing world. Largely a problem of distribution exacerbated by the poor's lack of social power and access to resources, water scarcity contributes to many symptoms of poverty, the most critical of which is food insecurity (Ahmad, 2003). Water scarcity is both a natural and human-induced phenomenon that is the result of physical or economic circumstances. Currently the effects of water scarcity are felt on every continent, with 1.2 billion people (one-fifth of the world's population) living in areas

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with physical water scarcity, while another 1.6 billion people (almost one quarter of the world's population) is affected by economic water scarcity (UNDP, 2006). The main cause of water scarcity is the uneven distribution of fresh water resources, compounded by inefficient water use, pollution of threatened water resources and unsustainable waste and resource management.

Poverty is more prevalent in the developing world and, in countries and regions with arid and semi-arid climates, water scarcity acts as the main limiting factor in biomass production, which contributes to lower crop yields, food insecurity and the poor's lack of access to other necessities of life, such as sanitation and building materials. Thus, if the issue of water scarcity is addressed, this is likely to hold positive implications on the status of food insecurity and poverty at the local and regional scales (Hanjra and Qureshi, 2010).

Under conditions of water scarcity fresh water resources are reserved for domestic use (i.e. drinking, cooking and cleaning) and sanitation, relegating the water needs of farm crops. In extreme cases only domestic uses are given priority, leaving crop production to the ravages of scarce and erratic precipitation. The main tenet of this paper is, therefore, that recycling treated waste water from domestic and sanitation uses for the irrigation of specifically designed peri-urban agroforestry systems could be a viable solution to the multi-faceted problems of water scarcity and food insecurity. The recycling of water for irrigation of agroforestry essentially connects the water cycle with the carbon cycle for the production of a variety of food products, carbon stocks in biomass and other environmental services.

A paradigm for the connection between the water and the carbon cycles is illustrated in this paper through the study of an irrigated, peri-urban agroforestry system at "La Huerta" in Texcoco, Mexico, a semi-arid area in South Central Mexico. The WaNuLCAS model (a model of **Wa**ter, **Nu**trient and **L**ight **C**apture in **A**groforestry **S**ystems, Van Noordwijk et al, 2011) is used to simulate the growth of crops and trees in an agroforestry system using the site conditions observed at La Huerta for model parameterization. The system consists of a mix of corn or maize (*Zea maiz*), a legume such as cowpea (*Vigna unguiculata*) and peach trees (*Prunus persica*) spatially organized in four linear zones. Simulation results are compared for scenarios of waste water irrigation and no irrigation (i.e. rain fed conditions which reflect water scarcity) at intervals over a time period of ten years. The performance of the systems in terms of carbon accrual (g/m^2) is compared based on a number of above- and below-ground carbon pools, namely: soil organic matter (SOM), tree biomass, harvested crop biomass, total carbon stocks and the resultant global warming effect of the entire system.

Methodology

Study Site Description

This study is based on field data collected from La Huerta agroforestry system at the Universidad Autonoma de Chapingo (UACh) in Texcoco, Mexico during July of 2012. UACh is located in the Valle de Mexico, east of

Mexico City. Dominant soil classes on site include haplic and luvic phaeozems of shallow to medium depth over volcanic bedrock (Cachón Ayora et al, 1974). This area has been under intense cultivation since pre-Hispanic periods when Aztec civilizations inhabited the area, thus contributing to the gradual depletion of soil nutrients over a long period of time. The landscape exhibits undulating foothills with sparse natural vegetation outside of extensively cultivated areas which constitutes the major land use in the area. The area receives unimodal rainfall with rains occurring from April to October totaling approximately 500-550mm per year, and a dry period running from December to March. The mean normal temperature is 18.5˚C ranging from 14 ˚C to 23.3 ˚C over the whole year. The mean normal temperature in the rainy season is 19.7 ˚C and 16.9 ˚C in the dry season.

La Huerta agroforestry system comprises 18 rows of peach (*Prunus persica*) and plum (*Prunus americana*) trees each separated with crop beds of maize, alfalfa, trefoil or maize mixed with beans. The total area of the agroforestry site is approximately 6,415 m^2. The site is primarily rain fed but is also irrigated using a ground water sprinkler system two times per month during the four month dry season. Following an unidentified pruning regime, prunings are removed from the site and composted with grass cuttings and livestock manure before being returned to the site. Compost is applied only to tree beds at a rate of ten kilograms per tree, per year. Trees on site are uniform in age and were approximately 12 to 15 years old at the time of the study. Photos of La Huerta agroforestry system are shown in Figure 1. For the purposes of this study, irrigation with waste water was simulated by using model parameterization options to mimic the nutrient concentrations reported in waste water in the area which receives little to no treatment. Waste water quality parameters were taken from the study by Vazquez et al (2007) which measured coliform and helminth contamination in waste water discharge to three rivers in the Valle de Mexico surrounding the city of Texcoco. Table 1 shows average values of contaminants, including heavy metals, found in waste water discharged to the three rivers measured at a number of discharge sites.

Modelling procedures

The WaNuLCAS model (Van Noordwijk et al, 2011) is used to simulate the growth of an agroforestry system using the site conditions observed at La Huerta in Texcoco, Mexico for model parameterization. The WaNuLCAS model uses the open STELLA modelling environment which ensures the model is modifiable by its user. The parameterized agroforestry system represents four soil layers with specified depths, and four spatial zones comprising trees and crops. Agroforestry systems in this model are defined on the basis of their spatial zones and a calendar of events for each zone including climate inputs, growing and harvesting trees and crops and fertilizer use. Interactions taking place within the agroforestry system that are most influential include shading by trees, competition for water and nutrients in topsoil between tree and crop roots, increased nitrogen availability to

Contaminant	Unit	Average value
Total N	mg L^{-1}	43.4
Total P		14.8
Pb		0.031
Zn		0.231
Ni		0.026
Cu		0.089
Cd		0.004
Helminth eggs	Number of eggs L^{-1}	2.03
Coliforms	Most probable number 100 mL^{-1}	2.46 x 10^8

Table 1 Waste water quality parameters measured by Vazquez et al (2007)

crop roots resulting from the death of tree roots following a pruning event or by direct transfer through contact with nodulated tree roots and long term effects on soil organic matter, erosion and soil compaction. Emphasis is placed on below-ground interactions where competition for water and nutrients is based on the effective root length densities of trees and crops and the current demand by both plant components (Van Noordwijk et al, 2011). A key feature of the model is the description of water and nutrient (N and P) uptake based on root length density, plant demand factors and the effective supply by diffusion at a given soil water content. The underlying principles which govern these processes are described in De Willigen and Van Noordwijk (1994) and Van Noordwijk and Van de Geijn (1996).

