A model to address adaptation of agricultural systems to climate change

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Abstract

Among the production sectors, agriculture is the most significantly influenced by the effect of climate change. Agricultural systems will be subject to enormous risks if theories and predictions about climate trends are realised. The assessment of the impact of climate change on agricultural systems and food security, to support decision makers to set up adaptation measures in vulnerable areas, are key issues for researchers, development agencies, civil society, business and governments.

This paper discusses the possible repercussions on agriculture of the rise in temperature due to climate change. To do so, a study area was outlined, for which three suitable, conventional and organic crop rotations were examined in order to identify the differences between the two cropping systems. We then went on to simulate the yields by using the MarkSim and ClimGen climate data generators and the Cropping System simulation model. More specifically, this study is aimed at understanding and measuring the changes that occur in agricultural systems due to climate, and at determining how changes in climate can affect sustainability of agriculture, considering agricultural productivity, as an indirect measure of the economic (farmers income) and social (food security) performance, and the resultant environmental impacts of agricultural systems. The CropSyst software was used, and a simulation model was generated and coupled to a Geographic Information System to obtain output linked to environment and plant productivity. This study considered two extreme scenarios: the first is based on the assumption that emissions will reduce fairly rapidly and there will even be a decrease by 2100, whereas the second is based on the assumption of unchanged gas emissions compared to current levels. The effects on agriculture have proved significant, above all in terms of a drop in yields, with the imaginable consequences for food safety. The results which can be obtained from simulations, such as those performed in this study, constitute a major work basis for decision-makers, who will be increasingly called upon in future to develop adequate measures of adaptation to the effects of climate change, rather than those of possible mitigation.

Introduction

In recent years, the global impact of climate change (CC) has dramatically affected air, land and water resources. The knowledge of its effects is fundamental not only for the development of sustainable agriculture, but also for food and water safety (Wheaton and Kulshreshtha, 2017).

The intrinsic characteristics of agriculture result in it being one of the sectors most affected by climate change, as it uses natural resources as production inputs, such as biodiversity, water and soil. So far, phenomena such as drought and excess humidity, or soil erosion and desertification have occurred more frequently in fragile areas. However, temperate zones are also experiencing alarming situations, which have a negative bearing on both dry and irrigated farming (Bischetti et al., 2014). Future scenarios for Europe predict that the rise in temperature due to human activity will have a greater impact than variations in rainfall (Moore and Lobell, 2014), which will be more intense (Bindi and Olesen, 2011).

The impact of CC on the agricultural sector is mainly due to the characteristics of the local environment, in which it occurs. In fact, CC influences agriculture's agronomic and subsequently economic performance, both of which are strictly linked to the local agricultural system and to the economic system in which the farm operates. Furthermore, the farmer's decisions and choices affect the farm's adaptability to the climate trend. At the same time, agriculture is one of the sectors responsible for climate change, due to the emissions ascribable to livestock breeding, to the use of chemical fertilisers and to intensive agricultural system management. On the other hand, agriculture also plays a role of mitigation, e.g. carbon capture (AEA, 2015). Agronomic adaptation e.g. sowing at a better time, introducing new cultivars, or reducing the use of fertilisers, also plays a major role in this context.

This paper discusses the possible repercussions on agriculture of the rise in temperature due to climate change. To do so, a study area was outlined, for which three suitable, conventional and organic crop rotations were examined in order to identify the differences between the two cropping systems. We then went on to simulate the yields by using the MarkSim and ClimGen climate data generators and the Cropping System simulation model.

Materials and methods

This study was divided into three phases:

1) The identification not only of the study area and its agronomic features, but also of the possible crop rotations, including production techniques.

2) The simulation of climate data compared to the reference scenarios for climate change, using the MarkSim and ClimGen climate data generators.

3) The simulation of crop yields, soil erosion, nitrogen and water balance by using the Cropping System simulation model (CropSys).

The study area covered the plain and hills around Lake Trasimeno in Umbria. The area features fertile lands, where numerous species can be grown and where the lake produces a mild, humid climate. The farms in the area are mainly small and few are irrigable, with a high percentage of arable land and timber cultivation. Although larger in size, organic farms represent a tiny percentage of the total. (Regione Umbria, 2014).

To assess the effects of CC in the area, we took into consideration crop rotations consisting of autumn-winter crops (wheat and barley) and annual non-irrigated crops, typical of the area (sunflower, lentil and cowpea). These enable the best analysis of the effects of climate change, especially of the temperature rise in years of drought. The rotations examined were: soft wheat-sunflower (Triticum aestivum- Helianthus annuus); soft wheat-lentil (Triticum aestivum - Lens culinaris); barley-cowpea (Hordeum vulgare - Vigna unguiculata). The crop plan was identified for each rotation, together with the main cropping operations (preparation of the seed bed, fertilisation, sowing, after-sowing operations and harvest).

