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Evaluation of conservation tillage and rotation with legumes as adaptation and mitigation strategies of climate change on durum wheat in Sardinia

Dr. Gianluca Carboni

Direttore della Scuola: Prof. Giuseppe Pulina

Referente di Indirizzo: Prof. Donatella Spano

Docenti Guida: Prof. Donatella Spano

Dr. Carla Cesaraccio

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ABSTRACT

Durum wheat is one of the most important crops of the Mediterranean and the main cereal grown in Italy. In recent years, both farmers and policy makers express concerns about the uncertainties of the yields obtained from the culture due to more frequent droughts and, in general, to the changing climatic conditions. The effect of increased temperature and changes in rainfall patterns are important factors in determining the yields, particularly for crops not irrigated. In addition, the growing awareness of the common European agricultural policy that has matured towards environmental sustainability has led to a growing interest in soil conservation tillage. Studies of this issue in the Mediterranean are limited and the observed effects on yield and grain quality are often contradictory. However, it is generally accepted that in the long term, conservation tillage can lead to an increase in carbon content in the soil.

Given the socio-economic importance of durum wheat for the Mediterranean area and the lack of studies concerning the evaluation of different agricultural practices (tillage and rotations), it was important to focus the study on these issues, especially considering the conditions of climate change.

Starting from this assumption, the study aimed to to i) improve knowledge about the effects of conservation tillage techniques and rotation with legumes on phenology and production of durum wheat and ii) evaluate the interaction of these agricultural practices with the projections of climate change, with the objective to iii) assess impacts and iv) suggest possible adaptation strategies to cope with climate change.

Experimental results were analyzed and the trends of the main climatic variables for the study area has been evaluated.

The CSM-CERES-Wheat model implemented in the beta software DSSAT 4.5, in combination with a stochastic weather generator (WG), were used for the evaluation of the impacts of climate change and adaptation strategies on durum wheat. The synthetic weather series representing the future climate, were generated by changing the parameters of the WG based on the characteristics of a series of climate change scenarios based on projections of three GCMs. Twenty-seven climate change scenarios, obtained with the

pattern scaling technique were used, considering three values of climate sensitivity and four emission scenarios for periods 2025, 2050 and 2075.

Alternative cropping systems were studied as a possible adaptation and mitigation strategies for changing climate conditions, exploring a wide range of climate scenarios and considering, separately, the direct and indirect effects of the change of CO_2 atmospheric concentration on the cultivation of durum wheat.

The results showed a substantial indifference between tillage practices on the yield whereas the crop rotation with legumes favoured grain yields and superior quality of production. Such behaviour has been observed either in field trials and in simulations carried out for the future climate scenarios. The latter showed a high variability depending on the wide range of climate scenarios used mainly in the more distant future periods. The uncertainties linked to climate sensitivity, emission scenarios and the effects of the increase in atmospheric CO2 concentrations are among the main causes of this wide variability.

The application of conservation tillage is recommended in this region because, by allowing the acquisition of similar yields to the conventional tillage, permits a management environmentally and economically more sustainable.

RIASSUNTO

Il frumento duro è una delle più importanti colture del Mediterraneo ed è il cereale maggiormente coltivato in Italia. Negli ultimi anni sia gli agricoltori che i decisori politici manifestano preoccupazioni legate alle incertezze delle rese ottenibili dalla coltura a causa di sempre più frequenti periodi di siccità e, in generale, alle mutate condizioni climatiche registrate. L'effetto dell'incremento della temperatura e di variazioni nel regime delle precipitazioni, sono fattori importanti nel determinare le rese, in particolare per colture condotte in regime non irriguo. Inoltre la crescente consapevolezza che la politica agricola comunitaria ha maturato verso la sostenibilità ambientale ha determinato un crescente interesse verso le tecniche di lavorazione conservative del suolo. Gli studi effettuati su questa tematica nell'area del Mediterraneo sono limitati e gli effetti osservati sulle rese e sulla qualità della granella sono spesso contraddittori. Tuttavia, è generalmente riconosciuto che, nel lungo termine, le lavorazioni conservative possono comportare un aumento del contenuto di carbonio nel suolo.

Considerata l'importanza socio-economica del frumento duro per l'area del Mediterraneo e la carenza di studi relativi alla valutazione di diverse pratiche agronomiche (lavorazioni del terreno e rotazioni), era importante focalizzare lo studio su queste tematiche, particolare considerando anche condizioni di cambiamento climatico.

Partendo da questi presupposti, lo studio si è proposto di i) migliorare le conoscenze sugli effetti delle tecniche di lavorazioni conservative e della rotazione con leguminose sulla fenologia e la produzione del frumento duro e ii) valutare le interazioni di queste pratiche agronomiche con le proiezioni di cambiamento climatico, con l'obiettivo iii) di valutare gli impatti e iv) di suggerire possibili strategie di adattamento per far fronte ai cambiamenti climatici.

Sono stati condotti due campi sperimentali nel sud della Sardegna al fine di valutare gli effetti delle lavorazioni conservative e degli avvicendamenti colturali con leguminose sulla coltura del frumento duro e stimare le interazioni esistenti tra queste tecniche e l'ambiente. Sono stati analizzati i risultati sperimentali e valutati gli andamenti delle principali variabili climatiche per l'area oggetto di studio.

Per la valutazione degli impatti dei cambiamenti climatici sul frumento duro, e delle strategie di adattamento, è stato utilizzato il modello CSM-CERES-Wheat, implementato nella versione beta del software DSSAT 4.5, in combinazione con un generatore stocastico di dati meteorologici (WG). Le serie meteorologiche sintetiche rappresentanti il clima futuro, sono state generate modificando i parametri del WG in base alle caratteristiche di una serie di scenari di cambiamento climatico basati sulle previsioni di tre GCMs. Sono stati quindi utilizzati ventisette scenari di cambiamento climatico ottenuti con la tecnica di Pattern scaling, tenendo conto di tre valori di climate sensitivity e di quattro scenari di emissione per i periodi relativi al 2025, 2050 e 2075.

Sono stati studiati sistemi alternativi di gestione colturale come possibili strategie di adattamento e di mitigazione alle mutate condizioni climatiche, esplorando una vasta gamma di scenari climatici, considerando separatamente gli effetti diretti e indiretti della variazione di concentrazione atmosferica di CO_2 sulla coltivazione del frumento duro.

I risultati ottenuti hanno mostrato una sostanziale indifferenza fra le tecniche di lavorazione sulla resa mentre l'avvicendamento colturale con leguminose ha favorito l'ottenimento di rese in granella e qualità superiori. Tale comportamento è stato osservato sia in campo che nelle simulazioni effettuate per gli scenari climatici futuri. Queste ultime hanno mostrato una variabilità elevata dipendente dall'ampia gamma di scenari climatici utilizzati soprattutto nei periodi futuri più distanti,. Le incertezze legate alla climate sensitivity, agli scenari di emissione e ed agli effetti dell'incremento di concentrazione di CO_2 atmosferica sono fra le principali cause di questa ampia variabilità.

L'applicazione delle tecniche di lavorazione conservative è raccomandabile nell'area di studio perché, consentendo l'ottenimento di produzioni simili alla tecnica convenzionale, permette una gestione maggiormente sostenibile sia dal punto di vista ambientale che economico.

1. INTRODUCTION

Durum wheat (*Triticum durum* Desf.) is one of the most cultivated crops in Sardinia and in Southern Italy. This extensive crop is widely diffuse due to his adaptability and ability to provide satisfactory productions even in drought environmental conditions.

In recent decades, cereal farmers of the Mediterranean area faced, with a greater frequency than in the past, years when poor harvests due to bad weather caused huge economic losses.

The variability of environmental factors, and especially of the weather, in arid and semi-arid regions is a crucial component for agricultural production. It is known that in these regions the seasonal variability of climate and, in particular rainfall, is the main risk factor for agricultural production (Duce *et al.*, 2004).

The durum wheat productions are strongly influenced by weather and therefore the environmental component is crucial in determining crop yields.

There is an extensive discussion on how large can be the effects of climatic changes in progress. The term "climate change" is usually defined as "a change in the statistical distribution of weather (e.g. temperatures and rainfall) over periods of time that range from some decades to millions of years" (IPCC, 2007a). The changes considered could be in the average weather or in the distribution of weather events around an average (e.g, greater extreme weather events) and may be limited to a region or across the whole Earth.

Agriculture is one of the major economic sectors involved, and the impacts that climate change may determine on agricultural production are one of the major concern worldwide.

The Intergovernmental Panel on Climate Change (**IPCC**) reviews and assesses the most recent information produced worldwide that are directly or indirectly linked to climate change. In the IPCC fourth assessment report (**AR4**), published in 2007, are stated that *warming of the climate system is unequivocal and evident from observation of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level* (Fig. 1) (IPCC, 2007b).

Various evidences confirm this statement: the linear increase (1906-2005) calculated (0.74 °C per century) in the AR4 is larger than the corresponding trend (0.6 °C from 1901 to 2000) estimated in the previous report of TAR (IPCC, 2007b). Furthermore, from 1995 to 2006 eleven of twelve years rank among the twelve warmest years in the instrumental record of global surface temperature since 1850.

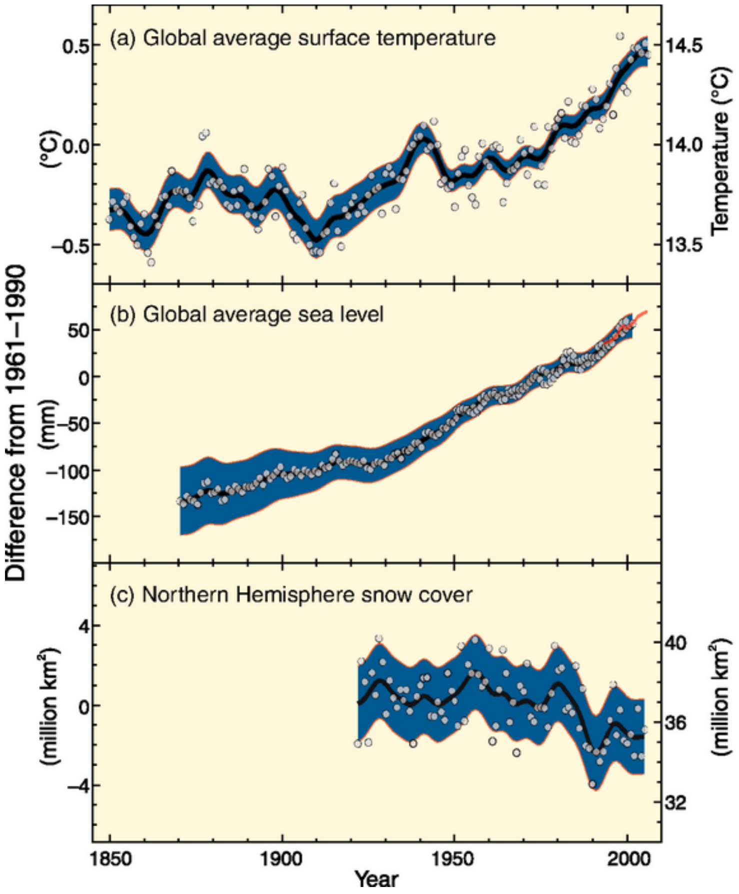

Fig. 1 - Observed changes in (a) global average surface temperature; (b) global average sea level from tide gauge (blue) and satellite (red) data; and (c) Northern Hemisphere snow cover for March-April. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c) (IPCC, 2007b).

The expected climate changes will vary depending on the geographic region considered. For Europe it is expected an increase of temperatures in all seasons and a significant change in rainfall distribution. For the Mediterranean basin there are projections that forecast a reduction in summer precipitation, while minor changes are expected in spring and autumn. The expected worsen weather conditions (higher temperatures and drought) in southern Europe are particularly critical because could happen in a area vulnerable for crop productivity (IPCC, 2007b).

Based on the above considerations, it is of considerable interest to study the impact that climate change could have on the cultivation of durum wheat and investigate on the possibility of adopting effective strategies for adaptation and mitigation in crop management.

Recent and past studies were performed to investigate the climate change impacts on agriculture in Europe (Bindi and Moriondo, 2005; Tubiello *et al.,* 2000), and on wheat in Europe (Šťastná *et al.*, 2002; Guereña, *et al.* 2001) and the Mediterranean Basin (Donatelli *et al.*, 1997).

In most of these studies ordinary crop management were evaluated. Moreover, some other aspects of crop management, such as the choice of the wheat cultivars or the choice of planting date and nitrogen fertilization, were also considered. However, other issues related to crop management have not been sufficiently investigated so far.

In fact, not many studies have been conducted to investigate the role of the agronomic practices as mitigation and/or adaptation strategies to climate change. One of the aspects that should be considered as mitigation and adaptation strategies in a Mediterranean environment, is the impact and the effectiveness of some agronomic practices. Although the most common agronomic practice considered in wheat cultivation is the conventional tillage, other types of tillage systems, consisting in reduced tillage and no tillage and different crop rotation, are continuously diffusing.

Valuable tools to perform such kind of investigation are the crop simulation models. Moreover, a set of reliable experimental data is necessary to calibrate a crop simulation model and then to evaluate the impact of climatic change on wheat for the study area considered.

1.1. Climate change: evidence and projections

The Intergovernmental Panel on Climate Change (**IPCC**) defines the c*limate change as a change in the state of the climate that can be identified (e.g. using statistical tests) in terms of changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer* (IPCC, 2007b). The IPCC refers to any change in climate, whether due to natural variability or as a result of human activity. Differently from the IPCC, the United Nations Framework Convention on Climate Change (**UNFCCC**) for climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that could be in addition to natural climate variability observed over comparable time periods (IPCC, 2007b).

Considering the causes of climate change, it is established in the AR4 that the drivers (both natural and anthropogenic) are changes in the atmospheric concentrations of greenhouse gases (**GHGs**). Increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic GHGs that are responsible to alter the energy balance of climate system by the absorption, scattering and emission of radiation within the atmosphere and at the Earth's surface. The resulting positive or negative changes in energy balance due to these factors are expressed in terms of the *radiative forcing*[1], which implies either warming (if it is positive) or cooling (if it is negative) influences on global climate (IPCC, 2007b). The most important GHGs considered includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphurhexafluoride whose emissions are covered by the UNFCCC. Another important GHG is water vapour (one of the most effective), although it is a natural GHG and the humans can hardly affect on its concentration.

GHGs differ in their warming influence on the global climate system because they have different radiative properties and lifetimes in the atmosphere. The warming influences of any GHG may be conveniently expressed through a common metric based on the

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[1] The IPCC AR4 defines *Radiative forcing* as a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. The radiative forcing values are expressed in watts per square meter (Wm^{-2}) (IPCC, 2007 b).

radiative forcing of CO_2. There are differences in terminology between CO_2 equivalent emission and CO_2 equivalent concentration:

- *CO_2 equivalent emission* is considered the amount of CO_2 emission that would cause the same time-integrated radiative forcing, over a given time horizon, as an emitted amount of a long-lived GHG or a mixture o GHGs. This is a standard metric for comparing emissions of GHGs but it not imply the same climate change responses;
- *CO_2 equivalent concentration* is the concentration of CO_2 that would cause the same amount of radiative forcing as a given mixture of CO_2 and other forcing components.

The largest growth in GHG emissions between 1970 and 2004 has come from energy supply, transport and industry. Residential and commercial buildings, forestry (including deforestation) and agriculture sectors have been growing at a lower rate. The global atmospheric concentrations of carbon dioxide, methane and nitrous oxide are the more factor responsible of climate change and is concentrations have been increasing considerably as a result of human activities since 1750 (Figs. 2 e 3). It is also clear that the first of them is the most important anthropogenic greenhouse gas (IPCC, 2007a).

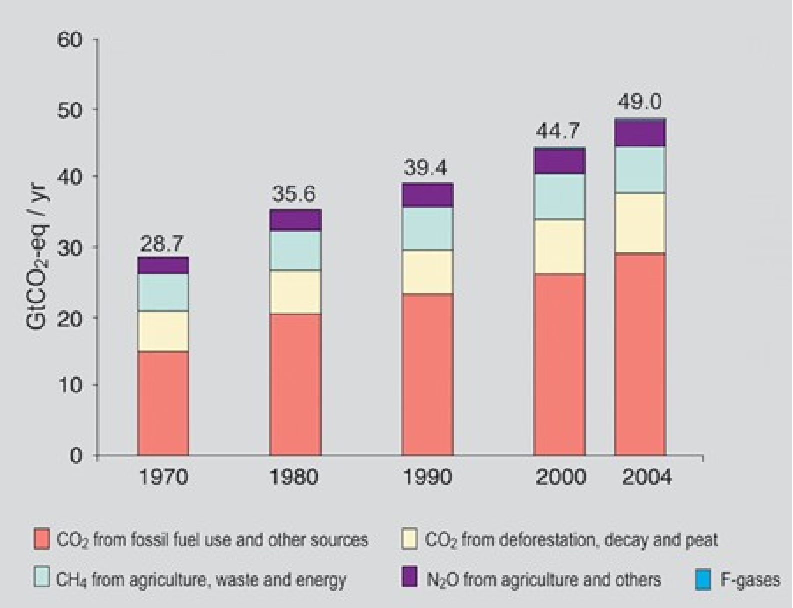


Fig. 2 - Global annual emissions of anthropogenic GHGs from 1970 to 2004 (IPCC, 2007a).

The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005. Similar increases are observed for methane and nitrous oxide (Fig. 3). The main causes of increases in CO_2 concentration are considered fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture (Figs. 3 and 4) (IPCC, 2007a).

The amount of emissions annually released into the atmosphere produced by agriculture is not less important than others economic activities: about one quarter of total CO_2 emissions is due to deforestation and soil organic carbon depletion, machine and fertilizer use, half of methane emissions is primarily due to livestock and rice cultivation, and three-fourths of nitrous oxide is due to fertilizer applications and manure management (Rosenzweig and Tubiello, 2007).

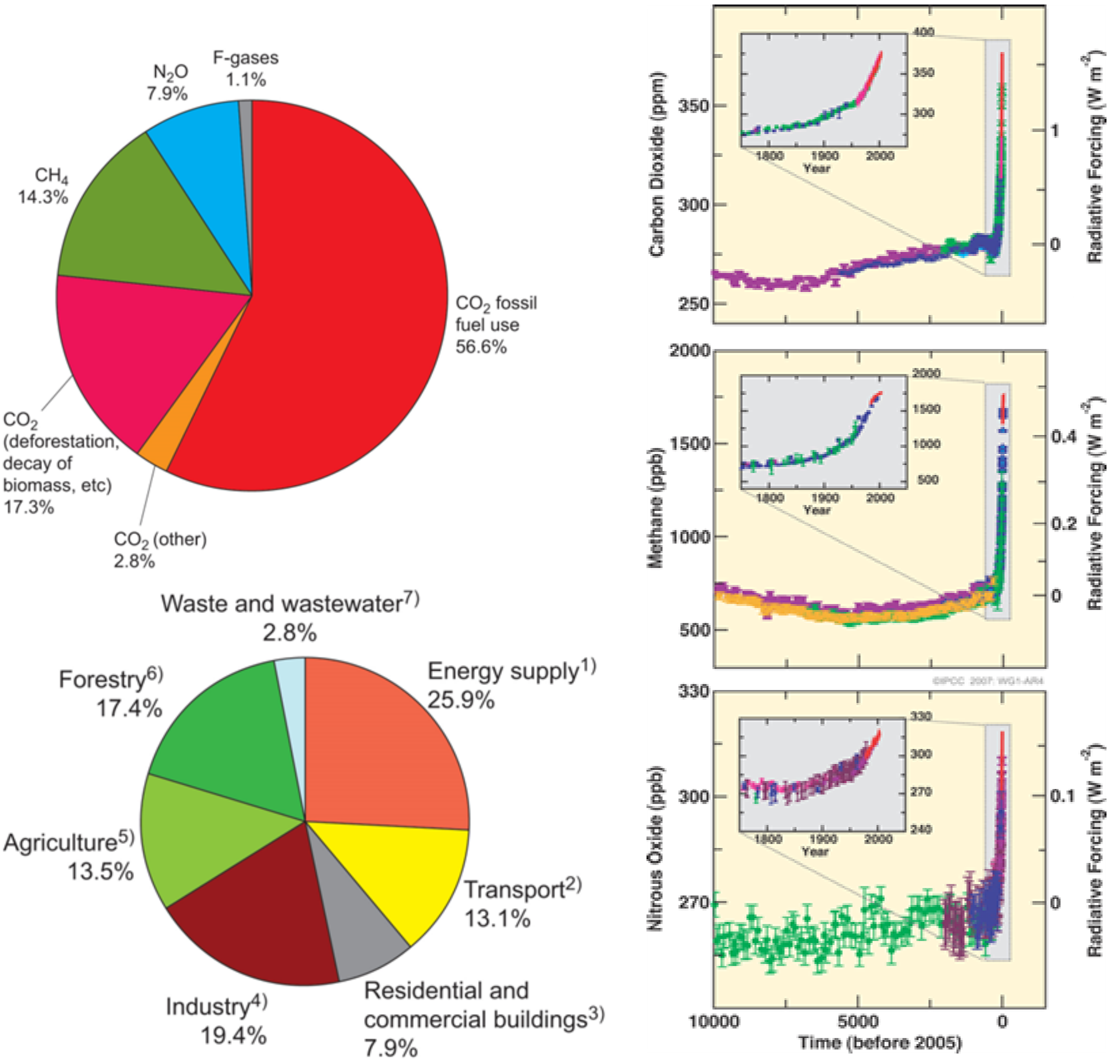


Fig. 3 - Share of different anthropogenic GHGs and in different sectors (left) emissions in 2004 in terms of CO_2-eq; Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (insert panels) (IPCC, 2007a).

The concept of *climate sensitivity* is crucial to fully understand the effect on climate of the GHGs emissions. The *climate sensitivity is defined as the equilibrium global average surface warming following a doubling of CO_2 concentration*. A progress in understanding physical processes has been achieved since the TAR. This report allowed assessing that the climate sensitivity is likely to be in the range of 2 to 4.5°C, with a best estimate of about 3°C. It is also very unlikely that climate sensitivity could be less than 1.5°C whereas values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good as for the firsts values (IPCC, 2007b).

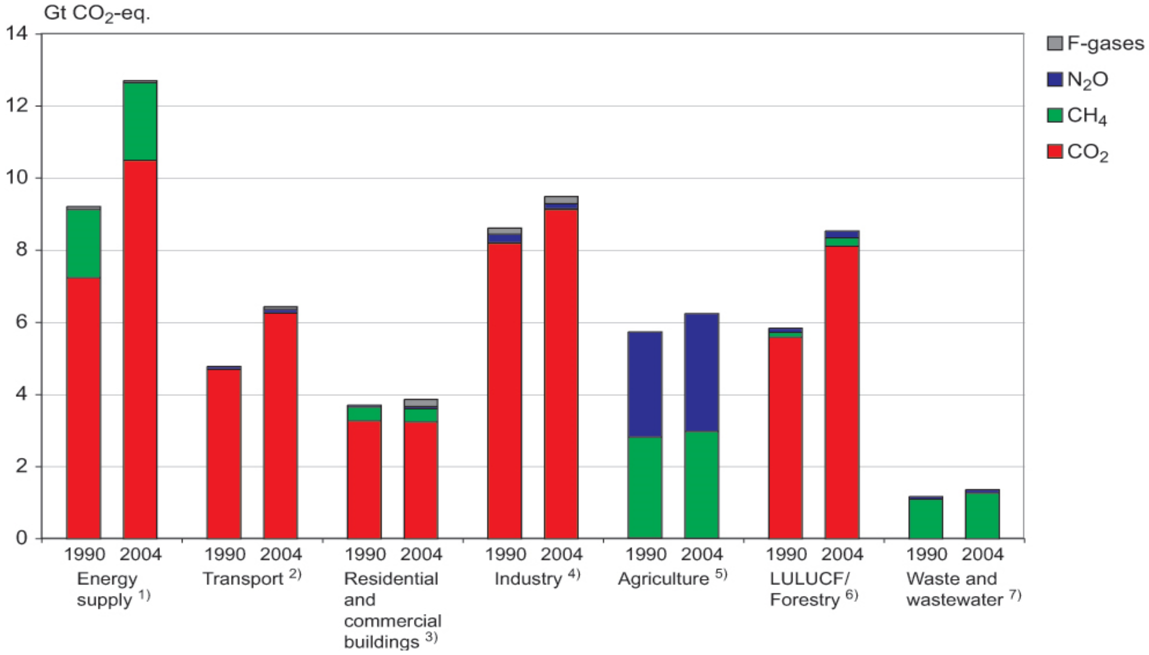


Fig. 4 - GHG emissions by sector in 1990 and 2004 100-year GWPs (IPCC, 2007d).

The anthropogenic warming and cooling influences of GHG on climate are estimated with a very high confidence. The global average effect of human activities since 1750 has been to warm with a radiative forcing of +1.6 W m^{-2} (Fig. 5). The effect of human action is articulated. The more important factor is the emission in long-lived GHGs with a radiative forcing of +1.66 W m^{-2} for CO_2 emissions, while for CH_4 and N_2O the contribution is +0.48 and +0.16 W m^{-2} respectively. On the other hand the anthropogenic contributions to aerosols (sulphate, organic carbon, black carbon, nitrate and dust) together produce a cooling effect, with a total direct radiative forcing of –0.5 W m^{-2} and an indirect cloud albedo forcing of –0.75 W m^{-2}. Aerosols also influence cloud lifetime and precipitation. Other factors that contributes to increase or decrease radiative forcing such as tropospheric ozone changes or changes in surface albedo, due to land cover changes, could determine lower effects (IPCC, 2007b).

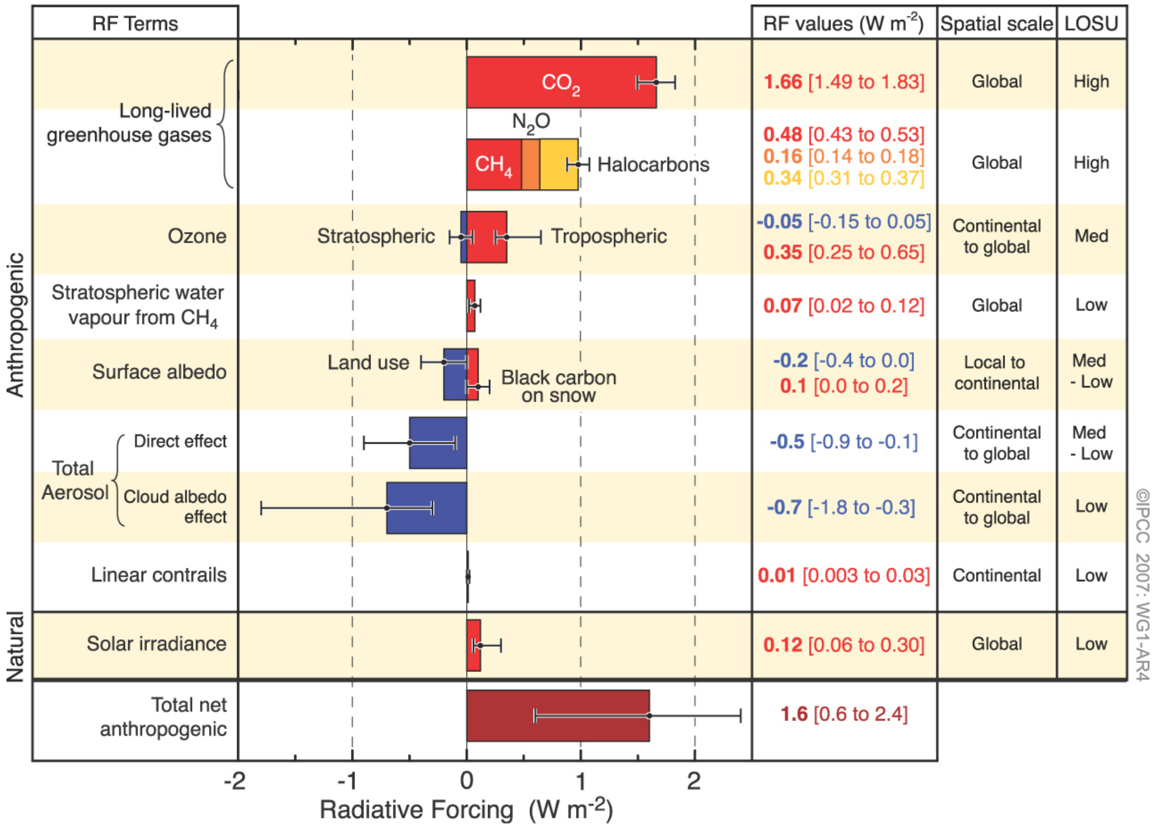


Fig. 5 - Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU) (IPCC, 2007b).

A global assessment of data available starting from 1970 has revealed that it is likely that the warming happened in this period has had a influence on many physical and biological systems. By mid-century annual water availability are projected to increase (10-40%) at high latitudes and in some wet tropical areas, whereas it has been estimated a decrease (10-30%) in dry regions at mid-latitudes and in the dry tropics.

Linked to these phenomena the crop productivity is expected to increase slightly at mid to high latitudes for local mean temperature increases of up to 1-3°C (depending on the crop). Beyond these temperatures, in some regions, it is projected a decrease in crop productions. At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is expected to decrease for small local temperature increases (1-2°C). This projection, together to socioeconomic conditions of this areas would increase the risk of hunger for population that live there (IPCC, 2007c).

Considering the projections for Europe, it is expected that climate change could enlarge regional differences already present in natural resources. Many projections now available predict an increased risk of floods and erosion caused by storms and sea level rise. It is expected that glaciers retreat and there will be reduced snow cover in mountains. These phenomena can induce species losses and reduction in economic activities like winter tourism in these areas. The expected worsen weather conditions (high temperatures and drought) in southern Europe are particularly critical because they could happen in region already vulnerable area to climate variability where the reduced water availability is a limiting factor for summer tourism and crop productivity. In these areas, climate change could increase the health risks due to heat waves and the frequency of wildfires (IPCC, 2007b).

1.1.1. Climate Change impacts on agriculture

There are many examples of the major projected impacts that climate change could cause on agriculture and forestry. In the AR4 of IPCC it is expected that climate change could cause reduced crop yields in warmer regions due to warmer environments, droughts and heat stress. At the same time there is a risk that soil erosion and inability to cultivate land due to heavy precipitation events, which determine waterlogging of soils, may occur with greater frequency. Other consequences of climate change could be a general land degradation that conduct to lower crop yields, increased risk of wildfires in consequence of drought increases and salinisation of soils and irrigation water as a consequence of extreme high sea level (IPCC, 2007b).

In contrast to the projections for warmer regions, in temperate regions (from medium to high latitude) moderate to medium increases in local mean temperature (1 to 3°C) are expected along with associated CO_2 increase and rainfall changes (in amount and distribution); these changes could have small beneficial impacts on crop yields, especially in cereal crops and pasture yields (Parry *et al.,* 2007).

It is important to highlight one of the major factors that can influence climate change impacts: the increase of extreme events that are predicted for the future.

Recent studies indicate that increased extreme events linked to heat stress, droughts and floods affects negatively crop yields and livestock. These negative impacts are larger than the impacts estimate taking into account mean climate changes and are expected to be important especially in low latitudes. Climate change and an increase in climate variability it is expected to modify the risks of fires, pest and pathogen outbreaks. Obviously this could affect negatively agriculture and forestry (Parry *et al.,* 2007). Furthermore, it is important to highlight that sequential extreme events can produce damages on crops: droughts followed by intense rain often reduce soil water absorption and increase the potential for flooding creating conditions for fungal infestations of leaf, root and tuber crops in runoff areas (Rosenzweig *et al.,* 2001). Moreover, the difficulties in predict extreme events, and to reproduce these in synthetic weather series, represent a problem for studying climate change impacts.

In general, a possible increase in the potential food production in the world is expected if the increase in global average temperature grows to about 3°C due to the effect of climate change, land use change and beneficial effects of CO_2. On the other hand, these advantages disappear by increasing temperatures with average of more than 3 °C and it is very likely to have a decrease in global food production (Parry *et al.,* 2007).

Even if many factors could affect crop yields, the weather remain one of the key affecting components. In some cases, it has been stated that 80% of the variability of agricultural production could be due to the variability in weather conditions, especially for rainfed production systems (Hoogenboom, 2000).

Air temperature is one of the main factors that affects crops because regulates the rate of development. Generally, an increase of temperature causes increase in vegetative and reproductive development rates and hence an acceleration in maturation time. However, at extremely high temperatures, the rate of development slow down as the temperature increases. These influence on rate development plays a role in the life cycle and could cause a reduction of crop yields. (Hoogenboom, 2000). On the other hand, in certain cases, an increase of temperatures (especially in cold environments) can put many crops closer to their optimal growth thermal range and promoting an increase of yields (Brassard and Singh, 2008). Linked to this aspect are the projections in the TAR, where it is expected that the climate warming could cause an expansion of the area of cereal cultivation northwards because of the better condition for cultivation. Moreover for wheat it is predicted that an increase in temperature will determine a small yield reduction that, however, will be compensated with moderate climate warming, by an increase in CO_2 air concentration that determines a net yield increase (IPCC, 2001).

Another important weather factor that indirectly affects many of the plant growth, the developmental processes and then crop productivity, is the precipitation: drier conditions associated with increase of temperatures may lead to lower yields for a greater evaporative demand. Precipitation extremes (i.e., droughts or floods) play also an important role in reducing crop productivity. While extremely heavy precipitation and floods could increase crop damages due to soil waterlogging, physical plant damages and pest (especially fungal diseases), greater drought frequency and increased evaporative demands cause greater need for irrigation and in areas where water resources are not available entire cropping systems could disappear. Furthermore in coastal agricultural regions, sea-level rise and associated saltwater intrusion can determine damages in crops through direct damage and soil salinisation. This could be most serious in countries with major crop-growing areas in low-lying coastal regions (Rosenzweig and Tubiello, 2007).

Another important environment factor that affects crop yields because influences plant growth and development is the positive effect of CO_2 enrichment, also called the *CO_2 fertilization effect* (or *direct effect* of CO_2). There are, however, important differences between C3 and C4 species in their response to increasing CO_2. C3 species (like wheat, rice and soybean) tend to respond more positively to increased CO_2 respect to C4 species (maize, sorghum etc.) due to different mechanism of carboxylation. With current air concentration of CO_2, C4 species have a more efficient mechanism to photosynthesize than C3 species, but with an enrichment of CO_2 concentration in the air, C3 species tend to increase more their efficiency because they reduced their photorespiration and do not have to pay the metabolic cost of CO_2 concentrating mechanism of carboxylation paid by C4 species in the bundle sheath cells (Long *et al.,* 2004).

However these environment factors should be considered together with crop management. For instance, crop responses to increase of CO_2 depending on environmental and management factors. It was noted that relative crop yield response to elevated CO_2 is greater in rainfed than in irrigated crops because of a combination of increased water-use efficiency and root water-uptake capacity (Tubiello and Ewert, 2002). Moreover low fertilizer nitrogen applications tend to depress crop responses to elevated CO_2 (Rosenzweig and Tubiello, 2007).

1.2. Wheat and cropping systems

Durum wheat with a growing area around 1.3 - 1.6 million of hectares is the main cereal in Italy (ISTAT, 2010).

Traditionally in Southern Italy and in the Mediterranean basin durum wheat is cultivated in a typical cropping system used extensively in rainfed areas consisting in durum wheat-fallow or continuous durum wheat crops for several years. The durum wheat-fallow system is an old agronomic practice applied to enhance water storage in soil, in order to ensure emergence and establishment of the wheat seedling for the next crop cycle (De Vita *et al.,* 2007). In the Mediterranean basin, in fact, soil moisture is one of the factors that strongly influences crop yields, because the typical weather conditions could cause a water deficit in late spring that determine stress in rainfed cereals during the grain filling stage. These deficits are responsible for the production variability and the low cereal crop yields.

The fallow technique refers to a management were soil is plowed and tilled in order to left soil unseeded during the growing season. This technique involved the use of moldboard plowing (25-35 cm working depth) as primary tillage followed by repeated secondary shallow tillage (10-15 cm) aimed to control weeds and reduce water consumption through evaporation. The practice of alternating wheat and fallow assumes that the water accumulated during the fallow period is stored in the soil and used by the durum wheat during the next crop season. Other advantages of this technique consists in the increase of available soil nitrogen due to mineralization of soil organic matter (**SOM**), and a reduced competition of weeds that are controlled during the fallow period. One risk of this technique lies in the exposure of soil while fallow, leaving it susceptible to wind and water erosion.

In the last decades farmers tended to gradually substitute the fallow technique with a wheat continuous cropping promoted by the European's Union Common Agricultural Policy (CAP). Starting from the 70s in the EU there was remarkable changes in crop cultivation methods with an increased use of fertilizer and plant protection products. This crop management changes were promoted by the policy of guaranteed prices especially for cereals. These economic incentives led to a rapid increase in the production of cereals and especially durum wheat that in the south Europe was one of the most promoted. The Mid-Term Review of CAP reform, with the application of the decoupling aids and the reduction of aids for durum wheat lead to a reduction in the total growing area for this crop. The new economic situation due to the Mid-Term Review that caused a lower cereal support has encouraged the application of Good Farming Practices (**GFP**) so that agronomic techniques such as rotation between cereals and legumes are now economically feasible.

Considering that nitrogen deficiency is one of the major yield limiting factors for cereals (McDonald, 1989), the capability of legume crops to fix the atmospheric nitrogen may be exploited in rotation with durum wheat. The crop precession with a legume crop permit to reduce nitrogen fertilization, cost for fertilizers and pesticides and improve the soil fertility. The wheat continuous cropping, in fact, can determine negative effects in chemical soil characteristics causing a decline of organic matter and nutrient contents (especially nitrogen) that could only partially overcome by an increase of nitrogen fertilization to obtain satisfactory grain yield.

Still today, farmers continue to use intensive "*conventional tillage*" (CT) that is a tillage system in which a deep primary cultivation (in general mouldboard ploughing) is followed by a secondary cultivation to create a seedbed. The continual soil inversion, which occurs with the mouldboard ploughing, may in some situations lead to a degradation of soil structure, leading to a compacted soil composed of fine particles with low levels of soil organic matter (Holland, 2004). In rainfed agriculture in semi-arid regions, conventional tillage is applied mainly to prepare a seedbed, to promote infiltration to conserve water within the soil profile and to prevent wind and water erosion.

Nowadays in European Union the intensive production methods developed in agriculture in earlier decades do not satisfy new criteria of sustainability. The European Community agricultural policy strongly encourages conservation tillage practices to reduce soil erosion and degradation and in these latest years in some areas of the Mediterranean basin these practice starting to be applied by farmers also to reduce cropping costs.

1.2.1. The conservation tillage techniques

Soil conservation tillage techniques were developed in USA to combat soil loss and preserve soil moisture. *Conservation tillage* is defined as a set of technologies that are utilized in agriculture to conserve water and soil (Lal, 1997). The main objective of these practices is decreasing soil disturbance and managing crop residues to protect the soil surface. Soil management practices adopted minimize the disruption of the structure, erosion and degradation of the soils. Conservation tillage encompasses any soil cultivation technique that helps to achieve this, including principally no-tillage (**NT**) or direct drilling or sod-seeding and reduced tillage (**RT**). There are other agricultural practice that be also used in conjunction to conservation tillage including strip tillage, cover cropping, contour farming, zero or chemical tillage, mulch tillage: this broader approach is termed "*conservation agriculture*" (Holland, 2004) but it is common to use the term *conservation tillage* for all these practices (Lal *et al.,* 2007a).

Conservation tillage is applied in regions where rainfall often causes soil erosion or where there are low rainfall and the preservation of soil moisture is an important objective to obtain.

The most widely applied practice of conservation tillage is the no-tillage or sod seeding technique which is concentrate in South America (47% of total), USA and Canada (39.6%) and Australia (9,4%).

In the last years conservation tillage was practised on 105 million of hectares (Basch, 2009). No-tillage areas are concentrate in the USA, Brazil, Argentina, Canada, Australia and Paraguay (Fig. 6). In only 1 million of hectares conservation tillage is practised in Europe mainly in Spain and France (Derpsch and Friedrich, 2009).

The best way to understand how the technical development from plowing to conservation tillage took place, is to go back to the start of diffusion of the plowing.

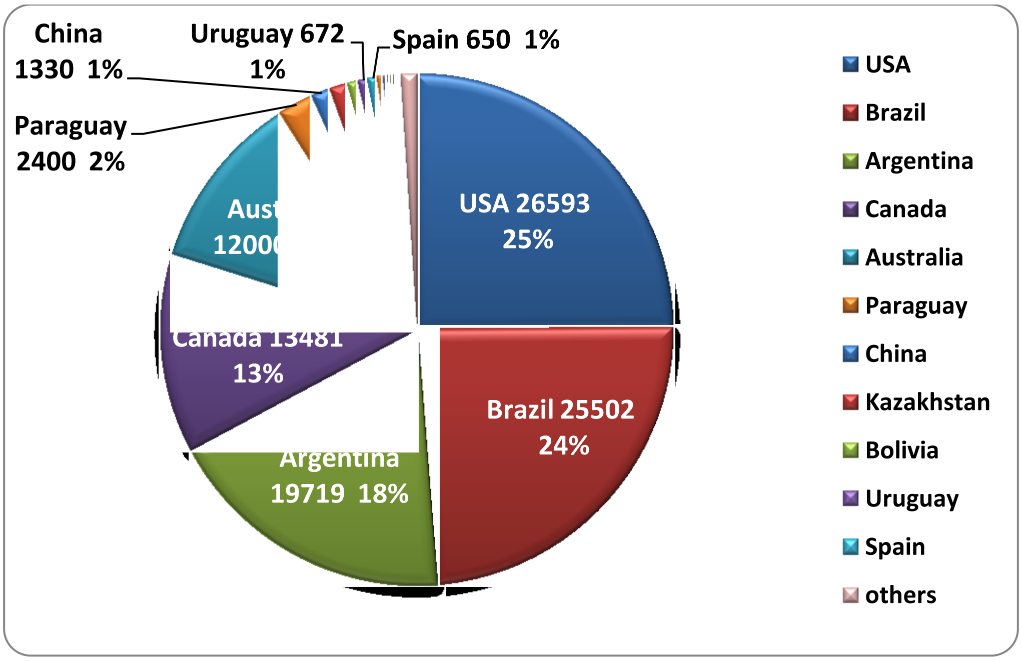


Fig. 6 – Principal countries where the no-till practices are spread in the world expressed in ha 10^3 and in percent (from Derpsch and Friedrich, 2009).