The effect of climate parameters is included via daily rainfall, average temperature and radiation data which are read from a linked spreadsheet. The effect of these conditions is reflected in potential growth rates of the plant components. The depth and physical properties of the four soil layers can be chosen within the model, which includes initial water and nitrogen content of the soil. The water balance of the system includes rainfall, canopy interception, exchange between spatial zones via subsurface lateral flows, evaporation, uptake and leaching. Both vertical and horizontal transport of water is considered. The N and P balance of the model includes inputs from fertilizer specified by amount and time of application, atmospheric N fixation, mineralization of soil organic matter and fresh residues and specific P mobilization processes. Leaching of mineral N and P is driven by the water balance and the N concentrations and adsorption constant in each layer. This allows for a ‘chemical safety net’ by subsoil nutrient adsorption. The actual growth of trees and crops is calculated on a daily basis by multiplying potential growth with the minimum of three stress factors; shading, water limitation and N/P limitation. A number of allometric equations are used to determine biomass accumulation in trees. Uptake of water and nutrients for both plant components is driven by demand on the basis of root length density and effective diffusion constants. The actual uptake of resources is given by Equation 1 and is calculated as the minimum of demand and potential uptake factors:

$$Uptake = \min(demand, potential uptake) \quad [1]$$

$$PotUpt(k) = \min\left[\frac{Lrv(k) \times Demand(k) \times PotUpt\left(\sum lrv\right)}{\sum_{k=1}^{n}\left[Lrv(k) \times Demand(k)\right]}, PotUpt(Lrv(k))\right] \quad [2]$$

Light capture is treated on the basis of the leaf area index (LAI) of all plant components and their relative heights in each zone. Potential growth rates for conditions where water and nutrient supply are non-limiting are used as inputs (potentially derived from other models) and actual growth is determined by the minimum of shade, water and nutrient stress (van Noordwijk et al, 2011).

Using the STELLA software and the linked Microsoft Excel files the WaNuLCAS model is parameterized to reflect the soil, climate and planting conditions observed at La Huerta agroforestry site. The cropping calendar shown in Figure 2 is part of the linked Excel table used for inputs to the model. Simulation run times were carried out for one, two, five and ten years in order to observe the system's development over time with respect to the observed variables, namely carbon and biomass accumulation. The system is divided into four zones, of which Zone 1 is populated with peach trees which remain through the entire simulation. Zones 2, 3 and 4 are planted with cowpea or maize on a two year rotational planting schedule. These crops were chosen for their similarity to the observed crops at La Huerta and based on existing data and parameters on their growth characteristics within WaNuLCAS tables.

In order to simulate waste water irrigation conditions at the agroforestry site reference values for water quality in the nearby Rio Texcoco were used for nutrient input values (Vazquez et al, 2007). Water from the Rio Texcoco is commonly used for irrigation of adjacent agricultural crops but is not transported to agroforestry systems in the region. The fertilizer and organic input schedule of the Crop Management model sector was used to simulate addition of nutrients to coincide with irrigation events, which were parameterized in the Weather sector of the model. Due to the untreated nature of waters from the Rio Texcoco which collects wastewater from nearby settlements and communities, nutrient concentrations and input volumes were applied at the highest values allowed within the external organic input parameters of the model. Figure 3 shows the graphic user interface (GUI) in the STELLA environment which is used to parameterize certain sections of the model and to execute and navigate the Run and Output sectors of the model. A view of the WaNuLCAS model layer in STELLA (Figure 4), showing only one section for tree water interactions, illustrates the modular complexity of the calculations involved in representing the myriad of natural processes considered within the model.

Results

The graphic results from WaNuLCAS model runs parameterized using La Huerta agroforestry site conditions are shown in Figures 5 through 8. Two scenarios are considered in the modelling: a) rain fed agroforestry where arid climate and water scarcity limits system development, and b) waste water irrigation conditions where water and nutrients are added to the system. Both scenarios are modelled for various time periods (i.e. one year, two years, five years and ten years) in an attempt to explore the long-term, cumulative effects of either water scarcity or waste water irrigation on agroforestry system development. Graphs generated in the WaNuLCAS output section show the accumulation of biomass (kg/m^2) by the crops and trees in each zone over time. For clarity's sake these results are synthesized in the graphs of Figures 9 and 10. Output tables in the WaNuLCAS interface show carbon accrual within individual above- and below-ground carbon pools including soil organic matter (SOM), tree biomass, harvested crops, as well as total carbon stocks accrued by the entire system and the system's global warming effect. A synthesis of carbon storage in these pools over the four timescales is shown in Table 2.

Discussion

This study seeks to compare the predicted performance of a peri-urban agroforestry system, in terms of biomass generation and carbon storage with a specific focus on food production, under conditions of water scarcity and waste water irrigation using the WaNuLCAS model. The aim is to demonstrate the advantages of connecting the water cycle with the carbon cycle, by re-using water that otherwise would be wasted, to sequester atmospheric carbon and to increase production of food crops. The issue of water scarcity is central to conditions of food insecurity and poverty, especially in the developing world (Rijsberman, 2005).