Once we had established the area and the crops, we moved on to simulate the climate data using the following climate generators. The first was MarkSim, a stochastic weather generator. The software enables future climate scenarios to be simulated and provides information on any part of the world, for which it uses historic daily data collected from 10,000 stations across the world over the last 15-20 years as its input (CIAT, 2014). MarkSim provides an output of up to 117 parameters, including daily rainfall, solar radiation and maximum and minimum temperatures. The second was another generator, ClimGen, which enables the effects of the increase in carbon dioxide on crop growth to be assessed depending on the use of water resources and crop solar radiation. By entering actual meteorological data, it produces daily climate data, e.g. rainfall, solar radiation, daily minimum and maximum temperature, wind speed and air humidity. The combined use of the two resulted in the simulation of daily meteorological data, which represented a statistical average for the individual year selected.

MarkSim enables climate scenarios to be used based on various emissions processed by the IPCC commencing from those years: these scenarios are named RCP (Representative Concentration Pathways) and are capable of providing estimates of future possible changes (Wayne, 2013). Their purpose is to provide simulations of the increase in the concentration of greenhouse gases (GHG) according to climate information (Wayne, 2013), in order to understand what the consequences could be arising from human-caused, global warming. The RCP were constructed, commencing with data regarding representative radiative forcing (or equivalent concentrations of CO2) of different greenhouse gases over time, which is why they are called representative concentration pathways (Wayne, 2013). Radiative forcing (RF) measures in watts per square metre (W/m^2) how the earth's energy balance (Stocker et al., 2013) (energy entering and exiting the Earth-atmosphere system (Wayne, 2013)) has changed in 2011 compared to 1975. Radiative forcing can be estimated either on the basis of the substance emissions from human activities, or according to mathematical models, observation and the properties of greenhouse gases (Stocker et al., 2013).

The four RCPs differ according to the different values of radiative forcing in 2100 compared to 1750: RCP 2.6 indicates a radiative forcing of 2.6 W/m^2, RCP 4.5 corresponds to an estimated 4.5 W/m^2, RCP 6 to a value of 6 W/m^2 and 8.5 W/m^2 for the RCP 8.5. This means that the higher the RCP recognition number, the higher global warming will be due to the increase in gas emissions (Figure 1).

This study considered the two extreme scenarios, RCP 2.6 and RCP 8.5: the first is based on the assumption that emissions will reduce fairly rapidly and there will even be a decrease by 2100, whereas the second is based on the assumption of unchanged gas emissions compared to current levels. MarkSim enabled the data from the two scenarios to be used to generate climate information over the period from 2010-2012, as a basic, current situation, and from 2065-2067 as a future, pejorative scenario. The output was returned on a monthly basis: by using the ClimGen weather generator, data was produced in the format required by CropSyst, the model used for the central part of the study. Actual data was not used, even though it was available, in order to avoid different types of errors between real and simulated series from generating unreliable results.