Historically, the moldboard plow was an essential practice for the early pioneers in settling the prairies of central and western USA and Canada. Since about 1850, farmers applying this kind of tillage were able to create a soil environment in which grain crops could grow obtaining good production and meeting the needs of the increasing population in these areas. On the other hand, plowing decreased the soil organic matter (**SOM**) concentration because of increase in rate of mineralization with a consequent release of plant-available nutrients (primarily N, P, S) and degraded soil from increased water, wind and tillage erosion. Although plowing improved the soil fertility and the agronomic productivity immediately, this practice caused a long-term trend of decline in soil structure that increase the susceptibility of soil to crusting, compaction and erosion (Lal *et al.* 2007a).

The “*Dust Bowl*” was an event linked to intensive tillage and soil degradation that had a great importance in encouraging the emergence of conservation tillage techniques. It was a phenomenon occurring in the Great plains during the drought of the thirties, when severe dust storms caused ecological and agricultural damage to American and Canadian prairies. In these lands due to poor agricultural practices (intensive tillage without applying crop rotation or cover crops), to years of serious drought and in consequence of the absence of natural anchor to keep soil in place, soils dried and turned to dust that blew away in large dark clouds reaching the East Coast. Much of the soil blew away ended up deposited in the Atlantic Ocean carried by prevailing winds which were in part created by the dry and bare soil conditions itself. The Dust Bowl was an ecological and human disaster caused by the combination of intensive tillage and drought resulting in millions of hectares of farmland that became useless, and hundreds of thousands of people were forced to leave their homes. Therefore, people developed a keen interest in farming methods that would reduce water and wind erosion (Lal *et al.* 2007a).

Hugh Hammond Bennett was one of the main proponents of conservation tillage. He led the soil conservation movement in the U.S. in the 1920s and 1930s and to congressional establishment of the Soil Conservation Act in 1935, a new federal agency, the Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS) in the U.S. Department of Agriculture (USDA). The importance of this calamitous event promoted by poor soil management with intensive tillage it can be inferred from the fact that in the same period were involved even the president Franklin D. Roosevelt that sent to the governors of all states legislation that would allow the formation of soil conservation districts to extend the battle against soil erosion (Lal *et al.* 2007a).

Despite being a negative event that are still remembered by Americans and Canadians, the Dust Bowl had the merit of creating a dispute about the usefulness of moldboard plow as a tool for seedbed preparation. In thirties and forties there were two strong but opposing schools of thought about tillage: no-till and plow tillage. The no-till movement was led by Edward Faulkner, who wrote the book ‘‘Plowman’s Folly’’ published in 1942 (Faulkner, 1942). In this book Faulkner stated that “*no one has ever advanced a scientific reason for plowing*...” and that farmers plow because they receive lots advice from papers, bulletins, and others sources from which receive suggestion and technical information to do so (Lal *et al.* 2007a). The opposite view, that were strongly in favor of using moldboard plow, was lead by Walter Thomas Jack that wrote a book published in 1946, ‘‘Furrow and Us’’, that was probably a response to Faulkner. The belief of Jack in the superiority of the practice of plowing was based on the common observations of increase in soil fertility through mineralization of SOM obtained by plowing (Lal *et al.* 2007a).

Since the 1950s, there has been a gradual transition from the moldboard plow to various forms of conservation tillage with minimum soil disturbance throughout the world.

New technologies made it possible to apply new farming practices. The no-till movement began with the invention of the herbicide 2,4-D after World War II, and the paraquat development. Although these new inputs were available, only few farmers start to adopt conservation tillage techniques. In 1962 at Wooster (Ohio State University) David Van Doren and Glover Triplett initiated the longest running no-till experiment in the world. But the diffusion of no-till practice was promoted by an agronomist, George Elvert McKibben, with the University of Illinois. He states the basic principles of no-till agriculture that include the following:

- Growing crops without using traditional tillage;
- Using special planting equipment that cuts through the residue mulch.
- Retaining surface residue that reduces erosion, evaporation and limits weed growth.
- Sowing directly into the soil covered by residue mulch.
- Improving water infiltration capacity by ameliorating effects of residue mulch which provides bioturbation and enhances macro-porosity despite some increase in bulk density.

Some of these issues and solutions have evolved over time occurred with different solutions depending on the geographic area and its environmental conditions. Contemporarily to the diffusion of the no-till technique there was an evolutions of implements that was specifically designed for the management of crop residue left on the soil surface. It is known than most tillage practices bury or remove large amounts of crop residue. With the no-till techniques, on the other hand, more crop residue than in conventional tillage are retained in soil surface, and so the seeders must be designed specifically to cut through the residue and sow seed in a small furrow. Residue mulch is essential to reducing losses by erosion.

No-till agriculture has gained acceptance in South America were the rate of conversion from plow tillage to no-till has been sensibly high than in rest of the world (Derpsch and Friedrich , 2009).

Curiously, the dissemination of this technique, born to soil and water conservation objectives, appears to meet the interest of farmers for reasons of cost and crop management especially saving time needed in the conventional plow-based method of seedbed preparation. In addition to erosion control, no-till also saves energy because it utilises less fossil fuel energy than plow tillage (West and Marland, 2002).

The spread of conservation tillage is definitely lagging in Europe in comparison to other continents (Derpsch and Friedrich, 2009). If this technique was primarily used to protect soils from erosion and compaction and to conserve soil moisture in Europe tend to be considered to reduce production costs (Holland, 2004). Despite soil erosion in Europe is considered one of the major problem, the negative effects do not affect farm operation and so farmers do not adopt this practice for this aim although are increasingly interested for the reduced fuel costs (Van De Putte *et al.,* 2010).

Most of the studies on conservation tillage were conducted prevalently in areas where this technique is diffused. Within these are the studies on conservation tillage conducted in the North (Brandt, 1992; Campbell, *et al.,* 1996; Lyon *et al.,* 1998; Mielke and Wilhelm, 1998; Arshad, 1999; Hao, 2001; Guy and Cox, 2002; Mcconkey *et al.,* 2003; Wright, *et al.,* 2007), Central (Fischer, *et al.,* 2002; Govaerts, *et al.*, 2005) and South America (Díaz-Zorita, *et al.,* 2002), in Australia (Latta and O'Leary, 2003, Thomas *et al.,* 2007), Africa (Mrabet, 2000; Erkossa, *et al.,* 2006) and Asia (Huang *et al.,* 2008). In Europe studied were conducted especially in Spain (López and Arrùe, 1997; López-Bellido *et al.,* 2000; Lopez-Bellido and Lopez-Bellido, 2001; Hernanz, *et al.,* 2002; Cantero-Martínez *et al.*, 2003; Lopez Fando and Pardo, 2009) and in U.K. (Knight, 2004). For Italy only few experiments of conservation tillage and crop rotation on wheat are reported (Giambalvo *et al.*, 1999; Pisante and Basso, 2000; Bonari *et al.,* 2005; Carboni *et al.,* 2006; De Vita *et al.,* 2007).

Variable results were obtained by these experiments depending on environment (weather and soil), implement used, crop and type of rotation considered. There is a general agreement in the conducted studies on the fact that soils under long-term no-till or reduced tillage systems generally tend to contain higher amounts of soil organic carbon (SOC) in the soil surface than under conventional tillage (Campbell, *et al.,* 1996; Stringi and Gianbalvo, 1999; Hernanz, *et al.,* 2002; Conant *et al.,* 2007; Thomas *et al.,* 2007, Sombrero and de Benito*,* 2010). The increase in the concentration of SOC is considered to be as a result of different factors promoted by the difference in the tillage implementations, such as less mixing of SOC, reduced soil disturbance, reduced surface soil temperature and higher moisture content in soil (Lopez Fando and Pardo, 2009).

In some studies it has been observed that the production of wheat grain yield with conservation tillage could be the same or higher than in conventional tillage especially in drier years (Giambalvo *et al.,* 1999; Guy and Cox, 2002; Fischer *et al.,* 2002; Sanchez-Giron, *et al.*, 2004; Carboni *et al.,* 2006; De Vita *et al.,* 2007). De Vita *et al.,* (2007) observed that in Southern Italy no-tillage technique was superior below a rainfall value of 300 mm, whereas more rainfall enhanced yield in conventional tillage. They conclude that no-tillage performed better with limited rainfall during the durum wheat growing season because of the lower water evaporation from soil combined with enhanced soil water availability. On the contrary, in other experimental barley trials, while conventional and reduced tillage provide similar grain yield the no tillage practice provide poor performance especially in arid sites (López and Arrùe, 1997).

In sub-humid areas, for wheat and maize, it has been observed yield improvements through zero tillage if associated with appropriate rotations and retention of sufficient residues compared to the common practices of heavy tillage before seeding, monocropping and total crop residue removal (Govaerts, *et al.,* 2005). On the other hand in a study conducted in Spain it has been observed an evident interaction between rainfall and tillage techniques in wheat grain yield: production with no tillage technique was lower than under conventional tillage in the wet years (López-Bellido *et al.,* 2000).

The tillage technique could affect qualitative characteristics of wheat. In a study conducted in Spain it has been observed a lower grain protein content and higher values of test weight and other quality indexes with no-tillage practice than with conventional tillage (Lopez-Bellido *et al.*, 1998). In Italy Gianbalvo *et al.* (1999) observed a similar trend for protein and gluten content and high values of test weight for no tillage technique respect to conventional tillage. In any case this positive effect of no-tillage was less than that promoted by crop rotations with legumes (López-Bellido *et al.,* 1998, Gianbalvo *et al.,* 1999). There were also observed significant interactions between experimental variables that reveal a close relationship among grain yield, protein content, grain quality and the wheat growth conditions, especially linked to rainfall amount and its seasonal distribution (López-Bellido *et al.,* 1998; De Vita *et al.,* 2007).

Recently Van De Putte *et al.* (2010) made a meta-regression analysis on European crop yields under conservation agriculture. In this work authors collected a dataset comparing crop yields of reduced tillage, no-tillage and conventional tillage in Europe composed by 47 studies on 75 sites about main crops grown in Europe: maize, winter and spring cereals, potato and sugar beet. In their analysis they conclude that under European conditions, the conservation tillage may reduce yields from 0 to 30%, depending on crop type, tillage technique, texture and crop rotation. Moreover it has been observed that yield loss shows a strong tendency to decrease with increasing tillage depth. In the same study it has been observed that there is a significant interaction between soil and weather: for example, while No-tillage performs better under dry conditions on clayey and sandy soils, the inverse was noticed on loamy soils. The authors explain that this phenomenon may be related to the higher water conserving effects of no-tillage that become more important when the water availability to plants is smaller like on sandy and clay soils. Another important finding is that the long-term viability of conservation tillage techniques, especially on cereals, appears to depend on the use of a proper crop rotation.

1.3. Adaptation and mitigation strategies in agriculture

In a climate change condition, the agriculture plays a double role: it is involved in the modification of crop management to adapt to a change in climate characteristics but should be involved also in the adoption of practices for climate change mitigation.

Adaptation and mitigation may be different but frequently are complementary strategies necessary to combat damages due to climate change. These strategies have various spatial and time scales and both are necessary to be applied because they tackle the problem from completely different point of view.

Adaptation could be seen as *direct* intervention to reduce damages due climate change, while mitigation could be intended *indirect* intervention for damage prevention. Generally adaptation has a local and shorter term action, while mitigation tends to have a more global and long term effect. However, the interactions between mitigation and adaptation measures can be mutually reinforced.

A wide range of adaptations to climate change could be applied by farmers to respond to changes in environmental conditions. Primarily they can choose the most favourable crops and cultivars, and modify cropping systems to maintain or increase crop yields under future climate change compared to current conditions (Tubiello *et al.,* 2000).

The choice of adaptation and mitigation strategies to adopt obviously depends on the costs and the related beneficial effects. So it is necessary to find the better equilibrium between the cost of adaptation and mitigation strategies and the cost that could be paid if we do not do anything to respond to climate change.

1.3.1. Adaptation strategies

In agriculture adaptation is the norm rather than the exception. In addition to changes driven by several economic factors (market conditions and policy frameworks), farmers always had to adapt to the unpredictability of weather (Rosenzweig and Tubiello, 2007).

In the TAR, *adaptation* is defined as an adjustment in ecological, social, or economic systems in response to actual or expected climatic change stimuli and their effects. Adaptation includes changes in practices and processes to diminish potential damages or to take advantage of opportunities associated with changes in climate. It involves adjustments to reduce the vulnerability of communities, regions, or activities to climatic change and his variability. Adaptation refers both to the process of adapting and to the condition of being adapted. Hence, it is important to understand the climate change stimuli that are described in terms of changes in mean climate and climatic hazards (extreme events).

The principal issue in the coming decades will be the rate of climate change compared to the adaptation capacity of farmers. Only if future changes are relatively smooth, farmers may adapt to changing climates and diminish negative impacts (Rosenzweig and Tubiello, 2007).

A wide range of adaptation options to climate change to reduce vulnerability to climate change is available. Adjustment of agronomic techniques that are already working well on current climates (adjusting planting dates, substituting cultivars, modifying irrigation and fertilization etc.), crop relocation and improved land management (erosion control and soil protection through tree planting) are some examples of planned adaptation strategies to be pursued to reduce negative impacts on agriculture and forestry (IPCC, 2007b).

It is clear that effective adaptation strategies vary with agricultural systems, location, and scenarios of climate change considered. For instance for cereals different adaptation strategies are recommended for winter crops, such as winter wheat and barley, compared to spring crops, such as maize and spring wheat for a specific area. In a crop simulation study done in the U.S.A. Tubiello *et al.* (2002) the application, at farm level, of an early planting date and the use of cultivars better adapted to warmer climates compared to those currently grown at specific locations in the Northern areas. To take advantage of changes in planting windows and to reduce heat and drought stress in the late summer months early sowing was simulated for spring crops. In the same study for winter crops, such as winter wheat and barley, was simulated performance of cultivars with increased length of the grain-filling period to increase the duration of this phase and obtain greater yields. These last simple adaptation strategies at farm level are effective for Northern regions where the study was applied but this is could fail in southern areas. For instance adapting winter cereal production by using longer-maturing cultivars could be a good strategy if in the area there are ordinarily enough precipitation to sustain the extended growing season. If the particular area or climate scenario considered consists of both warmer and drier conditions this particular strategy will likely not work (Rosenzweig and

Tubiello, 2007). Linked to this example there is the opportunity to modify land management systems shifting from rainfed to irrigated agriculture to obtain greater yields. This strategy can be applied if in the region considered there are enough availability of water for agriculture that depend on cost and competition with other economic sectors (Tubiello *et al.,* 2002; Rosenzweig *et al.,* 2004).

Climate change could determine a shift of cultivation areas from current traditional areas to new areas where new weather condition could promote better environmental conditions for crops considered than traditional areas determining new zonations for crops (Fischer *et al.,* 2001; Ortiz *et al.,* 2008).

Adaption considered until now are agronomic techniques that are applied by farmers or that are likely to be available soon in various areas of the world. More of these agronomic techniques have the main advantage to be known by farmers and to be applied easily and often their efficacy is easily tested by researcher with dynamic crop models under climate change in a variety of locations and scenarios (e.g., Savin *et al.,* 1995; Tubiello *et al.,* 2002; Luo *et al.,* 2009.).

The increase of extreme events that is predicted for the future represent an issue to take into account. If changes in the agronomic techniques considered above could mitigate the reduction in yield for mean changes in temperature and precipitation, for extreme events the objectives is the stability of production. To take this into account, rather than to consider only the mean yield associated to a specific techniques, is appropriate to evaluate the coefficient of variation (CV) of yield as a measure of system stability, and choosing as superior cropping techniques at given sites those that have contemporary high yields and low CV. Agronomic techniques that could enhanced the stability of farm production are cropping rotations (e.g. cereals with legumes), soil conservation, fallow techniques and integrated pest management (Rosenzweig and Tubiello, 2007).

The responses to climate change described above are defined by Tubiello and Rosenzweig (2008) as *autonomous* adaptation because they are actions taken by individual actors, such as single farmers or agricultural organizations, to distinguish from *planned* adaptation that can be promoted by regional, national and international policies in order to complement, enhance and/or facilitate responses by farmers and organizations.

A large range of intervention can be promoted by policymakers' like climate-specific infrastructure development (irrigation infrastructure, diffusion of efficient water use technologies, storage infrastructure, germplasm development programs), regulations (revision of land tenure arrangements including property rights) and incentives (land-use incentives, water pricing, accessible and efficient markets for products, inputs and financial services) (Tubiello and Rosenzweig, 2008).

The development weather and climate products, including advance information from nowcasting to seasonal forecasts, are becoming more and more useful in optimization of crop management (WMO, 2007): if the meteorological forecast become more reliable, especially for seasonal forecast, these could be used as input in dynamical crop models to optimize management (e.g. N fertilization in drought regions) by regional agrometeorological services that could offer an useful tool for farmers.

1.3.2. Mitigation strategies

Mitigation refers to a change and substitution of technological processes that reduce energy resource inputs and emissions per unit of output. Although there are several social, economic and technological policies that may be used, for climate change mitigation encompasses all implementing policies that reduce GHGs emissions and/or enhance sinks (Glantz *et al.,* 2009).

If agriculture and forestry have been indicated as sectors that probably are more affected by projected climate change, it should be noted that they are also, at the same time, one of the most responsible of cumulative carbon emissions in the past century. It has been calculated that from 1850 to 1998, approximately 270 Gt C has been emitted as carbon dioxide into the atmosphere due to fossil fuel burning and cement production. A large part of them (136 Gt C) has been emitted as a result of land-use change, predominantly from forest ecosystems (IPCC, 2000a).

Technological interventions can contribute to reduce the sources of greenhouse gases and the vulnerability of agriculture to climate change and contemporary preventing land degradation and sequestering carbon.

Among these kinds of intervention that can be classified as *mitigation strategies* we can list improved crop and grazing land management to increase soil carbon storage, crop rotations, improved fallows and maintaining vegetative cover, mulching and residue management, water management and salinity control, shrub, halophyte and forestry plantations (Thomas, 2008).

In agriculture possible mitigation approaches could be concentrated on two key components:

- sequestration of atmospheric C in crop soils, resulting in increased soil organic carbon (**SOC**) pools;
- reduction of greenhouse gas emissions to the atmosphere from agricultural operations (Rosenzweig and Tubiello, 2007).

Agriculture strategies of mitigation that can reduce emission of GHGs may be improved nitrogen fertiliser application technique that enhance nitrogen use efficiency (**NUE**) and reduce N_2O emissions. Improved rice cultivation techniques, livestock and manure management to reduce CH_4 emissions and improved energy efficiency in crop management are effective mitigation practice on agriculture (IPCC, 2007b).

An important difference among the two mitigation approaches is that soil carbon sequestration is not infinite: if it is true that conservative soil management will tend to increase the soil carbon pool obtained by increasing C inputs into the soil or by decreasing the decay rates of SOC, the SOC accumulation will proceed slowly and not indefinitely (about 50 years according to different authors). Furthermore, once sequestered, C remains in the soil as long as restorative land use and other recommended management practices (**RMPs**) like no-tillage technique, are followed. Moreover the sink capacity of soils and the permanence of SOC are related to various factors like clay content and mineralogy, structural stability, moisture and temperature regimes, and ability to form stable microaggregates in soil (Lal, 2004; Lal *et al.,* 2007b).

Obviously RMPs and, in general, management changes, that reduce carbon fluxes from agricultural operations, can last as long as the new management system is sustainable in both energy and ecological terms (Rosenzweig and Tubiello, 2007).

This kind of intervention is probably the most important mitigation strategy that may be adopted to reduce the negative contribution of agriculture to climate change.

1.3.2.1. *Carbon sequestration in agriculture*

Estimates of principal global C pools present on the Earth are available and comprise several fractions: oceanic (38000 Gt), geologic (4130 Gt), pedological (2500 Gt), atmospheric (760 Gt), and biotic (560 Gt). Considering these values, it is clear that the pool of soil is important among the pools of terrestrial vegetation (about four times) and in the atmosphere (about three times). These pools, that are not fixed, are interconnected by sizeable fluxes that, together, form the carbon cycle (Fig. 7). It is estimated that the atmospheric pool is increasing at the rate of 3.3 Gt C yr^{-1}. The oceanic pool, that is the bigger, is absorbing about 92 Gt C yr^{-1} and emitting 90 Gt C yr^{-1}, with a net gain of 2 Gt C yr^{-1}. The biotic pool that photosynthesizes about 120 Gt C yr^{-1} from the atmospheric pool, of which 60 Gt C yr^{-1} is returned to the atmosphere through plant respiration and the remaining in soil respiration. In the Earth there are two distinct components of pedological pool: soil organic carbon (SOC) and soil inorganic carbon (**SIC**) pools estimated at about 1580 Gt and 938 Gt to one meter depth, respectively (Lal *et al.*, 2007b).

Taking into account these pools it is clear that small increments of oxidation rate of SOC involve considerable emissions of CO_2 in the atmosphere. The role played by agriculture in this component of emission is not secondary if it is considered that 20% of the earth’s land area is utilize for crops and thus farming practice have great influence on C stored and released in the atmosphere as CO_2 (Lal *et al.,* 2007b).

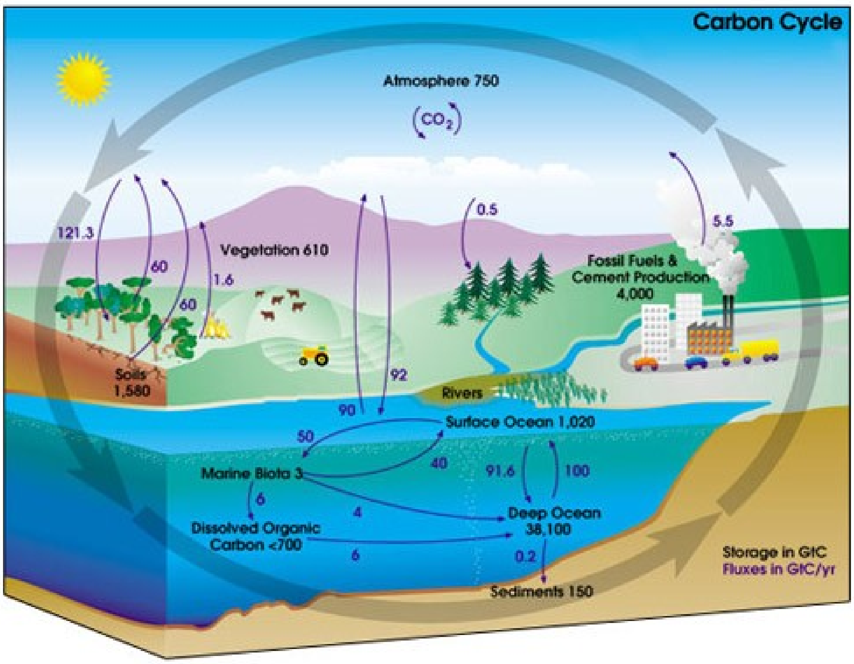


Fig. 7 - The Carbon Cycle (from NASA available at, http://earthobservatory.nasa.gov/Features/CarbonCycle/carbon_cycle4.php).

The reduction in C input in soil, that is caused by a decay in biomass production, imply a reduction in the fraction of C returned to the soil. The increase in C output is attributed to increase in oxidation of soil organic matter (**SOM**) as a result of change in soil moisture and temperature regimes, and an increase in C losses caused by soil erosion and leaching.

The croplands intensive tillage, and especially bare soil conditions, is the most important management practices leading to the decrease of SOM and SOC. These processes are not simple and the equilibrium of fluxes can be easily modified and have consequences in environment characteristic. For instance, serious depletion of the SOC pool degrades the soil quality and reduces biomass productivity that may be aggravated by projected global warming (Lal, 2004).

Estimates of the historic loss of SOC pool from world soils vary widely. The loss of C pool from world soils was estimated by 55 Gt by IPCC (1995) to 500 Gt. On a global scale, since 1850, Lal *et al.,* (2007b) estimated that CO_2 emissions are 270 ± 30 Gt from fossil fuel and 78 ± 12 Gt from loss of SOC.

Under undisturbed natural conditions, the soil C pool is in equilibrium and the input of C (litter fall and root biomass) is balanced by output (erosion, decomposition, and leaching). It is estimated that conversion of natural to agricultural ecosystems could cause decrease of the SOC pool by a range of a 60% to 75% or more respectively in soils of temperate regions and in cultivated soils of the tropics for oxidation (Lal, 2004).

The SOC pool in agricultural soils is much lower than their potential capacity. Considering that the depletion of the SOC pool leads to degradation in soil quality and declining agronomic productivity the conversion to restorative land uses (e.g., afforestation, improved pastures) and adoption of recommended management practices (RMPs) can increase SOC and improve soil quality. Important RMPs for enhancing SOC include conservation tillage, mulch farming, cover crops, integrated nutrient management including use of manure and compost, and agroforestry (Lal *et al.*, 2007b).

These practices could be useful for *carbon sequestration* that is *the provision of long-term storage of carbon in the terrestrial biosphere, underground, or the oceans so that the buildup of CO_2 concentration in the atmosphere will reduce or slow* (Department of Energy of the USA, 2006).

The global potential of SOC sequestration is estimated by Lal *et al.* (2007b), could be comprise between 0.4 to 1.2 Gt C year^{-1} (Fig. 8). The total potential of sequestration is made by 0.4 to 0.8 Gt C year^{-1} through adoption of RMPs in croplands (1350 Mha), 0.2 to 0.4 Gt C year^{-1} through restoration of degraded and desertified soils (1100 Mha), 0.01 to 0.3 Gt C year^{-1} through improvements of rangelands (savannas, natural grasslands, shrublands etc.) and grasslands (3700 Mha) and 0.01 to 0.03 Gt C year^{-1} on irrigated soils (275 Mha) (Lal *et al.*, 2007b).

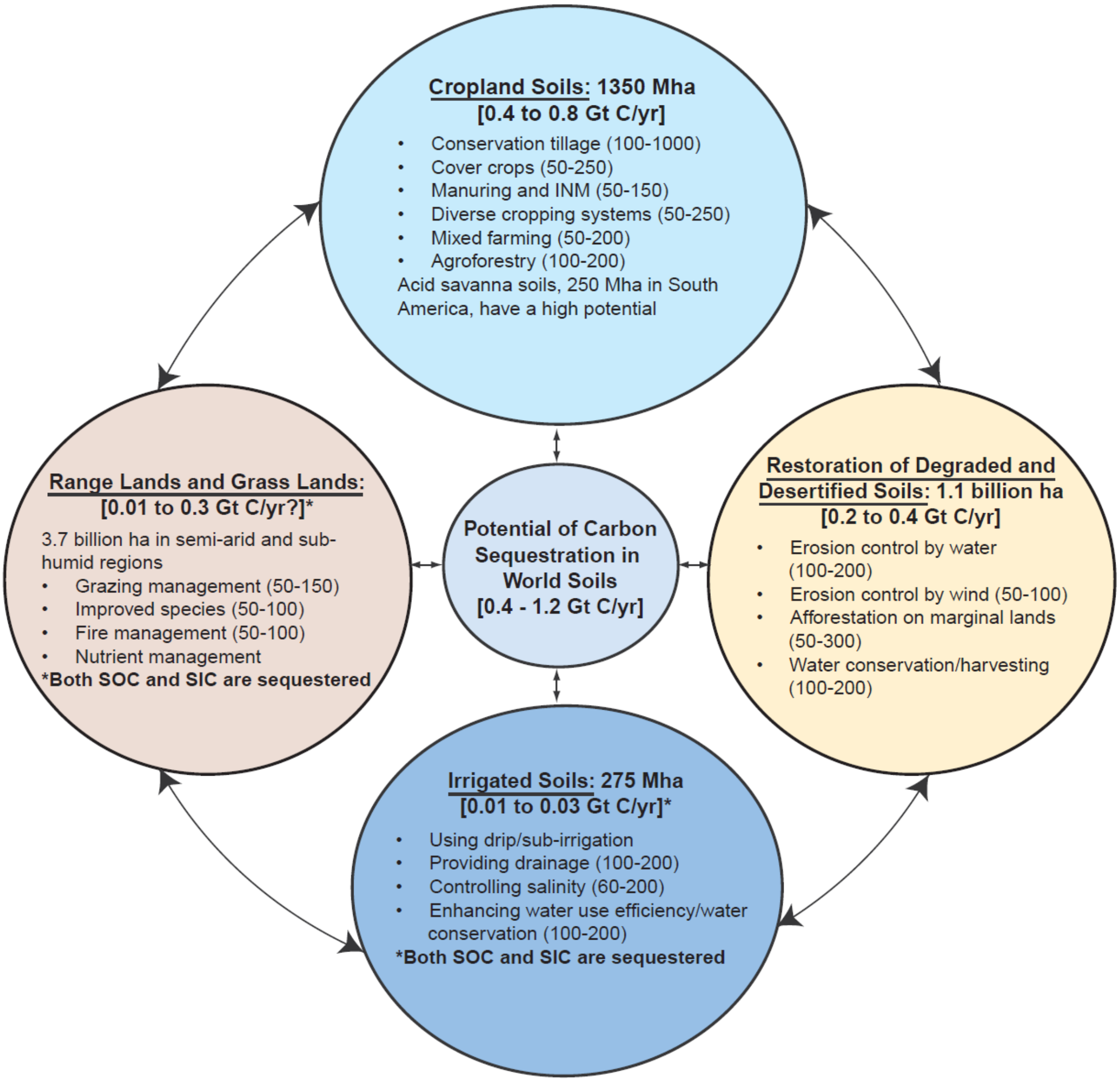


Fig. 8 – Potential of Carbon sequestration. Rates of C sequestration, given in parentheses, are expressed in kg C·ha^{-1}· year^{-1} (from Lal, 2004).

Reductions in SOC, as well as cause CO_2 emissions, involve damage to the potential productivities of soils. Indeed it has been evaluated that a loss of 1 t ha^{-1} of SOC from the 0-20 cm surface layer of soils with SOC contents below 42 t ha^{-1} could determine a reduction in grain yield of 40 kg ha^{-1} (Díaz-Zorita, 2002). Therefore the carbon sequestration in croplands, as well as being good for the environment, favour agronomic benefits.

Unfortunately carbon sequestration requires other nutrients because SOM is made up of the residues of plants and microorganisms, and these require many elements. It has been estimated that to sequester 1 t of C are needed 83 kg of N, 20 kg of P, and 14 kg of S (Lal *et al.*, 2007b). If these amounts are not available the process of carbon sequestration proceed slowly.

Several researchers estimated that carbon sequestration with RMP practices could achieve a practical upper limit in 40 – 50 years. Once that SOC is sequestered, it remains in the soil as long as restorative land use or RMP are followed, but it is important to highlight that it is sufficient one subsequent tillage operation to easily loss much of SOM that was accumulated in several years. In addition to this, the soil sink capacity and permanence is also soil and climate-specific since they are related to clay content and mineralogy, structural stability, landscape position, moisture and temperature regimes. Both the rate and magnitude of SOC sequestration are higher in heavy-textured than light-textured soils, in poorly drained than well-drained landscapes, in cool than warm climates, and in humid than dry ecoregions (Lal *et al.*, 2007b).

1.3.2.2. Conservation tillage as a mitigation strategy

Small reductions in SOC level due to oxidation processes, result in substantial emissions of CO_2 in the atmosphere. Emissions of CO_2 from agriculture are generated primarily from three sources of emissions:

- machinery used for cultivating lands;
- production and application of fertilizers and pesticides;
- mineralization of the soil organic carbon (SOC).

In a recent study West and Marland (2002) calculated the CO_2 emissions, associated with change in agronomic practices, for three crop types (corn, soybean and winter wheat) across three tillage intensities (conventional till, reduced till and no-till) for the US agricultural conditions (Fig. 9).

The amount of fertilizers and pesticides applied varies among crop types, crop rotations, and tillage practices. With the conventional tillage (CT) farmers use mouldboard plow and leave less than 15% of residue cover after planting. They use less pesticides but consume more fossil fuel essentially for plowing. With reduced or minimum tillage (RT) involves using disks or chisels and leaves 15–30% of residue cover. Farmers consume less fossil fuel but use a bit more pesticides. Ordinarily with no-till (NT) farmers leave greater than 30% of residue crops after planting and the soil relatively undisturbed. They use less fossil fuels for tillage but consume more pesticides.

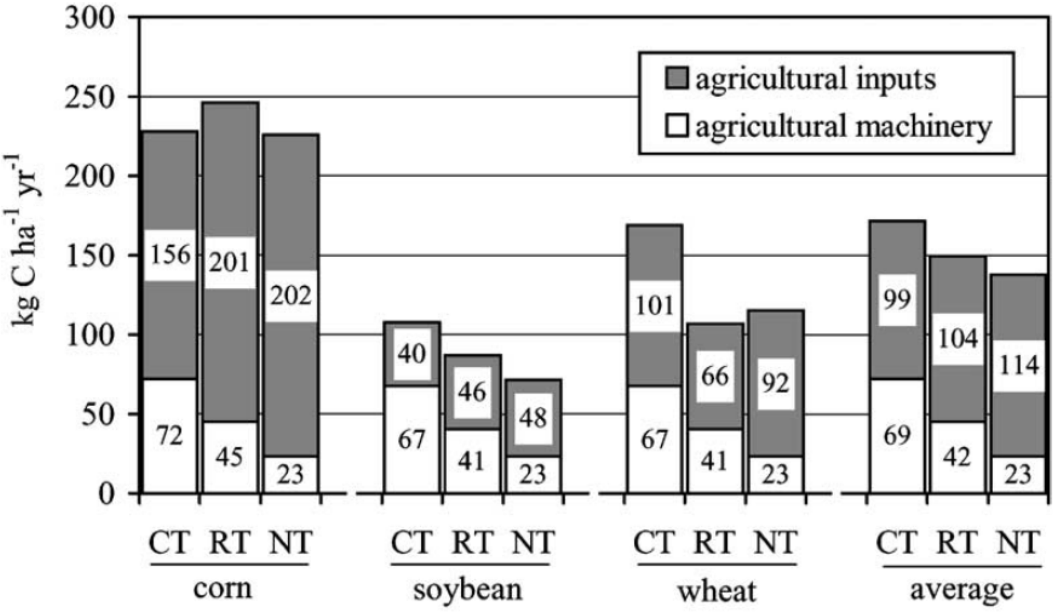


Fig. 9 - Total US average carbon dioxide emissions for three crop types using three different tillage practices. CT, RT, and NT are conventional tillage, reduced tillage, and no-till, respectively (West and Marland, 2002).

In this study emerges that average CO_2 emission due to fossil fuels decrease from conventional tillage to no-till, while emissions from the production process of agricultural inputs are sometimes greater in conservation tillage than with conventional. The total amount of CO_2 emissions is lower with conservation practice for wheat and soybean while there is no evidence for corn.

1.4. Tools for climate change impact assessment

In climate change impact studies several different tools are implied in order to first reproduce scenarios of climate change and afterwards evaluate climate change impacts on crops and test possible adaptation strategies.

In the following paragraphs some of these main tools and methodologies are described.

1.4.1. Emission scenarios

GHGs are considered to be one of the main drivers shaping the present climate and the increased GHG emissions are the main cause of the oncoming climate change. This was the main reason that motivated the IPCC to produce for the first time, a technical report of emission scenarios in 1992 that was made for supplying a necessary tool for driving global circulation models (**GCMs**) and develop climate change scenarios (IPCC, 2000b). In this first report, a first group of the emission scenarios corresponded to a particular set of assumptions about future population, economic development and land use change were developed. By the mid-1990s improvements in the understanding of the processes led to the development of a new group of scenarios. These were published in 2000 in the IPCC's Special Report on Emissions Scenarios (IPCC, 2000b), that are commonly called as **SRES** scenarios. They contain more recent driving force data for emissions and were constructed in a different way from the previous group. Each scenario starts from a narrative "*storyline*" that describe different demographic, social, economic, technological and environmental developments. Therefore each scenario represents a quantitative interpretation of one of four storylines and all scenarios based on the same storyline constitute a *"scenario family"* (Fig. 10) (IPCC, 2000b).

Overall, a set of 40 SRES scenarios regrouped in six scenario groups were developed from the four families (A1, A2, B1, and B2). The A1 scenario family are divided in three groups characterizing by alternative developments of energy technologies. Within each family and group of scenarios, some share "*harmonized*" ("HS") assumptions on global population, gross world product, and final energy while *others* ("OS") explore uncertainties in driving forces beyond those of the harmonized scenarios. For each of the six scenario groups an illustrative marker scenario (harmonized) is provided. In each storyline is assumed a distinctly different direction for future developments. Considering all scenarios together it is possible to explore much of likely uncertainties in the main driving forces and to encompass a significant portion of the presumable divergent future scenarios. The number of scenarios developed within each scenario group is shown in Fig. 10.

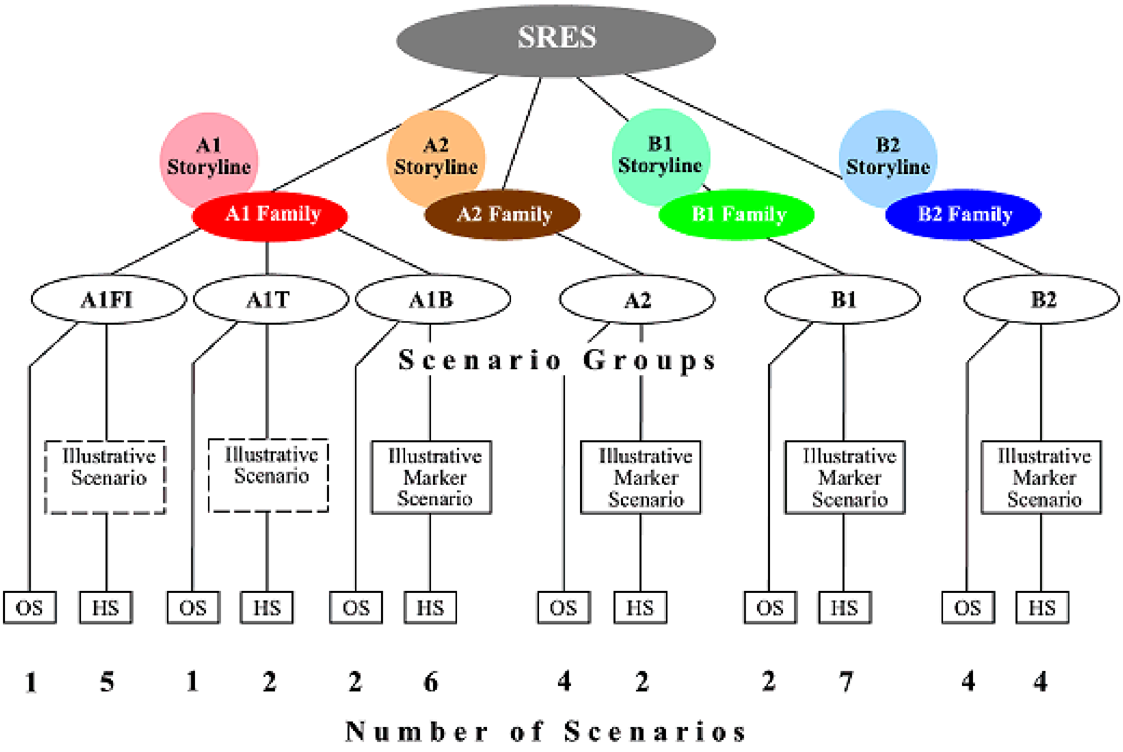


Fig. 10 – Schematic illustration of SRES scenarios. Four qualitative storylines yield four sets of scenarios called "families": A1, A2, B1, and B2. HS are harmonized scenarios whereas OS are others not harmonized.

1.4.1.1. The four emission scenario families

The ***A1 storyline*** and scenario family describes a future world with a very rapid economic growth, a rapid introduction of new efficient technologies and global population that reaches the highest number in mid-century and decrease thereafter. In these scenarios it is expected a convergence among regions with cultural and social interactions and an important reduction in regional differences in per capita income. The A1 scenario family is divided into three groups that describe alternative directions of technological change in the energy system: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (Fig. 11).

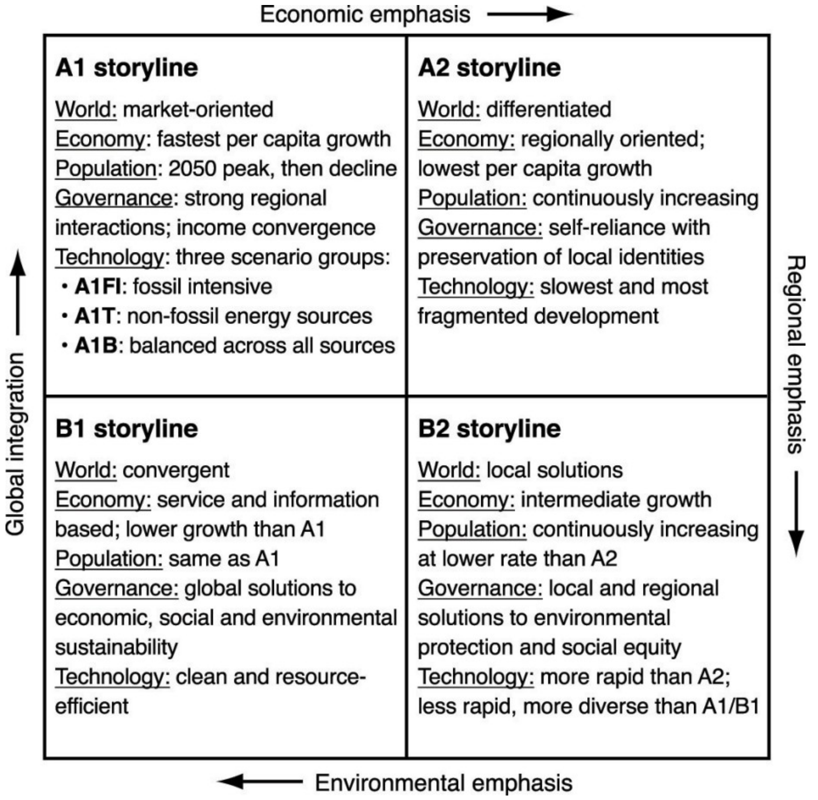


Fig. 11 - Summary characteristics of the four SRES storylines (IPCC, 2007 c).

The ***A2 storyline*** describes a very heterogeneous world. The self-reliance and preservation of local identities is the prior theme. Convergence in fertility patterns across regions will happen very slowly, and so it is expected an increasing global population. Economic development is primarily regionally oriented and, consequently, per capita economic growth and technological changes are fragmented and slower than in other storylines.