The results of simulations run in the WaNuLCAS model and based on La Huerta agroforestry system (Figures 5 through 8) show, over all

	1 year	2 years	5 years	10 years
	g/m² (grams per meter squared)			
SOM (lim)	3,100.0	3,044.1	3,267.6	3,217.3
SOM (ww)	3,573.3	3,923.5	5,070.1	6,233.3
Tree biomass (lim)	80.21	212.9	3,01.14	361.47
Tree biomass (ww)	114.52	389.26	1,639.5	4,578.98
Harvested crops (lim)	9.02	56.04	241.13	513.05
Harvested crops (ww)	84.04	340.51	1,365.46	2,685.31
Total C Stock (lim)	3,216.2	3,257.0	3,642.7	3,578.8
Total C Stocks (ww)	3,756.2	4,417.2	6,813.7	10,916.2

Table 2 Synthesized values of carbon storage in above- and below-ground biomass pools at intervals over a ten year period generated by the WaNuLCAS model representing La Huerta agroforestry system under water scarcity (lim) and waste water irrigation (ww) scenarios

timescales, a much greater, even erratic variability in biomass under conditions of water scarcity. It is also found that under waste water irrigation the production of biomass, SOM accrual and crop yields not only increase, but are also more sustained throughout the simulation period. The accrual of biomass and carbon in the waste water irrigated scenario increases significantly over time. As the agroforestry system matures these increases, relative to the rain fed scenario, become more significant. Total carbon stocks increase over time with waste water irrigation relative to the water limited scenario. This ensures that agroforestry farmers have a larger and more reliable harvest when treated waste water is recycled for irrigation purposes. By increasing crop yields this type of land-use management works towards improving food security at the household and community level, while simultaneously offering farmers the opportunity to sell surplus goods at market to supplement the household income. While the sale of farm goods is the most common method of farm income generation the production of ecosystem services, namely carbon sequestration, is a tangible way for farmers to diversify their income while improving the production performance of their farm (Wise and Cacho, 2007). The global warming potential of both systems (Figure 10), in terms of CO_2 equivalents per m^2, indicate that the mitigation capacity of the agroforestry system irrigated with waste water increases greatly over time, and is significantly greater than that of the water scarcity scenario. This is an added benefit to the enhanced food security that the waste water irrigated scenario represents.

The WaNuLCAS model was chosen for this analysis due to its consideration of many of the cooperative and competitive interactions which take place in agroforestry cropping systems. The parameterization of the system at La Huerta was made possible by the availability of different crop and tree species growth tables within supporting files to the model. Waste water irrigation is not a factor the model is designed to simulate, and so the parameterization of this scenario was executed in such a way that the model may not have been able to predict the associated effects with the same accuracy. Nevertheless, the results in this paper show clearly that enhanced food security and increased global warming mitigation can be synergistically achieved by connecting the water cycle to the carbon cycle using waste water irrigated agroforestry systems. These systems comprise a wide array of formats and functions that achieve goals of biodiversity conservation, food production and livelihood security (Droppelmann and Berliner, 2002, McNeely and Schroth, 2006).

While agricultural intensification and mechanisation can achieve increased crop yield in a monocropping system, indigenous agroforestry systems take advantage of the natural and successional variability of an area to generate a sustained and diverse array of products to achieve independent survival of the family and community unit (Alcorn, 1990). In this way, agroforestry as a small-scale farming practice can help to maximize resource use efficiency with respect to scarce natural resources (i.e. water, land, soil nutrients). This paper demonstrates that the water and carbon cycles can be effectively and efficiently connected to advantage, and that such systems can materialize, even under various conditions of water scarcity.

Conclusions

The results of this study and others referenced in this work yield a number of relevant conclusions.

1) Water scarcity is directly linked to conditions of poverty and food insecurity in arid regions of the world where unequal distribution of resources drives the cycle of poverty;

2) Under conditions of water scarcity crop irrigation is often forgone to assure adequate volumes of clean water are left for drinking, cooking and cleaning purposes. This results in low crop yields and food insecurity;

3) The application of agroforestry land use diversifies household income potential for small scale farmers;

4) Carbon storage, and thus biomass generation, in all pools is greater under waste water irrigation conditions. This is due to a greater availability of water during the driest season as well as nutrients (i.e. N and P) provided in the waste water;

5) At the end of the ten year simulation period harvested crop biomass (represented as carbon stocks) is five times greater under waste water irrigation than under the water limited scenario. This demonstrates positive relationship between waste water irrigation and food production, which leads to increased food security at the farm and community level;

6) At the end of the ten year simulation period carbon stocks accrued in tree biomass are more than ten times greater under waste water irrigation than under the water limited scenario. In this study where peach trees are planted in the agroforestry system additional benefits to food security and household income can be realized through fruit and timber harvesting;

7) Additional carbon storage in agroforestry farming systems provides farmers with the opportunity to receive payments for carbon sequestration on the voluntary carbon market. The global warming potential numbers under the waste water irrigated scenario show that, with a greater capacity to sequester carbon in biomass, the waste water irrigated system offers greater opportunity to farmers receiving payments for emission reductions. This benefits household income diversification, while synergistically having a positive impact on global climate change.

Overall, the agroforestry system irrigated with waste water performs better on all rankings than the system in the water limited scenario. This demonstrates that by diverting domestic waste water from the waste stream and recycling it to irrigate agroforestry farming systems, this conservative use of water can lead to increased carbon storage in tree and crop biomass. In this way we effectively connect the water cycle to the carbon cycle to achieve food security and climate change benefits at the local and global levels.