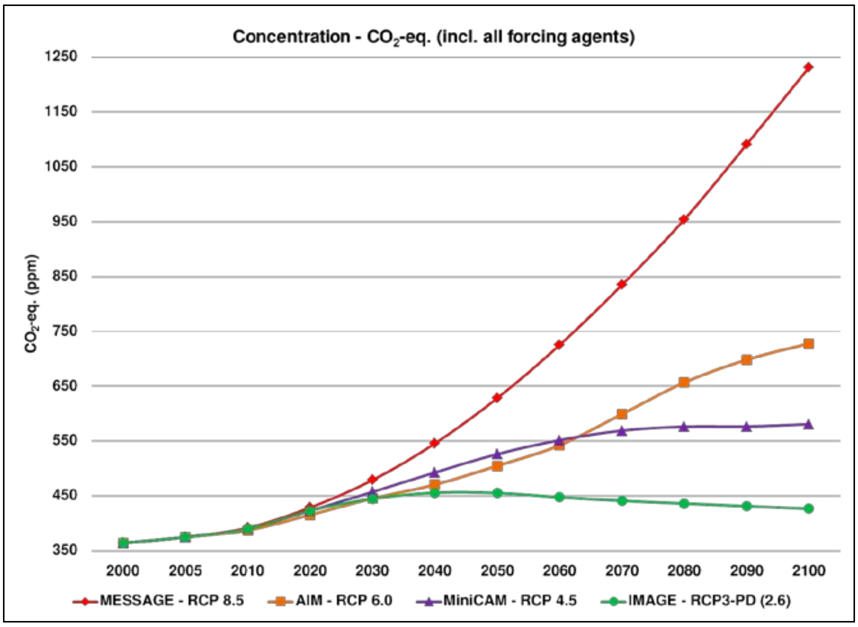


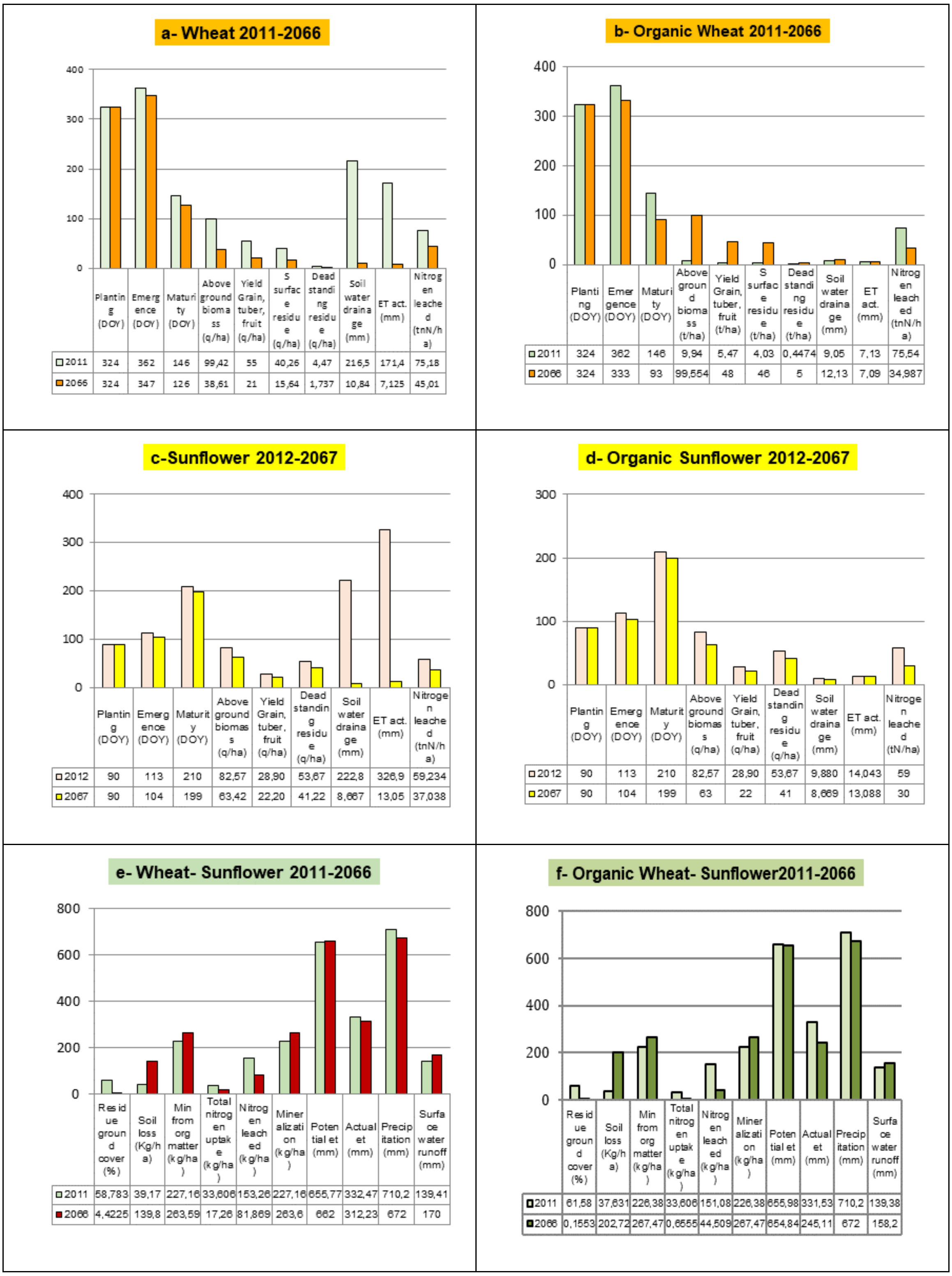
Figure 1: IPCC AR5 Greenhouse Gas Concentration Pathways (source: 5th assessment report IPCC, 2013)

All the climate and crop data was then used to perform the simulations using the CropSyst software (Cropping System simulation model) (Stöckle et al., 2003). CropSyst enables daily simulations to be carried out, based on several years and several crops. The variation in plant production is assessed according to specific crop and system management parameters, beginning from a single, biologically and physically, homogeneously manageable area of soil. The required parameters included not only meteorological data, simulated with the weather generators, and all management operations with all the crop growth data, but also specific species data, e.g. the phenology, morphology, growth, the demand for and presence of nitrogen, saline tolerance and response to increased CO2. CropSyst enables estimates to be made of production yields, although the latter must first be calibrated with real data over a basic period. This calibration phase is fundamental, as the software was designed to simulate the effects of climate change in tropical areas (CIAT, 2014). Yields would be underestimated without this calibration.

Results and discussion

Each rotation examined produced various output files for both conventional and organic cultivation for the basic period (2010-2012) and for the future period (2065-2067), in order to compare the changes in cultivation of the same crops under different climate situations and with different cropping techniques.

This paper is restricted to reporting two output files: "Harvest" and "Annual" for each rotation and for both cropping operations. However, the two outputs are of different importance. The "Harvest" file gave successive, annual information for both crops in a single agricultural year for each of the six years used in the simulations. The "Annual" file, on the other hand, returned data on the entire rotation, taking into account the three consecutive years overall, without distinguishing between the individual crops.