The ***B1 storyline*** describes a convergent world with the same population characteristic of the A1 storyline, but with rapid changes in economic structures toward a service and information economy. This kind of development implies reductions in material intensity use and an introduction of resource-efficient technologies. The emphasis is on global solutions to economic, environmental sustainability, including improved equity, but without additional climate initiatives.

The ***B2 storyline*** and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2 with intermediate levels of economic development. In this scenario development are less rapid and there are more diverse technological change than in the B1 and A1 storylines. While the scenario is oriented toward environmental protection and social equity, it focuses on local and regional levels.

The emissions scenarios developed by IPCC (2000b) have been constructed to explore socio-economic development and related pressures on the global environment in this century, considering primarily emissions of greenhouse gases into the atmosphere. It is considered that emissions of GHGs are linked to the behaviour of different systems which are influenced by socio-economic, demographic and technological changes, economic activity, energy use and land use change.

It is clear that future emissions and the evolution of their principal driving forces are highly uncertain. Scenarios are useful tools that addresses the uncertainties related emissions to known factors while the uncertainties related to unknown factors, obviously, can never be predicted by any approach. Scenarios are images of alternative futures but are not predictions or forecasts: each scenario is one alternative image of how the future might evolve. They are tools for scientific assessments, learning about complex systems behaviour and for policymaking and assist in climate change analysis, including climate modelling and the assessment of impacts, adaptation and mitigation (IPCC, 2007a).

The choice of scenarios is extremely important because influence the results of a climate impact assessment. At extreme scenarios correspond extreme impacts and conversely moderate scenarios may produce modest effects. Therefore the selection of scenarios is controversial and difficult. This is probably the main reason that explain why many scientist prefer to perform climate impact analysis using a set of scenarios that represent a good range of the uncertainties.

1.4.2. GCMs and climate scenarios

A General Circulation Model or Global Climate Model (**GCM**) is a mathematical model of the general circulation of a planetary atmosphere and ocean based on the Navier-Stokes equations on a rotating sphere with thermodynamic terms for various energy sources. GCMs are the most advanced tools currently available for simulating the response of the global climate system to increasing GHGs concentrations. They represent the three-dimensional climate system using equations that describe principally the movement of energy with the conservation of mass and water vapour (Wilby *et al.*, 2009). Equations used in any GCM are based on the fundamental laws of physics: conservation of energy (first law of thermodynamics), momentum (Newton's second law of motion), conservation of mass (continuity equation) and water vapour (ideal gas law). They can be solved only at discrete points on the entire surface of the Earth, at a fixed time interval (typically 10–30 min), and for separate layers in the atmosphere defined by a regular grid (Fig. 12)

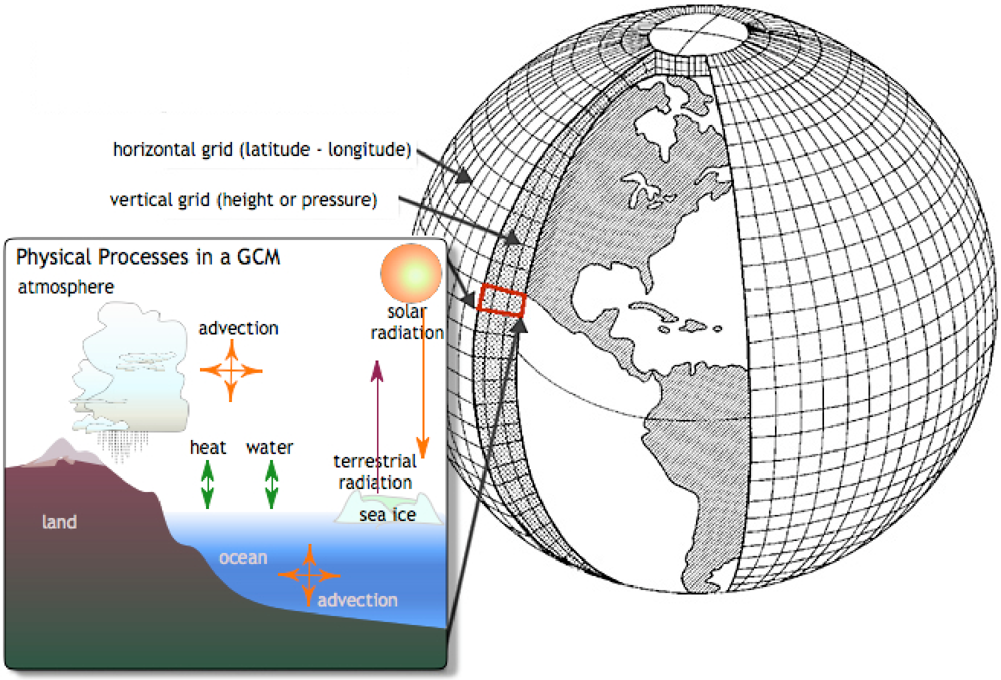


Fig. 12 - The regular grid of a GCM (from CMMAP – Center for Multiscale Modeling of Atmospheric Processes website. Avalilable on http://www.cmmap.org/learn/modeling/whatIs2.html).

The horizontal grid of GCMs is continuously reducing with time: before the IPCC First Assessment Report (**FAR**), produced in the 1980's, the mesh of the grid was about 500 km wide while in the AR4 it was about 110 km (Fig. 13). The vertical grid are compound of 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans. Unfortunately their resolution is quite coarse relative to the scale needed in most impact assessments. Moreover, many physical processes, such as those related to clouds that occur at smaller scales, cannot be properly modeled. For this processes their known properties must be averaged in a larger scale through a technique known as *parameterization*. This is one source of uncertainty in GCM-based simulations of future climate (IPCC, 2009).

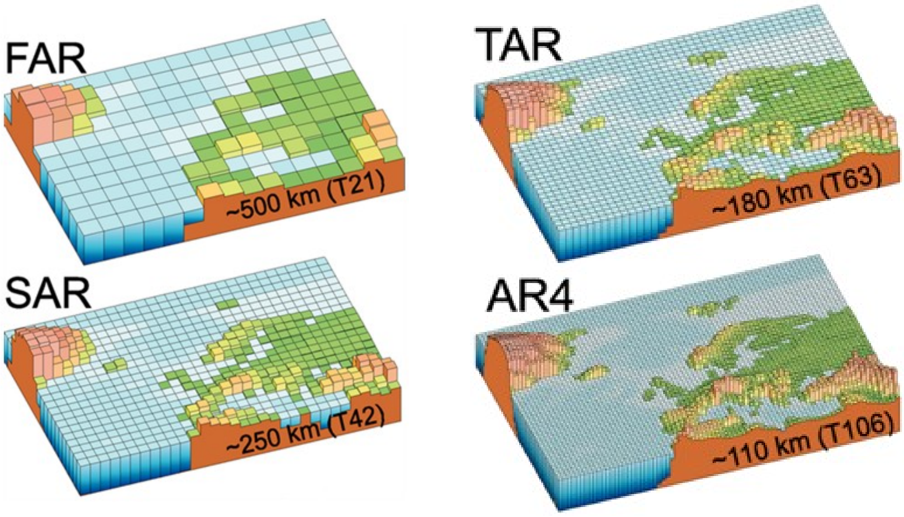


Fig. 13 - Geographic resolution characteristic of the IPCC Reports: FAR (IPCC, 1990), SAR (IPCC, 1996), TAR (IPCC, 2001), and AR4 (2007) (from Le Treut *et al.*, 2007).

The GCMs can be divided in three categories:

- *Atmospheric Global Circulation Models* (**AGCMs**): they are a particular category of GCM that represent only the atmosphere. In these models sea surface temperatures is imposed. This is valid as long as the other components (soil, oceans, ice...) are not modified, and practically these models are used for meteorological forecasts;
- *Oceanic Global Circulation Models* (**OGCMs**): they model the ocean (with fluxes from the atmosphere imposed) and may or may not contain a sea ice model.
- *Atmospheric Oceanic Global Circulation Models* (**AOGCMs**) take into account atmospheric and oceanic processes coupled together to form an atmosphere-ocean coupled general circulation model. These are the models used by climatologists.

Up to 20 different GCMs around the world have been developed, designed and run by many teams of scientists. The models do not take into account exactly the same considerations. Although they are based on common physical basis, some of them parameterize a given process (e.g. clouds) whereas others will not. The major difference between models, however, comes from their year of conception and thus depend on the knowledge of processes when they were developed.

Type of models and their degree of sophistication, as their spatial resolution, has greatly changed since the 1970's to these years. The first groups of models were essentially atmospheric and represented the evolution of air temperatures and precipitations under the forcing of additional CO_2 into the air (Fig 14).

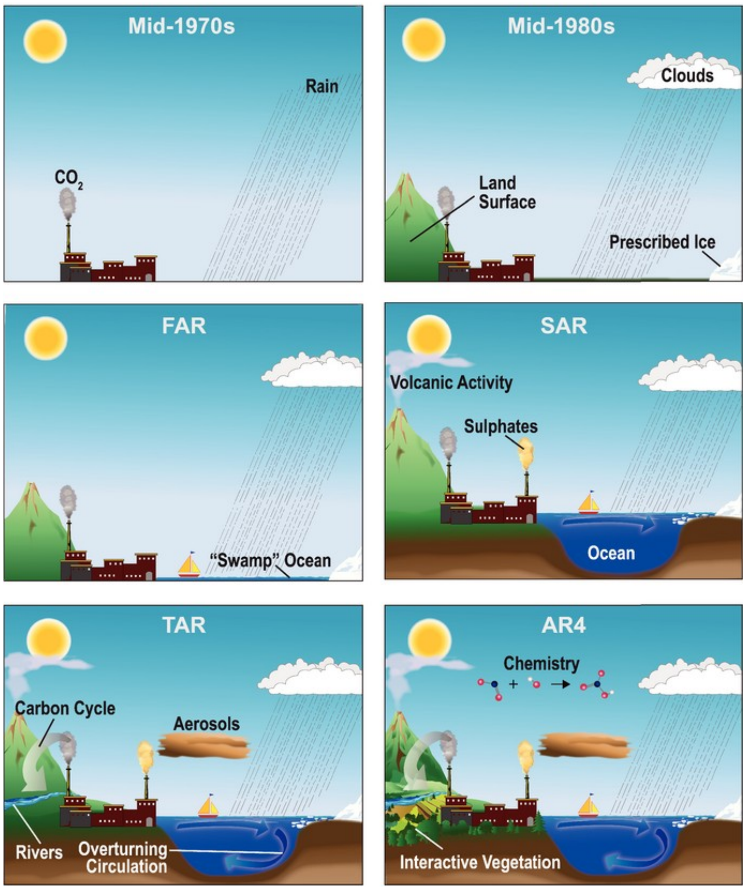


Fig. 14 - Evolution in complexity of climate models (from Le Treut *et al.*, 2007).

In the 1980's beginning to be considerate land occupation, clouds (parameterised) and sea iced. At the time of the FAR, ocean was considered, but without any large scale circulation taken into account. At the time of the Second Assessment Report (**SAR**), in 1995, models took into account aerosols, volcanic activity and large scale horizontal circulation of the ocean. In 2001, at the time of the TAR, took into account the ocean overturning, something of the carbon cycle, and rivers.

In 2007, at the time of the AR4, few models include atmospheric chemistry and dynamic vegetation that reacting in accordance to regional climate conditions. Despite the great evolution in complexity of GCMs the major conclusions given in the 1970's have not fundamentally changed.

Followings are represented the principal processes that are now represented in the most widely used GCMs:

- *energy exchanges* between ground, oceans, atmosphere and space, through electromagnetic radiation, sensible and/or latent heat;
- *radiative transfers* in the atmosphere, that depend on GHGs contained in the atmosphere;
- *large-scale atmospheric circulation* and the associated water transportation;
- the gradual increase and *melting of snow* and ice;
- *clouds* (often parameterised);
- *carbon cycle*, that is carbon exchanges between the ocean, the terrestrial ecosystems, and the atmosphere with a wide range of complexity between models. The most advanced models take into account feedbacks of a climate change on the vegetation.

In Appendix are displayed a brief table of the principal GCMs considered by the IPCC in the AR4.

The use of climate scenarios (provided by the GCMs) for impact and adaptation assessment, is crucial for the results that could be obtained. In the "general guidelines on the use of scenario data for climate impact and adaptation assessment" of the IPPC are individuated five criteria that should be met on the use of climate scenario data (Carter, 2007):

Criterion 1: **Consistency with global projections**. They should be consistent with a broad range of global warming projections based on increased concentrations of GHGs and according to the "equilibrium climate sensitivity" defined as an increment in global mean temperature for a doubling of atmospheric CO_2 concentration (ca 560 ppm).

Criterion 2: **Physical plausibility**. They should not violate the basic laws of physics. Hence, changes in one region should be physically consistent with those in another region and globally. In addition, the combination of changes in different variables (which are often correlated with each other) should be physically consistent.

Criterion 3: **Applicability in impact assessments.** They should describe changes in a sufficient number of variables on a spatial and temporal scale that allows for impact assessment. In other words scenarios have to provide data for impact models that may require input data on variables such as precipitation, solar radiation, temperature, at spatial scales ranging from global to site and at temporal scales ranging from annual means to daily or hourly values.

Criterion 4: **Representative.** They should be representative of the potential range of future regional climate change.

Criterion 5: **Accessibility.** They should be straightforward to obtain, interpret and apply for impact assessment. Many impact assessment projects include a separate scenario development component which specifically aims to address this last point.

1.4.2.1. MAGICC: a simple global model

Because the GCMs are tools computationally intensive and expensive, an alternative method for examining climate response to radiative forcing was developed. This method is based on the use of simpler models that generalise many of the processes simulated explicitly by GCMs. A one dimensional radiation balance-based climate model MAGICC has been used by the IPCC for its 1990, 1995 and 2001 assessments to investigate the effects of different emissions scenarios and climate sensitivities (Carter, 2007).

The MAGICC/SCENGEN (Hulme *et al.*, 2000) software package is a coupled gas-cycle/climate model (MAGICC = Model for the Assessment of Greenhouse-gas Induced Climate Change) that drives a spatial climate-change SCENario GENerator (=SCENGEN). The version 5.3, that is consistent with the IPCC last report produced by the first working group, is available on the web (http://www.cgd.ucar.edu/cas/wigley/magicc/).

In this relative simple software, global-mean temperatures from MAGICC are used to drive SCENGEN. SCENGEN uses a version of the pattern scaling method described in Santer *et al.* (1990) to produce spatial patterns of change from a database of atmosphere/ocean GCM (AOGCM) data from the CMIP3/AR4 archive.

This software comprises the following components (Fig. 15):

- Gas models for each of the main GHG, which convert emissions into atmospheric concentrations and subsequently compute radiative forcing. (Values of key parameters can be adjusted across a representative uncertainty range).
- An upwelling diffusion-energy balance (UD/EBM) climate model, which computes global mean temperature response to a given radiative forcing. The

parameters of the model can be altered to represent uncertainties in GCMs. For example, the climate sensitivity can be selected from a range of values, along with a factor accounting for the differential heating of land and ocean (observed in GCM results). This latter parameter is important for estimating the thermal expansion component of sea-level rise.

- An ice melt and thermal expansion models, which computes sea-level change.

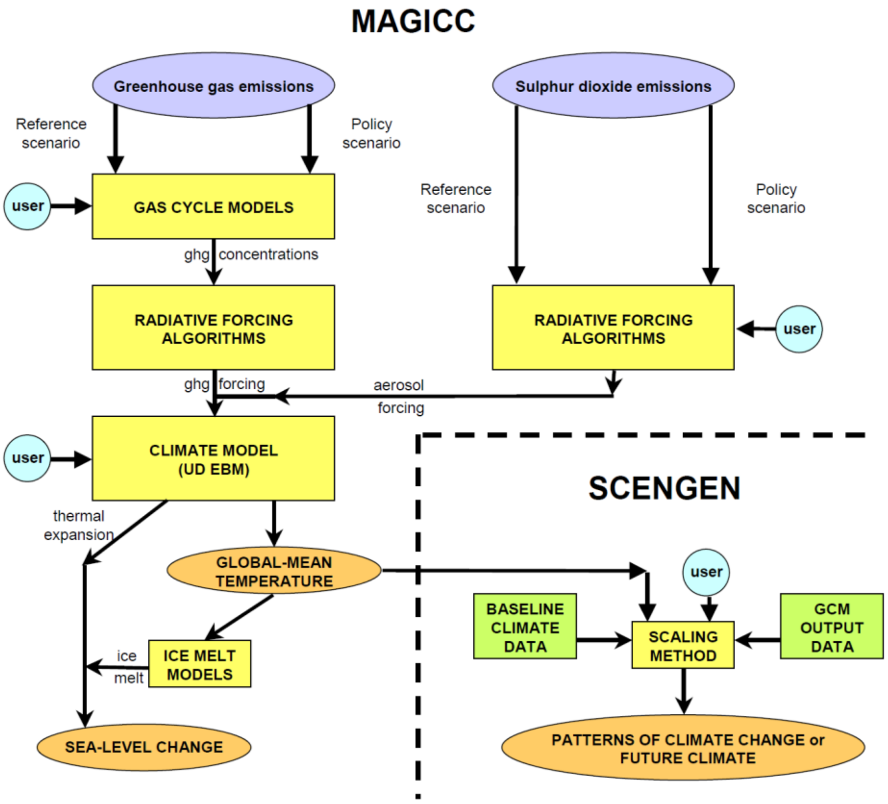


Fig. 15 - Schematic diagram of the MAGICC/SCENGEN model system (from Carter, 2007).

This model was used to estimate atmospheric concentrations, global temperature changes and sea-level rise for the principal SRES scenarios by the IPCC (Carter, 2007). There are several advantages to use such models because they:

- are simple to use;
- are computationally fast, and can examine a large number of socio-economic scenarios;
- produce scenarios of GHGs emissions, atmospheric concentrations, radiative forcing, temperature response and sea-level rise that are physically consistent;

- can provide convenient information for policy makers, for instance, enabling comparisons to the effects on climate alternative measures to limit GHGs emissions;
- can be linked with GCM outputs to develop regional climate scenarios (Carter, 2007).

1.4.3. Downscaling techniques

Data from GCMs cannot be used directly for agricultural impact studies because of their limitations due to the coarser resolution. Hence, it is necessary to develop tools for downscaling GCMs predictions of climate change to regional and local or station scales. In recent years, different downscaling methods have been proposed in a large number of studies around the world.

Schematically there are two basic groups of downscaling techniques (Wilby *et al.*, 2002):

- *dynamical downscaling* that has the potential for capturing mesoscale nonlinear effects, providing coherent information among multiple climate variables and are formulated using physical principles;
- *statistical downscaling* that use empirical relationships that have been derived from observed data, and apply these to climate model data. They are able to access finer scales than dynamical methods and applicable to parameters that cannot be directly obtained from the output of dynamical downscaling methods.

1.4.3.1. Dynamical downscaling

Dynamical downscaling consists in simulations of atmospheric processes and interactions between components of the climate system. It involves the nesting of a higher resolution obtained by a Regional Climate Model (**RCM**) within a coarser resolution of the GCM. The RCM uses the GCM to define time-varying atmospheric boundary conditions around a finite domain using horizontal grid spacing of 10-20 km. These models can credibly reproduce a broad range of climates around the world, which increases confidence in their ability to downscale realistically future climates.

The main drawbacks of dynamical models are first their computational cost, and second that the parameterizations used are valid for the current conditions, but in future climates may not be valid because may be operating outside the range for which they were designed (Christensen *et al.*, 2007).

The main advantage of RCMs is that they can resolve smaller-scale atmospheric features such as orographic precipitations better than the host GCMs (Wilby *et al.,* 2002).

Dynamic downscaling seems to be best way to obtain more detailed scenarios but should be stressed that frequently these resolutions may result still too coarse especially for morphological complex regions and this case the dynamic downscaling techniques are too complex and require long times for data processing and high costs.

1.4.3.2. Statistical downscaling

For statistical downscaling (**SD**) are intended a series of techniques based on the principle that the regional climate is conditioned by two factors: the large scale climatic state, and regional or local physiographic features like topography, land-sea distribution and land use. Therefore, regional or local climate information is derived by determining a statistical model which relates large-scale climate variables (that are *predictors*) to regional and local variables (*predictands*). Afterwards the output of GCMs is used in this statistical model to estimate the corresponding local and regional climate characteristics (Wilby *et al.,* 2004).

The assumptions and requirements for statistical downscaling are the following:

- predictors must be simulated successfully by GCMs;
- strong relationship between predictor(s) and predictand(s): predictor must explain large portion of predictands’s variance and have a physical linkage;
- stationarity of relantionship: relation between predictor and predictand should be constant in time (and it holds in a future climate).

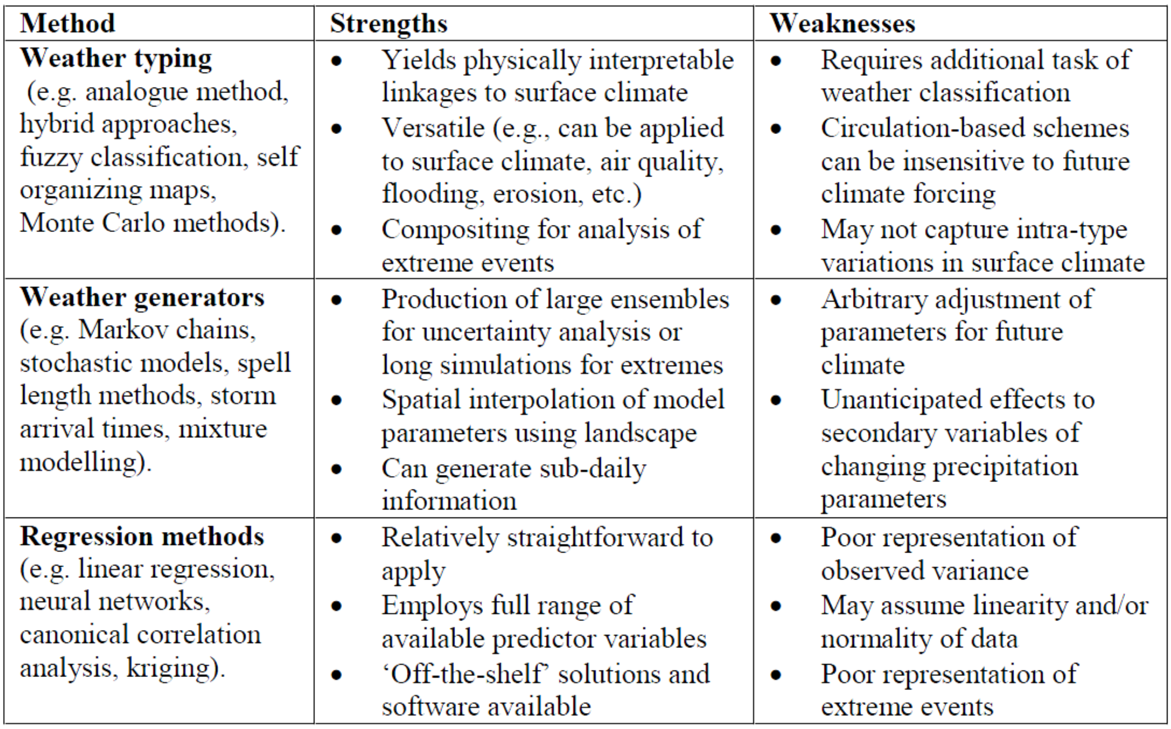
The spatial resolution of the SD can be: station (site-specific), well defined area (river basin) or gridbox of various size.

These methods have some advantages:

- they are computationally inexpensive;
- they can be easily applied to output from different GCMs;
- they can be used to provide site-specific information.

The major weakness of SD methods is that theoretically their basic assumption are not verifiable: the statistical relationships developed for the present day climate cannot be right under the different forcing conditions of possible future climates. However it is important to stress that this weakness is also a limitation of the physical parameterizations that are often implemented in dynamical models (Wilby *et al.*, 2004).

There are different methods of statistical downscaling, frequently distinguished in three categories: *weather typing*, *regression methods* and *weather generator.* Principal strengths and weaknesses of these approaches are resumed in the table below.



Method	Strengths	Weaknesses
Weather typing (e.g. analogue method, hybrid approaches, fuzzy classification, self organizing maps, Monte Carlo methods).	• Yields physically interpretable linkages to surface climate • Versatile (e.g., can be applied to surface climate, air quality, flooding, erosion, etc.) • Compositing for analysis of extreme events	• Requires additional task of weather classification • Circulation-based schemes can be insensitive to future climate forcing • May not capture intra-type variations in surface climate
Weather generators (e.g. Markov chains, stochastic models, spell length methods, storm arrival times, mixture modelling).	• Production of large ensembles for uncertainty analysis or long simulations for extremes • Spatial interpolation of model parameters using landscape • Can generate sub-daily information	• Arbitrary adjustment of parameters for future climate • Unanticipated effects to secondary variables of changing precipitation parameters
Regression methods (e.g. linear regression, neural networks, canonical correlation analysis, kriging).	• Relatively straightforward to apply • Employs full range of available predictor variables • 'Off-the-shelf' solutions and software available	• Poor representation of observed variance • May assume linearity and/or normality of data • Poor representation of extreme events

Fig. 16 - Principal categories, strengths an weakness of statistical downscaling (from Wilby *et al.*, 2004).

The *weather typing* approaches involve grouping local meteorological variables in relation to different classes of atmospheric circulation. Typically, they are defined by applying cluster analysis to atmospheric fields to distinguish some groups. Future regional climate scenarios are constructed, either by resampling from the observed variable distributions (conditional on the circulation patterns produced by a GCM), or by first generating synthetic sequences of weather patterns using Monte Carlo techniques and resampling from observed data. The main interest in this kind of approach is that it is based on linkages between climate on the large scale and weather at the local scale and is valid for a wide variety of environmental variables as well as multi-site applications (Wilby *et al.,* 2002).

Regression methods are based on techniques that representing linear or nonlinear relationships between local surface weather *(predictand)* from the larger-scale freeatmosphere characteristics *(predictors)* via transfer function. Commonly applied methods include multiple regression (Murphy, 1999), canonical correlation analysis (CCA) (von Storch *et al.*, 1993), and artificial neural networks. The main strength of this approach is the easy application. One of the main problems is that often this techniques explain only a fraction of the observed climate variability (especially for daily precipitation). Furthermore regression-based downscaling is highly sensitive to the choice of predictor variables and statistical transfer function. Another problem is the difficulty to simulate extreme events that is due to the regression that tends to exclude them (Wilby *et al.,* 2004).

Weather generators (**WGs**) or stochastic weather generators are tools based on statistics, rather than physics-based equations used in GCMs and RCMs. WGs are mathematical-statistical models that produce synthetic weather series (the site-specific surface weather series in most cases) replicate the statistical characteristics of a local climate variable (e.g. mean and variance) without repeating or partly repeating the observed sequences.

WGs are frequently used in studies of impact assessment by crop models. In this case, these tools are used to generate surface daily weather variables required by the applied crop model.

In general, to generate a weather series they do not need circulation characteristics of the atmosphere because consider only the stochastic structure of the surface weather. However there are stochastic models, such as the WG developed by Bardossy and Plate (1992), in which the rainfall is linked to atmospheric circulation patterns using conditional distributions and conditional spatial covariance functions (Bardossy *et al.*, 2001).

Some of the most used statistical models, that does not take into account atmospheric circulation patterns (as in the case of WGEN and M&Rfi WGs), are generally developed in two steps:

- in the first step the daily precipitation occurrence and amount is modelled;
- in the following step the remaining variables of interest are considered. These variables (often maximum and minimum air temperature, solar radiation, humidity and wind speed), are modelled conditionally on the precipitation occurrence (e.g., dry-days in summer may have on average more sunshine than wet-days).

Parameters of WGs are allowed to have different values for individual days or months of the year to account for the annual cycle in means and variability of the weather variables as well as in cross-correlations (Wilby *et al.,* 2004).

To generate series representing the changed climate, the parameters of the WG are modified according to the GCM-based climate change scenario or according to the user-defined scenario (e.g. as a part of the climate sensitivity analysis). The WGs, in fact, employ statistical models to generate long synthetic weather series which resemble (in terms of the statistical characteristics) the real weather series.

Depending on the processes that the user intends to model with the impact model (e.g. crop model), WGs can produce series with different time resolution (e.g. monthly, 10 day, daily or hourly step) and spatial resolution (single or multiple sites).

One of the best known approaches for developing WGs is the model introduced by Richardson (1981). WGs that are based on this approach, like the widespread WGEN, are often referred to as the "Richardson-type". At the first step precipitation occurrence (series of wet and dry days) is modelled using a Markov chain process. The amount of precipitation for the wet days is then determined by using a predefined frequency distribution (commonly the gamma distribution). The remaining variables are then modelled by the first-order autoregressive model which accounts for the correlations between variables and wet or dry status of each day. The Richardson-type of generator has been used very successfully in a range of applications in hydrology, agriculture and environmental management.

One disadvantage of the Richardson-type WGs is in its difficulties to describe the length of dry and wet series (persistent events such as drought and prolonged rainfall) that can be very important in some applications like agricultural impacts.

To overcome this problem, an alternative *serial* approach was developed (Semenov and Barrrow, 1997). In the serial-type of WGs the first step in the process consist in modelling of the sequence of dry and wet series. In the second step, other weather variables (e.g. precipitation amount and temperature) are modelled conditionally on the wet or dry status of a given day. The serial-type weather generator, first developed by Racsko *et al.* in 1991, has been updated (in LARS-WG) by Semenov *et al.* in 1998. His LARS-WG uses semi-empirical distributions to construct series, rather than the predefined distributions used in the earlier version described by Racsko *et al.* (1991).

The performance of the LARS-WG and WGEN weather generators has been compared in a variety of different climates by Semenov *et al.* (1998) and observed that the series-type WG, that use more complex distributions for weather variables and require more parameters to be calibrated, tended to match the observed data more closely than WGEN, although no WG can accurately reproduce all weather characteristics (Semenov *et al.,* 1998).

Several weather generators have been integrated in weather utility programs that analyze and prepare weather data for model applications, such as WeatherMan (Pickering *et al.,* 1994).

WGs have also been incorporated in several simulation software such as the DSSAT (Jones *et al.,* 2003), CropSyst (Stockle *et al.,* 2003) and others decision support system.

WGs require being calibrated using observed weather station data. To validate WG, it is important to have sufficiently long (at least 10 years) observed weather series. The calibration process produces a parameter file that contains the statistical characteristics of the observed data. Afterwards this file is used to generate series of synthetic data. One of the most important requirements in producing synthetic series is a realistic reproduction of low frequency and high magnitude events. This is one of the principal reasons to have as long a time series as possible in order to better capture these characteristics. In fact WGs can only simulate events based on the dataset used for calibration and is not able to simulate events which are not included in this set of data.

Validation of the WG is done by comparing the statistics of the synthetic data with those of the observed data set used to calibrate the model (*direct validation*).

One known problem with both types of WGs is that they tend to underestimate the variability of observed time series. This low-frequency variability can affect the crop yields in studies of climate change impact assessments (Porter and Semenov, 1999; Semenov, 2008). However, any insufficiency of the generator in reproducing stochastic structure of the weather series may be reduced by suitable modification of the model. This, however, usually leads to a greater complexity of the model and thereby to lower accuracy of parameters derived from the learning sample of given limited size (lower ‘stability’ of the model). For these reasons, before modifying the model of the generator, it is reasonable to perform the *indirect validation*, which may show whether the generator is applicable in a given application (Dubrovsky *et al.,* 2004).

The indirect validation is made by comparing statistical properties of output characteristics (e.g., crop yields) simulated with observed vs. synthetic weather series. The results of the indirect validation may show that the weather series created by a simpler generator, which fails in some direct validation tests, serves satisfactorily as an input for some simulation models (Dubrovsky *et al.,* 2004).

Stochastic weather generators, are often used in climate-change impact studies to provide synthetic weather series for present and changed climate conditions (Riha *et al.,* 1996; Mearns *et al.,* 1997; Semenov and Barrow, 1997; Trnka *et al.,* 2004a; Trnka *et al.,* 2004b; Dubrovsky *et al.,* 2004; Alexandrov and Eitzinger, 2005), used as inputs to crop growth models. The climate change impacts are thereafter assessed by comparing the results obtained with the weather series representing present and changed climates.

To generate weather series for future climate, the parameters of the WG derived from the observed data are modified according to climate change scenarios, which define increments in individual climate characteristics. These increments are derived from outputs of GCMs or RCMs or using the statistical downscaling method.

1.4.3.3. The pattern scaling technique

Various approaches can be used to produce weather series representing the changed climate, most of them rely on GCMs. However, in most case the GCM representation of future climate cannot be used directly as an input to the impact models. Instead, it is recommended to use climate change scenarios which represent differences or ratios in individual variables between some future climate and the current or control climate (Dubrovsky *et al.,* 2005).

The changes in the climatic variables for a given site can be obtained by interpolation of GCM-simulated values for the 4 corners of the GCM grid box in which the target area lies.

With a climate change scenario, 2 techniques are typically used to construct the weather series of the changed climate: (1) an observed weather series is modified (additively or multiplicatively) by the scenario parameters; (2) a weather series is produced by a weather generator whose parameters have been modified according to the scenario (Dubrovsky *et al.,* 2005).

Because of the uncertainties linked to the GCM-based climate change scenarios, it is widely recommended to use multiple scenarios in climate change impact studies. This is done by using a set of scenarios derived from several GCM simulations and for different emission scenarios.

Statistical post-processing is used to develop a ‘standardized’ scenario from a given GCM transient run. In developing the climate change scenario, it is hypothesized that the climate change pattern (both annual cycle and spatial pattern) is the product of the standardized scenario, which defines the response of the climate variables to a 1°C rise in global mean temperature (T_G), and ΔT_G. This type of procedure is known as *pattern scaling technique* (Santer *et al.,* 1990), which was used in the IPCC FAR (Mitchell *et al.*, 1990) and then widely adopted in constructing the climate change scenario (Dubrovsky *et al.,* 2005).

The use of the pattern scaling technique allows separating:

- the uncertainties in determining the climate change pattern:
  - differences between individual GCMs,
  - internal uncertainty of a given GCM,
  - uncertainty related to the regression technique used to determine the standardized scenario;
- the uncertainty in estimating the global mean temperature (T_G), which is often estimated using a simple climate model, (e.g. MAGICC/SCENGEN model).

Applicability of the pattern scaling technique is conditioned by the assumption that changes in climatic variables are proportional to ΔT_G.

The climate change scenario for any period and any emission scenario, for which ΔT_G can be estimated, is determined as:

$$\Delta X(t) = \Delta X_S \times \Delta T_G(t)$$

where ΔX_S is the standardized change in the variable X and ΔX is the change in X for a given future t and resulting from ΔT_G.

The standardized scenario (ΔX_S) may be determined by dividing the scenario related to a selected period by ΔT_G predicted by a given model for a given period:

$$\Delta X_S = \Delta X_{(tA\text{-}tB)} / \Delta T_{G(tA\text{-}tB)}$$

In a more sophisticated approach, the standardized scenarios are obtained from the transient GCM run by a linear regression (not passing through zero), in which the independent variable is ΔT_G, and the dependent variable is the change of a given variable in a given time, $\Delta X(t)$. Standardized change of climate characteristic X then coincides with the slope parameter in regression equation:

$$\Delta X_S = a \cdot \Delta T_G + b$$

Different GCMs give different standardized scenarios (ΔX_S).

In this process the ΔT_G values can be estimated by the MAGICC model described above. As reported before, in MAGICC a given emission scenario is converted to GHG and aerosol concentrations and radiative forcing, and the resulting ΔT_G and sea level are estimated assuming chosen value of the climate sensitivity factor.

Using this procedure the overall uncertainty in the change in global mean temperature (ΔT_G) is driven by uncertainties in two input parameters of the MAGICC model:

- choice of an emission scenario;
- climate sensitivity factor.

The *equilibrium climate sensitivity parameter* refers to the equilibrium change in T_G following a doubling of the atmospheric CO_2 concentration. In the IPCC AR4, it is assumed that this value lies in the range between 1.5°C to 4.5°C with 3°C being the best estimate.

To give an example of uncertainties in determining changes in $T_{G,}$ figure 17 shows a comparison of the range of ΔT_G simulated by a set of GCMs for emission scenario SRES-A2 with the values simulated by MAGICC model run at various climate sensitivities. This figure indicates that the range of GCM-simulated ΔT_G values is not representative for uncertainty in climate sensitivity. Therefore it implies that the set of climate change scenarios determined by the pattern scaling method in which we use different values of ΔT_G estimated by MAGICC run at various emission scenarios and climate sensitivities will better represent uncertainty in ΔT_G.

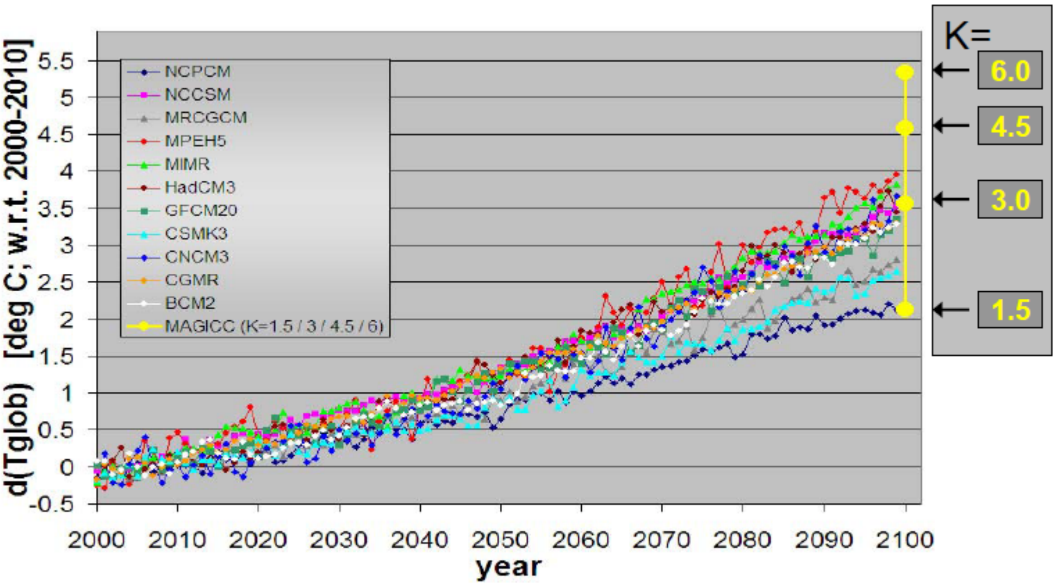


Fig. 17 - Range of ΔT_G simulated for emission scenario SRES-A2 by a set of GCMs from IPCC-AR4 (colour time series) and by MAGICC model run at various climate sensitivities (yellow bar on the right) (Dubrovský, 2009).

1.4.4. Crop simulation models

Crop simulation models are tools for studying crop growth and development.

Like other models they are a mathematical representation of a real-world system (a crop). Through simplifications, they simulate the interactions between growth and development processes of a crop and the environment (weather and soil). Because is impossible to include in a model all the possible interactions, the models are necessarily based on many assumptions and simplifications, especially when information that describes the real system is inadequate or unknown. One of the main purpose of crop simulation models is to estimate crop production as a function of weather, soil conditions and crop management (Hoogenboom, 2000).

The weather variables, such as air temperature, precipitation, and solar radiation, are key input variables for the crop models.

To develop a crop model it is necessary integrate knowledge from various disciplines, including agrometeorology, crop physiology, soil physics and chemistry and agronomy, and describe their relations into a set of mathematical equations to predict growth and development.

Crop growth models are based on physiology: they calculate growth and development considering causal relationships between plant functions and the environment. They use one or more sets of differential equations, and calculate both rate and state variables over time, normally from planting until maturity or harvest. They can also be identified as deterministic, when they make an exact calculation or prediction. This is different from stochastic or probabilistic models, which provide a different answer for each calculation (Hoogenboom, 2000).

Most of the diffused crop models are dynamic because they describe how the state variables evolve over time, and they describe a system as in a crop model there are several state variables that interact (Wallach, 2006).

A wide variety of crop models has been developed all over the world. One of the major crop modelling groups are in the USA, where many of them worked in the project IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer). This group developed the DSSAT (Decision Support System for Agrotechnology Transfer) system (Tsuji *et al.,* 1994; Hoogenboom *et al.,* 2004). Another important modellers group is in Australia where the system APSIM (Agricultural Production system SIMulator) was developed (McCown *et al.,* 1996; Keating *et al.,* 2003). Finally, many other studies were conducted in Europe, especially those of the groups that developed STICS (Brisson *et al.,* 2003) in France (INRA) and in the group of Wageningen in The Netherlands. There are other diffused modelling systems, such as CropSyst (Stockle *et al.,* 2003; Donatelli *et al.,* 1997), and the Erosion Prediction Impact Calculator (EPIC) (Jones *et al.,* 1991) that were specially developed to study the long-term sustainability of cropping systems.

Most of the modelling approaches used in crop models, developed around the world, are inspired by the work of the crop growth modelling school known as the '*School of de Wit'*. C. T. de Wit and his co-workers started developing crop models at the Department of Theoretical Production Ecology of the Wageningen Agricultural University (TPE-WAU) since 1960. This crop ecology team proposed an approach for developing models of cropping systems at three different levels of production (Van Ittersum *et al*., 2003) (Fig. 18):

I. *potential production*: crops are considered to have adequate water and nutrients and not to encountered any stress (biological or chemical) or any deficiency in management. The only factors that could affect growth are temperature, solar radiation, atmospheric carbon dioxide concentration and plant's genetic and physiology characteristics;

II. *water- and/or nutrient-limited production:* only water and nutrient (nitrogen and/or phosphorus) are considered as *limiting factors* for growth. Crop models that can simulated on this level allowed to study various effects of crop management:

rainfall limitations, irrigation management and nutrient management on growth and yield;

III. *actual production*: growth-reducing factors that can reduce growth are considered, both biotic (weeds, pests, diseases) and abiotic factors such as pollutants.