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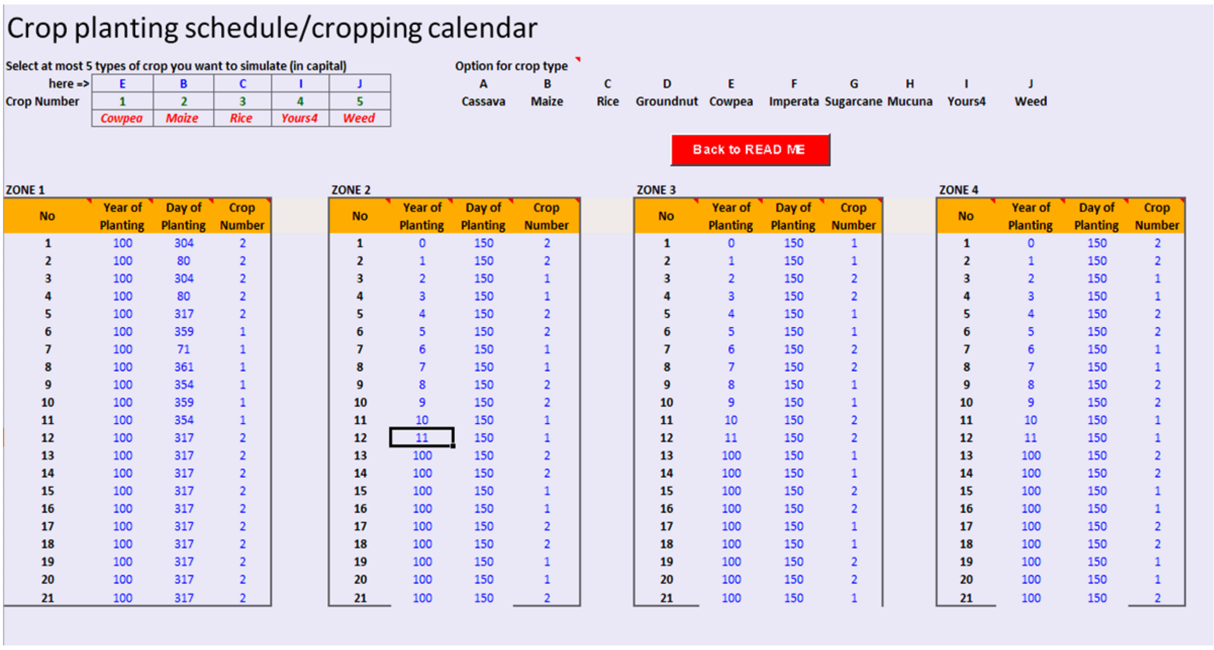
Appendix

Figure 1 Planting arrangements at the agroforestry system at La Huerta site in Texcoco, Mexico



Crop planting schedule/cropping calendar

Select at most 5 types of crop you want to simulate (in capital)

here =>	E	B	C	I	J
Crop Number	1	2	3	4	5
	Cowpea	*Maize*	*Rice*	*Yours4*	*Weed*

Option for crop type

A	B	C	D	E	F	G	H	I	J
Cassava	Maize	Rice	Groundnut	Cowpea	Imperata	Sugarcane	Mucuna	Yours4	Weed

ZONE 1

No	Year of Planting	Day of Planting	Crop Number
1	100	304	2
2	100	80	2
3	100	304	2
4	100	80	2
5	100	317	2
6	100	359	1
7	100	71	1
8	100	361	1
9	100	354	1
10	100	359	1
11	100	354	1
12	100	317	2
13	100	317	2
14	100	317	2
15	100	317	2
16	100	317	2
17	100	317	2
18	100	317	2
19	100	317	2
20	100	317	2
21	100	317	2

ZONE 2

No	Year of Planting	Day of Planting	Crop Number
1	0	150	2
2	1	150	2
3	2	150	1
4	3	150	1
5	4	150	2
6	5	150	2
7	6	150	1
8	7	150	1
9	8	150	2
10	9	150	2
11	10	150	1
12	11	150	1
13	100	150	2
14	100	150	2
15	100	150	1
16	100	150	1
17	100	150	2
18	100	150	2
19	100	150	1
20	100	150	1
21	100	150	2

ZONE 3

No	Year of Planting	Day of Planting	Crop Number
1	0	150	1
2	1	150	1
3	2	150	2
4	3	150	2
5	4	150	1
6	5	150	1
7	6	150	2
8	7	150	2
9	8	150	1
10	9	150	1
11	10	150	2
12	11	150	2
13	100	150	1
14	100	150	1
15	100	150	2
16	100	150	2
17	100	150	1
18	100	150	1
19	100	150	2
20	100	150	2
21	100	150	1

ZONE 4

No	Year of Planting	Day of Planting	Crop Number
1	0	150	2
2	1	150	2
3	2	150	1
4	3	150	1
5	4	150	2
6	5	150	2
7	6	150	1
8	7	150	1
9	8	150	2
10	9	150	2
11	10	150	1
12	11	150	1
13	100	150	2
14	100	150	2
15	100	150	1
16	100	150	1
17	100	150	2
18	100	150	2
19	100	150	1
20	100	150	1
21	100	150	2

Figure 2 Crop and planting calendar for La Huerta agroforestry system as shown in Excel tables linked to the WaNuLCAS model.

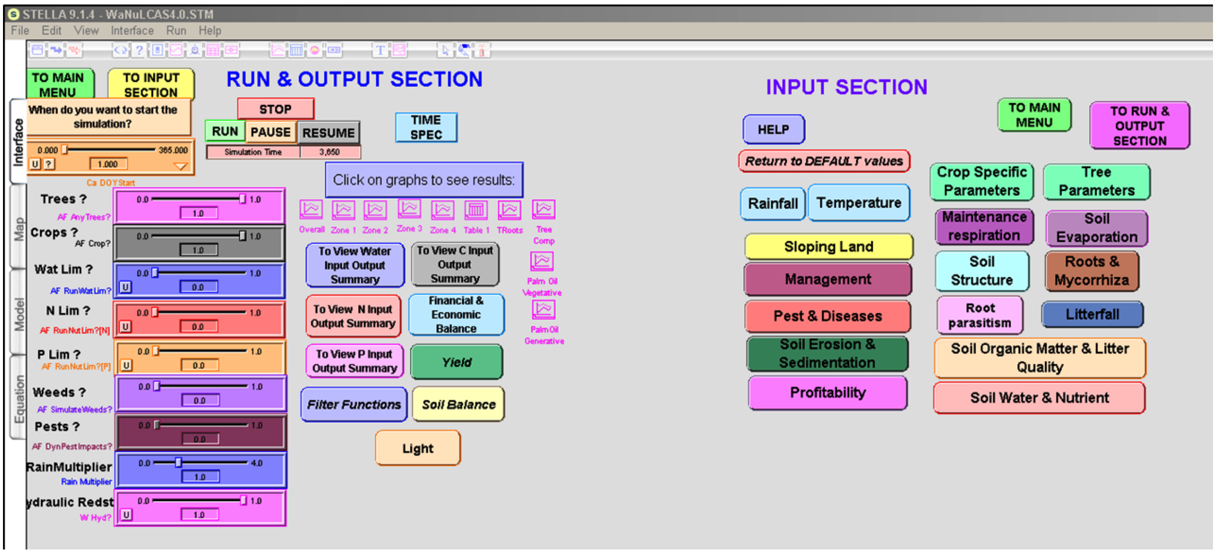


Figure 3 Graphic user interface of WaNuLCAS in the STELLA environment. This interface is used to operate certain model sectors including the Run and Output section where simulation results are viewed.