a- Wheat 2011-2066

	Planting (DOY)	Emergence (DOY)	Maturity (DOY)	Above ground biomass (q/ha)	Yield Grain, tuber, fruit (q/ha)	S surface residue (q/ha)	Dead standing residue (q/ha)	Soil water drainage (mm)	ET act. (mm)	Nitrogen leached (tnN/ha)
☐ 2011	324	362	146	99,42	55	40,26	4,47	216,5	171,4	75,18
■ 2066	324	347	126	38,61	21	15,64	1,737	10,84	7,125	45,01

b- Organic Wheat 2011-2066

	Planting (DOY)	Emergence (DOY)	Maturity (DOY)	Above ground biomass (t/ha)	Yield Grain, tuber, fruit (t/ha)	S surface residue (t/ha)	Dead standing residue (t/ha)	Soil water drainage (mm)	ET act. (mm)	Nitrogen leached (tnN/ha)
☐ 2011	324	362	146	9,94	5,47	4,03	0,4474	9,05	7,13	75,54
■ 2066	324	333	93	99,554	48	46	5	12,13	7,09	34,987

c-Sunflower 2012-2067

	Planting (DOY)	Emergence (DOY)	Maturity (DOY)	Above ground biomass (q/ha)	Yield Grain, tuber, fruit (q/ha)	Dead standing residue (q/ha)	Soil water drainage (mm)	ET act. (mm)	Nitrogen leached (tnN/ha)
☐ 2012	90	113	210	82,57	28,90	53,67	222,8	326,9	59,234
■ 2067	90	104	199	63,42	22,20	41,22	8,667	13,05	37,038

d- Organic Sunflower 2012-2067

	Planting (DOY)	Emergence (DOY)	Maturity (DOY)	Above ground biomass (q/ha)	Yield Grain, tuber, fruit (q/ha)	Dead standing residue (q/ha)	Soil water drainage (mm)	ET act. (mm)	Nitrogen leached (tN/ha)
☐ 2012	90	113	210	82,57	28,90	53,67	9,880	14,043	59
■ 2067	90	104	199	63	22	41	8,669	13,088	30

e- Wheat- Sunflower 2011-2066

	Residue ground cover (%)	Soil loss (Kg/ha)	Min from org matter (kg/ha)	Total nitrogen uptake (kg/ha)	Nitrogen leached (kg/ha)	Mineralization (kg/ha)	Potential et (mm)	Actual et (mm)	Precipitation (mm)	Surface water runoff (mm)
☐ 2011	58,783	39,17	227,16	33,606	153,26	227,16	655,77	332,47	710,2	139,41
■ 2066	4,4225	139,8	263,59	17,26	81,869	263,6	662	312,23	672	170

f- Organic Wheat- Sunflower2011-2066

	Residue ground cover (%)	Soil loss (Kg/ha)	Min from org matter (kg/ha)	Total nitrogen uptake (kg/ha)	Nitrogen leached (kg/ha)	Mineralization (kg/ha)	Potential et (mm)	Actual et (mm)	Precipitation (mm)	Surface water runoff (mm)
☐ 2011	61,58	37,631	226,38	33,606	151,08	226,38	655,98	331,53	710,2	139,38
■ 2066	0,1553	202,72	267,47	0,6555	44,509	267,47	654,84	245,11	672	158,2

Figure 2: comparison of the conventional-organic, wheat-sunflower rotation.

The graph in Figure 2 shows the results of the Harvest and Annual output files. More specifically, the first four graphs (a, b, c, d) record the output of each individual crop in the two reference years for both organic and conventional techniques. Graphs 2e and 2f, on the other hand, record the overall result of the rotation for conventional and biological farming, respectively. They take into account the three years of the current scenario (2010-2012) and of the future scenario (2065-2067). The same outline was also used to record the results of the other rotations in figures 4 and 6.

Conventional and organic cultivation is compared directly for the middle year of simulation of the future, pejorative scenario (2066). We decided not to record any temporal variation, but to focus more on the difference between the two production systems. Figure 3 shows the comparison for the wheat-sunflower rotation.

The results for the wheat-lentil rotation were recorded in the same way as for the wheat-sunflower rotation. Figure 4 shows the details of the two Harvest and Annual files and Figure 5 shows only those for conventional and organic systems for 2066.

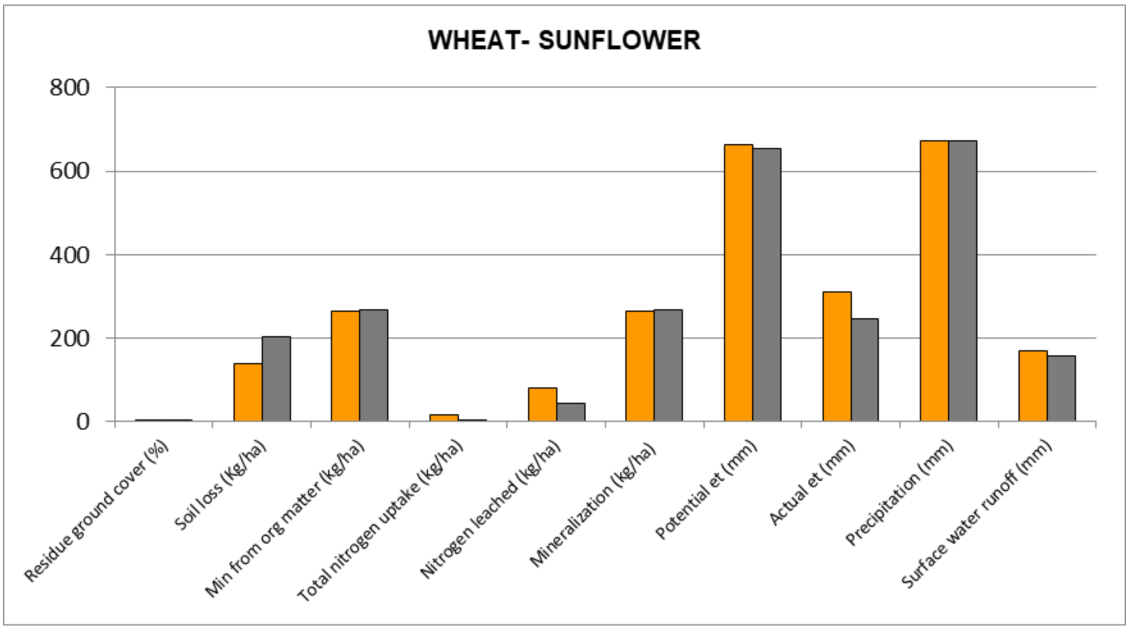


Figure 3: Comparison between the organic system (grey) and the conventional system (orange) for the year 2066