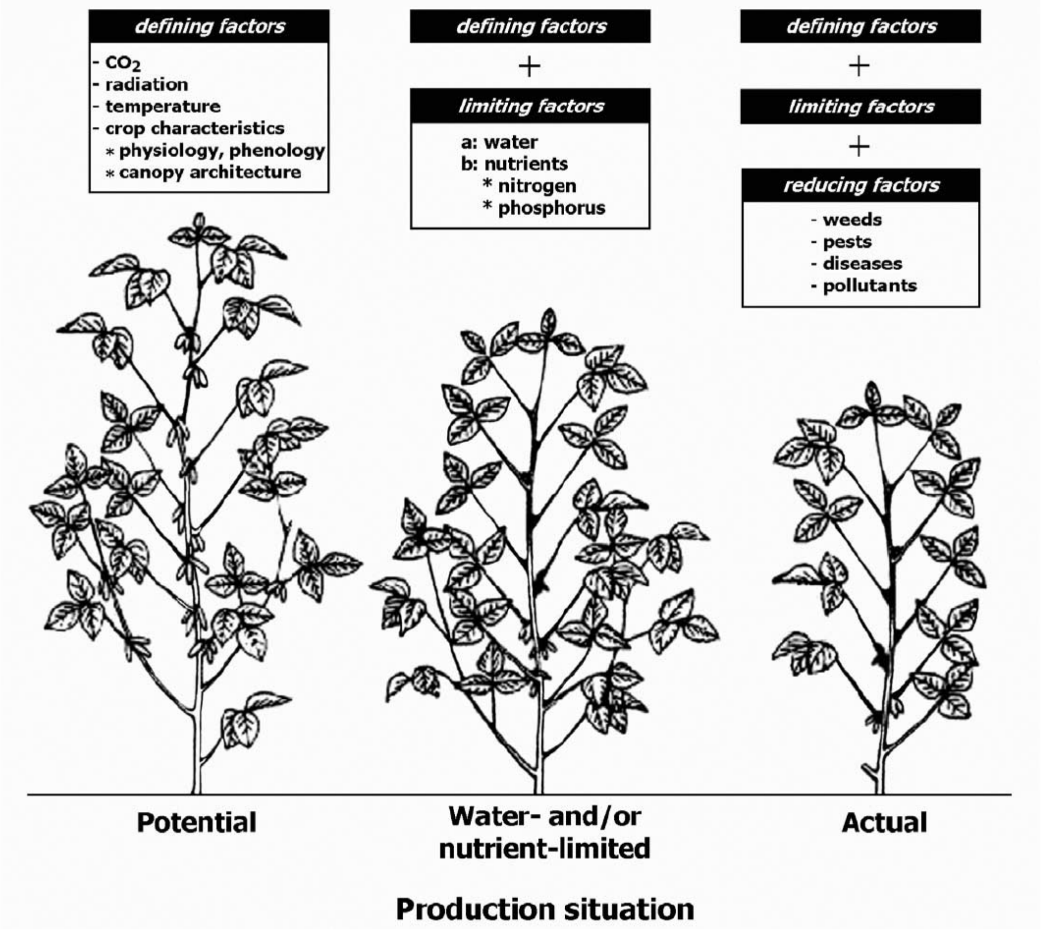


Fig. 18 – The three level of simulated production (from Van Ittersum *et al.*, 2003).

The models implemented in the DSSAT software package, and others like APSIM and STICS, are usually able to approximate crop and soil dynamics for a rather narrow range of factors that influence soil and crop growth processes under limited conditions. In these software many modules, that take into account pests effects, are developing.

1.4.4.1. The CSM-CERES-Wheat model in the DSSAT

The CERES-Wheat model, implemented in the DSSAT software package (Hoogenboom *et al.*, 2004), is one of the most used crop simulation models to study climate change impacts on wheat. This model has been tested in a wide range of environments.

The CERES-Wheat model (Crop Estimation through Resource and Environment Synthesis, Ritchie and Otter, 1985) were developed to predict the duration of growth, the average growth rate and the amount of assimilated partitioned to economic yields components.

CERES was one the three models initially developed by the USDA Agricultural Research Service (USDA-ARS). In its first version, developed in 1977 when the USDA-ARS was asked to improve the capability of the U.S. government to predict domestic and foreign wheat yields, it was a statistical model and its procedures were primarily based on monthly weather data (rain, temperature, etc.).

During its development the CERES-Wheat model was modified and designed to simulate the effects of cultivar, planting density, weather, soil, water, and nitrogen on crop growth development and yield, considering the important physiology processes for production and calculating its rate by biology laws already known. The model was developed for predictions at farm and regional level and it was used to test the best potential alternative management strategies that influence yield (Ritchie and Godwin, 2000). Afterwards, a family of improved models derived from the original version of CERES were developed and then implemented in software systems such as DSSAT.

The DSSAT (Decision Support System for Agrotechnology Transfer) was originally developed by an international network of scientists, cooperating in the IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project, to facilitate the application of crop models in a systems approach to agronomic research. The DSSAT software package is a collection of programs where crop simulation models are the core of the system. This software collected models to simulate growth and development of 25 crops derived from the CROPGRO and CERES models that are now implemented in the DSSAT-CSM (DSSAT Cropping System Model). This new cropping system model provide a better platform because it allows to easily compare alternative modules for specific components, to facilitate model improvements, evolution, and documentation (Jones *et al*., 2003).

The DSSAT-CSM is structured using the modular approach structure described by Porter *et al.* (2000) and consists of a main driver program, a land unit module, and primary modules for weather, management, soil, plant, and soil–plant–atmosphere interface components (Fig. 19).

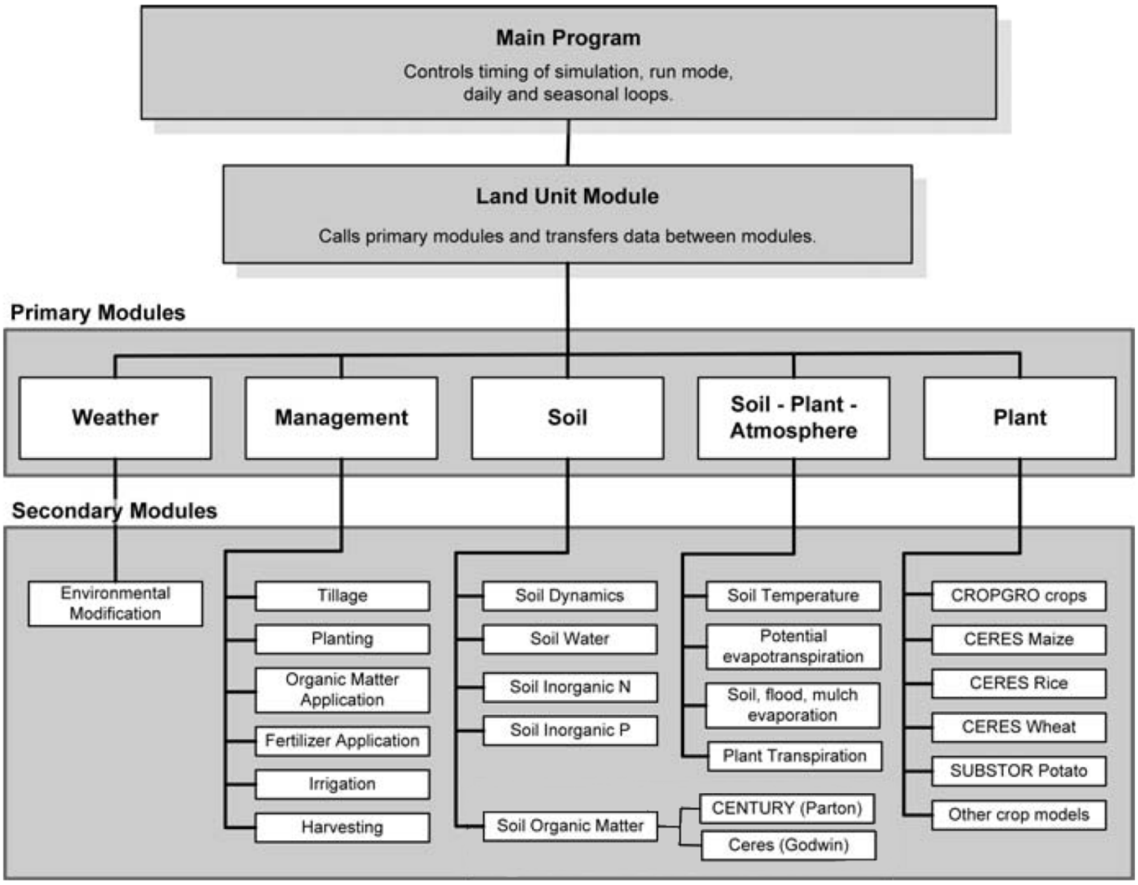


Fig. 19 - Overview of the components and modular structure of the DSSAT-CSM (from Porter *et al.*, 2009).

The Land Unit module calls each of the primary cropping system modules each day. The primary modules describe daily time changes in the soil and plants that occur on a single land unit in response to weather and management. The Land Unit and Primary modules link the secondary modules (in our case the CSM-CERES-Wheat module), and thus are used to aggregate processes and information describing successive components of the cropping system. The software designed in this way has some advantages. One of these is to facilitate model maintenance and to include new components to simulate cropping systems. Furthermore, this modular approach facilitates cooperation among different model development groups where each can focus on specific modules for expand (Jones *et al.*, 2003).

The CERES-Wheat model simulates daily growth and development processes of wheat integrating daily stress effects as feedback on growth and development processes. The model responds to many factors including genetic aspects, management, soil, weather, nitrogen and water stress (Jones *et al.*, 2007). The life cycle is divided into two stages:

- *vegetative growth period* that depend on temperature;
- *reproductive growth period* affected by temperature and day length.

This stages are also split into different phases (Tab. 1) .

Growth stage it is important for the model because determines which components are growing and may be experiencing stress (Ritchie and Godwin, 2000).

Tab. 1 - Growth stages of wheat as defined in CERES-Wheat (Ritchie and Godwin, 2000).

Stage	Event	Plant Parts Growing
7	Fallow or pre-sowing	-
8	Sowing to germination	-
9	Germination to emergence	Roots, coleoptile
1	Emergence to terminal spikelet initiation	Roots, leaves
2	Terminal spikelet to end of leaf growth and beginning of ear growth	Roots, leaves, stems
3	End of leaf growth and beginning of ear growth to end of pre-anthesis ear growth	Roots, leaves, ear
4	End of pre-anthesis ear growth to beginning of grain filling	Roots, stems
5	Grain filling	Roots, stems, grain
6	End of grain filling to harvest	-

The rate of development depends on the thermal time defined by growing degree-days (GDD). GDD computation is based on daily maximum and minimum temperatures. The number of GDD required to progress from one growth stage to the next one are either defined as a user input (through genetics coefficients), or are computed internally based on user inputs and assumptions about duration of intermediate stages.

One limit of this model is that the rate of development is not adjusted for stresses such as high temperature, water stress, nitrogen or other nutrient stress. Thermal time requirements for several stages are cultivar dependent traits and these characteristics are modified by genetic coefficients. For some stages they are computed internally and for others depend on the photoperiod. Daylength sensitivity is a cultivar specific user input.

Daily plant growth is computed by converting daily intercepted photosynthetically active radiation (PAR) into plant dry matter using crop-specific radiation use efficiency (RUE) parameter as demonstrated by Monteith (1977). RUE varies with temperature, vegetative nitrogen concentration, water stress, CO_2 atmospheric level and fertility of soil.

The potential growth rate is estimated by the following relation:

$$PCARB = \frac{RUE \cdot PAR}{PLTPOP} \cdot (1 - e^{(-k \cdot LAI)}) \cdot CO_2$$

where

PCARB - Potential growth rate, g · plant^{-1};

RUE - Radiation Use Efficiency (g Dry Matter · PAR^{-1})

PAR - Photosynthetically Active Radiation (MJ m^{-2}d^{-1})

PLTOP - Plant population, pl m^{-2}

k - Light extinction factor

LAI - Leaf area index

CO_2 - CO_2 modification factor

The light extinction factor vary depending on the species and it is -0.85 for wheat, barley, sorghum and millet, -0.65 for maize and -0.625 for rice.

Particularly important is the CO_2 modification factor. This takes into account the consequence in the photosynthesis due to variation in the concentration of CO_2 in the atmosphere: an increase in CO_2 concentration determines an increase in the efficiency of the process. This is obviously different for C3 and C4 species because of their different response to CO_2 fertilization.

In figure 20 the different values of CO_2 modification factor considered in the model are shown. The response of the increase of CO_2 atmospheric concentration is greater for C3 species (wheat, barley and rice) than for C4 species (maize and sorghum).

There are doubts and discussions about the correct interpretation of the effect of CO_2 fertilization by crop simulation model (Long *et al.*, 2006; Tubiello *et al.*, 2007a). Long *et al.* (2006) stated that the CO_2 fertilization factors used in crop simulation models, which were derived essentially from enclosure studies conducted many years ago, tend to overestimate the direct effect of increasing in CO_2 atmospheric concentration. They affirmed that a better estimate of this effect is studied thanks to the relatively new Free-Air Concentration Enrichment (FACE) technology and doing a meta-analysis of data from FACE and non-FACE studies (like greenhouses, laboratory controlled-environment chambers, and closed or open-top field chambers). In their meta–analysis they estimated that yields observed from the first type of experiments are about 50% less than in enclosure studies.

Tubiello *et al.* (2007a) responded to Long *et al.* and argue that crop models like CROPGRO and CERES implemented in the DSSAT, the CropSyst model and the AEZ model (agro-ecological zone model) consider the CO_2 fertilization by relation that, even if derived from non-FACE studies, do not differ substantially from estimates obtained in FACE studies.

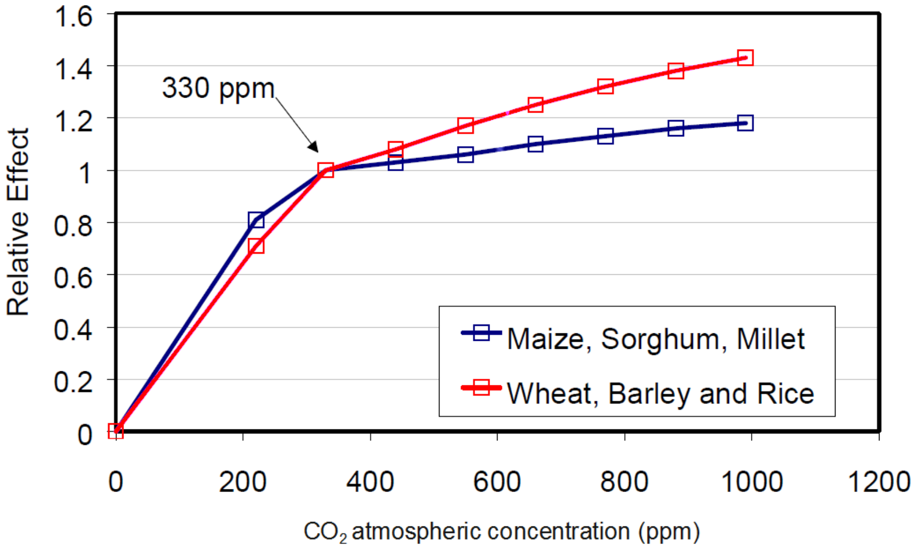
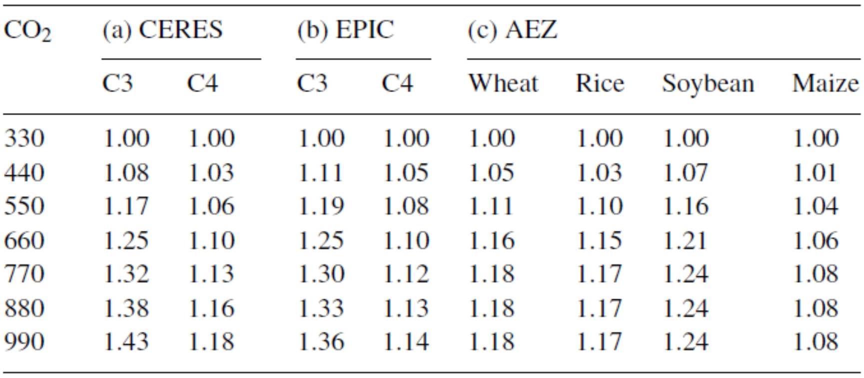


Fig. 20 – Effect of CO_2 atmospheric concentration on C3 and C4 crop growth rate (Jones *et al.*, 2007).

As an example, Tubiello *et al.* (2007a), reported that for DSSAT the modification factor for CO_2 concentration are closer to values reported by Long *et al.* (2006) for FACE experiments than non-FACE studies.

In the table 2 are reported some CO_2 factors used in DSSAT-CERES, EPIC and AEZ models.

Tab. 2 – Response ratios for CO_2 atmospheric concentration (ppm) in DSSAT- CERES, EPIC and AEZ models (Tubiello *et al.*, 2007a).



CO_2	(a) CERES		(b) EPIC		(c) AEZ			
	C3	C4	C3	C4	Wheat	Rice	Soybean	Maize
330	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
440	1.08	1.03	1.11	1.05	1.05	1.03	1.07	1.01
550	1.17	1.06	1.19	1.08	1.11	1.10	1.16	1.04
660	1.25	1.10	1.25	1.10	1.16	1.15	1.21	1.06
770	1.32	1.13	1.30	1.12	1.18	1.17	1.24	1.08
880	1.38	1.16	1.33	1.13	1.18	1.17	1.24	1.08
990	1.43	1.18	1.36	1.14	1.18	1.17	1.24	1.08

In the CSM-CERES-Wheat model the effect of an increasing CO_2 concentration on stomata is also simulated. This effect is calculated empirically by reducing potential transpiration demand via a multiplier, representing the reduction of maximum stomatal conductance as a function of CO_2 concentration (Tubiello and Ewert, 2002).

The relations considered by the system DSSAT-CERES concerning the effects of CO_2 as fertilization factor and as a factor that reduce stomatal conductance (that improve the water use efficiency of crops) are clearly fundamental for studies on climate change.

Development of all plant species in the CERES models proceeds with an initial period of early development in which leaves are the only above ground sink. In simulating the development of wheat, stem internodes elongation does not start until the end of the floral induction. After that, stems begin to elongate and the partitioning pattern of the assimilate changes rapidly. The stems are assumed to be the primary sink used during grain filling. Daily, assimilates are allocated primarily in the above ground biomass but, if at the end of each day there are carbohydrate that are not used, they are allocated to roots. Roots must receive, however, a specified stage-dependent minimum of the daily carbohydrate available for growth. Leaf area is converted into new leaf weight using empirical functions (Jones *et al.*, 2003).

Kernel numbers per plant are computed based on the cultivar’s genetic potential, canopy weight and average rate of carbohydrate accumulation during flowering. Temperature, water and nitrogen stresses are also considered. Once the beginning of grain fill is reached, the model computes daily grain growth rate based on a user-specified cultivar input (G3 cultivar coefficient) defined as the daily potential kernel growth rate (mg/(kernel d)) (Jones *et al.*, 2003).

Daily growth rate is modified by temperature and assimilate availability. If the daily pool of carbon is insufficient to allow growth at the potential rate, a fraction of carbon can be remobilized from the vegetative to reproductive sinks each day. Kernels are allowed to grow until physiological maturity is reached. If the plant depletes resources, growth is terminated prior to physiological maturity. In the same manner, if the grain growth rate is reduced below a threshold value for several days, growth terminated (Ritchie *et al.,* 1998).

1.4.4.2. The SOM models in the DSSAT

Soil Organic Matter (SOM) is an important component in soil because represents a source of plant nutrients that can be available by microbiological degradation depending on the environment. If the degradation of SOM could represent a positive process for nutrient availability, it is important remember that a good content of organic matter in soil has an important role in enhancing soil productivity by modification in soil characteristics, like a better structure and an increase in porosity and soil water availability.

In the last version DSSAT 4.5 was implemented a new component that simulate dynamics of SOM based on the CENTURY model (Parton *et al.*, 1988; Gijsman *et al.*, 2002) developed to simulate the dynamics of nutrients in low input cropping systems in degraded soils.

A module that could simulate efficiently the dynamic of SOM in the soil is very important when the effect of rotations is simulated using crop growth models, because it takes into account the crucial role of composition of SOM (very different, for instance, for residues of wheat or legume crops).

In simulating effect of rotation by crop growth models a module that could simulate efficiently the dynamic of SOM in the soil is very important because takes into account the crucial role of composition of SOM (very different, for instance, for residues of wheat or legume crops).

Two of the most cited and widely used SOM models in the world are the CENTURY model and the RothC model (Jenkinson and Rayner, 1977). They are very different in complexity (RothC is a simpler model than the CENTURY model) and both were evaluated over a range of environments. Other known models that simulated the dynamic of SOM in the soil like these above, however, are evaluated in a variety of environments with several datasets from long-term experiments without find one model that better performed than all others in all situations. The CENTURY model, however, was among the models that performed best (Smith *et al.,* 1997).

Starting from the version 4.0, the DSSAT includes two modules for simulating SOM and residue dynamics: the Ceres – Godwin model (Godwin and Jones, 1991; Godwin and Singh, 1998) and the CENTURY model.

In figure 21 is represented the flow structure and the carbon pool in the two modules available in the DSSAT. In low fertility soils with low input conditions the CENTURY model is recommended (Jones *et al.,* 2007).

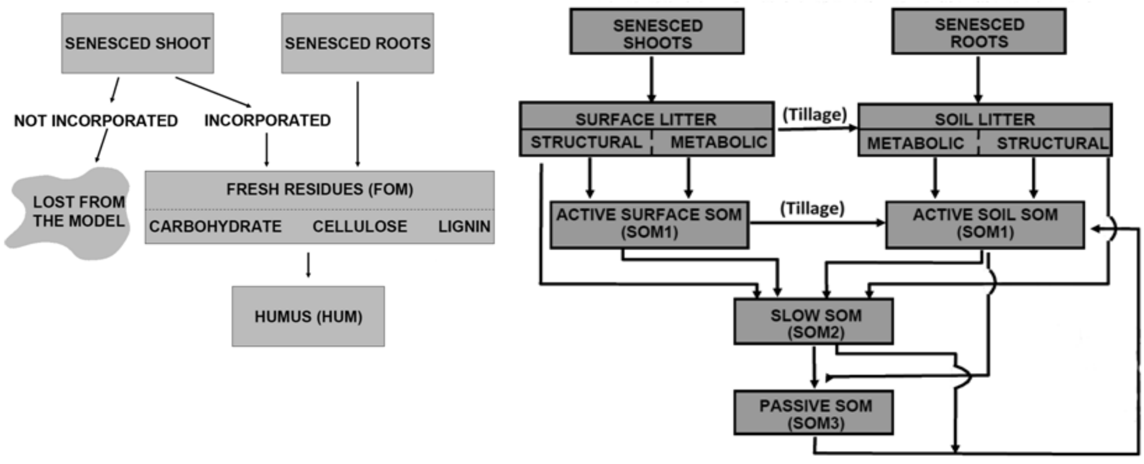


Fig. 21 – The pool and flow structure of the Ceres-Godwin (left) and the CENTURY-based SOM (right) (from Jones *et al*., 2007).

The Ceres-Godwin model is based on the PAPRAN model (Seligman and VanKeulen, 1981) that was adapted by Godwin and Jones (1991) for the CERES model in the DSSAT (Godwin and Singh, 1998) and after implemented in the CROPGRO model (Boote *et al.,* 1998). Developed for annual pastures and small-grain crops in a semiarid environment, the PAPRAN model and the derived Ceres-Godwin SOM module has several limitations:

- it recognizes only recently added residue (fresh organic matter – FOM) and one type of SOM (humus), whereas most models recognize more than only one and discriminate old organic matter with a low turnover rate from young organic matter with a rapid turnover;

- SOM recently formed is given to have a fixed C/N ratio of 10 that is not always true but vary depending on soil and on condition of nitrogen availability;
- it does not consider situations where there is a residue layer located on the soil surface. Hence the model do not consider practices where residues are not incorporated in the soil through tillage, like plowing or other land preparations, as frequently are applied in conservation tillage where residues of previous crop (especially for legumes) lie in the surface of soil and represent an important source of nitrogen for the following crop;
- the module does not distinguish litter N pools associated to three litter C pools (carbohydrates, cellulose, and lignin). This means that decomposition of different C pools has the same effect on availability in soil of nitrogen whereas each pool have different nitrogen concentrations.

For these reasons the CENTURY model, considered one of the best SOM models, was modified in the DSSAT cropping system model (CSM) (Gijsman *et al.,* 2002). This version of CENTURY was then implemented and integrated into the CSM (Jones *et al.*, 2003), but without including many interactions of soil organic matter with other important components that are implemented in it.

In the DSSAT-CSM v. 4.5 further improvements are added. Details on the adapted CENTURY model, on the simulated soil organic matter processes, and on the additional complexities and the opportunities to improve capabilities in modules that are linked to the CENTURY-CSM are described by Porter *et al.* (2009).

A scheme of the components considered in DSSAT-CENTURY model is shown in the figure 22.

The module considers three type of soil organic matter (SOM) pools and two pools of fresh organic matter (FOM or litter) both in and on top of the soil:

- **SOM** (*active SOM*) microbial or active material that is decomposed quickly;
- **SOM2** (*slow SOM*) material derived from lignin or cell walls that decompose slowly, decomposed SOM1 and stabilized microbial material (e.g., microbes physically protected by the soil structure);

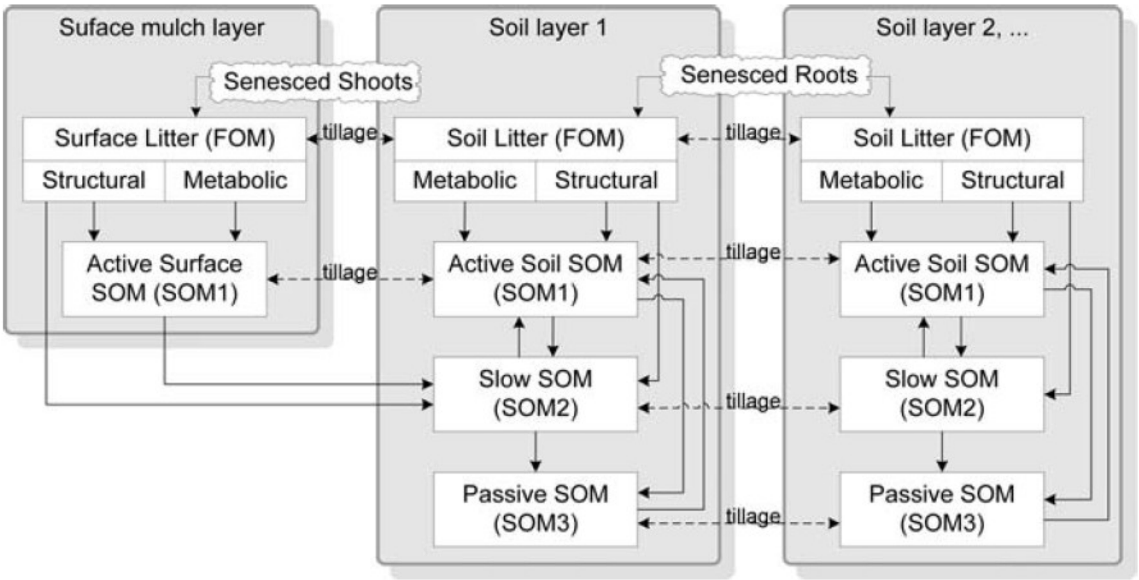


Fig. 22 - The carbon pool and flow structure of the DSSAT-CENTURY module (from Porter *et al.,* 2009).

- **SOM3** (*passive SOM*) inert material and stabilized microbial material.
- **Metabolic litter** fraction of FOM *easily decomposable* and composed by fresh residue (e.g., proteins, sugars);
- **Structural litter** *recalcitrant* fresh residue (e.g., lignin, cell walls).

The rapidity of decomposition is extremely different for SOM1 (in the order of days) than for the two others litter components (years for SOM2 and hundreds for SOM3). Nitrogen and phosphorus contained in SOM pools are considered separately in each pool for each surface and soil layer. To simulate adequately the dynamic of the various organic and inorganic pools in the soil it is necessary an accurate initialization. When is critical to obtain detailed data to precisely determine the initial conditions of simulations, the DSSAT-CENTURY model, opportunely modified, can overtake this problem because it has more flexibility and can run with user-supplied data. Initialization of SOM in this new version is determined by the type and quality of input data provided by users. The total soil organic matter could be divided into the two FOM pools and the three SOM pools. If the user has not detailed information about this fraction that are not collected, he can calculate them using information provided in the SOMFR045.SDA file where the initial SOM fractions are tabulated based on previous land management, soil type, number of years under this management and on initial carbon composition.

If the user has more detailed data he can insert them in the model and modify them. Each pool of SOM in each layer is updated daily in CSM based on the rates of decompositions and transformations among the pools. The decomposition of organic matter shifts the amounts of pools from more active forms (FOM and SOM1) to more stable forms (SOM2 and SOM3). A simplified scheme of the flow of matter between pools in the decomposition process is shown in figure 23.

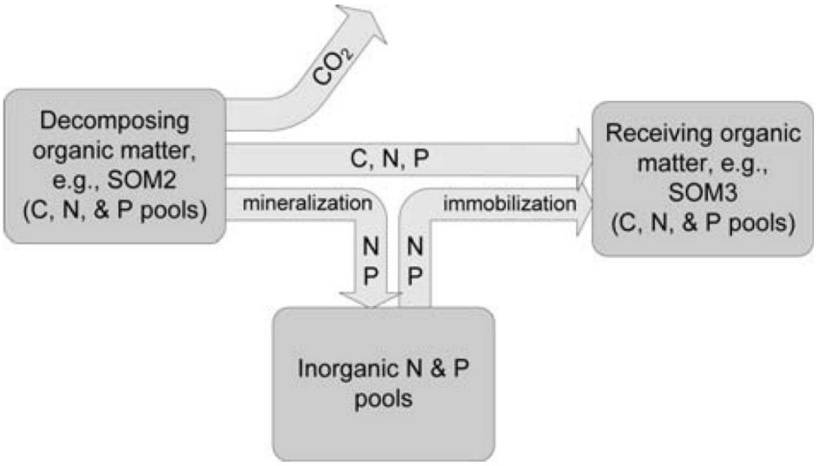


Fig. 23 – Example of flows of C, N and P from a decomposing organic matter pool (SOM2) to another organic matter pool (from Porter *et al.*, 2009).

As exposed in the scheme of figures 22 and 23, the carbon released by decomposition is partly mineralized to CO_2 and the remaining C is transferred to one or more other organic matter pools. Nitrogen and phosphorus are transferred by the same dynamics and can be available in soil for plants trough mineralization or used to form a now pool of organic matter by immobilization (Fig. 23). Flows of N and P are proportional to the C:N and C:P ratio of the composition of the SOM pools. If the nitrogen content of the SOM pool, that are the source of decomposing material, is greater than that required by the recipient pool, the inorganic nitrogen not required is released into the surrounding soil and becomes available for plants. On the contrary, if the nitrogen content of the decomposing material is less than that required by the recipient pool, the nitrogen needed for adding other carbon to the recipient pool is acquired by immobilizing inorganic nitrogen from the surrounding soil. Same processes are applied for phosphorus.

Decomposition rates are functions of first order rate that are modified by temperature, moisture, cultivation, and texture factors (Porter *et al.,* 2009):

$$\frac{\mathrm{dC}}{\mathrm{d}t} = -k_t \cdot \mathrm{C} \qquad \text{and} \qquad k_t = k_0 \cdot \mathrm{TF} \cdot \mathrm{WF} \cdot \mathrm{CF} \cdot \mathrm{TXF}$$

where C is the organic carbon present in the decomposing pool considered (kg ha^{-1}), t is the time step expressed in days, k_0 and k_t are the base and modified rate constants of decay (day^{-1}), TF, WF, CF and TXF are the temperature of soil, water content in soil, cultivation and texture factors, respectively. These factors are calculated by empirical relations in detail exposed in Porter *et al.* (2009).

The sensitivity of SOM models to some of these factors is studied by Bauer *et al.* (2008) that find that for models and conditions considered in the study the reductions in soil temperature involved a reduction in decomposition ranging from 6 to 7 times of reduction in moisture.

Distribution of organic matter and its components in each layer can be modified when tillage occurs or when the organic matter applications are applied into the soil. If occurs incorporation of surface residues by tillage, the surface residues are mixed into the soil layers interested to the depth and at an incorporation percentage specified in a file (TILO045.SDA) that contains characteristics of different tillage operations and that can be modified by the user. These aspects are specified in the following paragraph.

Differently from the CERES-Godwin model in the DSSAT-CENTURY model residues or distribution of organic matter applied without incorporation can be considered in the surface mulch layer. This is particularly important when considered conservation tillage management like sod seeding where dynamics of SOM in the surface soil play an important role.

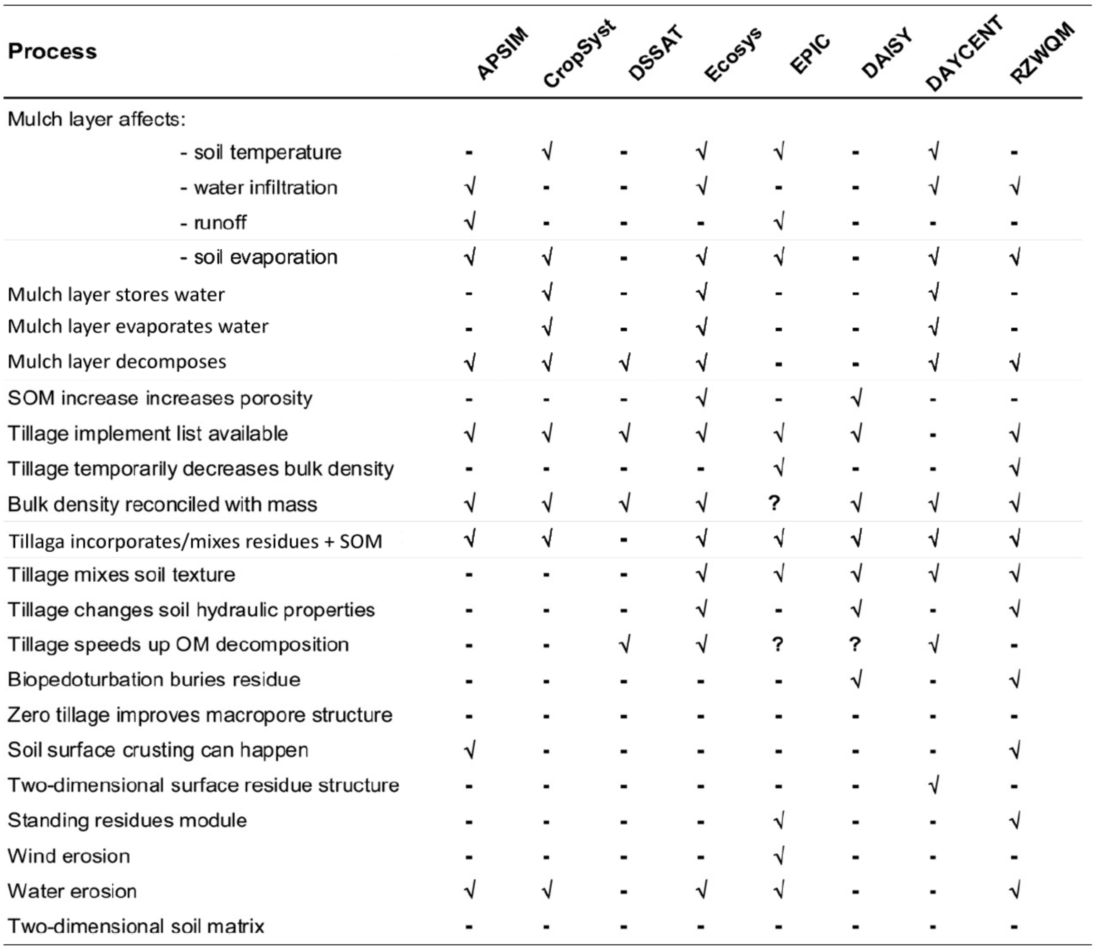
If there are additions of organic matter, this can be input in the experimental file where are inserted residue application date, type of organic matter, amount, concentrations of N and P, incorporation percentage, incorporation depth, and application method. Additional information on lignin, nitrogen and phosphorus contents for various residue crop types and for organic matter application is provided in the RESCH045.SDA file of the DSSAT that can be modified by the user. For crop residues surface and sub-surface compositions are reported.

1.4.4.3. The Tillage model in the DSSAT

Tillage is an important crop operation which is made for modifying the soil environment in order to improve the conditions for a good seed germination and crop growth. There are a large availability of crop growth models but very few are able to simulate tillage modification of soil environment where there are applied. Commonly application considered in crop growth models includes the optimization of irrigation and fertilizer management and the assessment of the potential impacts of climatic change. However, these applications are often constrained because very few models explicitly considering tillage and its consequences on structure, physical and chemical soil characteristics (Sommer *et al.,* 2007; White *et al.,* 2009).

In the DSSAT 4.5 new routines are implemented in the CSM (Cropping Systems Model) to simulate tillage and field operations (White *et al.,* 2009). These enhanced characteristics are not included in the previous DSSAT versions, and also are not implemented in a wide range of models, as described in table 3 (Sommer *et al.*, 2007).

Tab. 3 - Crop–soil-simulation model and its capabilities to simulate process on residue and tillage management. This table consider a previous version of DSSAT (from Sommer *et al.*, 2007).



Process	APSIM	CropSyst	DSSAT	Ecosys	EPIC	DAISY	DAYCENT	RZWQM
Mulch layer affects:								
- soil temperature	-	√	-	√	√	-	√	-
- water infiltration	√	-	-	√	-	-	√	√
- runoff	√	-	-	-	√	-	-	-
- soil evaporation	√	√	-	√	√	-	√	√
Mulch layer stores water	-	√	-	√	-	-	√	-
Mulch layer evaporates water	-	√	-	√	-	-	√	-
Mulch layer decomposes	√	√	√	√	-	-	√	√
SOM increase increases porosity	-	-	-	√	-	√	-	-
Tillage implement list available	√	√	√	√	√	√	-	√
Tillage temporarily decreases bulk density	-	-	-	-	√	-	-	√
Bulk density reconciled with mass	√	√	√	√	?	√	√	√
Tillaga incorporates/mixes residues + SOM	√	√	-	√	√	√	√	√
Tillage mixes soil texture	-	-	-	√	√	√	√	√
Tillage changes soil hydraulic properties	-	-	-	√	-	√	-	√
Tillage speeds up OM decomposition	-	-	√	√	?	?	√	-
Biopedoturbation buries residue	-	-	-	-	-	√	-	√
Zero tillage improves macropore structure	-	-	-	-	-	-	-	-
Soil surface crusting can happen	√	-	-	-	-	-	-	√
Two-dimensional surface residue structure	-	-	-	-	-	-	√	-
Standing residues module	-	-	-	-	√	-	-	√
Wind erosion	-	-	-	-	√	-	-	-
Water erosion	√	√	-	√	√	-	-	√
Two-dimensional soil matrix	-	-	-	-	-	-	-	-

In the DSSAT plant growth below the surface of soil proceed in response to water and nutrient availability, depending on soil temperature and a root growth weighting factor (WR) which varies with soil depth, and that indicates the hospitability for roots. The value of WR ranges from 1 (the most hospitable) to 0 (soil inhospitable) (Ritchie, 1998). Soil characteristics are registered in the soil file (.sol) where properties of the soil like soil surface characteristics (albedo, potential runoff and a drainage factor) are collected. Soil are divided in layers that are identified by depth increments (e.g., 0–5 cm, 5–25 cm). In each layer are registered some parameters for the water retention characteristics, bulk density, soil texture, soil carbon and nutrient levels. Water from precipitation (or irrigation) infiltrates into the soil or could be lost through surface runoff. Water may evaporate from the soil surface, drain versus the profile that are below, or be absorbed by roots (White *et al.,* 2009).

Runoff varies with daily rainfall, the runoff curve number (CN) and the wetness of soil at the time of the rainfall event. The runoff curve number (CN), is an empirical method, derived from a modification of the curve number method of the USDA-Soil conservation Service (SCS), to estimate runoff and varies from 0 for no runoff to 100 for maximum runoff. Conceptually little runoff occur for low rainfall when near surface conditions are dry. Surface residues that lie in the soil surface affect infiltration and runoff. Infiltration is assumed to be the difference between precipitation and runoff. The infiltrated water is allocated from the upper layer down through other soil layers following the ‘tipping bucket’ approach (Ritchie, 1998; White *et al.,* 2009).

For each given soil layer, water contents at saturation (SSAT) and drained upper limit (SDUL) are calculated by relations based on texture. The difference between (SSAT) and the current soil water content determines the capacity of the layer to hold additional water. If the volume of water to be infiltrated exceeds this amount, the excess water is allocated to the next layer until all infiltrated water is distributed among soil layers. A more complete explanation is given by Ritchie (1998) (White *et al.,* 2009).

Nutrient availability on soil depend on fertilization and decomposition of organic matter as explained previously. The processes involved are affected by soil moisture and temperature, but also effects of tillage are important although they are indirect. Tillage involve incorporation and mechanical degradation of surface crop residues, mixing of soil layers, and changes in bulk density and saturated hydraulic conductivity (K_{SAT}).

The tillage routines used in CSM of DSSAT 4.5 are based on procedures first developed by Dadoun (1993) for maize and refined by Andales *et al.* (2000) for the CROPGRO-Soybean model (Nanja *et al.,* 2008; White *et al.,* 2009). The date and type of tillage are specified in the crop management input file (file experiment) in the tillage section where are collected information like an identifier for the tillage event, the date of the event, an implement code to identify the implement used, the depth of tillage, and a name or description. The implement code is important because links to a parameter file that specifies the effects of different implements (the TILO045.SDA file). In this file for each implement code (TIMPL) are describe the implement effects of each type of tillage trough two sets of parameters.

The first set of parameters are the percent change in curve number (CN) immediately after an operation (CN2T), the percent of surface residue incorporated (RINP), the percent of the soil surface area that is disturbed by the field operation (SSDT), the mixing efficiency of tillage event (MIXT) and the percent reduction in hard pan (HPAN) if depth is sufficient to reach pan. For each implement code in the following rows and for each layer considered specified by the soil layer depth (SLB), are considered the change in bulk density just after field operation (SBDT) and the change in saturated hydraulic conductivity or K_{SAT} (SKST) (White *et al.,* 2009).

2. OBJECTIVES

Durum wheat is one of the most important crops in the Mediterranean area. Stakeholders and policymakers are concerned about the uncertainties in expected yields due to frequent droughts and modification on climate conditions in recent decades. In addition, the variability of the environmental components becomes crucial in the case of rainfed crops.