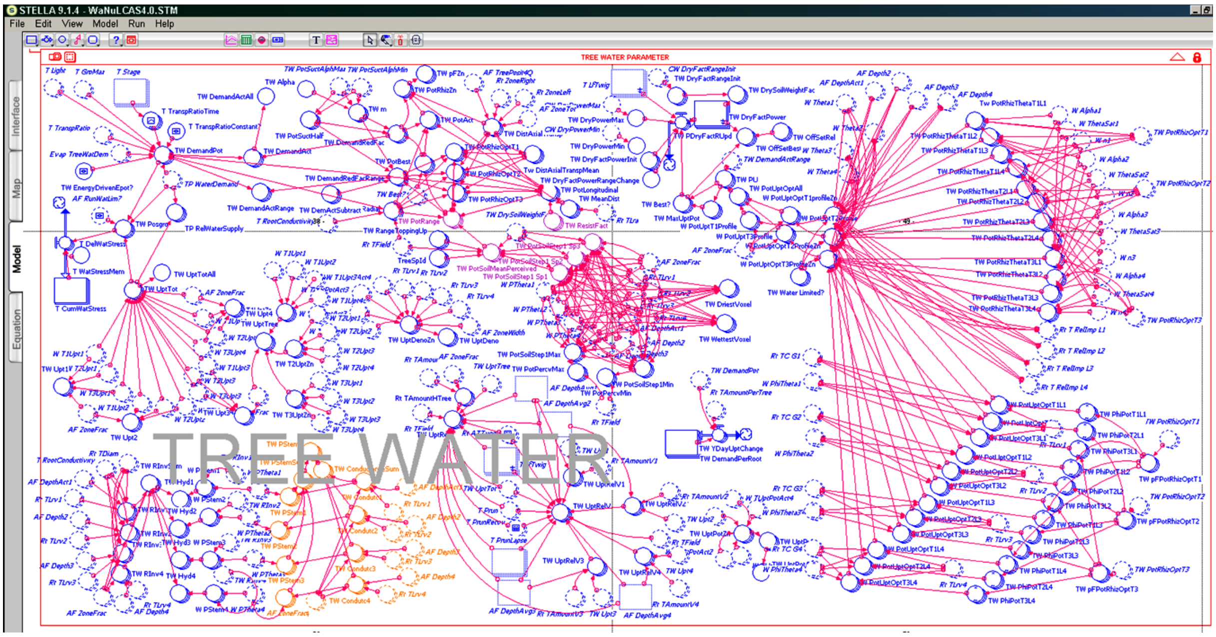


Figure 4 View of agroforestry system component interactions considered in tree-water calculations carried out within the WaNuLCAS model. Each pink line in this figure indicates the calculation of one relationship that represents a complex ecological process.