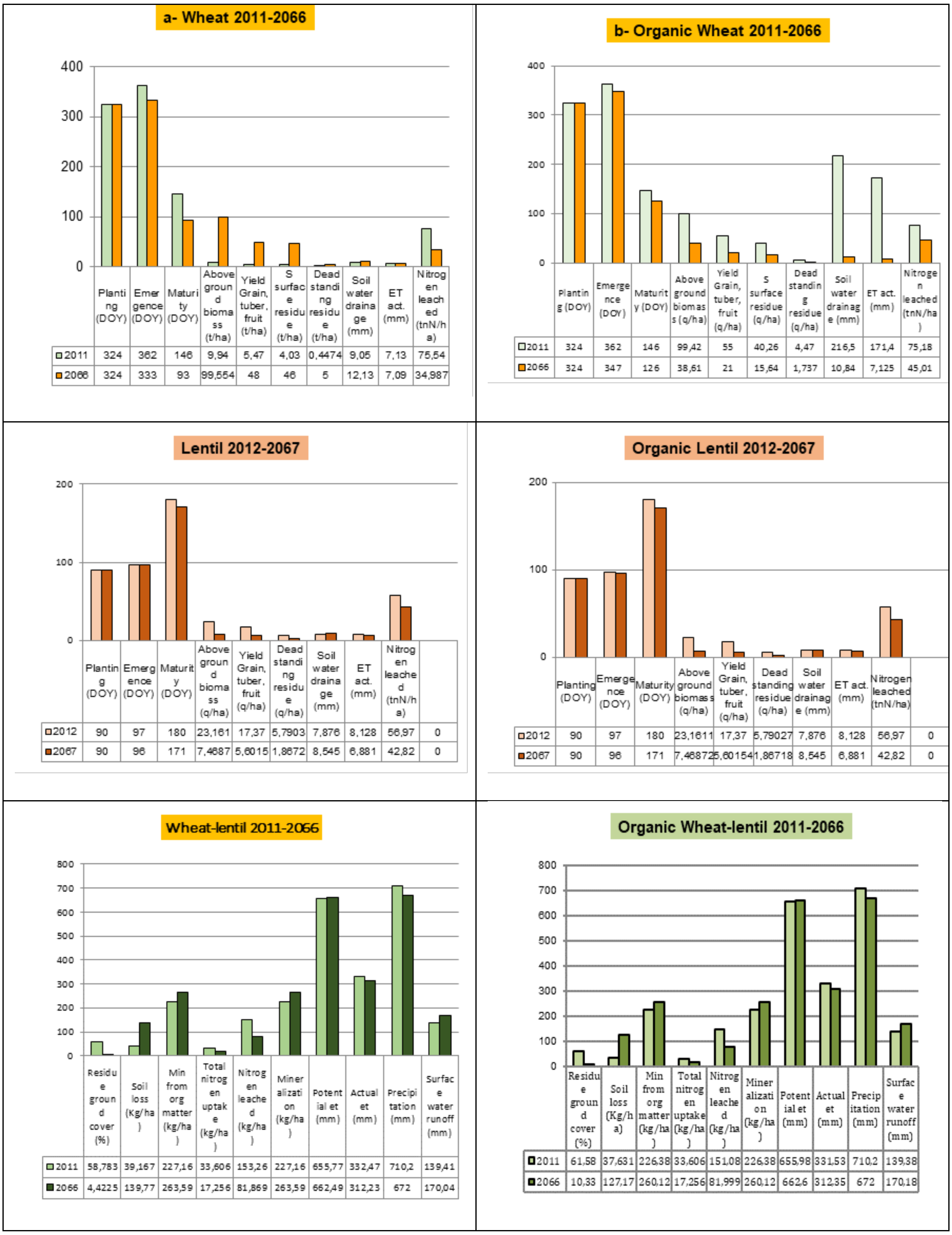


Figure 4: comparison of the conventional-organic, wheat-lentil rotation

The direct comparison between organic and conventional systems shows similar behaviour between organic and conventional cultivation (Figure 5).