Global and European economic framework, which has changed in recent years, has also implied further pressure on farmers who operate in a sector with low profit margins. The growing awareness of ecology and sustainability by the Common Agricultural Policy has determined a review of agricultural practices and a growing interest in managements that are, at the same time, environmentally and economically sustainable.

Conservation tillage is one of the most recommended practices that are applied in the European Union. However, not many experimental studies on this topic have been performed, especially in the Mediterranean basin. Consequently, the effects of this practice on yields and on grain quality has not yet been well understood. Sometimes results of experimental studies are contradictory whereas it is generally recognized that the applications of these techniques involves a long-term increase in organic carbon content in soil and can therefore act as a function of retention in soil.

Considering the socio-economic importance of durum wheat in the Mediterranean area and the lack of studies related to this topics, the aims of this work was (i) to investigate the effect of conservation tillage and rotation techniques with legume crops on durum wheat, (ii) to evaluate their impacts under climate change conditions, and (iii) to develop appropriate adaptation strategies.

The specific objectives of this research are:

- to evaluate the effects of conservation tillage and crop rotation with legume crops on durum wheat in the Mediterranean area;
- to assess the effects of climate change on durum wheat production and phenology in two typical Mediterranean soils where durum wheat is ordinarily cultivated using these agronomic practices;
- to provide some sustainable mitigation/adaptation strategies for durum wheat in response to climate change.

To meet the objectives, the main activities conducted regard two agronomical experiments on conservation tillage and rotation with legume crops in two different type of soil and the use of the CSM-CERES-Wheat model in conjunction with a wide range of future climate change scenarios.

3. MATERIALS AND METHODS

3.1. AGRONOMIC SECTION

3.1.1. Sites

Field experiments were conducted in the experimental station "S. Michele" of the Department for research in crop productions of AGRIS, the Agricultural Research Agency of Sardinia (Italy), in southern Sardinia (39°25'29'' N, 09°04'55'' E, 99 m above sea level), on two different types of soil:

- Benatzu. Inceptisol with vertic characteristics (Vertic Epiaquept) according to the U.S.D.A. soil taxonomy classification (Soil Survey Staff, 1999) with good fertility for cereal growing;
- Ussana. Alfisol (Petrocalcic Palexeralf) according to the U.S.D.A. soil taxonomy classification with ordinary fertility for cereal growing.

The two locations representative of a large cereal growing area in Southern Italy, are distant about 1 km from each other. Thus weather conditions are similar in the same cropping season (Fig. 24).

Fig. 24 – The two locations of field trials in "S. Michel" experimental station.

3.1.1.1. Soil characteristics

A summary of the main physical and chemical soil characteristics in the first 30 cm of depth are reported in table 4 for each site.

Tab. 4 – Main soil characteristics.

Characteristic	**Ussana**	**Benatzu**
Texture	Sandy Clay Loam	Loam
sand (%)	55.8	44.0
silt (%)	18.2	30.1
clay (%)	26.0	25.9
pH in water	7.8	8.4
Organic Matter (%)	1.3	2.1
Total Nitrogen (‰)	0.8	1.0
P (Olsen) (ppm)	20.8	16.2
K (NH_4Ac) (ppm)	140	159
Na exch. (ppm)	43.3	23.1
C.E.C. (me/100g)	15.9	18.5
E.S.P. (%)	1.2	0.5

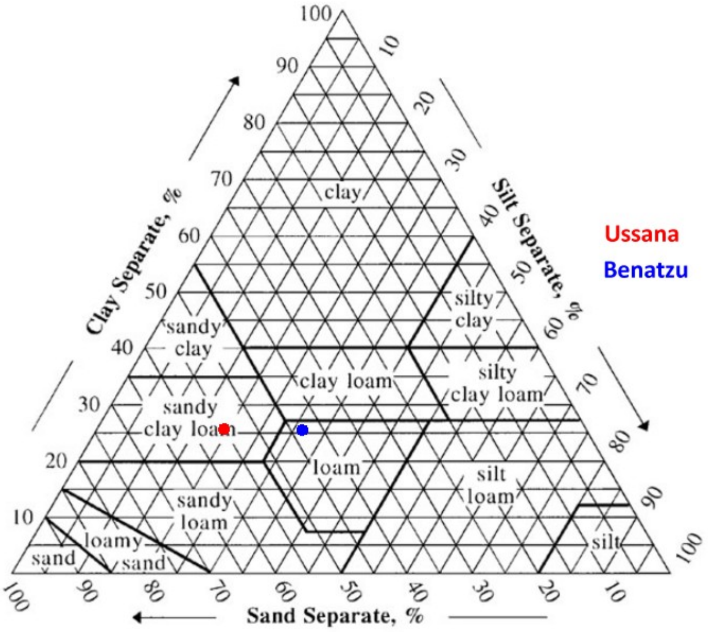


Fig. 25 – Soil texture triangle (USDA).

Before carrying out the field experiments, a soil profile has been done dipping with an excavator until 1,50 m deep. Each profile has been studied, photographed and described using the standards of soil profiles related to the U.S.D.A. (Soil Survey Staff, 1999) (Fig. 26).

Fig. 26 – Soil profile of Benatzu (left) and Ussana (right).

Benatzu is a Vertic Epiaquepts belinging to the order of Inceptisols. These are a wide range of soils spread over a wide range of climates and cover about 15-17% of the non polar continental land area on Earth (Fig. 27). They are soils just starting to show horizons development because the soil is quite young. In the Aquept soils natural drainage is poor (in Benatzu moderately good) and, if the soils have not been artificially drained, ground water is near the soil surface at some time during normal years. In the Epiaquepts the ground water commonly flows from a level near the soil surface to below a depth of 200 cm. The Vertic Epiaquepts, like the soil of Benatzu, crack within 125 cm of the mineral soil surface that are 5 mm or more wide through a thickness of 30 cm or more for some time in normal years. These soils have a gray to black surface horizon and a gray subsurface horizon with redox concentrations that begins at a depth of less than 50 cm (Soil Survey Staff, 1999).

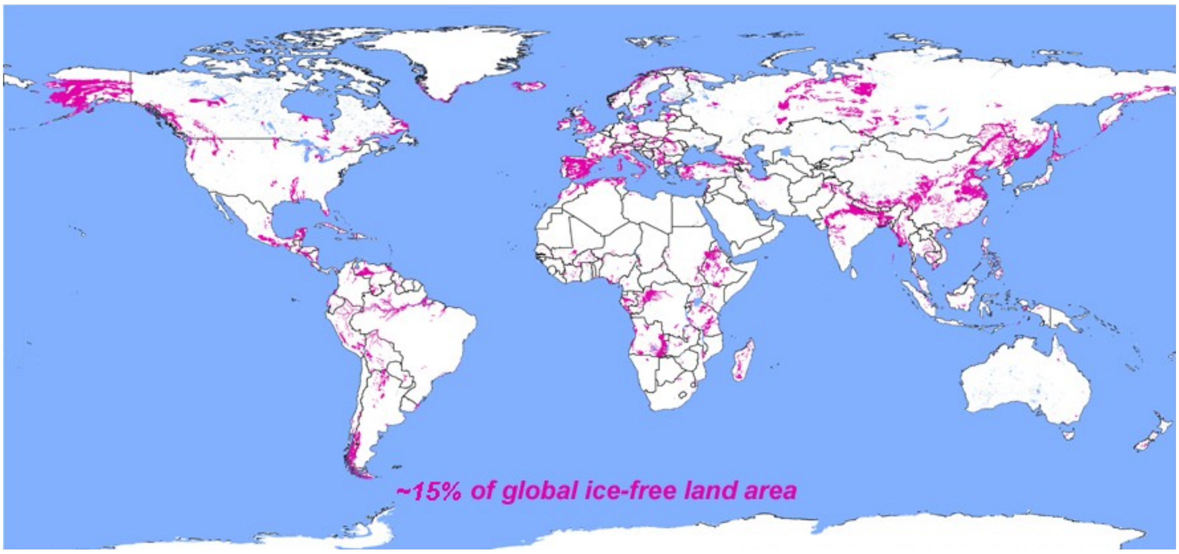


Fig. 27 - Overview of the world-wide occurrence of Inceptisols (From USDA-NRCSa).

Ussana is a Petrocalcic Palexeralf belonging to the order of Alfisols that occupy about 10 percent of the non polar continental land area on Earth (Fig. 28). As its name implies, a xeralf has a xeric moisture regime. In fact these soils result from weathering processes that leach clay minerals and other constituents out of the surface layer and into subsoil where they can hold and supply moisture and nutrients to plants. They are dry for extended periods in summer, but in autumn or in winter the moisture moves through the soil to deeper layers in at least occasional years. The xeralf soils are spread over regions showing a Mediterranean climate but are spread over also South Africa, Chile, Australia, Western U.S. In these soils winter annuals crops are common where there is no irrigation and grapes and olives if the climate is thermic (Soil Survey Staff, 1999).

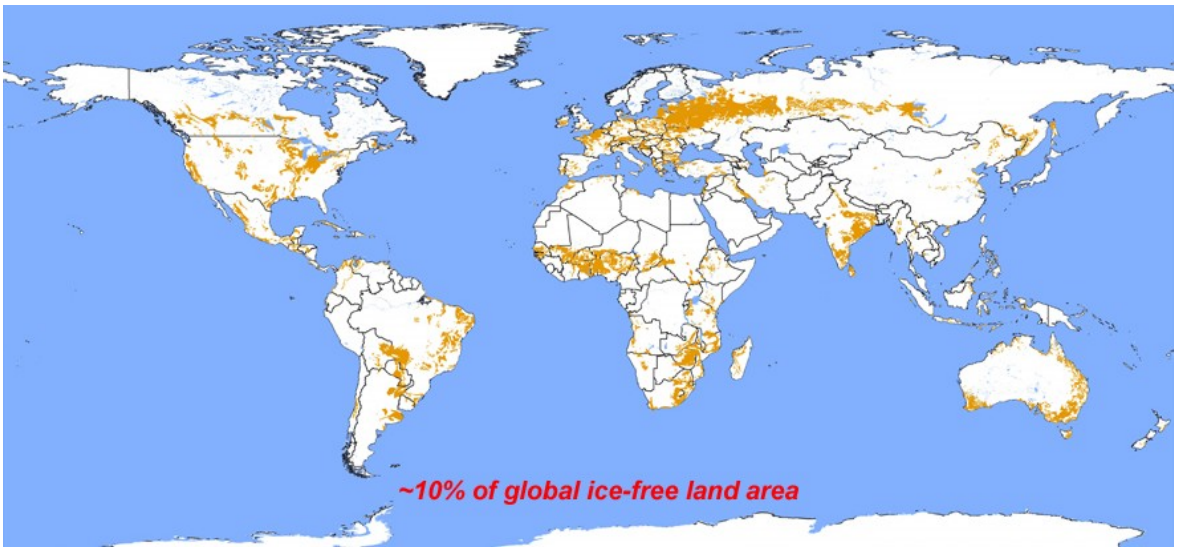


Fig. 28 - Global distribuition of Alfisols (From USDA-NRCSb).

In order to have more precise information on the evolution of physical and chemical characteristics before the sowing season, samples of soil were taken in the first 30 cm from each subplot to carry out chemical analysis on both sites every year since 2003. This large database was used to produce a .SOL file of DSSAT useful for calibration and evaluation of CSM-CERES-Wheat model and that allowing to work on plot scale.

3.1.1.2. *Climate and meteorological analyses*

The climate of Sardinia is generally classified as internal Mediterranean with mild and relatively rainy winters and warm and dry summers (Chessa and Delitala, 1997).

Owing to their nearness, climate of Ussana and Benatzu are similar. In order to describe the climate of the study site, daily data were collected for the time span 1973-2009, using an automatic weather station (model SILIDATA AD2, SILIMET srl, Modena, Italy) located within the S. Michele experimental station of AGRIS Sardegna.

The variables considered were:

- Maximum air temperature (°C);
- Minimum air temperature (°C);
- Precipitation (mm).

When the weather series periods presented missing data, it was necessary to reconstruct the missing values through spatial interpolation techniques. In particular, daily series were reconstructed from meteorological stations of the Regional Agency for the Environmental Protection (ARPAS Sardegna), located in areas surrounding the "S. Michele" experimental farm. For daily maximum and minimum air temperatures a multilinear regression using kriging method was used. Descriptive statistics of average maximum air temperature, minimum air temperature and cumulative monthly precipitation for the period 1973-2009 were calculated on monthly, seasonal, and annual basis. For the same period values of standard deviation, maximum and minimum and median values were also calculated.

The series obtained were analyzed with the non parametric Mann-Kendall test to evaluate possible trends in the variation of temperature and cumulative precipitation for the thirty-six years of reference (1973-2009). The Mann–Kendall test is applicable to detect a monotonic trend of a time series and thus no seasonal or other cycle is present in the data (Salmi *et al.*, 2002). For this reason it was used for annual, season and months averages separately.

The Mann–Kendall test is applicable in cases when the data values x_i of a time series can be assumed to obey the model:

$$x_i = f(t_i) + \varepsilon_i (1)$$

where $f(t)$ is a continuous monotonic increasing or decreasing function of time and the residuals ε_i can be assumed to come from the same distribution with zero mean. It is therefore assumed that the variance of the distribution is constant in time.

To test the null hypothesis of no trend, H_0, i.e. the observations x_i are randomly ordered in time, against the alternative hypothesis, H_1, where there is an increasing or decreasing monotonic trend.

The Mann-Kendall test was applied using MAKESENS, an Excel Template Application (Salmi *et al.*, 2002) that estimate also the slope of a linear trend with the non parametric Sen's method (Gilbert, 1987). In the computation of the Mann-Kendall test the normal approximation (Z statistics) was used because applied for time series with more of 10 data.

The presence of a statistically significant trend was evaluated using the Z standardized values. A positive (negative) value of Z indicates an upward (downward) trend. To test for either an upward or downward monotone trend (a two-tailed test) at α level of significance, H_0 is rejected if the absolute value of Z is greater than $Z_{1-\alpha/2}$, where the $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables. In this application, the tested significance levels α are 0.001 (***), 0.01 (**), 0.05 (*) and 0.1 (+).

To estimate the true slope of an existing trend (as change per year) the Sen's nonparametric method is used. The Sen's method can be used in cases where the trend can be assumed to be linear. This means that $f(t)$ in equation (1) is equal to

$$f(t) = Qt + B (2)$$

where Q is the slope and B is a constant. More information of the non parametric Sens's method used to estimate the true slope of an existing trend are available on the manual of the MAKESENS application (Salmi *et al.*, 2002).

3.1.1.3. Estimate of global solar radiation

Global solar radiation (MJ m^{-2}) daily data were available only for the last 13 years of the whole period. For the remaining years, the solar radiation daily data were estimated using the software RadEst v. 3.0 (Donatelli *et al.,* 2003).

The RadEst program allows evaluating daily global solar radiation values for a location at a given latitude, and it allows estimating daily values. In this program four model, derived from the model proposed by Bristow and Campbell, are available to estimate daily radiation from air temperature data.

Radiation is calculated as a product by atmospheric transmittance (estimated from air temperature) time potential radiation outside the Earth atmosphere as reported below:

$$EstRad_i = tt_i \cdot PotRad_i$$

where:

EstRad = estimated radiation (MJ m^{-2})

tt_i = transmissivity in the *i* day

PotRad = potential radiation (MJ m^{-2})

i = day of the year

To calculate daily transmissivity was used the Campbell-Donatelli model (Donatelli and Campbell, 1998) that take into account situations in which the night air temperature cooling is less than the corresponding clear day. Also, it accounts for the date using the air average temperature. Transmissivity in the day *i* is calculated using the formula

$$tt_i = \tau \cdot \left[1 - \exp\left(-\mathrm{b} \cdot \mathrm{f}(\mathrm{Tavg}) \cdot \Delta\mathrm{T}_\mathrm{i}^2 \cdot \mathrm{f}_1(\mathrm{Tmin})\right)\right]$$

where:

tt_i = transmissivity in the *i* day

τ = clear sky transmissivity

$\mathrm{Tavg} = (\mathrm{Tmax}_\mathrm{i}+\mathrm{Tmin}_\mathrm{i})/2$

$\mathrm{f(Tavg)} = 0.017 \cdot \exp[\exp(-0.053 \cdot \mathrm{Tavg})]$

$\Delta\mathrm{T}_\mathrm{i} = T\max_i - \left(T\min_i + T\min_{i+1}\right)/2$

$\mathrm{f}_1(\mathrm{Tmin}) = \exp(\mathrm{Tmin}/\mathrm{Tnc})$

b e Tnc are empirical parameters used to calibrate the model by iterative process.

3.1.2. Experimental design and field trials management

The study was conducted across five cropping seasons: from 2004/05 to 2008/09 as part of a long-term experiment started in 2003. In order to obtain the correct precession for the rotation treatments in each plot, the first year 2003/04 was necessary to achieve a right plot arrangement.

The experiment was designed as a randomized complete block with a split–plot arrangement and three blocks. In the main plots, each one with an area of 2400 m^2, three types of tillage systems were applied: conventional tillage (CT), reduced or minimum tillage (RT) and no tillage or sod seeding (NT). In subplots, each one with an area of 600 m^2, two different crop rotations were applied: continuous wheat (CW) and legumes–wheat crops (LW) consisting in faba bean from 2003/04 to 2005/06, and field pea from 2006/07 to 2008/09. Each rotation was duplicated to obtain data for all crops on a yearly basis. Hence, data coming from the CW are twice than those obtained with LW. In figures 29 and 30 the maps of the experimental design of two consecutive years (2007/08 and 2008/09 at Ussana) are shown.

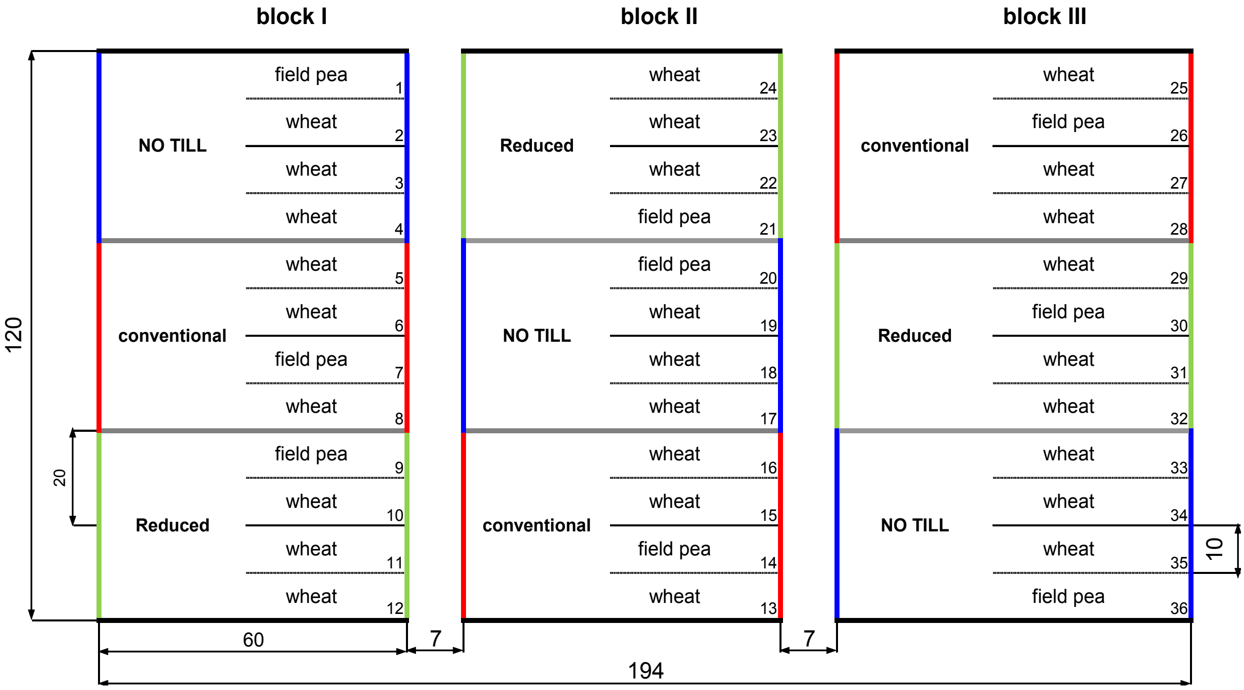


Fig. 29 – Cropping systems trial. Ussana 2007/08: map of the experimental design.

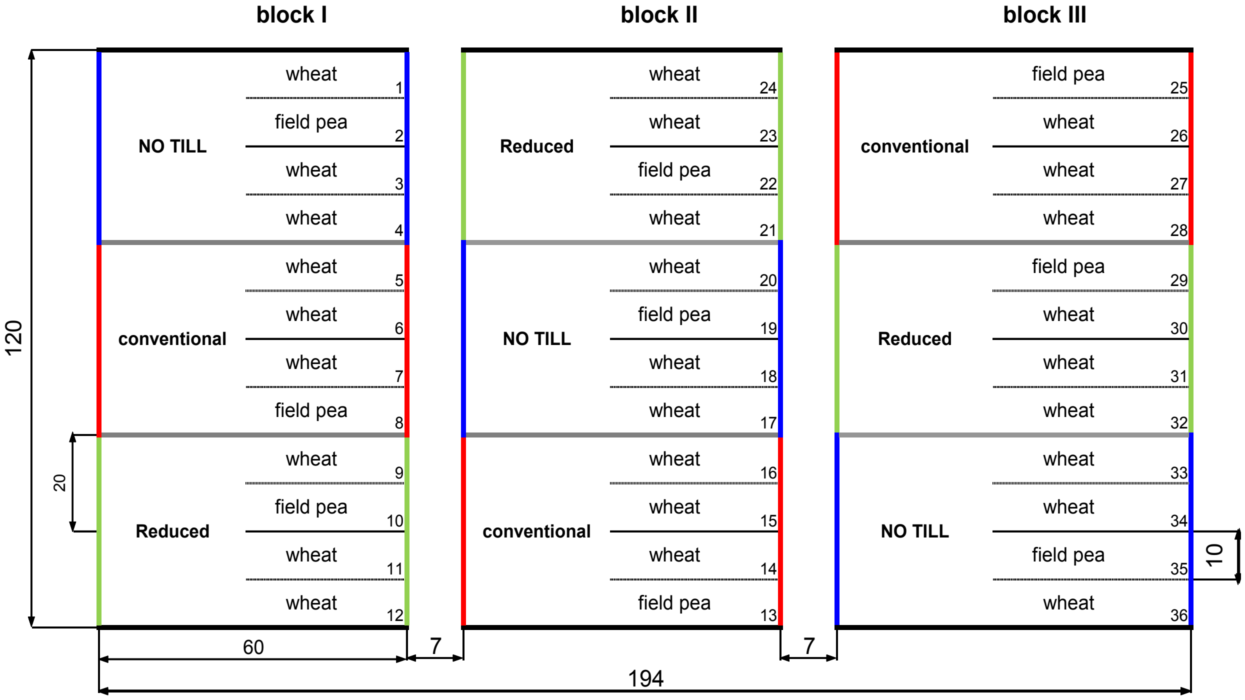


Fig. 30 – Cropping systems trial. Ussana 2008/09: map of the experimental design.

Durum wheat (*Triticum durum* Desf.) was planted in 17.5 cm wide rows from December to February depending on meteorological and field conditions at a seeding rate of 190-200 kg ha^{-1} using the Simeto cultivar. Faba bean (*Vicia faba* L. var. *minor*) and field pea (*Pisum sativum* L.) was planted in the same periods at a rate of 200-220 kg ha^{-1} using the Prothabat 69 and the Hardy cultivar respectively.

The CT treatment included moldboard plowing (25-30 cm depth) and disk harrowing (15 cm depth) and tine harrow (5-7 cm depth) to prepare a proper seedbed. The RT treatment consisted in a simple disk harrowing (15cm depth) after a treatment with glyphosate (4-5 l ha^{-1} of commercial product) to eliminate weeds. Same treatment were applied in NT whose were planted with a no-till drill. CT and RT plots were planted with the same ordinary drill.

Fertilizers were applied to wheat plots (200 kg ha^{-1} of diammonium phosphate) at sowing, and incorporated by drill for CT and RT and surface-broadcast in NT plots. At the beginning of wheat tillering stage another fertilization was applied for reaching 80 units of N per hectare.

Weeds within the growing season were controlled for wheat by specific herbicides in mixture of products consisting of Clodinafop-propargyl (250 ml ha^{-1}) and Tribenuronmethyl (20 g ha^{-1}). For faba bean weeds were controlled by a pre-emergence treatment of Pendimethalin (5 kg ha^{-1}) and for field pea by a post-emergence treatment with Imazamox (1 kg ha^{-1}).

To exclude a possible overestimation in production due to border effects, wheat and legumes grain were harvested using an experimental plot combine harvester (Hege 140), and at the centre of each subplot, three sub-sampling of 30 m^2 were made to the aim of evaluating the real field yields. In particular for wheat, samples were made to evaluate the following variables: humidity (%), protein content (% dry matter), gluten (% dry matter), gluten index (%) (ICC Standard 158), 1000-kernel weight (g), test weight (kg hl^{-1}). For legumes and grain legume the following variables were analyzed: humidity (%) and 1000-kernel weight (g).

3.1.3. Statistical analyses

To understand the effects of tillage and rotation a combined analysis of variance (ANOVA) over 5 years considered (2004/05, 2005/06, 2006/07, 2007/08 and 2008/09) for Ussana and Benatzu site was separately performed. In ANOVA, orthogonal contrasts were also used for assessing the effect of conservation and conventional tillage (first contrast) and between reduced and no-tillage practices (second contrast). In the ANOVA all the interactions between years, tillage and rotations were also taken into account.

All statistical analyses were performed using the GenStat v.12 software (Payne *et al.,* 2009).

3.2. MODELING SECTION

3.2.1. Why using the DSSAT v.4.5?

In this study the CSM-CERES-Wheat model implemented in the DSSAT v.4.5 software package (Hoogenboom *et al.,* 2009) was applied.

The main reasons for choosing the CSM-CERES-Wheat model are related to its ability to simulate yield and crop phenology over a wide variety of areas in the world, as highlighted by several authors (Savin *et al.*, 1995; Guereña *et al.*, 2001.; Alexandrov and Eitzinger, 2005; Alexandrov *et al.*, 2002; Šť'astná *et al.*, 2002; Brassard and Singh, 2008; Wei *et al.*, 2009). Moreover, this model allows the possibility to set atmospheric CO_2 concentration when simulations are performed, which is extremely recommended for evaluating climate change impacts on crops.

The new DSSAT 4.5 beta version represents an improvement version of the previous DSSAT 4.0.2 (Jones *et al.,* 2003). One of the most important changes is related to the implementation and the possible application of the CENTURY-based soil carbon and nitrogen model module. This module is aimed to improve the model performance in simulating low input agricultural systems. To better simulate carbon sequestration processes a separate module was also considered and added in the CSM.

In addition, the recent DSSAT 4.5 include: (1) a new version of the Weather Data Manager (WeatherMan) tool, which is used for entering, analyzing and generating weather and climate data, (2) a new tillage module (White *et al.,* 2009), (3) a new method to simulate soil water redistribution and soil evaporation according to the recent method of Suleiman and Ritchie (2003) (Ritchie *et al.,* 2009), and (4) a modified Soil Conservation Service (SCS) Runoff Curve Number method to determine quantity of surface runoff on a daily basis (Porter *et al.,* 2009) (Fig. 31).

This new version is still under development but are it was already used by scientist that have already published several scientific papers (Nanja *et al.,* 2008; White *et al.,* 2009; Porter *et al.,* 2009).

Taking into account the advantages of the implemented new version of the DSSAT 4.5, and considering the objectives of this thesis, it was decided to use this latest version which was kindly accorded by Professor Gerrit Hoogenboom, Washington State University, US.

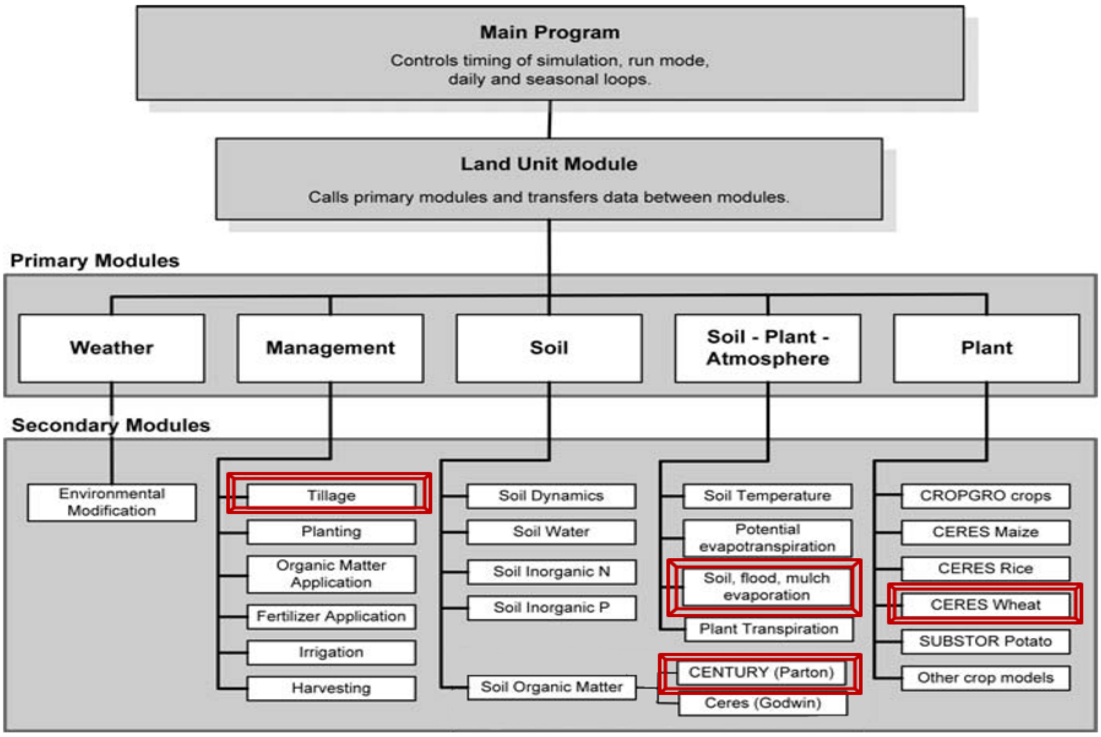


Fig. 31 - Modular structure of DSSAT 4.5: the principal secondary modules and the useful enhancements are circled in red (modified from Porter *et al*., 2009).

In this thesis, the DSSAT-CENTURY model as recommended for low input agricultural systems (Jones *et al.,* 2003) was used for calibration and validation. Some parameters used in the CENTURY model (such as total organic carbon and total nitrogen for each layer considered) were obtained by field measurements and insert in the soil file (.sol) whereas others parameters, for instance fresh organic matter from previous crop, are estimated and insert in the experiment file (.whx).

In table 5 the set of parameters included in the tillage model used in this thesis are reported. These parameters are collected in the tillage file (TILO045.SDA). The CN2T parameter is the percent change in CN immediately after a tillage operation, the RINP parameter defined the percent of surface residue incorporated, the SSDT is the percent of the soil surface area that is disturbed by the field operation, the MIXT is a parameter used for the mixing efficiency of tillage event. For each field operation (and implement code) are also specified, for each layer considered, the soil layer depth (SLB), the change in bulk density just after field operation (SBDT), and the change in saturated hydraulic conductivity or K_{SAT} (SKST).

Tab. 5 - Parameters used in the TILO045.SDA file that describe effects of different tillage practices simulated in the cropping systems model.

Implement	**Implement code**	**Change in curve no** CN2T (%)	**Residue incorporated** RINP (%)	**Soil surface disturbed** SSDT (%)	**Mixing efficiency** MIXT (%)	**Soil layer depth** SLB (cm)	**Change in bulk density** SBDT (%)	**Change in K_{SAT}** SKST (%)
Moldboard plow 30 cm (CT)	TI043	-10	95	100	90	5	-10	10
						15	-5	5
						30	10	-5
Harrow tine (CT)	TI015	-5	15	100	20	7.5	-10	10
Disk, tandem (RT)	TI044	-10	50	100	50	15	-5	5
Drill, no-till (NT)	TI045	0	20	20	10	5	1	-2

3.2.2. Evaluation of the CSM -CERES-Wheat model

3.2.2.1. Statistical indexes for model evaluation

The performance of the model was determined using several indexes applied to comparing estimates (Ei) against measurements (Mi) data.

The evaluation of the CERES-Wheat is essentially based on the difference E_i-M_i, designated as model residual and on the correlation-regression E_i vs. M_i for anthesis and yield values.

Indexes calculated were the correlation coefficient (*r*) and the coefficient of determination (R^2), the root mean squared error (RMSE), the relative root mean squared error (GSD), modelling efficiency index (EF), coefficient of residual mass (CRM), mean bias error (MBE), mean absolute error (MAE), and Index of agreement (*d*-Index) for the predicted and observed yield and anthesis values.

The Pearson product-moment correlation coefficient (PPMD) or the well-known Pearson correlation coefficient (r) is the correlation coefficient between measured and estimated (or simulated) values defined as:

$$r = \frac{\sum_{i=1}^{n}(E_i - \overline{E}) \cdot (M_i - \overline{M})}{\sqrt{\sum_{i=1}^{n}(E_i - \overline{E})^2 \cdot \sum_{i=1}^{n}(M_i - \overline{M})^2}}$$

where E_i and M_i indicate the simulated and measured values n the number of values.

The coefficient *r* lies within the range of -1 and +1. A value of +1 indicates that there exists a perfect positive linear relationship between simulated and observed values although this does not necessarily imply having a perfect model. The main problem is that the magnitude of r cannot be consistently related to the accuracy of the model. Willmott (1982) pointed out that the main problem of r and R^2 are that they are not consistently related to the accuracy of prediction where the accuracy of a model is the closeness of simulated values versus the measured values.

To measure the accuracy of the model some indexes of squared differences were used.

1. The Root mean squared error (RMSE) is defined as the variation, expressed in the same unit of the data, between estimated and measured values (Fox, 1981):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_i - M_i)^2}{n}}$$

RMSE represents the typical size of model error because it measures the average magnitude of the error. The lowest limit of RMSE is 0, which means full adherence between model estimates and measures.

2. The general standard deviation (GSD) (Jørgensen *et al.*, 1986) is a RMSE expressed as a coefficient of variation and obtained by dividing it by the mean of the measured data.($\overline{M}$):

$$GDS = \sqrt{\frac{\sum_{i=1}^{n}(E_i - M_i)^2}{n}}\frac{100}{\overline{M}} = RMSE\frac{100}{\overline{M}}$$

3. The modelling efficiency index (EF) (Greenwood *et al.*, 1985):

$$EF = 1 - \frac{\sum_{i=1}^{n}(E_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \overline{M})^2}$$

EF values greater than 0 indicate that the model estimates are better predictors than the average measured value, whereas negative values indicating the opposite. A EF value equal or near 1 means a perfect or near perfect estimates.

To measure the tendency of the model to overestimate or underestimate the measured values two kind of statistic indexes of simple difference were used: the coefficient of residual mass (CRM) (Loague and Green, 1991) an the mean bias error (MBE) (Addiscott and Whitmore, 1987).

$$CRM = 1 - \frac{\sum_{i=1}^{n} E_i}{\sum_{i=1}^{n} M_i}$$

$$MBE = \sum_{i=1}^{n} \frac{E_i - M_i}{n}$$

For both indexes the ideal value is 0. For MBE a positive value indicates that, on average, the model over-estimates the measurements. Conversely, for a negative value the model under-estimates the measurements. By contrast a negative value of CRM indicates a tendency of the model toward overestimation (Loague and Green, 1991).

Another index considered that is based on absolute differences is the mean absolute error (MAE) (Schaeffer, 1980)

$$MAE = \sum_{i=1}^{n} \frac{|E_i - M_i|}{n}$$

MAE values near or equal to zero indicate a better match along the 1:1 line comparison of estimated and observed values.

Willmott (1981) propose an Index of agreement (d) defined as:

$$d = 1 - \frac{\sum_{i=1}^{n} (E_i - M_i)^2}{\sum_{i=1}^{n} (|E_i - \overline{M}| + |M_i - \overline{M}|)^2}$$

If the model is perfect, then observed values are equal to simulated values and *d*=1. If the model predictions are identical in all cases and equal to the average of the observed values, d=0. These limiting values are the same as for EF but the two criteria will have different values (Wallach, 2006).

3.2.2.2. Calibration of CERES-Wheat model

Calibration of CERES-Wheat model was made using data at plot level collected from the agronomic experiments already described above. This approach was applied to better use all the available soil data with the aim of obtaining more details in the calibration simulations.

Calibrations of cultivar Simeto was already done for Sardinia region by other authors (Dettori, 2006; Mereu, 2009; Dettori *et al.*, 2011) but they used data from variety trials that were conducted only under conventional tillage and in plots of approximately 10 m^2. These kind of experiments, in general, provide an overestimate of yields because it is known that no planted borders (areas between plots that are left without plants and serve as markers or walkways) generate less competitions (in water, fertilizer, radiation etc.) in borders plants and therefore they develop in better environment conditions from those in the plot's centre. As a consequence of these conditions, yields are often overestimated.

In the agronomical trials used for calibration and evaluation in this thesis, yields were measured harvesting by an experimental plot combine and making three sub-sampling of 30 m^2 at the centre of each plot to better evaluate the real field production (Fig. 32).

Fig. 32 - Harvest of a ordinary plot (10 m^2) in a variety trial (left) and overview of a field used for calibration with plots of 600 m^2 (right).

In general, calibration of a new wheat variety is made determining the seven genetic coefficients which characterize each variety in the file WHCER045.cul of the DSSAT 4.5.

In this study, a new ecotype in the WHCER045.ECO file was developed. This was done especially to adjust phenological stages. This new ecotype was then used in the WHCER045.CUL for calibrating genetic coefficients. The values of the seven genetic coefficients were obtained, using either direct observation of crop characteristics through experimental trials and by the application of an iterative procedure of "trial and error". This latter procedure minimizes the difference between measured and corresponding simulated data through a tuning of the genetic parameters of the CERES model.

The meaning of the seven coefficients calibrated in the CERES-Wheat model is resumed below:

- **P1V**, *days at optimum vernalizing temperature required to complete vernalization*. This coefficient reflects the differing vernalization requirements of varieties or rather requirements of exposure to relatively low temperatures before spikelet formation can begin. This is higher for winter wheat respect to spring wheat. Daily vernalization effectiveness are calculate considering minimun and maximum daily air temperatures. In the model spring wheat varieties have a low sensitivity to vernalization. Although vernalization is important especially for winter wheat it be considered also for spring wheat varieties with lower values of P1V (in general < 5) (Ritchie *et al.,* 1998).

- **P1D**, *percentage reduction in development rate in a photoperiod 10 hour shorter than the threshold relative to that at the threshold*. This coefficient take into account the sensitivity of varieties to photoperiod. Being a long day plant wheat reduced its development during short days. In the WHCER045.cul file it is expected to have value between 0 and 200, depending on cultivar.

- **P5** *Grain filling (excluding lag) phase duration (°C d)*. This coefficient determines the grain filling duration based on thermal time (degree days above a base temperature of 1 °C).

- **G1** *Kernel number per unit canopy weight at anthesis (n/g)*. This parameter indicates the number of kernel differentiate at anthesis per unit of canopy weight.

- **G2** *Standard kernel size under optimum conditions (mg)*.

- **G3** *Standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (g).*

- **PHINT** *Interval between successive leaf tip appearances (°C d).*

The calibration were made considering first anthesis date (days after planting, DAP) by tuning the P1V, P1D and P5 coefficients. Then the coefficients related to the grain filling characteristics (G1, G2, G3) and the PHINT coefficient considering the grain yield (kg ha^{-1} of dry matter) were calibrated.

The values of genetic coefficients used for calibration were derived from 1) literature sources (Rinaldi, 2004; Rezzoug *et al.*, 2008; Dettori *et al.*, 2011), 2) experimental trials results, and then 3) optimized through the iterative procedure.

Calibration was performed using the available dataset from the experimental site of Ussana whereas evaluation (validation) of the model were made using data from Benatzu site.

3.2.2.3. Evaluation (validation)

Validation is a term often used to refer to a procedure made for determining whether a model is adequate for its intended purpose or not. This definition emphasizes two important facts:

- a model should be judged with reference to an objective;
- the result of a procedure of validation exercise is “yes” (the model is valid) or “not” (not valid).

Except when the choice is pretty obvious, in practice this categorical decision is not so simple. For these reasons often researchers prefer to use the term *evaluation* to highlight the aim to determine the value of a model (Wallach, 2006).

To evaluate (validate) the CERES-wheat model the same set of indexes used to evaluate fitting of calibration were used. Hence different test criteria have been used to evaluate the performance of the model, e.g., r, R^2, RMSE, GSD, EF, CRM, MBE, MAE, and *d*-Index, to better understand different aspects of model agreement.

3.2.3. Climate change scenarios

In this thesis a set of 9 climate change scenarios, which results from a combination of three GCMs used to determine the standardised scenarios and three values of ΔT_G (low, intermediate, high) used to scale the standardized scenarios, was used.

The three ΔT_G values are based on following combinations of the emission scenario and climate sensitivity factor (see table 6): low estimate of ΔT_G is determined as a lowest ΔT_G value of the four main emission scenarios for the low climate sensitivity (1.5°C) and given future period; high estimate of ΔT_G is determined as a maximum ΔT_G value of the four emission scenarios for the high climate sensitivity (4.5°C); intermediate estimate of ΔT_G is determined as the average of the two intermediate ΔT_G values for the intermediate climate sensitivity (3°C). The ΔT_G was estimated for three future periods: 2025, 2050 and 2075.

The set of three GCMs used to derive the standardised scenarios include HadCM3, ECHAM5 and NCAR-PCM. These 3 GCM were chosen because of their different characteristics in simulating the present climate conditions in Mediterranean regions.

Due to the demands of the presently used CERES-Wheat crop growth model, the following 4 variables were used from the GCM outputs:

- precipitation (PREC),
- daily maximum and minimum air temperature (T_{max} and T_{min}),
- solar radiation (SRAD).

Site-specific scenarios were developed from each of the 3 GCMs. The scenarios consist of changes in monthly means of T_{max}, T_{min}, PREC and SRAD that were obtained by spatial interpolation of GCM-simulated grid-specific values.

The future values of CO_2 concentration required by the crop model were also based on the MAGICC model simulations (Tab. 6).