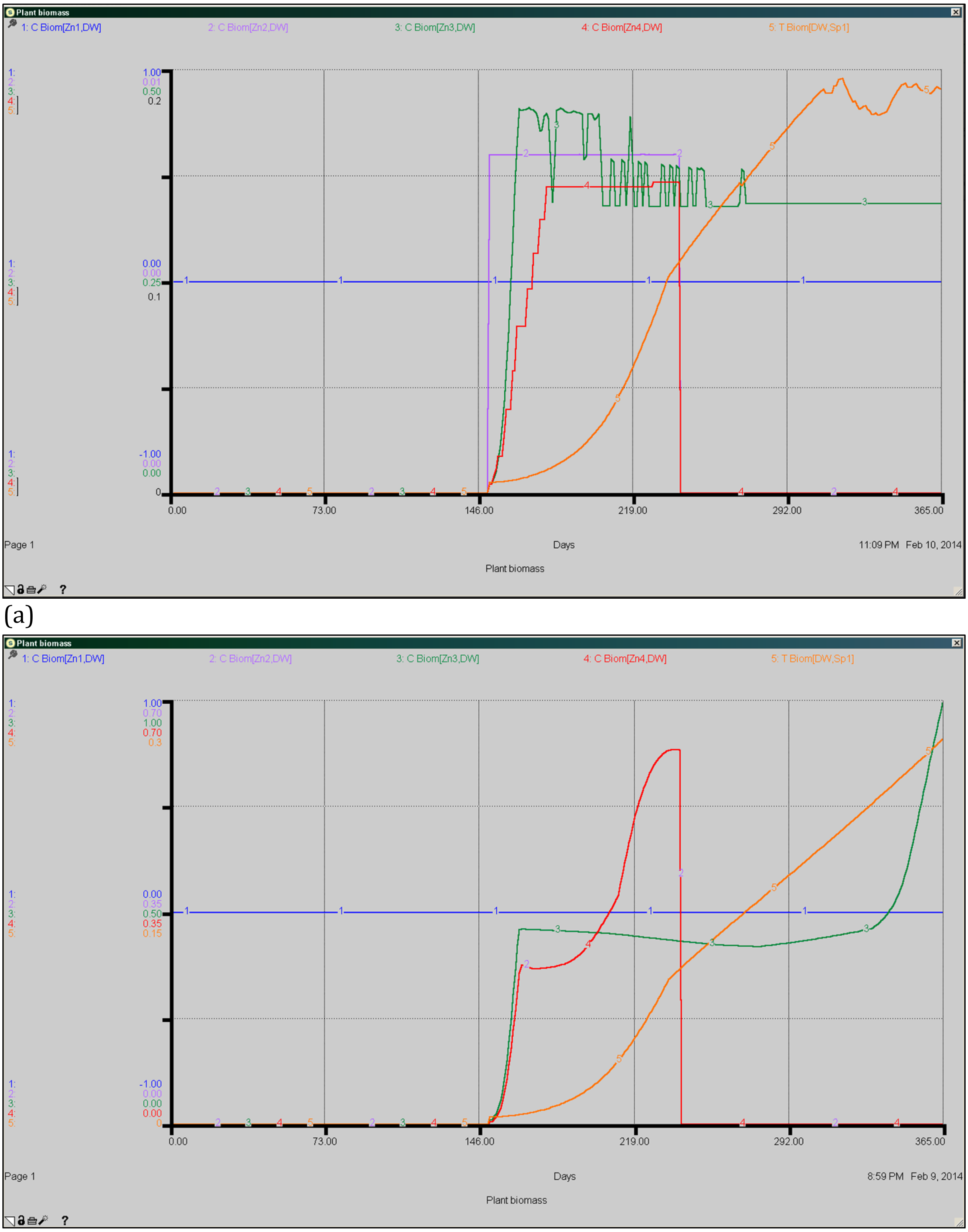
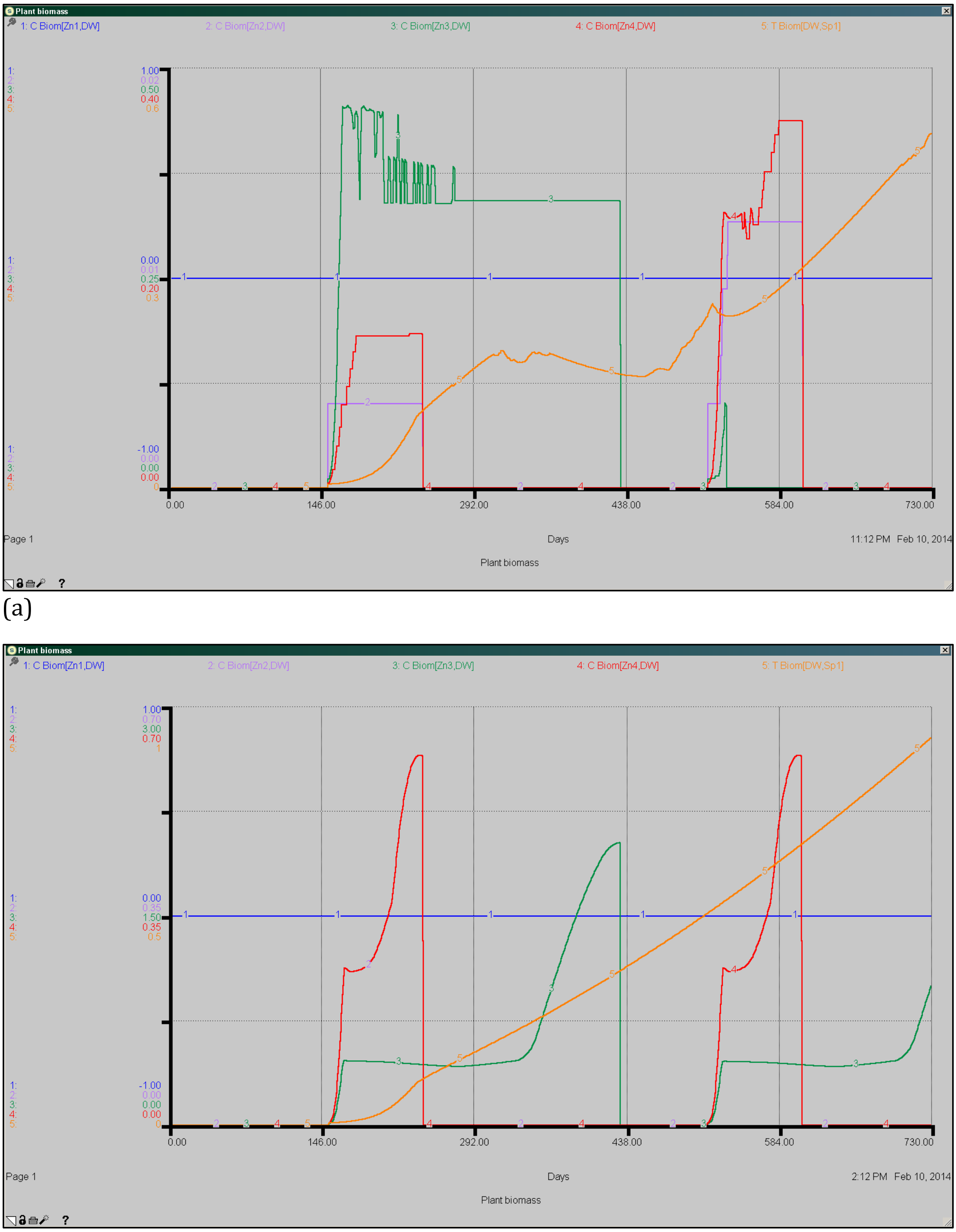