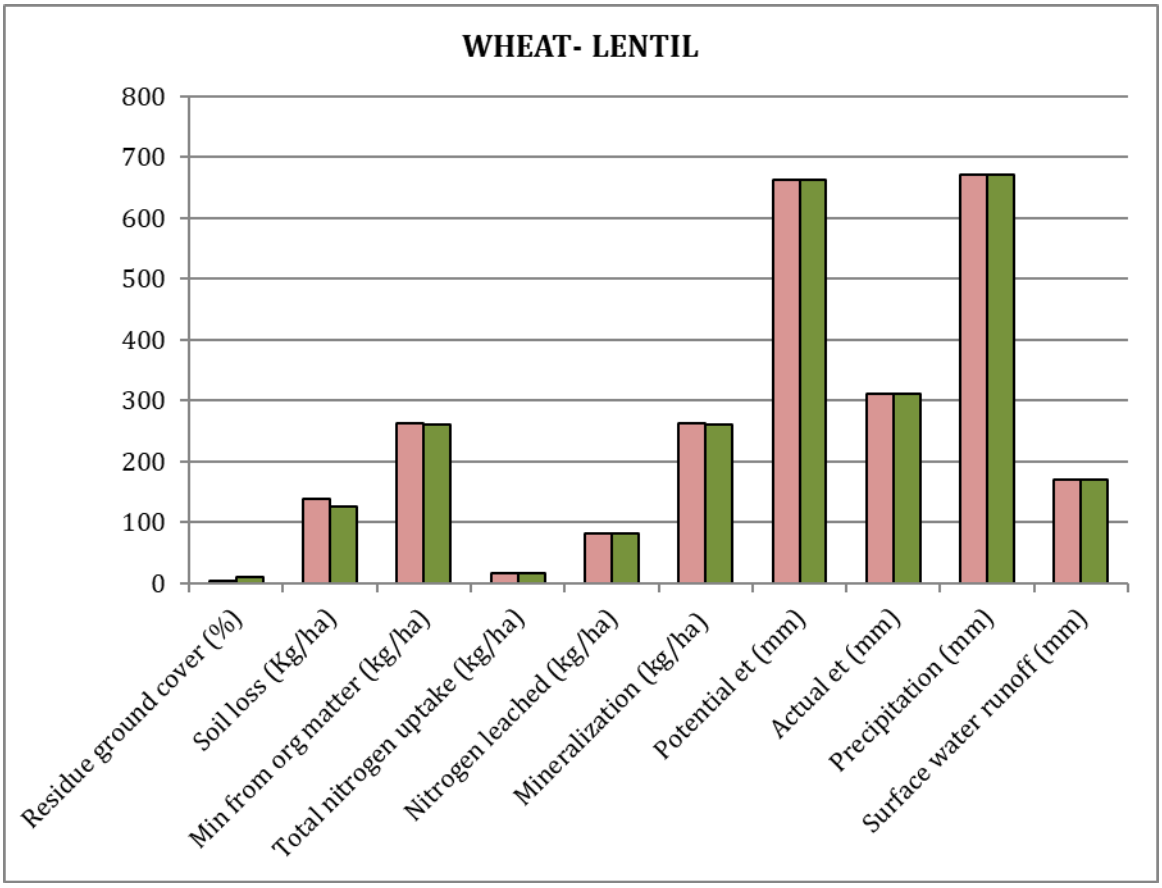


Figure 5: comparison between the organic system (green) and the conventional system (orange) for the year 2066

Figures 6 and 7 show the results of the last rotation (barley-cowpea) in a similar way to those described above.