Tab. 6 - Changes in global mean temperature, ΔTG, calculated by the MAGICC model. Baseline period: 1961–1990; baseline CO2 level: 333 ppm. Climate sensitivities: low $\Delta T_{2\times}$ = 1.5°C; intermediate $\Delta T_{2\times}$ = 3°C; high $\Delta T_{2\times}$ = 4.5°C. The bottom row gives the low, intermediate and high values of ΔTG used in a present study. (From Mereu, 2009).

FUTURE PERIOD	**2025**				**2050**				**2075**			
Climate sensitivity (°C)	**1.5**	**3**	**4.5**	**CO_2 (ppm)**	**1.5**	**3**	**4.5**	**CO_2 (ppm)**	**1.5**	**3**	**4.5**	**CO_2 (ppm)**
SRES B1	0.4	0.66	0.84	**416.0**	0.68	1.17	1.51	**469.8**	0.93	1.64	2.17	**501.0**
SRES B2	0.45	0.74	0.93	**425.7**	0.8	1.35	1.74	**476.1**	1.14	1.97	2.59	**542.2**
SRES A1B	0.44	0.71	0.89	**437.7**	0.96	1.58	2.02	**555.2**	1.41	2.41	3.13	**631.7**
SRES A2	0.41	0.68	0.86	**432.5**	0.9	1.49	1.90	**533.3**	1.54	2.59	3.33	**705.3**
ΔT_G	**0.4**	**0.70**	**0.93**		**0.68**	**1.42**	**2.02**		**0.93**	**2.19**	**3.33**	

Hence 27 climate change scenarios are used here: 3 GCMs (HadCM3, ECHAM5 and NCAR) scaled by 3 values of ΔTG for 3 future periods (2025, 2050 and 2075).

Having the climate change scenarios, the 100-year synthetic daily weather series (values of SRAD, T_{max}, T_{min} and PREC) were produced by the stochastic weather generator M&Rfi, which was calibrated using the observed weather data and whose parameters was then modified according to the climate change scenario.

M&Rfi is a update and more flexible version of Met&Roll WG (M&Rfi = Met&Roll flexible), which is a parametric single-station 4-variate stochastic daily weather generator based on Markov chain, Gamma distribution and autoregressive model (Dubrovský, 1997; Dubrovský *et al.,* 2004).

In the present thesis synthetic weather series were developed by Martin Dubrovský. The M&Rfi's settings correspond to the latest version of Met&Roll described in Dubrovský *et al.* (2004) and thereafter used in several experiments (e.g. Trnka *et al.*, 2004a; Trnka *et al.*, 2004b): similarly to other WGs, precipitation occurrence is a primary (= generated in the first step) characteristic modelled by a two-state Markov chain (order = 0, 1, 3), precipitation amount is fitted by Gamma distribution, and solar radiation and daily extreme temperatures are modelled by first-order autoregressive model with means and standard deviations being conditioned on precipitation occurrence.

In figure 33, the scheme of using the weather generator to produce synthetic weather series representing present and future climate conditions is shown.

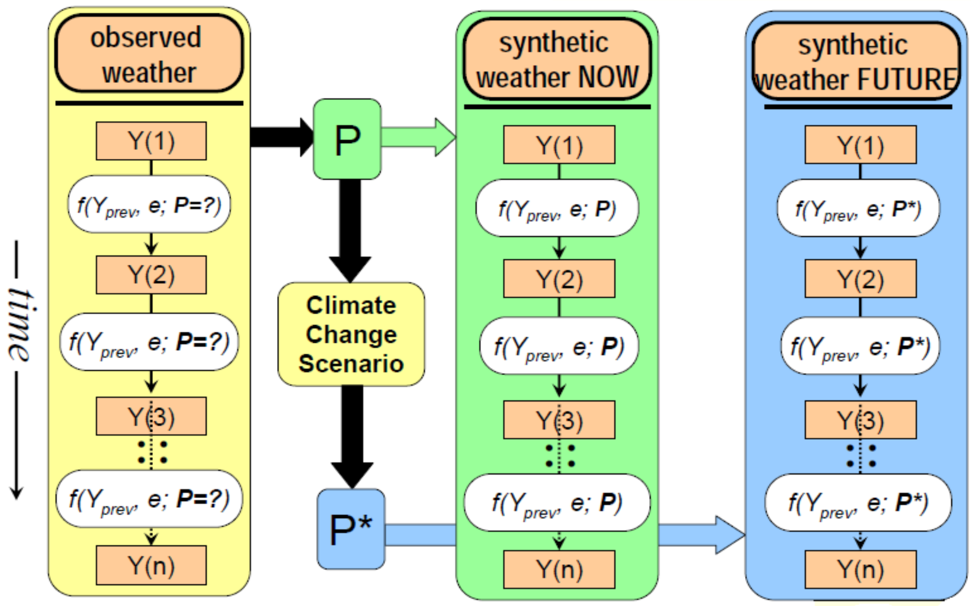


Fig. 33 - Scheme of using the weather generator Y(t) = surface weather series; f(.) = underlying model of the weather generator; e = white noise (uncorrelated random vector time series; P = set of WG parameters derived from the observed series; P* = WG parameters representing future climate and obtained by modifying P according to the climate change scenario (from Dubrovský, 2009).

3.2.4. Climate change impact assessment

The methodology for climate change impact assessment used in this thesis, was originally developed by Semenov and Porter (1995), and subsequently adapted and applied in other studies (Zalud and Dubrovsky, 2002; Trnka *et al.,* 2004; Mereu, 2009) (Fig. 34).

The method is based on the comparison of the outputs from multiannual crop growth model simulations run for a “representative” year with synthetic weather series representing present and changed climates. The “representative” year, for each treatment, resumed the crop management (planting details, fertilization regime, etc..) and soil properties, that reflect the ordinary agronomic practices applied in the experiment.

For each treatment and in each experimental site, 27 above-mentioned climate change scenarios were used (low, middle and high versions of 3 GCM–based scenarios for the 3 future periods).

For each climate change scenario, a 99-year simulation with synthetic series was carried out considering a fixed value of CO_2 (380 ppm) and also considering a projected level of CO_2 concentration in the atmosphere for a respective period.

Therefore, indirect effect of increased CO_2 concentration (related to changed weather conditions) and a combination of both direct (or CO_2-fertilisation effect) and indirect effect of increased CO_2 concentration on crop yields, was evaluated.

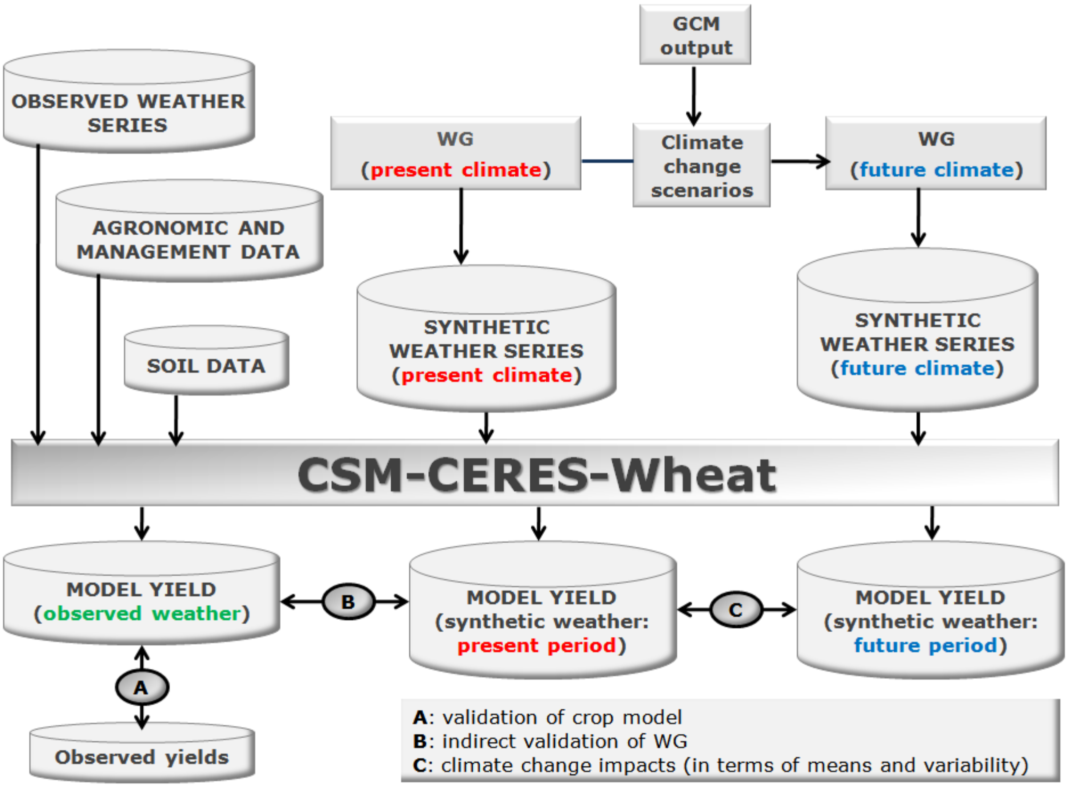


Fig. 34 - Scheme of methodology (modified from Dubrovský, 2009).

The resultant yields and anthesis dates under present and changed climate conditions were analyzed using the statistical program GenStat v.12. A two-way analysis of variance (ANOVA) for crop managements × climatic scenarios was applied. Means were compared using the Tukey's Multiple Test at the 5% of significance level.

3.2.4.1. Weather Generator validation

The indirect validation of the weather generator was made by comparing statistical properties of crop model output characteristics (crop yield and anthesis) simulated by CERES-Wheat with observed weather data versus outputs obtained with synthetic weather series for current period generated by the weather generator.

CERES-Wheat model simulations were run in the two experimental sites, with 34-year observed weather series and 99-year synthetic weather series using the same "representative" year as in the climate change impact assessment.

Yields and anthesis simulated with synthetic weather series were compared to those simulated with the observed weather series. The Student’s *t*-Test was performed using the GenStat v.12 software, for both equal or unequal variance.

3.2.5. Adaptation strategies evaluation

In this thesis different management options were tested as adaptation and mitigation strategies.

A first assessment can be made using the results of the study of the impacts of climate change with the application of different combinations of crop management of durum wheat that has been considered.

Secondly several adaptation strategies were evaluated. In particular will be considered:

- the effect related to variation of planting date in order to provide useful technical advice to farmers to tackle climate change with practices that can be easily and immediately applied (*variation in planting date*);
- the effect associated with the use of a virtual variety (with early or late anthesis) with the aim of providing useful information to breeders for genetic improvement of durum wheat (*simulations implying genetic improvement*).

Concerning the variation in planting date, starting from the planting date of the “representative year” (D), for each treatment and for each site (similarly to the study of climate change impacts), the 99-year crop model were run for the different climate scenarios and different values of CO_2 considering two early planting dates (D-20 days and D-40 days) and one later date (D+20 days).

The simulations implying genetic improvement were applied modifying genetic coefficients of Simeto obtained in calibration in order to obtain two virtual cultivar:

- “*Early Simeto*” that under current conditions, reaches the stage of anthesis with seven days prior respect to the current cultivar;
- “*Late Simeto*” that under current conditions, reaches the stage of anthesis with seven days later respect to the current variety.

In order to obtain these varieties the P1D genetic coefficient, already calibrated for the Simeto cultivar, was modified and calibrated using a synthetic climatic series of current climate and the “representative year” already used for climate change impacts. An iterative procedure of "trial and error" was followed for tuning the P1D with the aim to obtain the advance and delay of anthesis for the two virtual cultivars.

4. RESULTS

In this chapter the results obtained in this study will be presented in different section as following summarized:

- **Agronomic section**. Statistical analyses of results obtained in the experimental trials to understand management × environment interactions;
- **Crop modelling section.** Calibration and evaluation of the CSM-CERES-Wheat model considering an measure of production (yield) and a phenological stage (anthesis);
- **Climate change section.**

  In this last section will be shown:
    - analysis of climate trends in the study area;
    - analysis of climate change scenarios composed by three GCMs (HadCM3, NCAR-PCM and ECHAM5), three climate change scenarios (low, mid and high) that depend on climate sensitivity and emission scenarios, and three future periods (2025, 2050, 2075);
    - validation of the Weather Generator utilized to obtain climate change scenarios;
    - analysis of climate change impacts using the 27 climate change scenarios developed and considering first the indirect effect of increased CO_2 concentration (changes in temperatures, solar radiation and precipitation) and then both indirect and direct effect of increased CO_2 concentration (CO_2 fertilization) on yield and anthesis;
    - adaptation strategies evaluation, consisting on agronomic practices, sowing date shift and virtual simulation of genetic improvement.

4.1. AGRONOMIC SECTION

In this section results from the analyses of the data obtained during the experimental trials in the time span 2004-2009 (five years) will be presented.

Statistical analyses were performed considering all years and each location (Ussana and Benatzu) separately, to study the effect of conservation tillage in comparison with conventional tillage and the differences between reduced and no-tillage. In the same analyses were considered the effect of preceding crop (wheat or legumes) and the interaction with tillage over years were considered.

4.1.1. Statistical analyses

Since results of field experiments were analyzed separately for each location, first will be presented the results obtained at Ussana followed by the results for Benatzu.

Ussana

The mean grain yield obtained in five years in Ussana was 1.97 t ha^{-1} that is a production slightly lower to the long term (1973-2004) yield registered (about 2.5 – 3 t ha^{-1}). This is probably due to the lower amount of precipitation recorded in average between October to June periods during the five years considered (360.6 mm) respect to the average for the same months recorded over the long-term period (394.9 mm). In fact, in these environments, characterized by low precipitations, rainfall play an important role in determining grain yields.

Grain yield was highly variable in different years and this is probably due to the different meteorological conditions: in the growing season 2007/08, characterized by low rainfall (192 mm from October to June), mean grain yields were the lowest (0.90 t ha^{-1}) of the five years considered (Tab. 7).

Yields obtained with different tillage techniques are not significantly different: this is true for conservation vs. conventional tillage or between conservation tillage management. On the other hand, the effect of precession with legumes (or rotation effect) was highly significant: with continuous wheat crops were obtained yields of 1.76 t ha^{-1} while the precession with legumes determines higher grain yields (2.19 t ha^{-1}). The interaction rotation × years ($p \leq 0.001$) and rotation × tillage practices ($p \leq 0.05$) show a varying response over the years and the complex relationships between tillage and rotations. At Ussana the reduced tillage management seems to be advantaged in precession with legumes (2.32 t ha^{-1}) with respect to continuous wheat (1.67 t ha^{-1}) (Tab. 8).

Tab. 7 - Statistical analysis of results of 5 years from Ussana site.

	Grain yield (t ha^{-1})	Heading (DAP)	Plant height (cm)	Number of spikes (n. m^{-2})	Test weight (kg hl^{-1})	1000-kernel weight (g)	Protein content (% d.m.)	Gluten Index (%)
Year (A)	***	***	**	***	***	***	***	***
2004/05	2.68	107.8	64.9	251.4	77.6	39.8	14.0	81.8
2005/06	1.50	117.5	65.9	205.9	77.1	42.2	12.9	68.3
2006/07	2.58	111.3	79.1	222.5	76.6	37.6	12.7	73.5
2007/08	0.90	101.1	63.0	147.1	67.0	27.0	15.8	56.1
2008/09	2.21	86.0	66.3	230.3	78.2	39.7	11.4	77.5
Tillage (B)	**n.s.**	***	**n.s.**	**n.s.**	*	**n.s.**	**n.s.**	**n.s.**
Conventional vs conservation T.	***n.s.***	***	***n.s.***	***n.s.***	*	***n.s.***	***n.s.***	***n.s.***
conventional	1.95	103.5	67.5	213	76.1	37.7	13.3	72.4
conservation tillage	*1.98*	*105.3*	*68.0*	*211*	*75*	*37.1*	*13.4*	*71.0*
NO-Tillage vs reduced Tillage	***n.s***	**	***n.s***	***n.s***	***n.s***	***n.s***	***n.s.***	***n.s***
reduced tillage	1.99	104.9	68.1	211	75.0	37.2	13.4	70.7
NO-Tillage	1.98	105.8	67.9	210	74.8	37.0	13.3	71.2
Precession (C)	***	***	**	***	**n.s.**	**n.s.**	**	**n.s.**
Wheat	1.76	105.3	66.9	199	75.5	37.3	13.1	71.7
Legumes	2.19	104.2	68.8	224	75.1	37.2	13.6	71.2
Interaction A × B	**n.s.**	***	**n.s.**	**n.s.**	*	**n.s.**	**n.s.**	**n.s.**
Interaction A × C	***	**	**n.s.**	***	***	**n.s.**	**n.s.**	**n.s.**
Interaction B × C	*	**n.s.**	**n.s.**	*	**	**	**n.s.**	*
(Conventional vs conserv. Till.) × C	n.s	n.s.	n.s.	n.s.	**	***	n.s.	**
(NO-Till vs reduced Till) × C	**	n.s.	n.s.	**	n.s.	n.s.	n.s.	n.s.
Interaction A × B × C	**n.s.**	**n.s.**	**n.s.**	***	**n.s.**	*	**n.s.**	**n.s.**
mean	**1.97**	**104.7**	**67.8**	**211**	**75.3**	**37.3**	**13.4**	**71.4**
CV	*13.1*	*1.1*	*4.0*	*6.6*	*1.7*	*5.4*	*5.5*	*7.5*

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001**

Considering the number of spikes per m^{-2}, which is an important component of production, there are several common aspects with trends of grain yield: not significant differences between tillage practices were observed whereas the number of spikes is larger after precession with legumes (224 spikes m^{-2}) respect to continuous wheat (199 spikes m^{-2}). The same significant interaction was observed years × precession and tillage × precession.

The tillage practices applied did not affect plant height and no significant interactions between years, tillage and rotations were observed. Significant ($p \leq 0.01$) difference in plant height was observed in years probably due to different meteorological conditions over years. The precession with legumes led to a significant increase in plant height. On average, plants cultivated after legumes are significantly ($p \leq 0.01$) higher (68.8 cm) than plants cultivated in continuous wheat conditions (66.9 cm). This effect is more conspicuous in conventional tillage (Tab. 8).

Tab. 8 - Results for tillage and rotation treatments in Ussana: CW = continuous wheat; LW = rotation legumes-wheat.

Agronomic management		**Grain yield (t ha^{-1})**	**Heading (DAP)**	**Plant height (cm)**	**Number of spikes (n. m^{-2})**	**Test weight (kg hl^{-1})**	**1000-kernel weight (g)**	**Protein content (% d.m.)**	**Gluten Index (%)**
Conv. tillage	**CW**	1.77	103.8	66.0	196	76.9	38.9	12.9	74.7
	LW	2.14	103.2	69.0	230	75.2	36.4	13.7	70.1
Reduced tillage	**CW**	1.67	105.4	67.4	195	75.0	36.6	13.2	69.8
	LW	2.32	104.3	68.8	227	75.0	37.7	13.6	71.5
NO-tillage	**CW**	1.82	106.6	67.2	204	74.7	36.4	13.3	70.4
	LW	2.13	105.1	68.6	217	74.9	37.5	13.4	72.0
LSD (p=0.05)		*0.25*	*0.8*	*2.2*	*14.4*	*1.4*	*2.3*	*0.7*	*4.5*

The number of days from planting to anthesis, expressed in DAP (DAP= Days After Planting), were different both for tillage and rotations with high level of significativity ($p \leq 0.001$). Trends of this parameter were diversified over years as demonstrated by the significativity of years ($p \leq 0.001$) and the interactions: years × tillage ($p \leq 0.001$) and years × precession ($p \leq 0.01$). In these experiments was observed that conservation tillage tends to lengthen crop cycle: on average, it needs 105.3 days to achieve anthesis with conservation tillage and 103.5 days with conventional tillage. Sod seeding tends to lengthen crop cycle more than reduced tillage (105.8 and 104.9 days to reach anthesis respectively). These results could be explained as an adaptation response of durum wheat to dry environments where plants tend to shorten phenological phases in order to complete their life cycle before occurring water stress. Under these conditions, it could happen that the application of different tillage can modify the water retention curve, and that the water content of soils where conservation tillage is applied is higher than in conventional tillage.

Test weight and 1000-kernel weight are important grain quality parameters. They have similar trends because they are dimensional parameters of kernels. In general test weight values lower to 78 kg hl^{-1} are considered as indices of poor grain quality. The mean value of test weight is different for years and depends on meteorological condition.

The lowest value was registered for the season 2007/08, when kernels were shrunk due to the dry spring conditions. Significant ($p \leq 0.05$) higher test weight for conventional (76.1 kg hl^{-1}) respect to conservation tillage (75.0 kg hl^{-1}) were observed whereas there were no significant differences between the two conservation techniques. Accordingly, there were no significant differences in test weight between crop precessions. This parameter varies over years and there were some significant interactions: years × precession ($p \leq 0.001$), years × tillage ($p \leq 0.05$), and tillage × precession ($p \leq 0.01$). This shows that the trends of test weight strongly depend on meteorological conditions that interact with treatments applied. Focusing on the interaction between tillage and rotation, the combination of conventional tillage with continuous wheat determined the highest value (76.9 kg hl^{-1}) of test weight whereas no significant differences between other agronomic practices were observed (Tab. 8).

The same considerations can be extended to the 1000-kernel weight parameter. Again, yields and grain quality are affected by the meteorological characteristics of the specific year. A significant interaction ($p \leq 0.01$) was observed for tillage practices × rotation. With the application of conventional tillage with continuous wheat the highest value of 1000 kernel weight (38.9 g) was observed.

Protein content of kernels is a parameter of at most importance for durum wheat. An high protein content of kernels are required to process semolina into a final pasta product. Another important parameter for durum wheat is the Gluten Index (G.I.) (ICC Standard 158). This is a index of gluten strength and one of the most important of technological quality as far as pasta making is concerned. High G.I. values, corresponding to a strong gluten, are considered positively in terms of pasta making (D'Egidio *et al.,* 1990).

Protein content was variable over the years with a high value in 2007/08 (15.8 %). Nevertheless high values of protein content, as seen in 2007/08, are often associated with low values of the test weight (67 kg hl^{-1}), 1000-kernel weight (27.0 g) and the Gluten Index (56.1 %). These results remark the poor quality of production obtained in this year. In fact, in 2007/08 low yields and shrivelled kernels were definitely due to the scarcity of spring rains. When grains are shrivelled the protein content is high but their quality is bad owing to low content of starch. The poor grain quality is confirmed by the low Gluten Index.

In this experiment the only treatment that statistically influenced positively protein content was the precession with legumes (13.6% versus 13.1% obtained with continuous wheat) ($p \leq 0.01$). No significant interactions were observed for the protein content between factors in study.

Also for G.I. a significant ($p \leq 0.05$) interaction between tillage practices and rotations was observed. Moreover G.I. was significantly higher with conventional tillage combined with the continuous wheat cultivation (74.1%) compared to rotations with legumes. On the other hand, in the case of reduced tillage and sod seeding were not observed differences between different rotations.

Benatzu

Mean grain yields obtained at Benatzu in the field experiments from 2004/05 to 2008/2009 was 2.7 t ha^{-1} (Tab. 9). As for Ussana the mean yield in this period is lower than the long term yields observed in this site (from 3.5 to 4.5-5 t ha^{-1}) in the last twenty years. Again the lower amounts of precipitation (especially in the year 2007/08) probably play an important role in causing these low levels of productivity.

As reported for Ussana, grain yields were strongly different over the years because of the environmental conditions: the low amount of precipitation occurred in the year 2007/08 (especially from February to May) determined low grain yields (0.57 t ha^{-1}) that, despite the same meteorological conditions, were lower respect to yields obtained in the same year in the Ussana site (0.9 t ha^{-1}). This is probably due to higher silt content at Benatzu compared to Ussana which causes difference in water retention curves between the two sites. The higher silt content in Benatzu reduces the water availability for durum wheat roots and so, in years characterized by very low precipitations, the plants tend to suffer at Benatzu an higher water stress than at Ussana.

Different tillage techniques did not influence grain yields: the lower yields obtained with the application of reduced tillage technique (2.58 t ha^{-1}) are not statistically different from yields obtained either with conventional tillage or sod seeding (respectively 2.79 and 2.76 t ha^{-1}). The effect linked to previous crop was highly significant ($P \leq 0.001$) with higher production obtained with rotation with legumes (2.95 t ha^{-1}) respect to continuous wheat (2.48 t ha^{-1}). The beneficial effect of rotation with legumes was not the same over the years as it is evident from the significant interaction ($p \leq 0.01$) year × precession.

Spikes density varies over the years. As for grain yields, significant differences in spikes density for different tillage practices were not observed. Instead, precession with legumes determines a significant ($p \leq 0.01$) higher density of spikes (225 spikes m^{-2}) respect to continuous wheat (225 spikes m^{-2}). No interactions between years, tillage and rotation for this variable of productivity were observed.

Tab. 9 - Statistical analysis of results of 5 years from Benatzu site.

	Grain yield (t ha^{-1})	**Heading (DAP)**	**Plant height (cm)**	**Number of spikes (n. m^{-2})**	**Test weight (kg hl^{-1})**	**1000-kernel weight (g)**	**Protein content (% d.m.)**	**Gluten Index (%)**
Year (A)	***	***	***	*	***	***	***	***
2004/05	4.15	104.8	73.4	268.8	80.7	51.4	11.8	88.5
2005/06	3.14	117.6	72.6	249.9	79.8	47.9	11.4	73.7
2006/07	2.29	112.4	75.9	193.0	76.0	39.1	12.7	70.2
2007/08	0.57	99.2	61.9	155.4	68.5	26.3	15.3	53.8
2008/09	3.41	85.1	71.5	215.9	81.1	48.2	11.1	71.2
Tillage (B)	**n.s.**	***	**n.s.**	**n.s.**	***	**n.s.**	*	*
Conventional vs conservation T.	***n.s.***	***	***n.s.***	***n.s.***	***	***n.s.***	***n.s.***	*
conventional	2.79	102.0	70.7	227	78.0	43.0	12.3	73.8
conservation tillage	*2.67*	*104.7*	*71.2*	*211*	*76.8*	*42.4*	*12.6*	*70.3*
NO-Tillage vs reduced Tillage	***n.s***	***	***n.s***	***n.s***	*	***n.s.***	***	***n.s.***
reduced tillage	2.58	103.6	71.0	211	77.2	43.1	12.3	70.9
NO-Tillage	2.76	105.9	71.4	212	76.5	41.6	12.8	69.8
Precession (C)	***	***	***	**	*	**n.s.**	***	**n.s.**
Wheat	2.48	104.1	69.9	208	77.5	43.0	12.1	71.6
Legumes	2.95	103.5	72.2	225	77.0	42.2	12.8	71.3
Interaction A × B	**n.s.**	***	**n.s.**	**n.s.**	*	**n.s.**	**n.s.**	**n.s.**
Interaction A × C	**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**
Interaction B × C	**n.s.**	**n.s.**	***	**n.s.**	***	**	***	**
(Conventional vs conserv. Till.) × C	n.s	n.s	***	n.s.	***	**	***	**
(NO-Till vs reduced Till) × C	n.s	n.s	n.s.	n.s.	**	*	n.s.	*
Interaction A × B × C	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s**	**n.s.**	**n.s.**	**n.s.**
mean	**2.71**	**103.8**	**71.0**	**217**	**77.2**	**42.6**	**12.5**	**71.5**
CV	*17.9*	*0.6*	*2.8*	*13.2*	*1.6*	*6.6*	*6.3*	*7.1*

n.s., *, **, * = not significant, significant respectively at $p \leq 0.05$, $p \leq 0.01$, $p \leq 0.001$**

Despite a slight variability of the height of the plants in the years, with lowest plants in 2007/08 (61.9 cm), this trait was not influenced by the application of different tillage techniques. However, the application of different rotation influenced plant height. In particular, rotation with legumes determined taller plants (72.2 cm) than continuous wheat (69.9 cm). The effect of rotation interacted ($p \leq 0.001$) with tillage techniques and the higher rotation effect was observed in conventional tillage respect to conservation tillage techniques (see tables 9 and 10).

Tab. 10 - Results for tillage and rotation treatments in Benatzu: CW = continuous wheat; LW = rotation legumes-wheat.

Agronomic management		Grain yield (t ha^{-1})	Heading (DAP)	Plant height (cm)	Number of spikes (n. m^{-2})	Test weight (kg hl^{-1})	1000-kernel weight (g)	Protein content (% d.m.)	Gluten Index (%)
Conv. tillage	**CW**	2.54	102.0	68.1	213	79.0	44.5	11.4	76.3
	LW	3.04	101.9	73.3	241	77.0	41.5	13.1	71.3
Reduced tillage	**CW**	2.48	103.9	70.8	205	77.6	43.7	12.0	71.3
	LW	2.69	103.3	71.3	217	76.8	42.5	12.5	70.4
NO-tillage	**CW**	2.41	106.3	70.7	207	75.9	40.7	12.8	67.3
	LW	3.11	105.5	72.1	217	77.1	42.5	12.9	72.2
LSD (p=0.05)		*0.42*	*0.8*	*2.0*	*24.8*	*0.9*	*2.2*	*0.6*	*5.1*

In the environmental of the experiment, time between sowing and anthesis, expressed in days after planting, was influenced by the year, tillage and rotation with a high level of statistical significativity ($p \leq 0.001$) whereas no significant interaction between these factors was observed. As for Ussana, the conservation tillage techniques tend to lengthen crop cycle. With conservation tillage, on average, it took 104.7 days from planting to anthesis compared to 102 days with conventional technique. Considering the two kinds of conservation tillage, the no-tillage technique, tends to lengthen the crop cycle more than the reduced tillage (105.9 and 103.6 days to reach the anthesis from sowing respectively) (Tab. 9).

Grain quality parameters were influenced by years, tillage and rotation and a significant interaction between them was often observed. The numerous significant interactions between factors in study show that there are complex relations between them that are difficult to foresee.

Test weight and 1000-kernel weight show the same trends. A significant variability over the years and the worst values were obtained in the year 2007/08 whit a mean of 68.5 kg hl^{-1} and 26.3 g for test weight and 1000-kernel weight respectively. These results account for the poor grain quality of that year, as already seen for Ussana. Test weight was different in response to tillage: the mean value of test weight with the application of conventional tillage (78.0 kg hl^{-1}) was significantly higher compared to 76.8 kg hl^{-1} obtained with conservation tillage ($p \leq 0.001$). Considering sod seeding and reduced tillage, the former showed lower mean value (76.5 kg hl^{-1}) statistically different to 77.2 kg hl^{-1} observed in the latter. This trend was different in the years as can be deduced by the significant ($p \leq 0.05$) interaction year × tillage. Accordingly a statistical significant ($p \leq 0.05$) an higher value of test weight was obtained with continuous wheat (77.5 kg hl^{-1}) compared to precession with legumes (70.0 kg hl^{-1}). Again a highly significant ($p \leq 0.001$) interaction tillage × rotation was registered. In table 10 the complex relations between the two factors can be seen. While for conventional tillage with continuous wheat a significant higher mean value (79.0 kg hl^{-1}) respect to precession with legumes (77.0 kg hl^{-1}) was obtained, with conservation tillage the rotation effect is different: for reduced tillage there were not significant difference between rotation whereas for sod seeding the rotation effect was opposite respect to conventional (75.9 kg hl^{-1} with continuous wheat compared to 77.1 kg hl^{-1} with legumes as previous crop).

The same trends were observed for 1000-kernel weight although less conspicuous. Indeed, differences between mean values obtained with tillage and rotation are not significant, whereas their interaction was significant ($p \leq 0.05$). The combination of continuous wheat and conventional tillage induces the highest 1000-kernel weight (44.5 g), whereas a opposite rotation effect was observed with sod seeding: a higher mean value of 1000-kernel weight was obtained with legumes as previous crop (42.5 g) than for continuous wheat cultivation (40.7 g).

Protein grain content was influenced by year, tillage and rotation. The highest mean value obtained in the year 2007/08 (15.3%) is not a good value of the index of grain quality since it was due to shrunk seeds with low semolina yield. Moreover, the low value of G.I. (53.8%) confirms the low grain quality obtained in this year. The tillage technique that induces the highest protein content in kernels was sod seeding (12.8%). This value was significantly higher than conventional and reduced tillage (12.3%). The beneficial effect of legumes as previous crop has been confirmed by the protein content of kernels (12.8%

with legumes compared to 12.1% with continuous wheat cultivation). Combined effects of tillage and rotation are complex as underscored by the highly significant interaction ($p \leq 0.001$) between them. The rotation effect is higher with conventional tillage (13.1%) with legumes as previous crop, compared to 11.4% obtained with continuous wheat cultivation. Oppositely, with conservation tillage the rotation effect was not significant (Tab. 10).

Similarly to Ussana, Gluten Index varies over the years. The highest mean value of G.I. was obtained with conventional tillage (73.8%) significantly higher respect to conservation tillage techniques (70.3%). In this field experiment a significant interaction ($p \leq 0.01$) tillage × rotation was observed. An opposite rotation effect was registered among conventional and no tillage. In fact, with no tillage the highest G.I. was obtained with legumes as previous crop (72.2% compared to 67.3 with continuous wheat cultivation). In the case of conventional tillage, the best values were obtained with continuous wheat cultivation (76.3%). With reduced tillage no significant differences between the two rotation considered were registered.

4.2. CROP MODELING SECTION

In this section the results of the CSM-CERES-Wheat model calibration and evaluation will be shown. Calibration was made using dataset from Ussana and Benatzu in the years 2004/05 and 2008/09 whereas evaluation was performed with results in 2005/06 and 2007/08 experimental trial.

Will be exposed the principal indexes for evaluating the CSM-CERES-Wheat model calibration and evaluation for the variety Simeto with different agronomic practices applied.

First of all will be explained the calibration. After will be reported the indexes for individual combination of tillage practices (CT=Conventional Tillage, RT=Reduced Tillage, NT=No-Tillage) with the two type of rotation (CW=Continuous Wheat and LW= Legumes-Wheat rotation) applied obtained from the field experiments conducted in 2004/05 and 2008/09.

Afterwards will be showed the evaluation of the model using the dataset of 2005/06 and 2007/08 field experiments.

To evaluate the calibration and evaluation of the CSM-CERES-Wheat model were considered two variables: a variable of development (anthesis expressed as day after planting - DAP) and a variable of growth (yield).

4.2.1. Calibration

The calibration of the model was performed using data plots from the Ussana and Benatzu experimental trials for the years 2004/05 and 2008/09. The year 2006/07 was excluded because of characterized by pathological problems due to root rot problems probably caused by *Fusarium* spp., and. *Gaeumannomyces graminis* Von Arx var. *tritici* Walker.

The statistical indexes related to yield and anthesis calibration are shown in table 11.

Tab. 11 – Statistical indexes for the calibration of CSM-CERES-Wheat model related to grain yield (t ha^{-1}) and anthesis (DAP=day after planting) obtained using data plot.

Calibration		Yield (t ha^{-1})		Anthesis (DAP)	
		OBS	SIM	OBS	SIM
Mean	**Mean**	2.78	2.80	102.7	101.0
Standard deviation	**SD**	0.94	0.78	9.9	7.7
Minimum	**Min**	1.25	1.70	89.0	90.0
Maximum	**Max**	5.33	4.32	117.0	110.0
Number of samples	**N**	72		72	
Pearson coefficient	**r**	0.86***		0.97***	
Coefficient of	**R^2**	0.74		0.95	
Root Mean Square Error	**RMSE**	0.48		3.31	
General standard	**GSD (%)**	17.0		3	
Modeling Efficiency	**EF**	0.93		0.96	
Mean Bias Error	**MBE**	0.02		-1.65	
Mean Absolute Error	**MAE**	0.38		2.54	
Coefficient of Residual	**CRM**	-0.01		0.02	
Index of agreement	**d-Index**	0.98		0.99	

*** $p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$; ns=not significant.**

Generally the indexes obtained in calibration are better for anthesis than for yield.

The mean value of days after planting simulated for anthesis (101days) is slightly lower compared to the mean of observed values (102.7 days). Values of standard deviation for simulated anthesis are lower (7.7) respect to observed data (9.9).

The Pearson's r value (r = 0.97) is very good and significant for $p<0.001$. The coefficient of determination R^2 indicates that 95% of the total variation is explained by the model. The graphic of comparison between observed and estimated anthesis are shown in figure 35.

The equation of the linear regression of simulated values vs. observed values indicates a pretty good correlation with a slope of 0.76 and an intercept of 23.

The RMSE index value is fairly low (3.31 days) and the percentage of the general standard deviation too (3%). This index indicates that the model works well in simulating the anthesis that is one of the most important phase for durum wheat.

Values of the modelling efficiency index (EF = 0.99) and of the index of agreement (d-index = 0.98) confirm the good concordance between values observed and values estimated by the CSM-CERES-Wheat model, although the positive value of the coefficient of residual mass (CRM = 0.02) indicates a slight tendency of the model to underestimate the appearance of anthesis expressed in days after planting (ADAP).

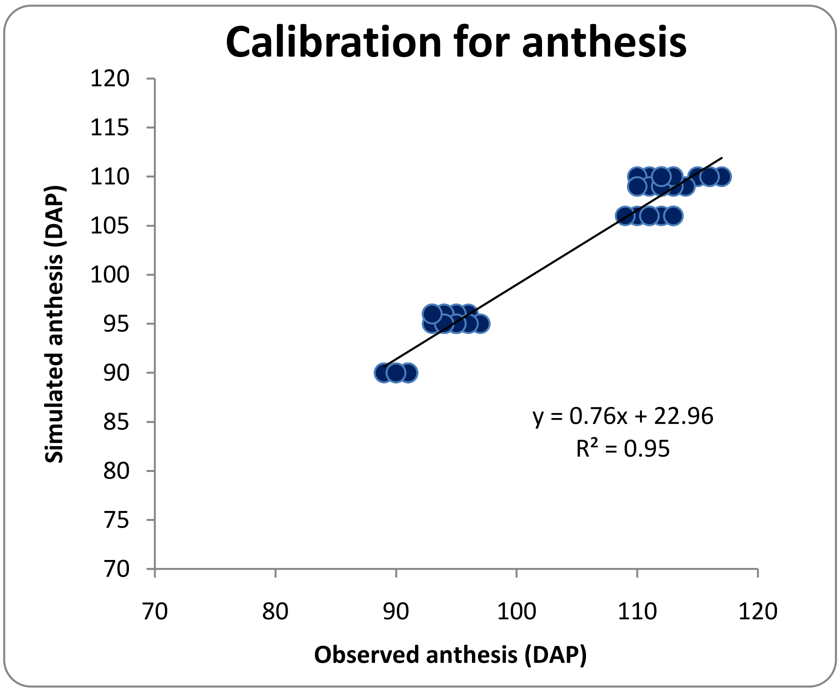


Fig. 35 – Calibration of anthesis. The data used come from trials conducted in 2004/05 and 2008/09 and are expressed in days after planting (DAP).

Considering yields, the mean of estimated yields (2.80 t ha^{-1}) are slightly higher than the mean of observed values (2.78 t ha^{-1}). The standard deviation of simulated yields are lower (0.78 t ha^{-1}) than observed (0.94 t ha^{-1}) so the model tends to reduce the variability of simulated yields respect to variation observed in fields.

The coefficient of Pearson (r), with a value of 0.86, is significant for $p < 0.001$ for a number of samples of 72. The coefficient of determination R^2 explains about 74% of the total variation. Figure 36 shown the fairly good correlation between simulated and observed data with the equation of the linear regression. Slope (b = 0.71) and intercept (a = 0.80) are less good than those obtained for anthesis, but are quite satisfactory.

Considering the indices based on differences between estimated and observed data there were obtained a low value of RMSE (0.48 t ha^{-1}) that associated at a relatively low value of the GSD index of 17% permit to affirm that it has been obtained a good calibration. The low negative value of CRM (-0.01) confirm a good calibration although there is a slight tendency of the model to overestimate yields.

Modelling efficiency index (EF=0.93) and the Index of agreement (d-index = 0.98) confirm good predictive capacity of the model.

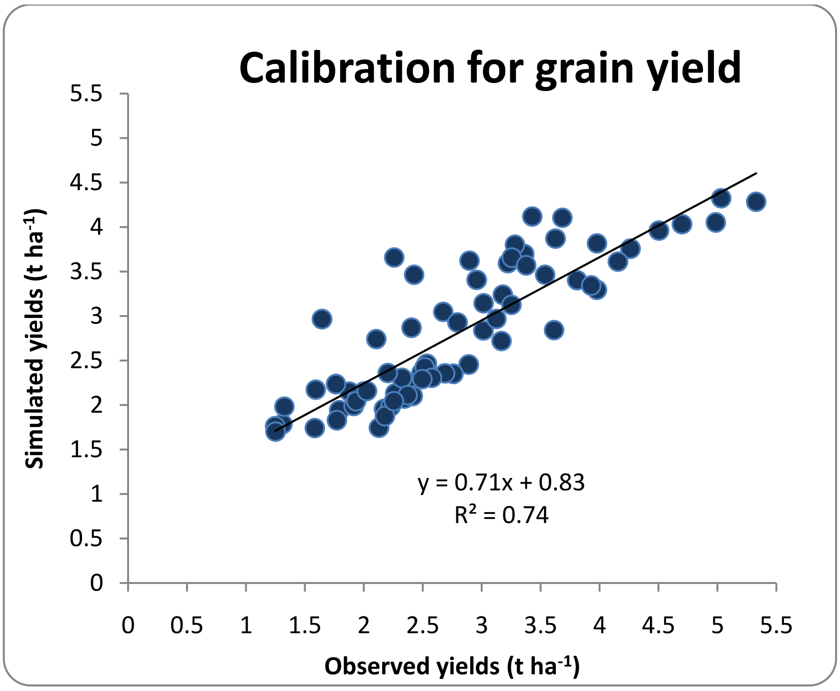


Fig. 36 – Calibration of yield. The data used come from trials conducted in 2004/05 and 2008/09 and are expressed in t ha^{-1}.

In the figure 37 are represented graphics of calibration considering the combinations of agronomical practices between tillage and different rotations. Graphics and statistical indexes are pretty good. The variances explained by the model is fairly good except for the continuous wheat cultivated with reduced tillage (R^2= 0.45). Grain yields means obtained by the model are closer to means obtained in the four experimental years considered (Tab. 12), except for continuous wheat with reduced tillage (2.64 t ha^{-1} simulated compared to 2.35 t ha^{-1} observed) and with conventional tillage (2.72 t ha^{-1} simulated compared to 2.43 t ha^{-1} observed).

Tab. 12 - Grain mean yields simulated and observed in calibration.