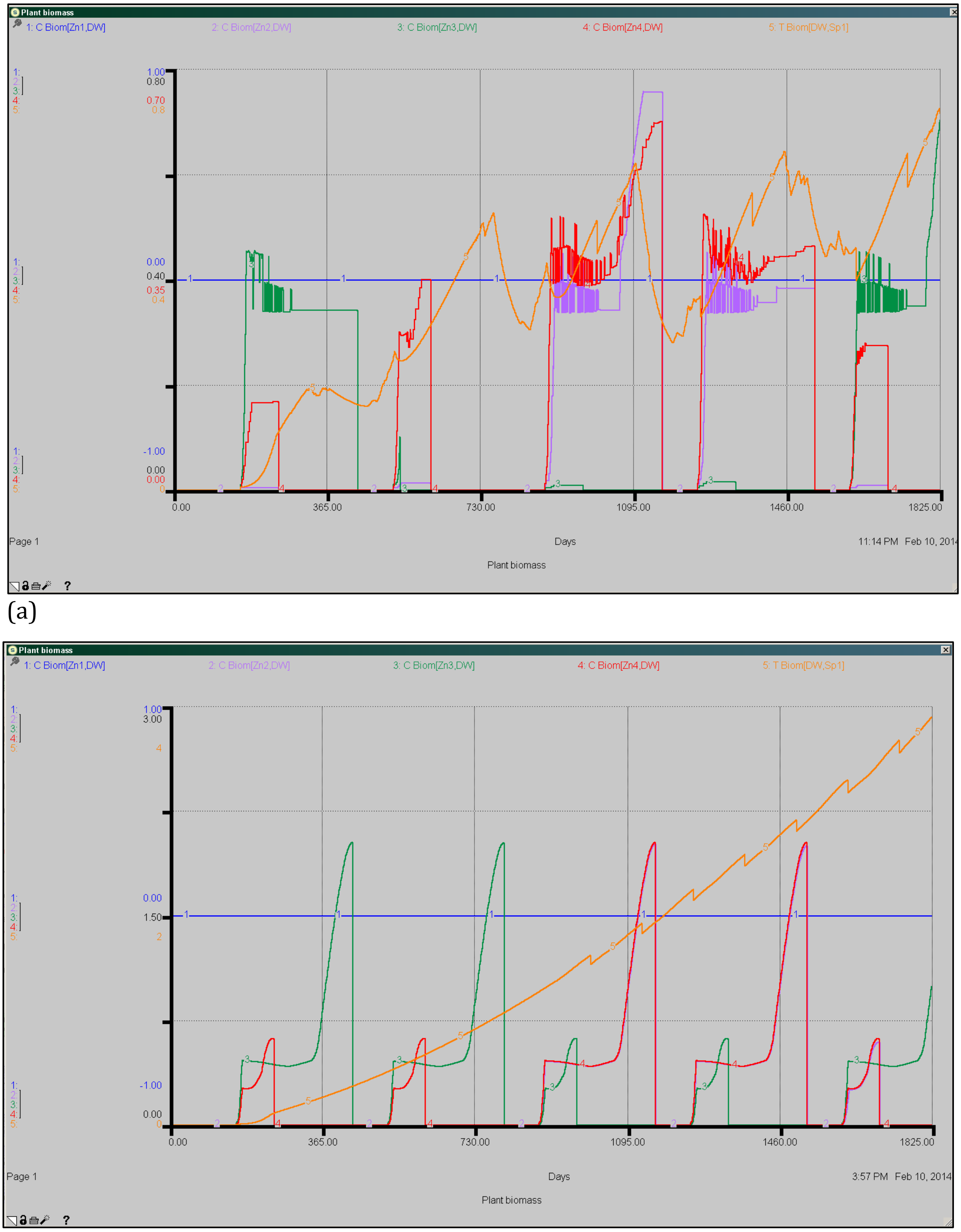
Figure 5 WaNuLCAS graphs showing biomass accumulation in kg/m² under (A) water limitation and (B) waste water irrigation. Simulation period: one year



(a)

(b)

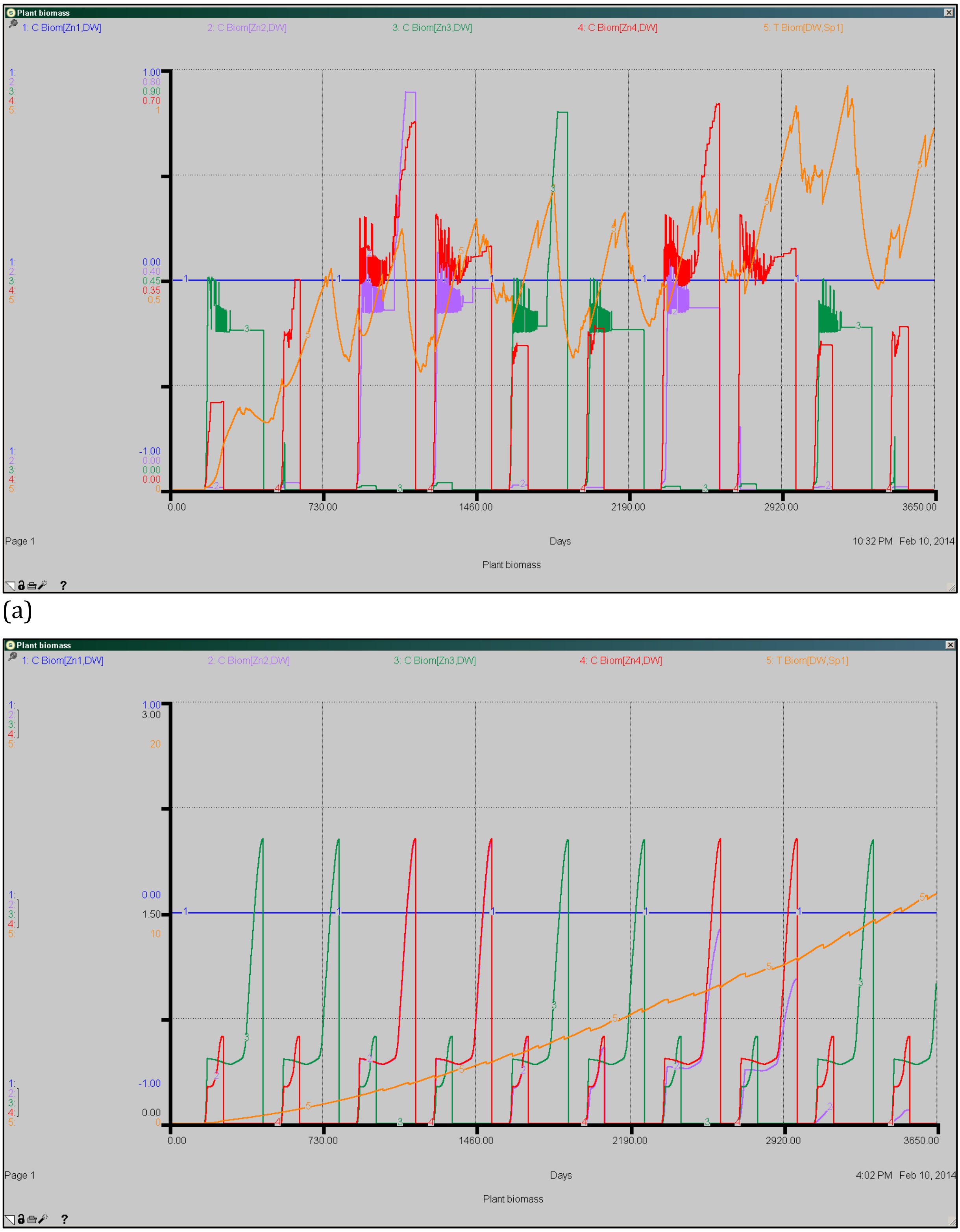
Figure 6 WaNuLCAS graphs showing biomass accumulation in kg/m² under (A) water limitation and (B) waste water irrigation. Simulation period: two years



(a)

(b)

Figure 7 WaNuLCAS graphs showing biomass accumulation in kg/m² under (A) water limitation and (B) waste water irrigation. Simulation period: five years



(a)

(b)

Figure 8 WaNuLCAS graphs showing biomass accumulation in kg/m² under (A) water limitation and (B) waste water irrigation. Simulation period: ten years.