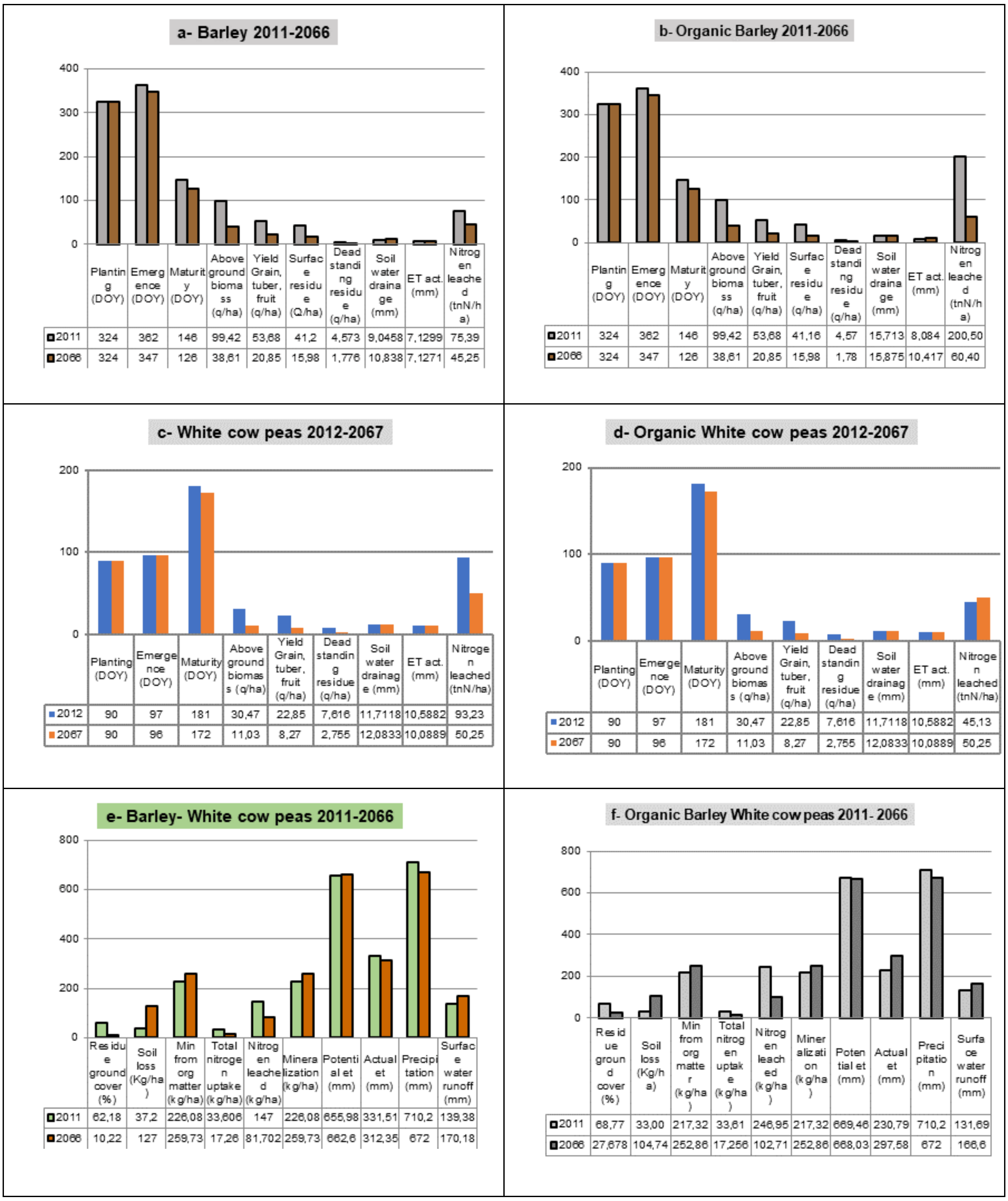


Figure 6: comparison of the conventional-organic, barley-cowpea rotation

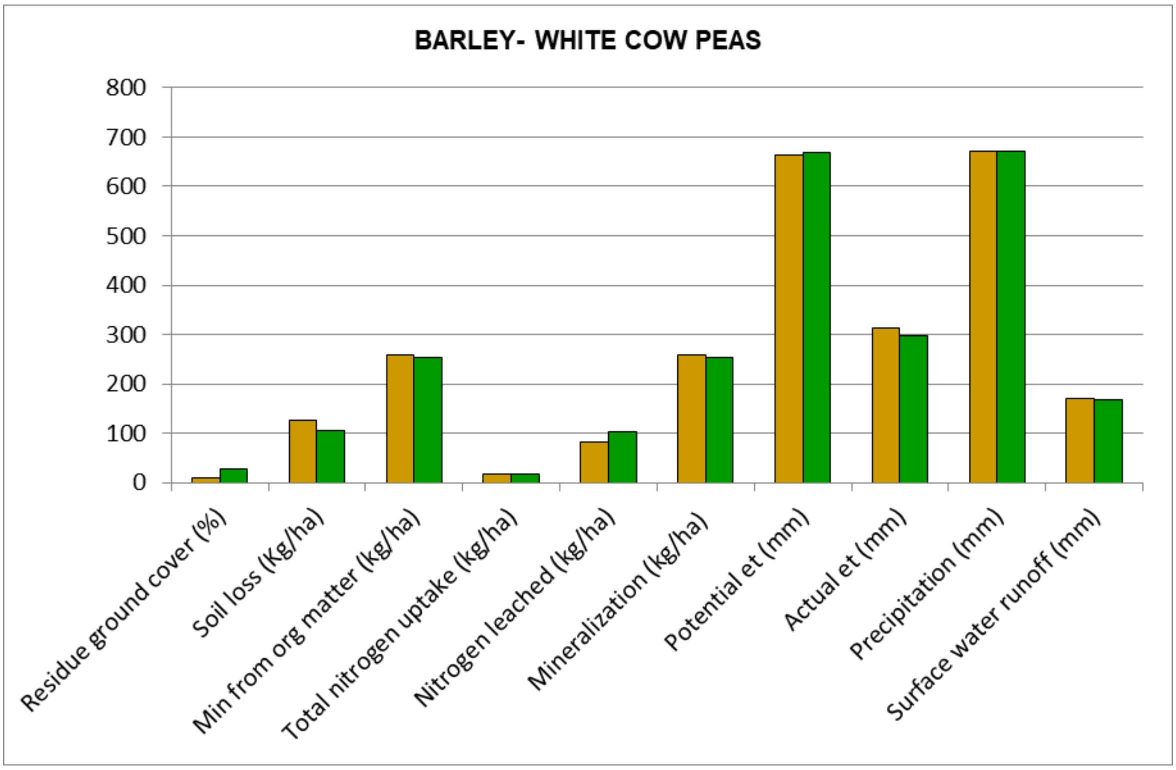


Figure 7: comparison between the organic system (green) and the conventional system (mustard) for the year 2066

Looking at the overall data, we can see that from the same day of sowing for the same crop in the two different periods, the future period shows early emergence and ripening, which is particularly marked in the case of the cereals. A comparison of organic and conventional methods in the wheat-sunflower rotation shows the greatest difference between conventional and organic cropping, with the latter clearly earlier. The other two rotations, however, showed very little difference.