Agronomic practices		Simulated yield (t ha^{-1})	Observed yield (t ha^{-1})	Differences
NO-tillage	**CW**	2.76	2.83	-0.07
	LW	3.03	3.14	-0.11
Reduced tillage	**CW**	2.64	2.35	0.29
	LW	2.92	2.89	0.03
Conv. tillage	**CW**	2.72	2.43	0.29
	LW	2.93	3.03	-0.10

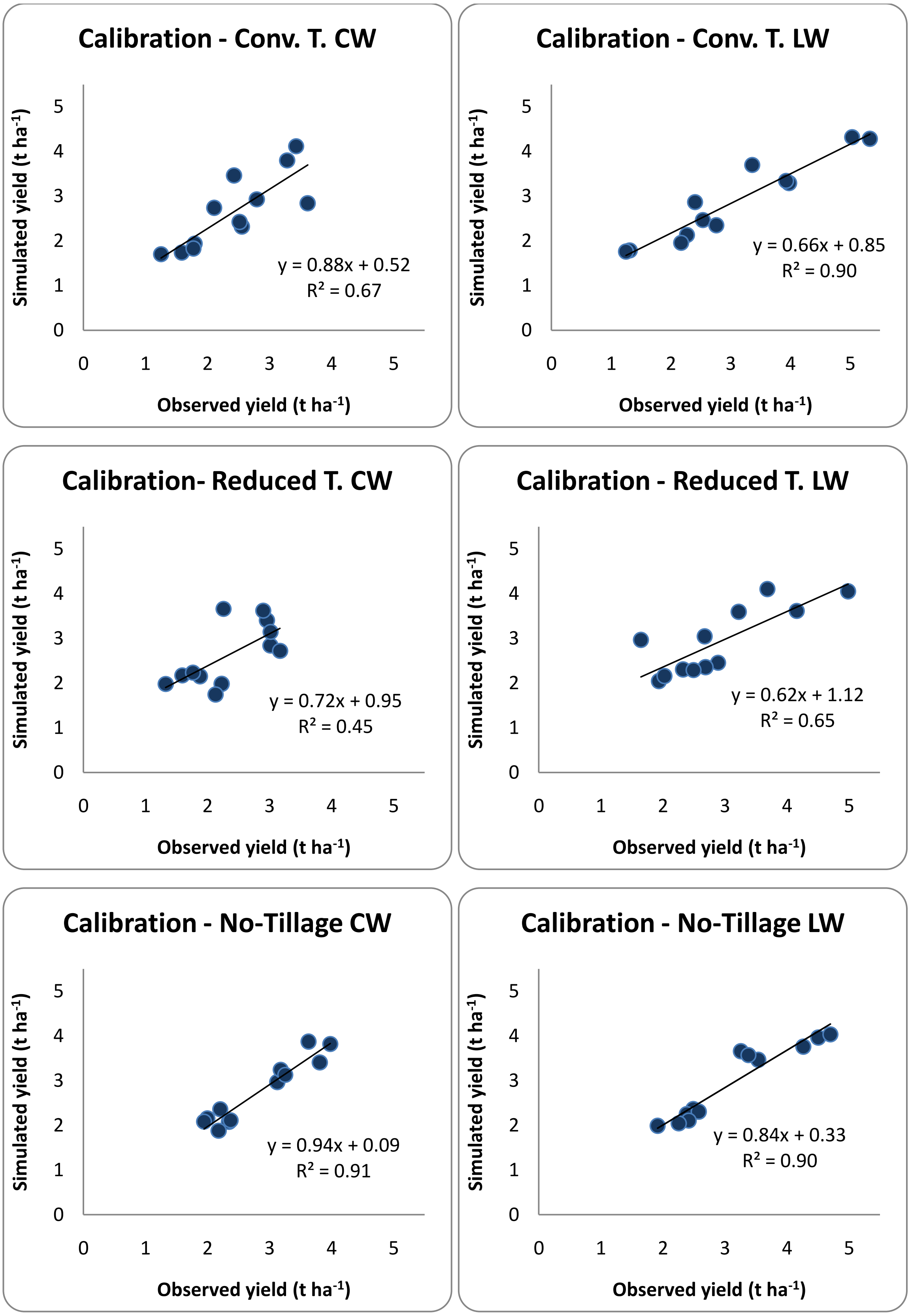


Fig. 37 – Calibration of yield for individual practice management (t ha^{-1}).

4.2.2. Evaluation

As for calibration, statistical indexes obtained in model evaluation are better for anthesis than for grain yield (Tab. 13).

Tab. 13 – Statistical indexes for the evaluation of CSM-CERES-Wheat model related to grain yield (t ha^{-1}) and anthesis (DAP=day after planting) obtained using data plot.

Evaluation		**Yield** (t ha^{-1})		**Anthesis** (DAP)	
		OBS	**SIM**	**OBS**	**SIM**
Mean	**Mean**	1.37	1.53	116.3	118.0
Standard deviation	**SD**	1.00	0.99	8.9	8.4
Minimum	**Min**	0.17	0.10	104.0	109.0
Maximum	**Max**	4.37	4.01	128.0	127.0
Number of samples	**N**	72		72	
Pearson coefficient	**r**	0.87***		0.98***	
Coefficient of	**R^2**	0.77		0.95	
Root Mean Square Error	**RMSE**	0.52		2.56	
General standard	**GSD (%)**	37.7		2.2	
Modeling Efficiency	**EF**	0.73		0.92	
Mean Bias Error	**MBE**	0.16		1.71	
Mean Absolute Error	**MAE**	0.41		2.15	
Coefficient of Residual	**CRM**	-0.11		-0.01	
Index of agreement	**d-Index**	0.93		0.98	

*** $p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$; ns=not significant.**

The mean value of days after planting simulated for anthesis (118 days) is slightly higher than observed values (116.3 days). Values of standard deviation for simulated and observed data are closer: 8.4 days for simulated compared to 8.9 days for observed.

The Pearson's r value (r = 0.98), is very good and significant for p <0.001. The coefficient of determination R^2 indicates that 95% of the total variation is explained by the model. The graphic of comparison between observed and estimated anthesis are shown in the figure 38.

The equation of the linear regression of simulated values vs. observed values indicates a good correlation with a slope of 0.92 and an intercept of 11.07.

The RMSE index value is fairly low (2.56 days) and the percentage of the general standard deviation too (2.2%). Low values of this index indicates the low level of error of the model in predicting the appearance of anthesis.

Values of the modelling efficiency index (EF = 0.98) and of the index of agreement (d-index = 0.99) confirm the good concordance between values observed and values estimated by the model. The low negative value of CRM (-0.01) confirm a good calibration although there is a slight tendency of the model to overestimate yields.

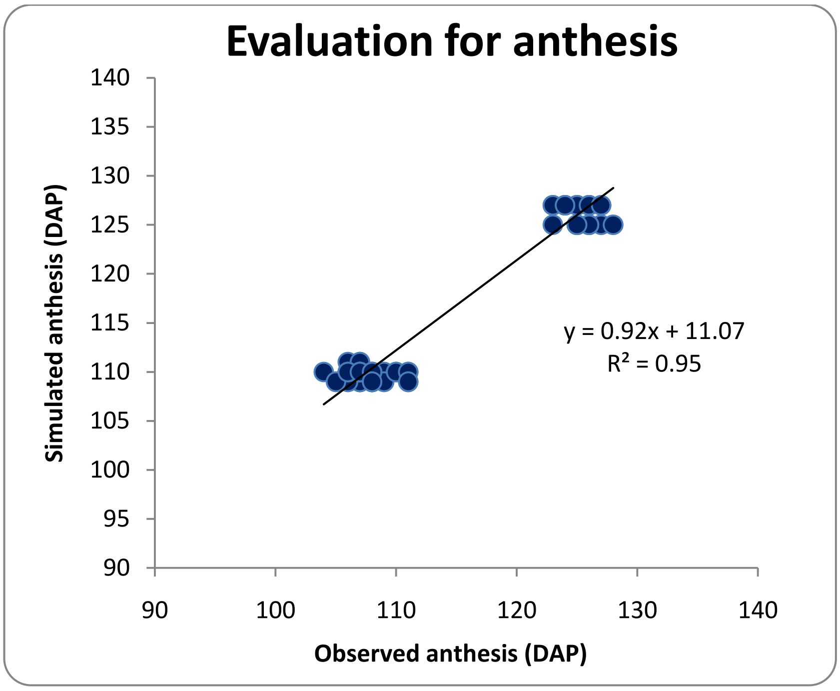


Fig. 38 – Evaluation of model for anthesis. The data used come from trials conducted in 2005/06 and 2007/08 and are expressed in days after planting (DAP).

The mean of estimated yields (1.53 t ha^{-1}) are slightly higher than the mean of observed values (1.37 t ha^{-1}). The standard deviation of simulated values (0.99 t ha^{-1}) is closer to observed (1.00 t ha^{-1}). The coefficient of Pearson (r), with a value of 0.87, is significant for $p<0.001$ for a number of samples of 72. The coefficient of determination R^2 explains about 77% of the total variation. In the figure 39 are shown the good correlation between simulated and observed data with the equation of the linear regression. Slope (b = 0.86) and intercept (a = 0.33) are less good than these obtained for anthesis.

The statistical indexes based on differences between estimated and observed data show a low value of RMSE (0.51 t ha^{-1}) that, associated at a relatively low value of the GSD index of 37%, permit to affirm that it has been obtained a good calibration. The negative value of CRM (-0.11) point out a slight tendency of the model to overestimate yields.

Modelling efficiency index (EF=0.74) and the Index of agreement (d-index = 0.93) confirm good predictive capacity of the model.

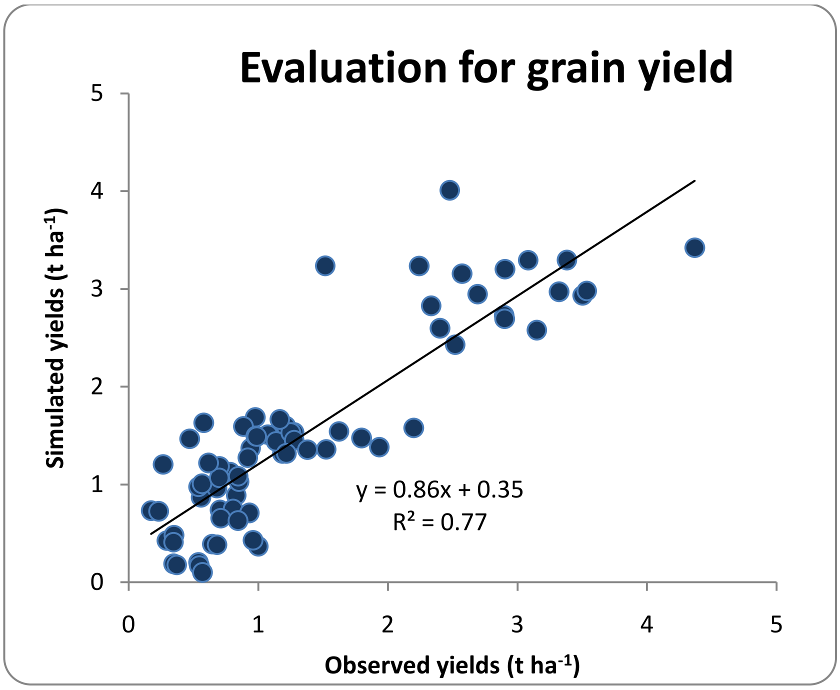


Fig. 39 – Evaluation of model for grain yield. The data used come from trials conducted in 2005/06 and 2007/08 and are expressed in t ha^{-1}.

As for the calibration, in the figure 40 are represented graphics of evaluation considering the all combinations of agronomic practices between tillage and rotations. Again, graphics and statistical indexes are pretty good. The variances explained by the model is fairly good except for the continuous wheat cultivated with conventional tillage (R^2= 0.62). Grain yields means obtained by the model are closer to means obtained in the four experimental years considered (Tab.14) except for continuous wheat with reduced tillage (1.64 t ha^{-1} simulated respect to 1.37 t ha^{-1} observed) and conventional tillage (1.61 t ha^{-1} simulated respect to 1.27 t ha^{-1} observed).

Tab. 14 - Grain mean yields simulated and observed in evaluation.

Agronomic practices		Simulated yield (t ha^{-1})	Observed yield (t ha^{-1})	Differences
NO-tillage	**CW**	1.33	1.23	0.10
	LW	1.67	1.55	0.12
Reduced tillage	**CW**	1.64	1.37	0.27
	LW	1.38	1.33	0.05
Conv. tillage	**CW**	1.61	1.27	0.34
	LW	1.54	1.49	0.06

Summarizing, the results obtained for model calibration and evaluation are very good for anthesis, as shown by several statistical indexes considered. So, the model can be evaluated to be able to simulate correctly the phenological phases of durum wheat development.

More complex is the evaluation of the model capability to simulate yields. In general, in the conditions of this study, it has been observed that the model tends to simulate correctly grain yields, although, considering the combination of agronomic practices, for continuous wheat management, with conventional and reduced tillage, tends to overestimate grain yields.

For these reasons, in the following analysis on climate change impacts, only the combination of agronomic practices that gave reliable results in this conditions both in calibration and in evaluation will be considered, i.e. the continuous wheat with NO-tillage practice and rotation with legumes crops for all tillage practices considered.

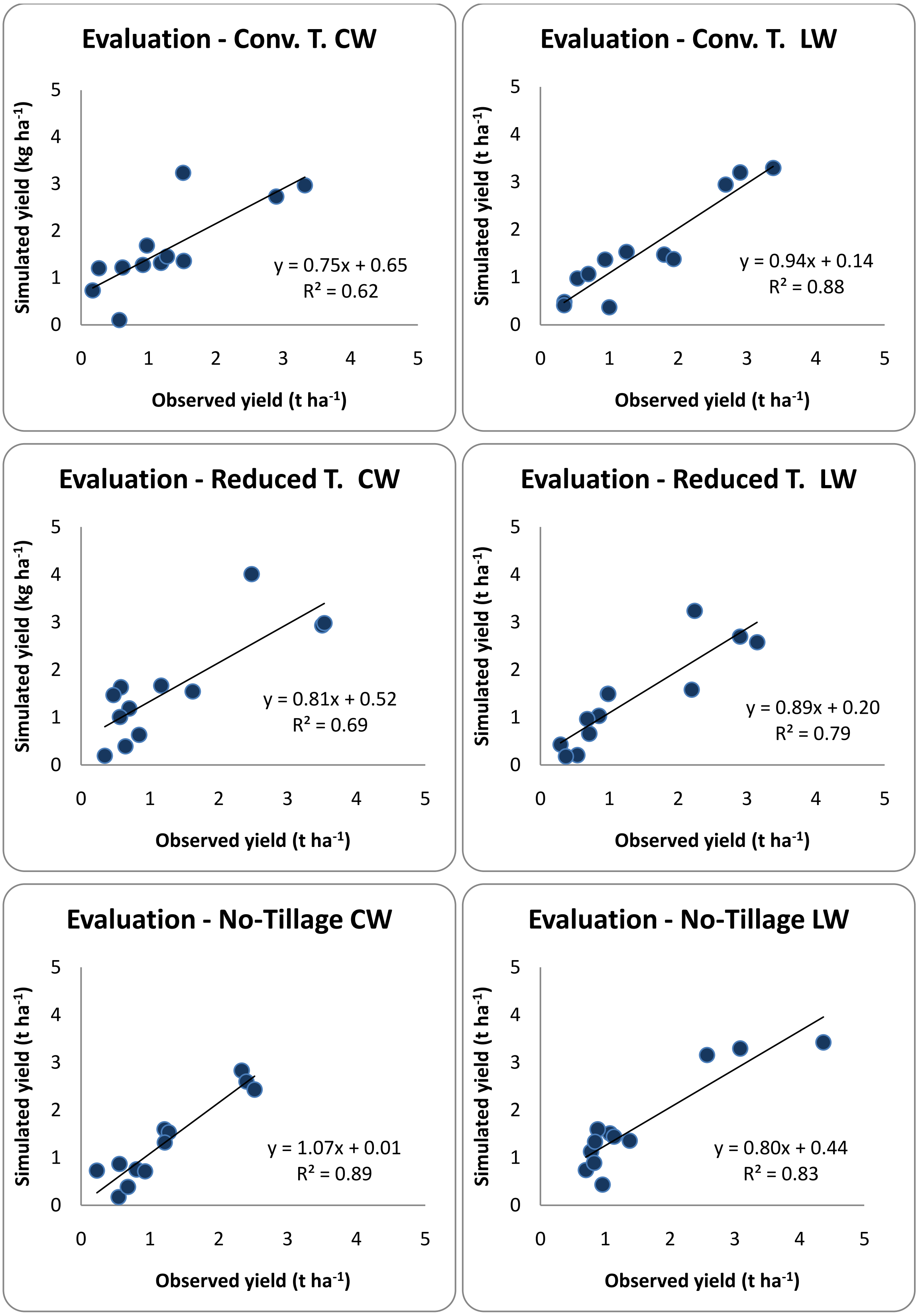


Fig. 40 – Evaluation of yield for individual practice management (t ha^{-1}).

4.3. CLIMATE CHANGE SECTION

This section shows the results of the analyses performed about climate change scenarios and their impacts on durum wheat.

First of all will be exposed the climatic characteristics of the study site and trends of some key climate variables (maximum and minimum air temperature, and precipitation).

Then will be show the Weather Generator validation.

After that will be reported the analysis of climate characteristics of the 27 scenarios used in this thesis: three GCMs (Hadley, NCAR and ECHAM) for three climate change scenarios (low, intermediate and high) for three future periods (2025, 2050 and 2075). For each scenario, percentage changes in annual and quarterly precipitation and monthly differences in maximum and minimum air temperatures, in comparison to current climate, were computed.

Then will be exposed climate change impacts on durum wheat for each experimental site and management. For each site was evaluated the impact of climate change on yield and anthesis, considering all climate change scenarios. Statistical differences between scenarios and agronomic practices were analyzed by ANOVA and Tukey's Test. For grain yields, the effects of climate change impacts were analyzed separately considering the climate change impact without increasing in CO_2 atmospheric concentration (indirect effect), and climate change with projected changes in CO_2 atmospheric concentration (Indirect effect + CO_2 fertilization effect). To facilitate the interpretation of results, in graphics are also show yields simulated for each scenario compared to those simulated using the synthetic current scenario. For anthesis, the comparison was made only for fixed values of CO_2 because, as for agronomic practices, do not have effects on shift of the anthesis date.

Finally the results of several adaptation strategies will be shown. In particular, the effect of agronomic practices, the effect of variation of planting date (*variation in planting date*) and the effect of the use of virtual varieties with early or late anthesis (*simulations implying genetic improvement*) were reported. The analysis was conducted considering the three different GCMs previously described, and the only the middle climate change scenario.

4.3.1. Climate of the study site and trends

In this paragraph the results of meteorological time series analysis for Ussana site for the period 1973-2009 has been presented. The focus is on the following variables:

- Maximum air temperature, T_{max} (°C);
- Minimum air temperature, T_{min} (°C);
- Precipitation (mm).

In particular, annual averages of annual, seasonal and monthly maximum and minimum air temperatures were considered (see appendix A). For precipitation was made a statistical analysis of annual, seasonal and monthly cumulative data.

Trends of these variables are shown according to series calculated on an annual basis.

The annual analysis of meteorological data on experimental station "S. Michele" for the period 1973-2009 (resumed in the appendix) showed an annual average T_{max} of 23.0 °C with a standard deviation (σ) of 1.1 °C and a variation range between 21.1 °C (1974) and 25.5 °C (2006). The month characterized by the highest T_{max} is August with a value of 32.8 °C with a σ of 2.0 °C and variation range between 28.8 °C (1999) and 38.2 °C (2003). January with 14.9 °C recorded the lowest average monthly value of T_{max} ($\sigma = 1.7$ °C) with monthly values between 9.6 °C (1985) and 19.6 °C (2008). Seasonal values follow the characteristic of Mediterranean climate with highest values of T_{max} in Summer (31.3 °C ± 1.7) and lowest in Winter (15.8 °C ± 1.4).

Annual trends of average T_{max} of years, seasons and months were estimated by the MAKESENS Excel Template Application. In table 4 are resumed trend characteristics of annual average T_{max} were the significativity of trends is calculated by Mann–Kendall test whereas slope is estimated by Sen's method.

There were discovered increasing trends of both annual and seasonal (except for winter) with a high level of significativity (α=0.001) (Tab.15).

Tab. 15 - The statistic trends of T_{max}.

	Mann-Kendall test		Sen's slope estimate	
Time series	**Test Z**	**Signific.**	**Q**	**B**
Annual	4.72	***	0.078	21.71
Winter	1.43		0.033	15.11
Spring	5.22	***	0.132	22.50
Summer	4.80	***	0.093	29.70
Autumn	4.09	***	0.054	19.17
Jan	0.24		0.005	14.81
Feb	0.22		0.008	14.80
Mar	1.95	+	0.056	16.59
Apr	3.41	***	0.101	17.80
May	4.26	***	0.142	22.53
Jun	5.04	***	0.145	26.99
Jul	3.73	***	0.120	30.29
Aug	3.86	***	0.122	30.77
Sep	2.54	*	0.054	27.92
Oct	3.20	**	0.077	23.49
Nov	3.00	**	0.061	17.96
Dec	0.93		0.024	15.58

n.s., +, *, **, * = not significant, significant respectively at $p \leq 0.1$, $p \leq 0.05$, $p \leq 0.01$, $p \leq 0.001$.**

The trends are different for seasons, with higher values in Spring with a mean increase of 1,3 °C in ten years. The increasing trend of mean annual T_{max} values are about half of the Spring values (0.78 °C in ten years).

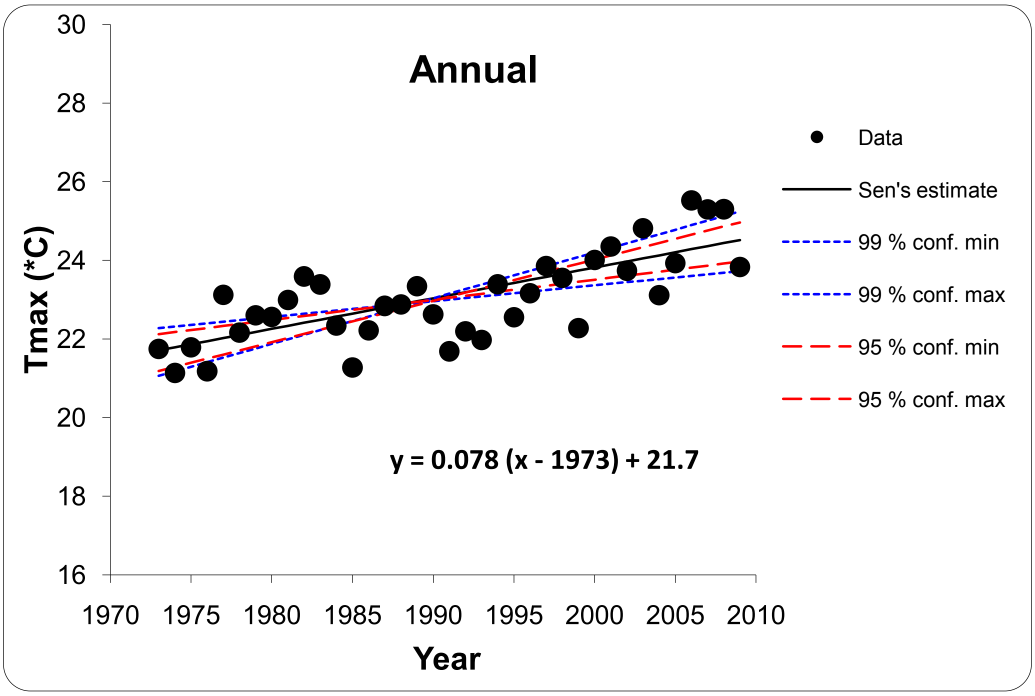


Fig. 41 - The trend of annual Tmax in Ussana site.

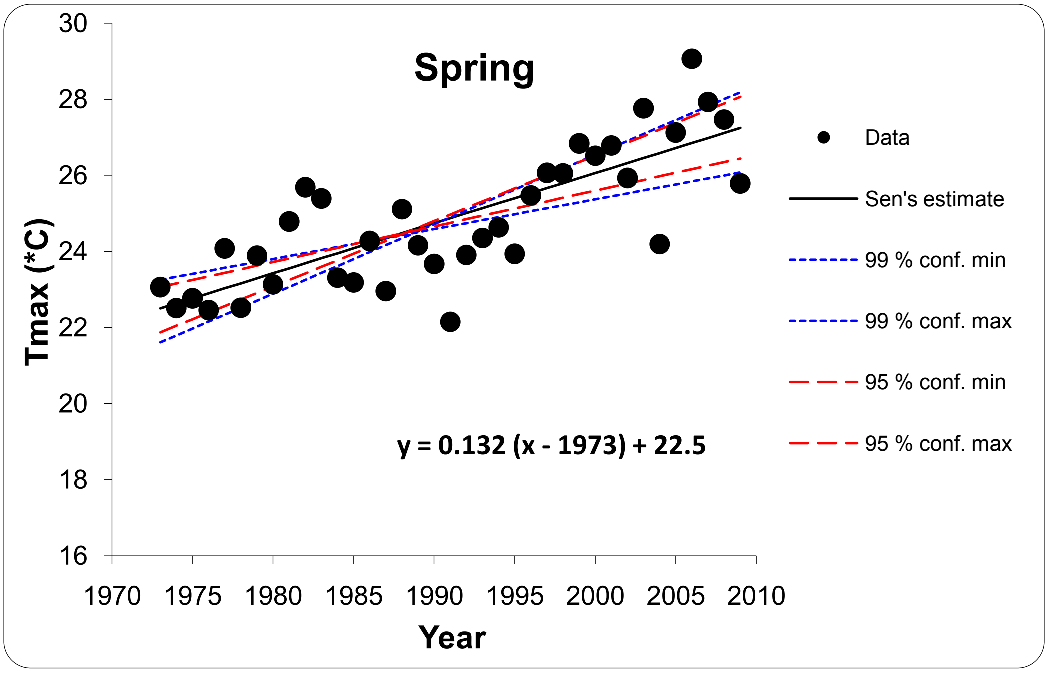


Fig. 42 - The trend of Spring Tmax in Ussana site.

The annual average Tmin in Ussana for the period considered is 10.8 °C with a standard deviation of 0.7 °C and a variation range between 9.4 °C (1985) and 12.2 °C (2006). The months characterized by the lowest T_{min} are January and February with a mean value of 4.8 °C, a σ of 1.5 °C and a variation range between 2.1 °C (January 2000) and 8.2 °C (February 1987). Seasonal values of T_{min} follow the tipical values of Mediterranean climate, with highest values in Summer (17.1 °C ± 1.2) and lowest in Winter (5.2 °C ± 1.0).

In table 16 are resumed trend characteristics of T_{min} observed in Ussana. In general trends of T_{min} are less pronounced that for values of T_{max} observed in the same period. There were observed less level of significance in trends and the annual, seasonal and monthly Sen’s slope are lower.

The increasing trend of mean annual T_{min} values (0.34 °C in ten years) are less than half of that observed for T_{max} (α=0.01). Increasing trend is more evident in Summer in which there were observed the highest observed increasing trend (0.65 °C in ten years) with a high level of significativity (α=0.001).

Tab. 16 - The statistic trends of Tmin.

	Mann-Kendall test		Sen's slope estimate	
Time series	**Test Z**	**Signific.**	**Q**	**B**
Annual	2.94	**	0.034	10.24
Winter	-1.48		-0.025	5.70
Spring	2.63	**	0.041	10.77
Summer	3.68	***	0.065	15.89
Autumn	3.20	**	0.044	8.49
Jan	-0.67		-0.017	5.28
Feb	-1.27		-0.039	5.51
Mar	-0.64		-0.016	6.04
Apr	1.05		0.024	7.42
May	1.84	+	0.040	10.60
Jun	2.94	**	0.060	13.95
Jul	2.92	**	0.075	16.24
Aug	4.43	***	0.079	16.68
Sep	2.66	**	0.049	14.95
Oct	2.29	*	0.061	11.83
Nov	2.94	**	0.052	8.14
Dec	1.43		0.024	5.73

n.s., +, *, **, * = not significant, significant respectively at $p \leq 0.1$, $p \leq 0.05$, $p \leq 0.01$, $p \leq 0.001$.**

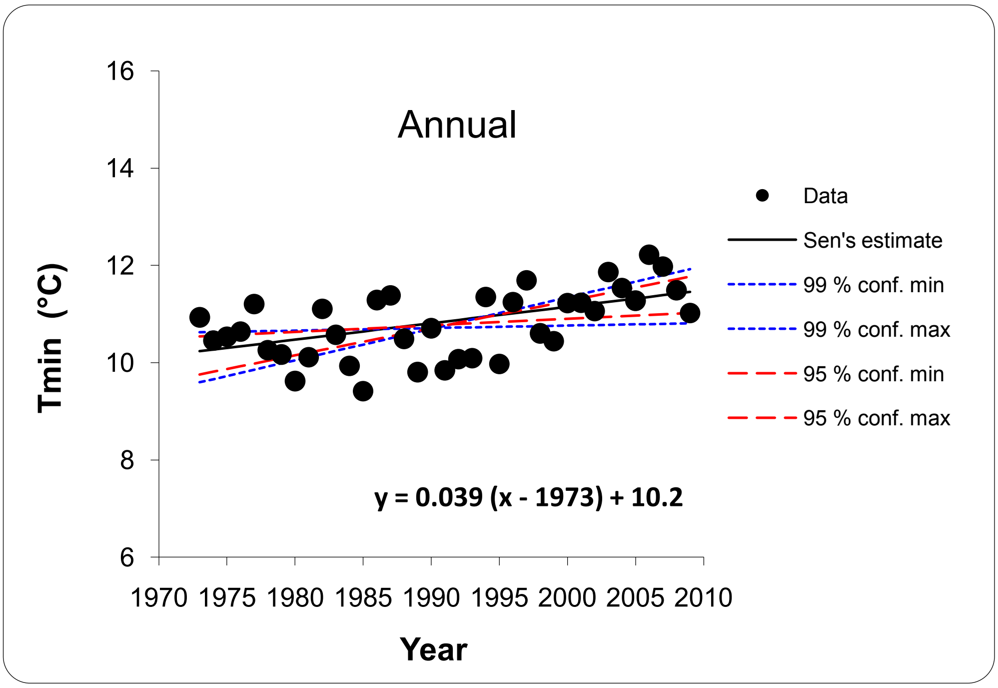


Fig. 43 - The trend of annual Tmin in Ussana site.

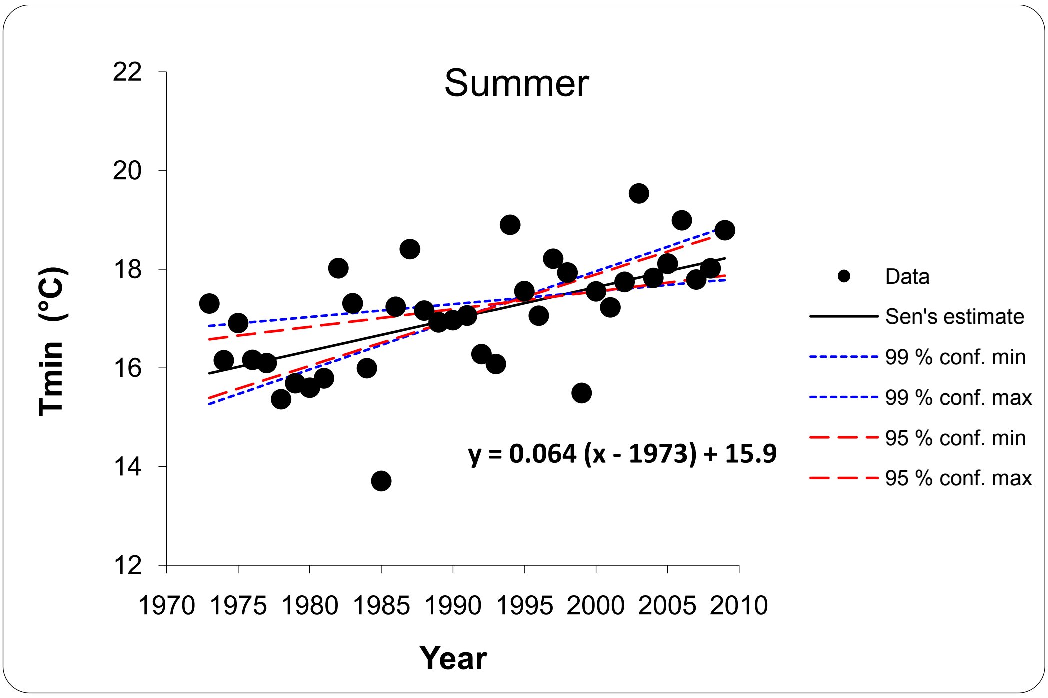


Fig. 44 - The trend of Summer Tmin in Ussana site.

The average annual rainfall amount of Ussana for the period 1973-2009 is 432 mm with large annual fluctuations (σ 136 mm). As often happens in the Mediterranean climate, the rainy season is the Autumn (174 mm) and the dry season is the Summer (46 mm). November with an average sum of 65 mm is the wettest month while July with an average amount of precipitation of 7 mm is the driest month.

There were not observed any trend in precipitation for the period 1973-2009 (Tab. 17).

Tab. 17 - The statistic trends of precipitations.

	Mann-Kendall test	
Time series	**Test Z**	**Signific.**
Annual	-0.34	n.s.
Winter	-1.60	n.s.
Spring	0.34	n.s.
Summer	0.65	n.s.
Autumn	-0.04	n.s.
Jan	-0.47	n.s.
Feb	-0.96	n.s.
Mar	-0.61	n.s.
Apr	1.10	n.s.
May	0.04	n.s.
Jun	0.56	n.s.
Jul	-0.74	n.s.
Aug	0.34	n.s.
Sep	0.69	n.s.
Oct	-1.16	n.s.
Nov	0.65	n.s.
Dec	0.71	n.s.

n.s., +, *, **, * = not significant, significant respectively at $p \leq 0.1$, $p \leq 0.05$, $p \leq 0.01$, $p \leq 0.001$.**

4.3.2. Weather Generator Validation

The weather generator validation was made by comparing crop model outputs obtained with observed vs. synthetic weather series. In particular anthesis (expressed in days after planting) and grain yield values for each experimental site, were compared.

Results for Ussana and Benatzu site are shown in Table 16. Considering the anthesis phase (expressed as days after planting) with Synthetic Weather Series (**SWS**) mean values of DAP are lightly lower than for those simulated (116.8 at Ussana and Benatzu site) using the Observed Weather Series (**OWS**) (117.1 at Ussana and 117.3 at Benatzu) but this difference are not significant for the Student *t*-Test. Standard deviation of DAP are lower for simulations performed using SWS than for OWS, although differences are not significant.

Comparing the simulations of grain yields, mean values obtained in the Benatzu site are the same for SWS and OWS, whereas the standard deviation of grain yields are lower using SWS (0.8 with SWS against 1.2 with OWS).

In the Ussana site the mean values of grain yield obtained with the SWS are lightly higher (2.8 t ha^{-1}) than those obtained with OWS (2.7 t ha^{-1}) but this difference are not significant. Standard deviation of grain yields, that is lower for SWS (0.6 t ha^{-1}) respect to yields obtained using OWS (0.9 t ha^{-1}), (Tab. 18).

Tab. 18 - The Weather Generator validation in terms of crop model-simulated yield (t ha^{-1}) and anthesis (DAP) for Ussana e Benatzu site obtained with observed weather series (Obs. WS) and synthetic weather series (Synt. WS). Results for Student's *t*-test (α=0.05) are shown.

		Obs.WS (N=34)		Synt.WS (N=99)		Student's *t*-Tests	Two-tailed test p-value
		AVG	STD	AVG	STD		
Benatzu	**Anthesis** (DAP)	117.3	4.5	116.8	2.9	-1.40	0.164
	Yield (t ha^{-1})	4.7	1.2	4.7	0.8	-0.12	0.906
Ussana	**Anthesis** (DAP)	117.1	4.4	116.8	2.9	-0.78	0.436
	Yield (t ha^{-1})	2.7	0.9	2.8	0.6	0.79	0.431

4.3.3. Climate change scenarios

This paragraph is about the analyses performed on climate data and scenarios.

First will be shown the analyses of annual and monthly mean changes in precipitations (mm) from current to future periods for the three GCMs (HadCM3, NCAR-PCM and ECHAM5) and three future periods (2025, 2050 and 2075) only for climate scenarios that consider an intermediate sensitivity (3°C). Then will be reported differences in annual and seasonal precipitations from current to future periods: to improve the understanding of these graphs, the intermediate sensitivity scenario is not considered, thus in graphs were represented only the extremes (low and high) climate change scenarios.

Afterwards, will be analyzed changes in annual and monthly temperatures (maximum and minimum), from current to future periods, for the three GCMs (HadCM3, NCAR-PCM and ECHAM5) and for three future periods (2025, 2050 and 2075) only for climate scenarios that consider intermediate sensitivity. Then will be reported in graphs the differences in monthly temperatures from current to future periods: to improve the understanding of the graphs were represented only the extremes (low and high) climate change scenarios.

Finally will be shown the analyses of annual and seasonal global solar radiation (MJ m^{-2}) from current to future periods for the three GCMs (HadCM3, NCAR-PCM and ECHAM5) and three future periods (2025, 2050 and 2075) only for climate scenarios that consider an intermediate sensitivity (3°C). Then will be reported in graphs differences in annual and seasonal global solar radiation from current to future periods considering only the extremes (low and high) climate change scenarios.

4.3.3.1. Precipitation (PREC)

In table 19 are presented annual and monthly expected changes in precipitations (mm) from current to future periods, taking into account only an intermediate sensitivity for the study site.

A decrease in rainfall is expected for all months and GCMs since 2025. Considering the annual amount, a decrease in rainfall is expected for all GCMs since the 2025. The projected changes in precipitation increasing from 2025 to 2075 are appreciably lower for the NCAR GCM (-57.6 mm in the 2075) respect to HadCM3 (-100.9 mm in the

2075) and primarily ECHAM5 (-138.5 mm in the 2075). In scenarios derived from HadCM3 and especially ECHAM5, in fact, a higher diminution of rainfall respected to NCAR is expected.

If the total amount of annual precipitation is a useful general index of reduction in rainfall, it is relevant to point out that, in Mediterranean area, precipitations that occur in Spring and especially in March and April are key factor for durum wheat growth. The differences in precipitation between scenarios based on different GCMs are relevant in March and April. The expected diminution of rainfall with NCAR are the lowest respect to scenarios based on others GCMs. As an example in these months for the 2075 it is expected a reduction of only 1.5 mm of precipitations for NCAR respect to 26 mm of HadCM3 and 32.6 mm of ECHAM5 that can cause appreciable reduction in grain yields.

Tab. 19 - Annual and monthly changes in precipitation (mm) from current to future periods with the three GCMs with intermediate climate sensitivity.

	Now (1973-2009) (mm)	**2025**			**2050**			**2075**		
		ECHAM5	HadCM3	NCAR	ECHAM5	HadCM3	NCAR	ECHAM5	HadCM3	NCAR
Year	**432.4**	**-63.7**	**-48.9**	**-34.0**	**-102.9**	**-75.6**	**-46.4**	**-138.5**	**-100.9**	**-57.6**
Jan	**42.3**	-3.6	-3.2	-2.1	-5.8	-5.1	-2.9	-8.0	-7.0	-3.8
Feb	**47.3**	-5.0	-3.4	-4.2	-8.6	-5.6	-7.2	-12.1	-7.8	-10.1
Mar	**40.3**	-5.9	-5.0	-0.6	-9.2	-7.5	1.3	-12.3	-10.0	3.3
Apr	**45.4**	-10.1	-8.2	-4.1	-15.5	-12.2	-4.4	-20.3	-16.0	-4.8
May	**24.8**	-3.2	-2.4	-2.5	-6.8	-5.3	-5.5	-9.9	-8.0	-8.2
Jun	**12.0**	-0.3	-1.4	-3.2	-0.7	-2.7	-5.6	-1.0	-4.0	-7.4
Jul	**3.0**	-0.6	-0.7	-0.8	-0.8	-1.0	-1.2	-1.0	-1.3	-1.5
Aug	**7.4**	-1.1	-1.4	0.0	-2.0	-2.5	0.0	-2.8	-3.4	0.0
Sep	**35.8**	-11.5	-10.6	-6.9	-17.1	-15.7	-9.1	-21.6	-19.9	-11.3
Oct	**49.0**	-7.7	-3.6	-4.2	-13.8	-6.3	-7.5	-19.3	-9.0	-10.7
Nov	**65.5**	-5.6	-3.5	1.0	-9.5	-5.5	3.6	-13.2	-7.6	6.4
Dec	**59.5**	-9.0	-5.4	-6.3	-13.0	-6.1	-7.8	-16.9	-6.8	-9.4

In figure 45 are represented graphs of annual and seasonal changes in precipitations considering the two extremes climate scenarios (with high and low sensitivity). As expected, in scenarios with high sensitivity reductions in rainfall are greater (often two times) than low sensitivity scenarios.

Reductions in rainfall augment from 2025 to 2075. Changes in precipitation projected by scenarios based on ECHAM5 and HadCM3 show the same trend, but ECHAM simulates greater reductions than HadCM3 especially for the Autumn, Winter and Spring that are seasons involved in durum wheat crop cycle. Once again it is interesting to note that scenarios based on NCAR show different rainfall reductions respect other GCMs: they are sensibly lower respect to ECHAM5 and HadCM3 from Autumn to Spring.