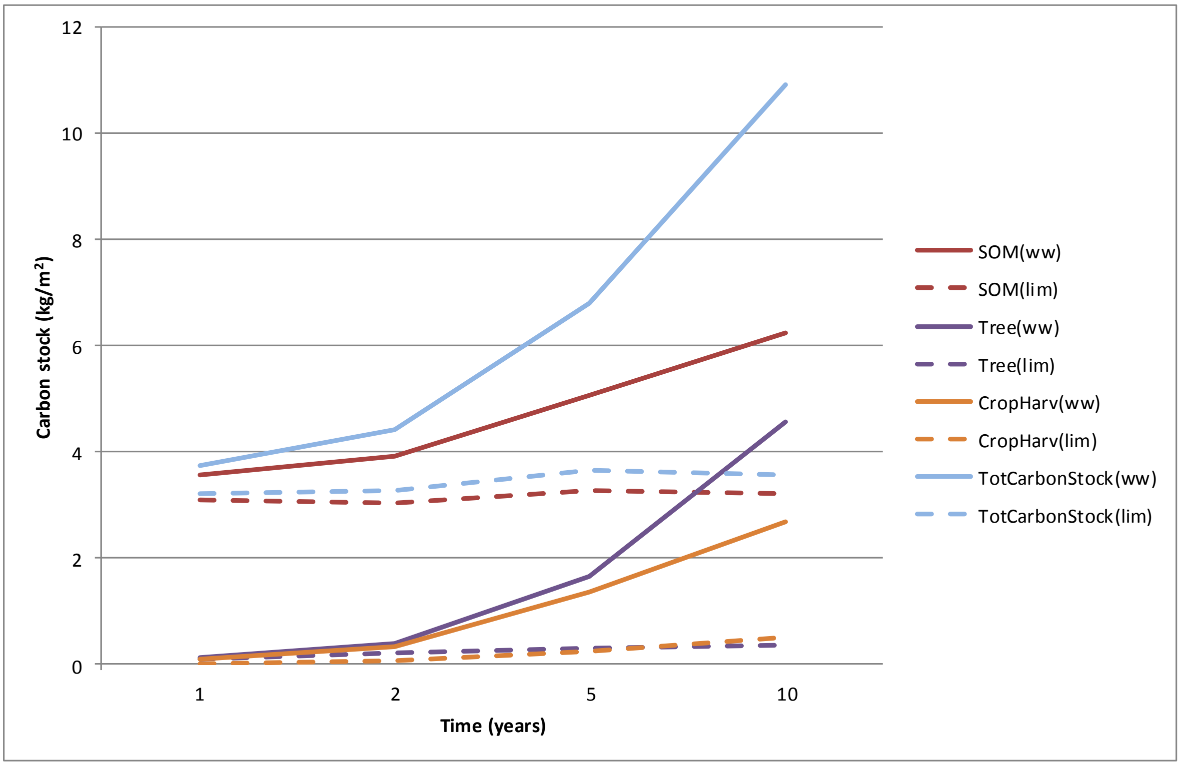


Figure 9 Carbon storage in above- and below-ground pools in La Huerta agroforestry system as predicted by the WaNuLCAS model for waste water irrigated agroforestry (ww) and the same agroforestry system under water scarcity conditions (lim).

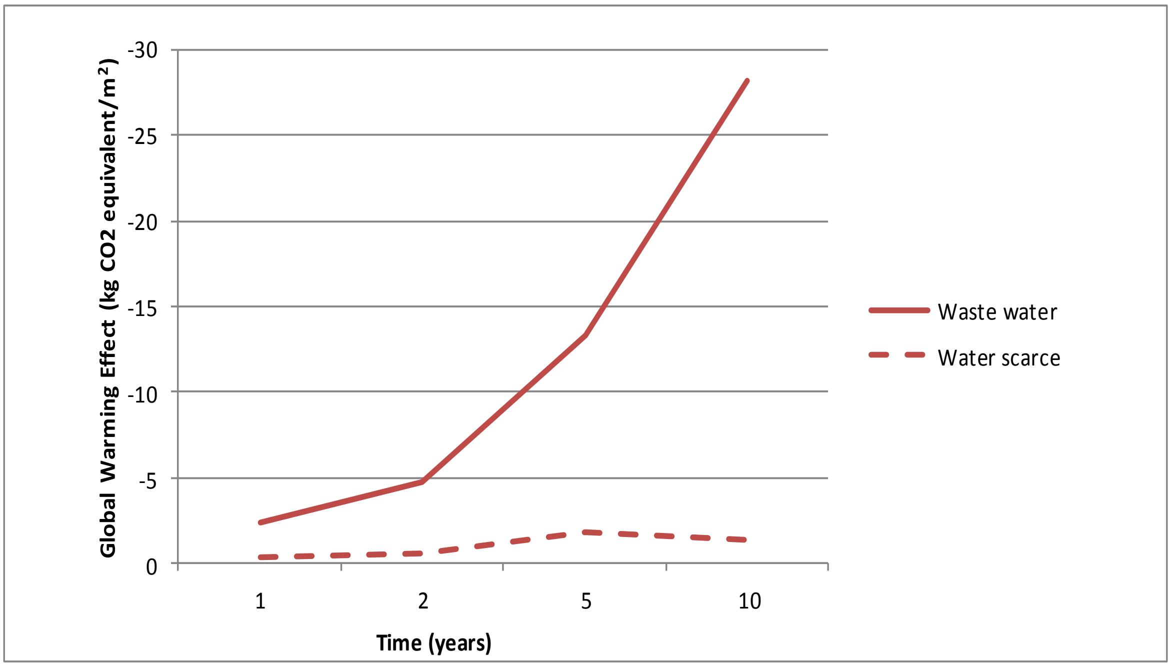


Figure 10 Total global warming potential of La Huerta agroforestry system as predicted by the WaNuLCAS model for waste water irrigated conditions (waste water) and water scarcity conditions (water scarce)