Biomass production, both before harvesting and the yield in grain, straw and stubble, decreased in all rotations. More specifically, the comparison between organic and conventional methods showed a greater drop in the organic than in the conventional barley-cowpea rotation. The other rotations did not show clear differences between the two methods.

In the light of these results, we can assume that the rise in temperatures will cause the drop above all during the period of growth as emergence is not as early as ripening. This drop leads to a decrease in yields and, therefore, in marketable production. The datum is comparable to other research studies, which identify a yield drop due to the rise in temperatures for cereals both globally (Asseng et al. 2014) and in the Mediterranean regions of Europe (Bindi and Olesen, 2002). It should be noted that this reduction in Mediterranean areas is not counterbalanced by increased yields at higher latitudes (Peltonen-Sainio et al., 2018).

Let us move on to an analysis of the behaviour of nitrogen. All organic and conventional crops showed an equal absorption level of nitrogen in the first year the rotation was applied, which then dropped in subsequent years. In the case of the wheat-sunflower rotation, after an initial, identical year, absorption decreased considerably, rising once again in the third year. The total results of the two productive systems over the three years were similar, with the exception of the wheat-sunflower rotation, which recorded a lower result.

Nitrogen mineralisation tends to increase for all crops in the future scenario. The conventional wheat-lentil rotation showed a greater level than the organic rotation, whereas the other rotations held similar values. This confirmed what has been proved by forecasts made under conditions of higher temperatures, which will increase the speed at which the organic substance decomposes (Bindi and Olesen, 2011).

Nitrogen leaching decreased for all the crops. With the exception of the wheat-sunflower rotation, in which the contrary occurred, although leaching would decrease in the future, it proved to be greater in organic systems compared to conventional techniques. Decreased leaching has also been shown by other simulations (Bindi and Olesen, 2011), and is mainly due to a reduction in rainfall frequency, even though this will be more intense.

The percentage of surface covered by residues decreased for all the rotations. When comparing conventional and biological surface areas, the latter were larger for the wheat-lentil and barley-cowpea rotations. On the contrary, the wheat-sunflower rotation showed the opposite trend, where the conventional surface area was greater. This phenomenon is linked to soil loss, which tended to increase for all the crops. The loss for wheat-lentil and barley-cowpea rotations was greater in the case of conventional production, whereas the wheat-sunflower lost more tons per hectare under organic conditions. Another concause of soil loss was without doubt the presence of more intense and, therefore, more soil aggressive rainfall (Bindi and Olesen, 2002).

The effects of climate change will also be felt on evapotranspiration. Potential evapotranspiration dropped in the first year of simulation and then showed a slight increase in subsequent years. On the other hand, actual evapotranspiration remained fairly unvaried, even though it had a tendency to decrease slightly. This was probably due to less rainfall with fewer risks of soil salinisation via phreatic rise, thus reducing the danger of less fertile soil. Looking at the individual years, potential evapotranspiration dropped in the first year, only to rise slightly in subsequent years. Organic wheat-sunflower and barley-cowpea rotations showed a distinct drop in the first year, which was contained in the second year and then increased slightly in the third year. The actual evapotranspiration decreased no less clearly. Conventional and organic crops differed very little, with the exception of the organic wheat-lentil and barley-cowpea rotations, which were slightly higher than the conventional crop rotations.

Surface run-off water for all the crops continued to increase, and it increased more during the first year. The level proved greater for conventional wheat-lentil and barley-cowpea rotations than for the organic crops, whereas conventional and organic wheat-sunflower rotations were similar.

Water drainage was slightly greater for all the crops, except for the sunflower, which decreased slightly. A comparison between conventional and organic crops showed that all the latter rotations had greater drainage compared to the former. Surface run-off and water drainage will increase as rainfall becomes more intense.

The comparison between conventional and organic cultivation showed no clear differences. The differences appeared to be ascribable more to the characteristics of the individual crops than to the type of management. This can be seen as a good result as, if organic and conventional methods are similar, the former type of management would be preferable, in order to enable emissions to be reduced and agriculture's contribution to climate change to be restricted. At the same time, we should note how other authors indicate management systems with closer local ties, such as agro-ecological methods, as more effective solutions in terms of adaptation and mitigation (Altieri et al., 2015).

Conclusions

Climate change is an impending reality for human society. The consequences this will have on our productive systems are largely unpredictable. Nevertheless, the knowledge and study of the possible development of production are fundamental factors for us to be able to offer a solution. Without knowing the possible development of the scenarios, we will be unable to apply strategies of mitigation or adaptation.

This paper comes in the wake of literature aiming to assess and analyse the possible evolution of the climate in contained areas and the subsequent developments in production. By analysing a case study, we analysed a possible scenario of evolution, in which man is unable to develop in order to contrast his own contribution to climate change. In the current, international, political framework, that scenario appears to be probable at least. The effects on agriculture have proved significant, above all in terms of a drop in yields, with the imaginable consequences for food safety. The results which can be obtained from simulations, such as those performed in this study, constitute a major work basis for decision-makers, who will be increasingly called upon in future to develop adequate measures of adaptation to the effects of climate change, rather than those of possible mitigation. Only by increasing our knowledge and ability to forecast will it be possible to make technical, management and in some cases structural changes, which may allow our agro-ecosystems to adapt to the new climate conditions and reduce not only the environmental, but also the economic consequences of the changes in progress.

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