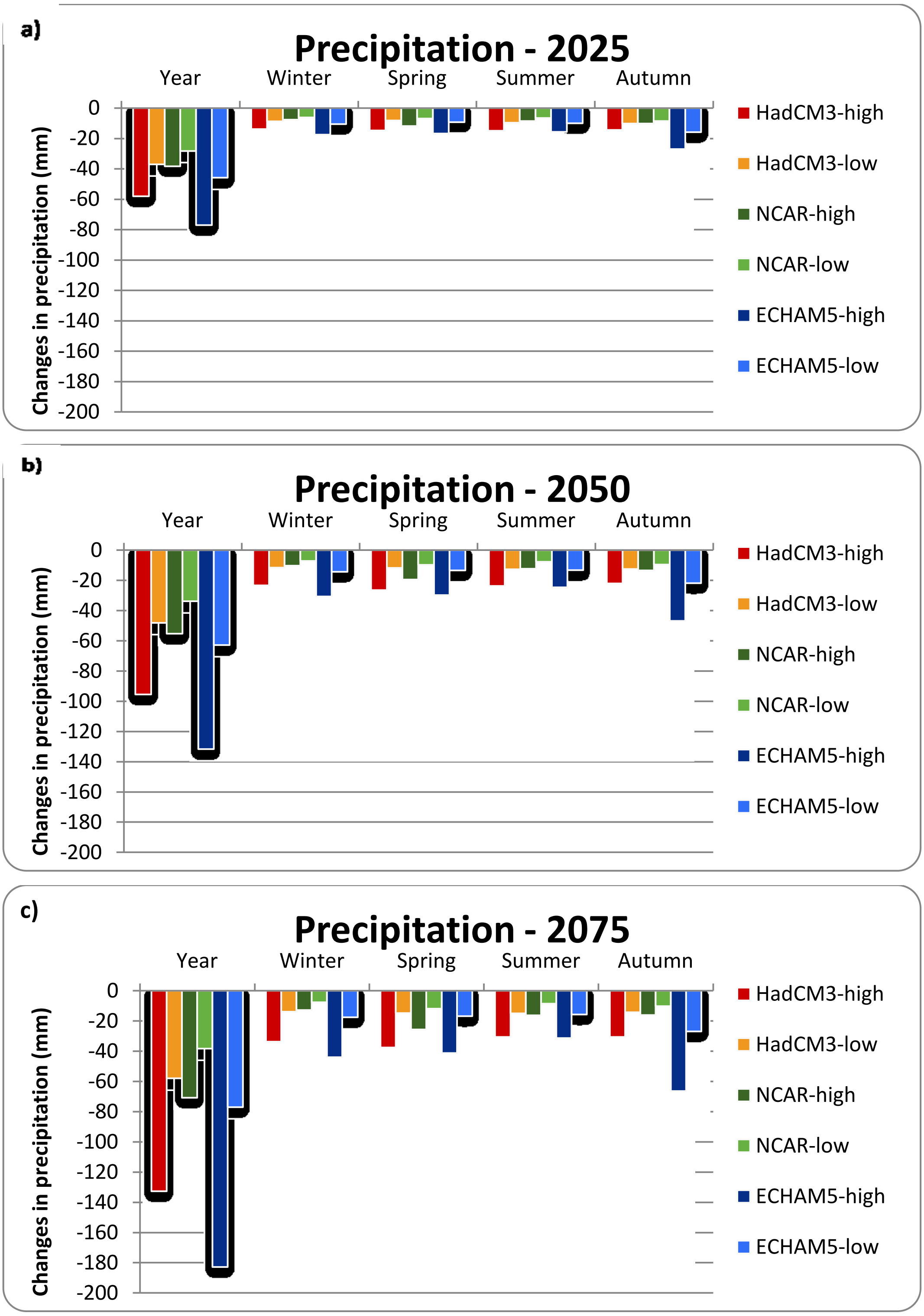


Fig. 45 – Annual and seasonal precipitation changes for current and future periods 2025 (a), 2050 (b), 2075 (c), with three GCMs and two extremes climate scenarios (high and low).

4.3.3.2. *Maximum air temperature* (T_{max})

In table 20 are represented annual and monthly expected changes in maximum air temperatures (°C), from current to future periods taking into account an intermediate climate sensitivity, for the study site.

It is expected an increase in annual T_{max} means and for all months for any GCMs starting from the 2025. Increments in T_{max} rise from 2025 to 2075 and the highest values were projected by scenarios based on NCAR-PCM. Lower increments are expected in scenarios based on ECHAM5.

The increases in T_{max} are similar for all GCMs, and considering the spring months, the higher increases are projected by NCAR. The highest increments in T_{max} during the year are expected in Summer months especially for scenarios based on HadCM3.

Tab. 20 - Annual and monthly changes maximum air temperatures (°C) from present to future periods with the three GCMs and middle climate scenario.

	Now (1973-2009) (°C)	2025			2050			2075		
		ECHAM5	HadCM3	NCAR	ECHAM5	HadCM3	NCAR	ECHAM5	HadCM3	NCAR
Year	**23.0**	**0.6**	**0.6**	**0.6**	**1.2**	**1.3**	**1.4**	**1.9**	**2.0**	**2.2**
Jan	**14.9**	0.6	0.6	0.7	1.3	1.1	1.4	1.9	1.7	2.1
Feb	**15.2**	0.8	0.8	0.9	1.3	1.4	1.6	1.9	2.1	2.4
Mar	**17.4**	0.3	0.2	0.4	0.8	0.8	1.1	1.4	1.4	1.8
Apr	**19.8**	0.6	0.5	0.6	1.1	1.1	1.2	1.7	1.6	1.8
May	**25.0**	0.5	0.6	0.7	1.0	1.2	1.4	1.6	1.8	2.2
Jun	**29.7**	0.4	0.5	0.5	1.0	1.2	1.3	1.6	2.0	2.1
Jul	**32.4**	0.7	0.8	0.9	1.4	1.7	1.7	2.2	2.6	2.7
Aug	**32.8**	0.6	0.7	0.7	1.4	1.7	1.6	2.2	2.7	2.5
Sep	**28.8**	0.8	0.9	0.7	1.6	1.9	1.5	2.4	2.9	2.3
Oct	**24.7**	0.8	0.7	0.8	1.6	1.5	1.7	2.4	2.3	2.6
Nov	**19.2**	0.7	0.7	0.7	1.4	1.4	1.5	2.1	2.1	2.3
Dec	**16.1**	0.5	0.4	0.3	1.1	1.0	0.9	1.9	1.6	1.5

In figure 46 are represented graphs of monthly changes of T_{max} taking into account the two extremes climate scenarios (with high and low sensitivity). As expected, in scenarios with high sensitivity, the increments in T_{max} are greater respect to low sensitivity scenarios. These differences are amplified from 2025 to 2075 especially for scenarios based on NCAR-PCM. The maximum differences in T_{max} in 2075 vary: this is only 1 °C for low sensitivity, and varies between 3 and 4 °C (depending on the month considered) for high sensitivity.

The highest increases are projected for summer and autumn months, whereas in winter and spring, when there are important phases of growth and development for durum wheat, the increments in T_{max} are lower.

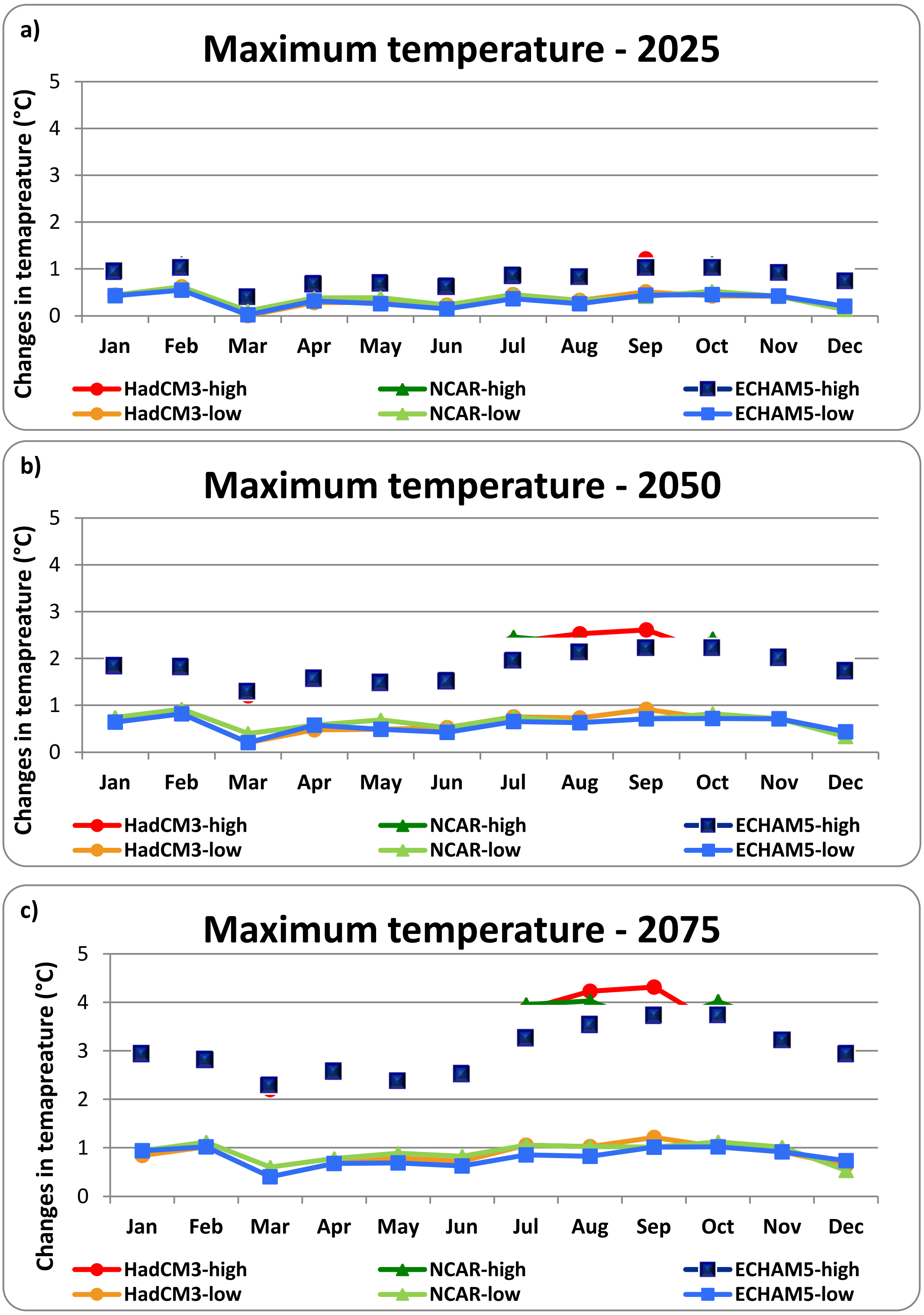


Fig. 46 – Monthly maximum air temperature changes for present and future periods 2025 (a), 2050 (b), 2075 (c), with three GCMs and two extremes climate scenarios (high and low).

4.3.3.3. Minimum air temperature (T_{min})

In table 21 are represented annual and monthly expected changes in minimum air temperatures (°C), from current to future periods taking into account an intermediate climate sensitivity, for the study site.

Trends of increase in temperature observed in Tmin are very similar to Tmax. As observed for Tmax, it is expected an increase in annual and monthly means for any GCMs starting from 2025. Annual increase in temperatures rise from 2025 to 2075 and the highest values were projected by scenarios based on NCAR whereas lower increments are expected in scenarios based on ECHAM5.

The increases in Tmax are similar for all GCMs, and taking into account winter and spring months, the higher increases are projected by NCAR. The highest increments in Tmax during the year are expected in Summer months especially for scenarios based on HadCM3.

Tab. 21 - Annual and monthly changes minimum air temperatures (°C) from present to future periods with the three GCMs and middle climate scenario.

	Now (1973-2009) (°C)	2025			2050			2075		
		ECHAM5	HadCM3	NCAR	ECHAM5	HadCM3	NCAR	ECHAM5	HadCM3	NCAR
Year	**10.8**	**0.6**	**0.7**	**0.7**	**1.3**	**1.3**	**1.4**	**2.0**	**2.1**	**2.2**
Jan	**4.8**	0.8	0.7	0.8	1.4	1.2	1.5	2.1	1.8	2.2
Feb	**4.8**	0.8	0.9	1.0	1.4	1.5	1.7	2.0	2.1	2.4
Mar	**5.9**	0.5	0.5	0.6	1.0	1.0	1.3	1.6	1.6	2.0
Apr	**7.8**	0.5	0.5	0.5	1.0	1.0	1.1	1.6	1.6	1.8
May	**11.4**	0.4	0.5	0.6	0.9	1.1	1.3	1.5	1.7	2.1
Jun	**14.9**	0.4	0.6	0.6	1.0	1.3	1.3	1.7	2.0	2.1
Jul	**17.4**	0.7	0.8	0.8	1.4	1.6	1.7	2.2	2.5	2.6
Aug	**18.1**	0.6	0.7	0.7	1.4	1.7	1.6	2.3	2.7	2.5
Sep	**15.9**	0.8	1.0	0.8	1.6	1.9	1.6	2.5	2.9	2.4
Oct	**12.9**	0.8	0.8	0.9	1.6	1.5	1.7	2.5	2.4	2.7
Nov	**8.9**	0.8	0.8	0.8	1.5	1.5	1.6	2.2	2.2	2.4
Dec	**6.2**	0.5	0.5	0.4	1.2	1.1	1.0	1.9	1.7	1.6

Taking into account the two extremes climate scenarios (with high and low sensitivity), greater increments in T_{min} with scenarios with high sensitivity are expected, respect to scenarios based on low sensitivity scenarios (Fig. 47). These differences are amplified from 2025 to 2075 especially for scenarios based on NCAR-PCM. As observed for T_{max}, the maximum differences in T_{min} in 2075 vary: this is only 1 °C for low sensitivity, and between 3 and 4 °C (depending on the month considered) for high sensitivity. The highest increases are projected for summer and autumn months, whereas in winter and spring, when there are important phases of growth and development for durum wheat, the increments in T_{max} are lower.

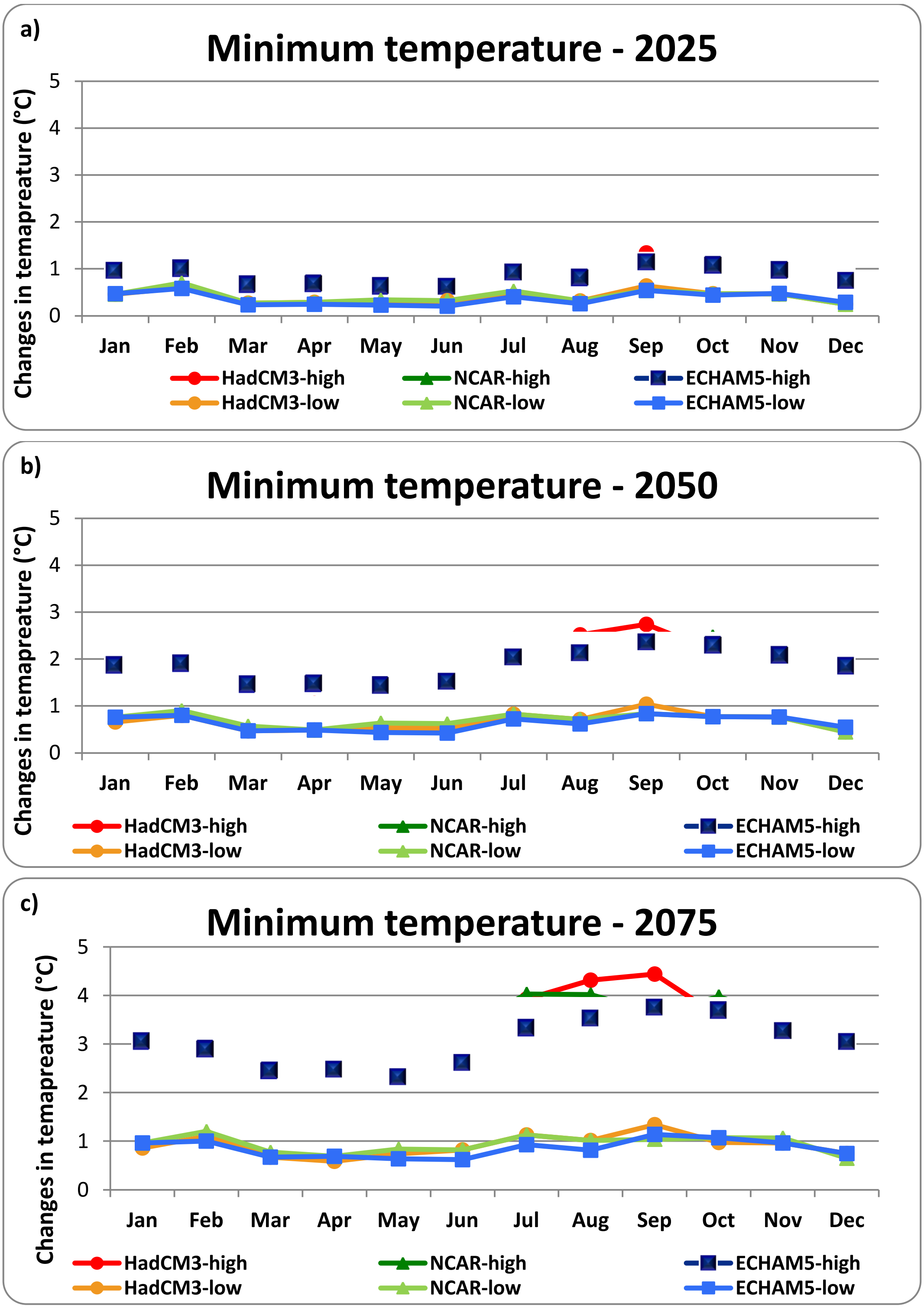


Fig. 47 – Monthly minimum air temperature changes for present and future periods 2025 (a), 2050 (b), 2075 (c), with three GCMs and two extremes climate scenarios (high and low).

4.3.3.2.Solar radiation (SRAD)

Changes in annual and seasonal global solar radiation amounts (MJ m^{-2}) are shown in table 22. In this table are summarized changes in solar radiation accumulated taking into account the three GCMs, considering intermediate climate sensitivity, respect to current values .

The highest increases in annual solar radiation are projected by HadCM3 for all future periods. Scenarios based on HadCM3 have the highest increase in seasonal solar radiation (winter and spring).

Tab. 22 – Annual and seasonal changes in global solar radiation (MJ m^{-2}) from current to future periods with the three GCMs with intermediate climate sensitivity.

	Now (1973-2009) (MJ m^{-2})	2025			2050			2075		
		ECHAM5	HadCM3	NCAR	ECHAM5	HadCM3	NCAR	ECHAM5	HadCM3	NCAR
Year	**5212.6**	**39.6**	**67.0**	**39.5**	**73.1**	**131.1**	**72.9**	**106.7**	**207.3**	**121.5**
Winter	**792.8**	9.0	9.0	5.9	18.1	15.2	11.8	27.1	24.3	23.7
Spring	**1920.8**	9.2	27.3	12.2	18.3	57.5	24.4	27.5	87.8	39.6
Summer	**1844.9**	12.2	27.7	15.3	21.3	52.3	27.5	30.5	80.0	45.9
Autumn	**654.1**	9.2	3.0	6.1	15.4	6.1	9.2	21.6	15.3	12.3

In the figure 48 are represented graphs of annual and seasonal changes in global solar radiation amount (MJ m^{-2}) considering the two extremes climate scenarios (with high and low sensitivity). In scenarios produced considering high sensitivity increase in solar radiation are greater (often three times) respect to low sensitivity scenarios.

Increments in solar radiation augment from 2025 to 2075. Changes in solar radiation projected by scenarios based on ECHAM5 and NCAR show similar trends. The highest differences in solar radiation amounts respect to current period are projected for scenarios based on HadCM3 especially for Spring which is an important season involved in durum wheat crop cycle.

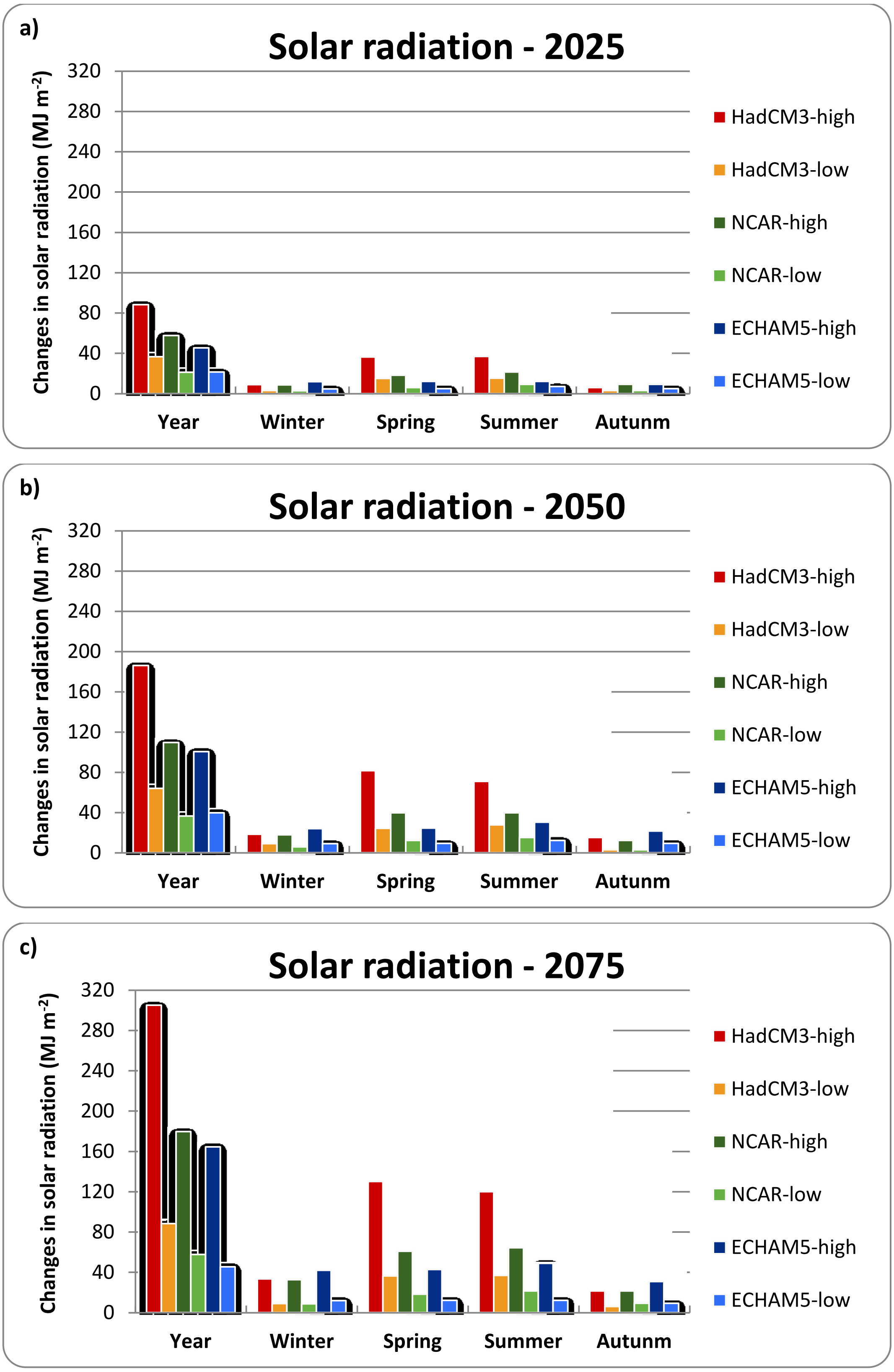


Fig. 48 – Annual and seasonal changes in solar radiation (MJ m^{-2}) for current and future periods 2025 (a), 2050 (b), 2075 (c), with three GCMs and two extremes climate scenarios (high and low).

4.3.4. Climate Change Impact Assessment

In this paragraph will be described the analyses of climate change impact results obtained in simulations of CSM-CERES-Wheat using the 27 scenarios for each experimental site.

First of all will be shown the impact of climate change on anthesis. Then will be described impacts on yield. Climate change impacts were evaluated considering the four agronomic managements calibrated with the CSM-CERES-Wheat (sod seeding with continuous wheat cultivation and all tillage managements coupled to rotation with legume), the three GCMs (ECHAM5, HadCM3 and NCAR), the three levels of climate sensitivity and emission scenarios (low, intermediate and high) and three periods (2025, 2050 and 2075).

In graphs are represented mean values to better understand trends whereas the results of statistical analyses were collected in tables in order to consider the significant differences between mean values.

Since the two experimental sites are distant about 1 km from each other, and the phenology basically being dependent on the meteorological conditions, there is no difference for anthesis between the two sites considered. Moreover this comparison was made only for fixed values of CO_2 atmospheric concentration because this factor does not have effects on the anthesis date.

The results of yields, were analysed both considering the indirect effect of CO_2 increase (that does not take into account variation in CO_2 atmospheric concentration) and the direct effect of changes in CO_2 concentration along with climate change.

4.3.4.1. Impacts on anthesis

Taking into account that the development depends mainly on temperature, for the impact study on anthesis (considering DAP – days after planting), and considering that the two study sites are distant just 1 km from each other and the weather conditions are similar, only a single study site was considered for this variable. Moreover agronomic management in crop growth models, like in the CSM-CERES-Wheat model, do not play a role in simulating development and hence on phenology. Therefore, the differences in achieving the anthesis phase between future periods, the scenarios based on the three GCMs and the three climate sensitivities were considered.

A general shortening of the crop cycle from current period towards the future has been observed (Fig. 49 and Tab. 23).

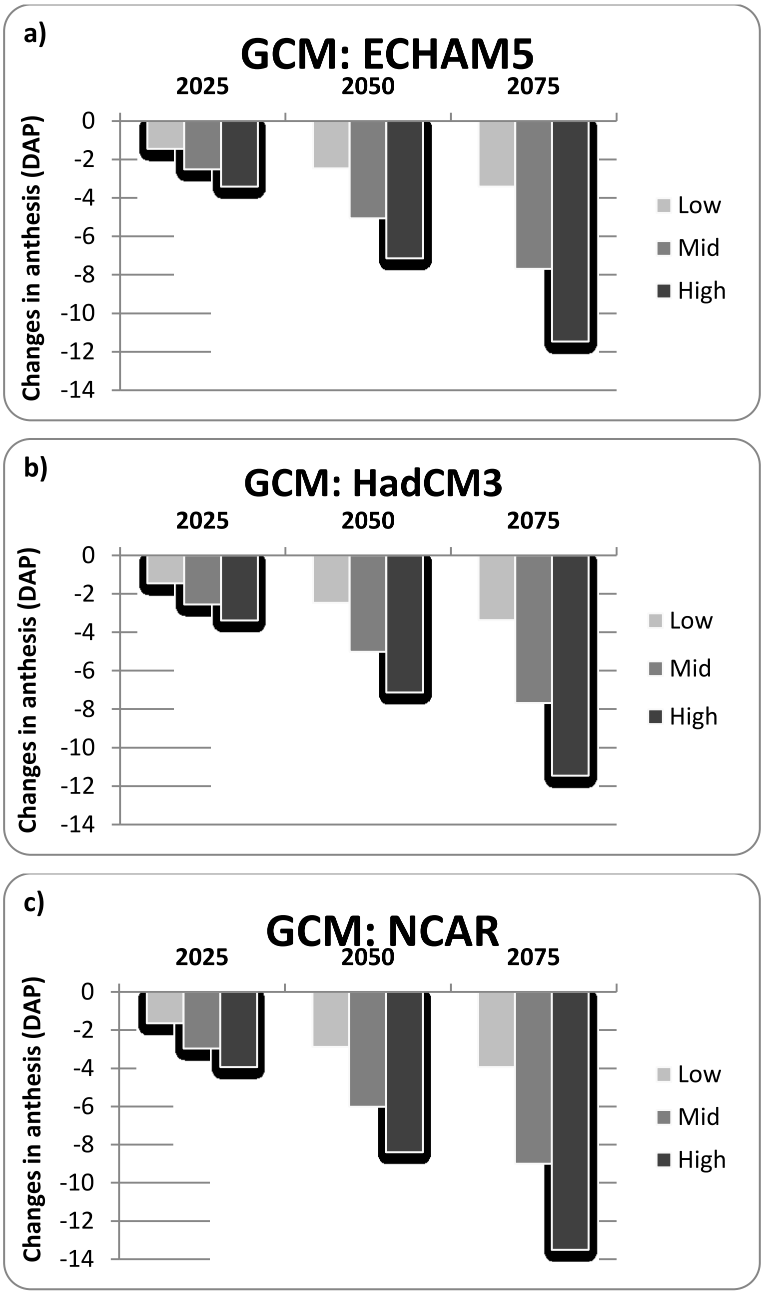


Fig. 49 – Changes in anthesis expressed in days after planting (DAP) for ECHAM5 (a), HadCM3 (b) and NCAR (c) GCMs, three future periods (2025, 2050, 2075) and three level of climate sensitivities (low, mid, high).

For each period considered the shortening of crop cycle increases in moving from low to high climate sensitivities. The reductions of DAP are very similar between ECHAM5 and HadCM3 and lower respect to decreases observed for NCAR (Fig. 49).

Moreover, it is evident an increase in uncertainties due to climate sensitivities starting from 2025 to 2075. Taking into account the NCAR GCM, the shortening of crop cycle might vary between 2 and 3 days in 2025 compared to 4 and 13 days in 2075. These differences, that depend on climate sensitivity factor, indicate a clear acceleration of the crop development that might lead to a lower accumulation of dry matter and, hence, lower grain yields.

Statistical differences between absolute values of DAP are reported on table 23.

Highly significant differences (P≤0.001) between values of DAP for all scenarios were observed (Tab. 23).

Tab. 23 - Comparison of results for anthesis, expressed in days after planting (DAP), for current and future periods, simulated with different GCMs and climate scenarios.

		ECHAM5	HadCM3	NCAR	ALL GCMs
Scenario		***	***	***	***
NOW		**116.8 a**	**116.8 a**	**116.8 a**	**116.8 a**
2025	low	115.3 b	115.3 b	115.1 b	115.3 b
	mid	114.3 c	114.3 c	113.8 c	114.1 c
	high	113.4 d	113.4 d	112.8 d	113.2 d
2050	low	114.3 c	114.3 c	113.9 c	114.2 c
	mid	111.7 e	111.8 e	110.8 e	111.4 e
	high	109.6 f	109.7 f	108.4 f	109.2 f
2075	low	113.4 d	113.4 d	112.8 d	113.2 d
	mid	109.1 g	109.1 g	107.8 g	108.6 g
	high	105.3 h	105.3 h	103.3 h	104.6 h
	CV (%)	*2.6*	*2.6*	*2.6*	*2.6*

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001; means in columns followed by different letters are significantly different at p= 0.05 according to Tukey's test.**

The lowest value of DAP was observed for NCAR GCM in 2075 with high sensitivity scenario (103.3 days compared to 116.8 days in current period). In this conditions it is expected an earlier anthesis compared to projections obtained using others GCMs (105.3 days). Differences in anthesis date between NCAR and others GCM are probably due to higher increases in temperature foresee by NCAR for winter and spring months (Tables 20 and 21).

4.3.4.2. Impacts on yield

Ussana

The results of climate change impacts on grain yields (t ha^{-1}) at Ussana are shown in table 24 and in figures 50 and 51.

In the first four rows of table 24 are represented mean grain yields for the different agronomic management considered. In the following rows were considered mean grain yields projections based on the three GCMs for the three periods and three combined-values of climate sensitivities factors and emission scenarios (low, mid and high). For each GCM the *indirect effect* of CO_2 atmospheric concentration was taken into account, that is the effects on meteorological variables (Climate Change effect only), and the *direct effect* of projected changes of CO_2 concentration in atmosphere (CO_2 effect) coupled with the indirect effect. In the latest columns the statistical analysis performed considering grain yields for all GCMs together is reported.

For all GCMs no significant interactions between agronomic managements and scenarios considered were observed. The absence of significant interactions, resulting in similar behaviours of the agronomic practices for each climatic scenario, permits to consider separately and independently the effect of the agronomic practices from the different scenarios.

In this paragraph will be described trends linked to different studied scenarios, whereas the response of agronomic practices in different scenarios will be shown in the paragraph dedicated to adaptation strategies.

Taking into account the only *indirect effect* of CO_2, or the meteorological effect of climate change impacts (without considering the variation in CO_2 atmospheric concentration), there is a clear tendency to a reduction of production both in ECHAM5 and HadCM3 scenarios, whereas lower decreases for NCAR were observed.

In figure 50 projected decreases of grain yields are shown. Trends in reduction of grain yields, which tend to rise starting from 2025 towards the 2075 and from low to high sensitivity are evident. In table 24 the significant differences in yields between scenarios are shown. Yield differences between low, mid and high scenarios rise from 2025 to 2075 for all GCMs, (especially for HadCM3 and ECHAM5) as is represented in figure 50.

Tab. 24 - Comparison of grain yield (t ha^{-1}) for current and future periods simulated with different practices, GCMs, and climate scenarios at Ussana.

		ECHAM5		**HadCM3**		**NCAR**		**ALL GCMs**	
		CC effect only	**CC + CO_2 effect**	**CC effect only**	**CC + CO_2 effect**	**CC effect only**	**CC + CO_2 effect**	**CC effect only**	**CC + CO_2 effect**
Agronomic Practice (A)		***	***	***	***	***	***	***	***
	Conventional Till. LW	2.33 **a**	2.85 **a**	2.49 **a**	3.05 **a**	2.74 **a**	3.31 **a**	2.50 **a**	3.08 **a**
	Reduced Till. LW	2.33 **a**	2.85 **ab**	2.50 **ab**	3.05 **a**	2.75 **ab**	3.31 **a**	2.50 **a**	3.09 **a**
	NO-Till. LW	2.37 **a**	2.89 **b**	2.53 **b**	3.09 **b**	2.78 **b**	3.34 **b**	2.54 **a**	3.12 **a**
	NO-Till. CW	2.20 **b**	2.64 **c**	2.35 **c**	2.80 **c**	2.54 **c**	2.99 **c**	2.34 **b**	2.82 **b**
Scenario (B)		***	***	***	***	***	***	***	***
NOW		**2.80 a**	**2.80 c**	**2.80 a**	**2.80 cd**	**2.80 a**	**2.80 f**	**2.80 a**	**2.80 def**
2025	**low**	2.65 **ab**	2.83 **bc**	2.69 **ab**	2.88 **c**	2.76 **a**	2.95 **ef**	2.70 **ab**	2.89 **de**
	mid	2.54 **bc**	2.82 **c**	2.62 **b**	2.90 **bc**	2.74 **ab**	3.01 **e**	2.63 **bc**	2.91 **d**
	high	2.44 **c**	2.68 **cd**	2.56 **bc**	2.80 **cd**	2.73 **ab**	2.96 **ef**	2.58 **c**	2.81 **ef**
2050	**low**	2.55 **bc**	3.01 **ab**	2.63 **b**	3.09 **a**	2.73 **ab**	3.20 **cd**	2.64 **bc**	3.10 **c**
	mid	2.25 **d**	2.87 **bc**	2.42 **c**	3.06 **ab**	2.69 **abc**	3.32 **c**	2.45 **d**	3.08 **c**
	high	2.00 **e**	2.45 **e**	2.27 **d**	2.74 **d**	2.64 **bc**	3.12 **de**	2.30 **e**	2.77 **f**
2075	**low**	2.44 **c**	3.06 **a**	2.56 **bc**	3.18 **a**	2.73 **ab**	3.34 **c**	2.58 **c**	3.19 **b**
	mid	1.93 **e**	2.87 **c**	2.22 **d**	3.21 **a**	2.64 **bc**	3.63 **b**	2.26 **e**	3.24 **b**
	high	1.48 **f**	2.70 **de**	1.91 **e**	3.31 **a**	2.57 **c**	4.02 **a**	1.98 **f**	3.34 **a**
Interaction (A) × (B)		**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**
	CV (%)	*27.4*	*24.9*	*25.2*	*22.0*	*24.6*	*21.6*	*27.2*	*24.0*

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001;**
means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

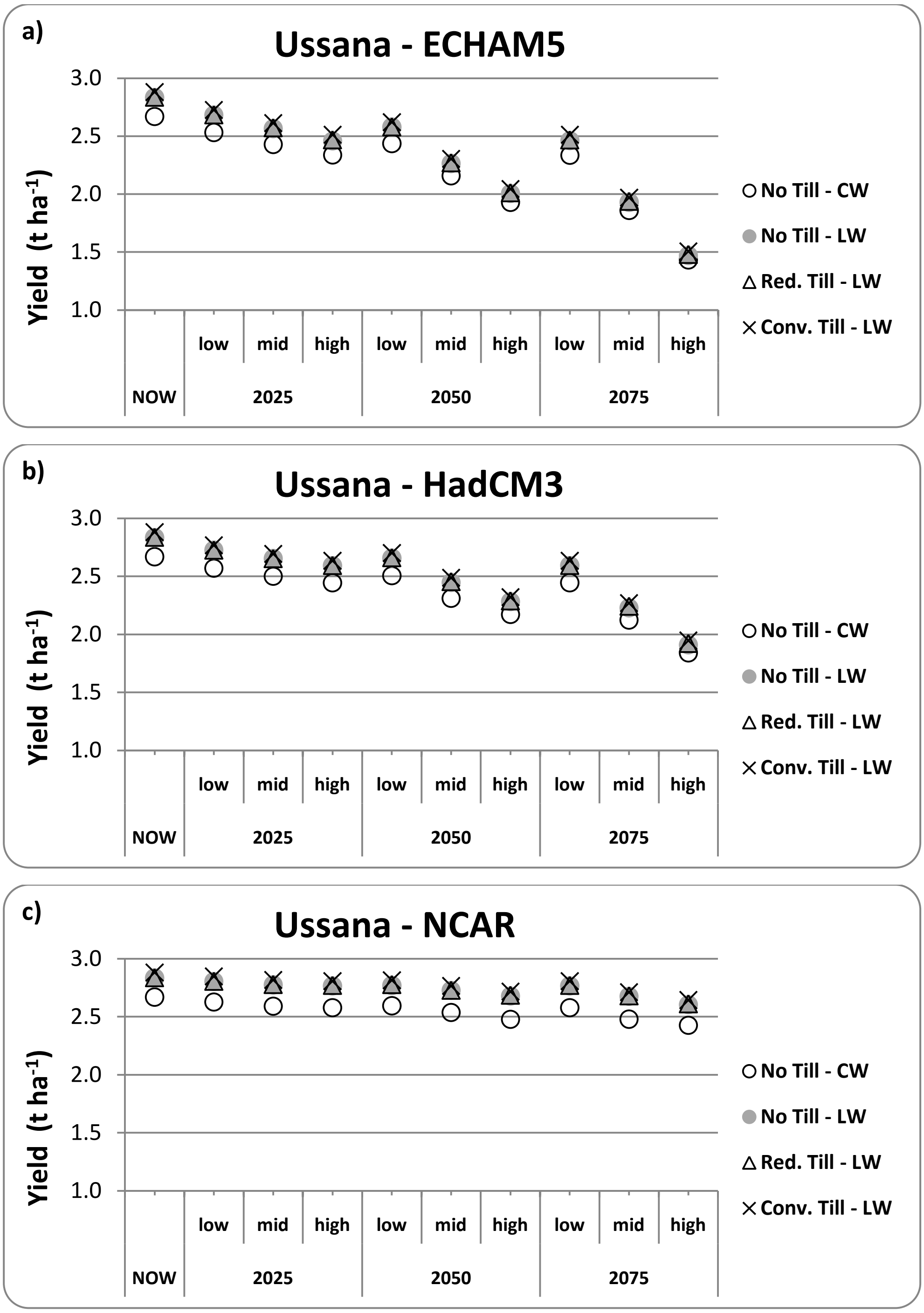


Fig. 50 - Grain yields (t ha^{-1}) from current to future periods, with current CO$_2$ concentration (380 ppm), with ECHAM5 (a), HadCM3 (b) and NCAR (c) GCMs and three climate scenarios (low, mid and high) for each agronomic management at Ussana site.

The highest decrease in grain yield is expected for ECHAM5 with a reduction near to 50% (from 2.80 to 1.48 t ha^{-1}) in 2075 for high scenario (Tab. 24).

The grain yield reductions observed for the indirect effect of CO$_2$ are already statistically significant in the 2025 for mid and high scenarios (lower than 2.54 t ha^{-1} and 2.62 t ha^{-1} for ECHAM5 and HadCM3 respectively). The indirect effect of CO$_2$, considering scenarios based on NCAR, are clearly slighter respect to the others considered: projections of grain yields are significant lower than for current climate only for high scenario in 2050 and mid and high scenarios in 2075 (Tab. 24).

The projected differences between scenarios based on different GCMs could be explained mainly considering the different future distribution of precipitations, especially in March and April, that play an important role in determining durum wheat yields. The lower reduction in yield observed with scenario based on NCAR, in fact, could be explained by rainfall reduction that is expected to be lower compared to HadCM3 and especially to ECHAM5 that foresees the highest decreases in precipitations (Tab. 19). Taking into account the statistical analysis of all GCMs considered together, trends and mean yields simulated are similar to those estimated using HadCM3 scenarios (Tab. 24).

The combined effects, *direct and indirect,* of CO_2 atmospheric concentration, show wide differences in projections between scenarios (Tab. 24 and Fig. 51). Scenarios based on NCAR are very optimistic and foresee increases in yield that rise starting from the 2025 towards the 2075, reaching 45% (4.02 compared to 2.80 t ha^{-1}) for the high scenario. These projected levels of production could be due to the combined effect of the most optimistic GCM considered (the NCAR as seen above) and the high CO_2 atmospheric concentration (705 ppm) for this scenario, calculated by the MAGICC model (Tab. 6). With this high concentration of CO_2, in fact, the CSM-CERES-Wheat model considers a direct effect of CO_2 near 30% (see values of CO_2 modification factors for CERES in table 2). On the other hand, considering scenarios based on ECHAM5, projected grain yields are not different from current period in 2025; the same considerations are valid for 2050 and 2075 for intermediate climate scenarios, whereas for the same periods, grain yields are higher for low scenarios. Lower grain yields are expected for high climate sensitivity either for 2050 and 2075 (Tab. 24). In this last case, despite the high CO_2 air concentration (705 ppm), worse climate conditions determine lower yields respect to current period.

The expected yields obtained with HadCM3 scenarios are not different in 2025 respect to current period. Starting from 2050 simulated yields are higher than current period except for the 2050 considering the high scenario (Tab. 24).

The highest increments in grain yields, either considering HadCM3 scenarios and also all GCMs together, are estimated to be about 19% (3.34 t ha^{-1}) in 2075 compared to current period (2.80 t ha^{-1}).

As seen above, grain yields estimated using HadCM3 scenarios are very similar to results obtained considering all GCMs together.

To sum up results obtained at Ussana for yields, and considering all GCMs scenarios, it would seem that the *direct effect* of CO_2 increase is able to compensate the decrease in yield due to *indirect* CO_2 *effect*. The CO_2 fertilization effect is particularly evident in the 2075 when it is expected that the CO_2 atmospheric concentration will reach values from 501 to 705 ppm, respectively for low and high scenarios.

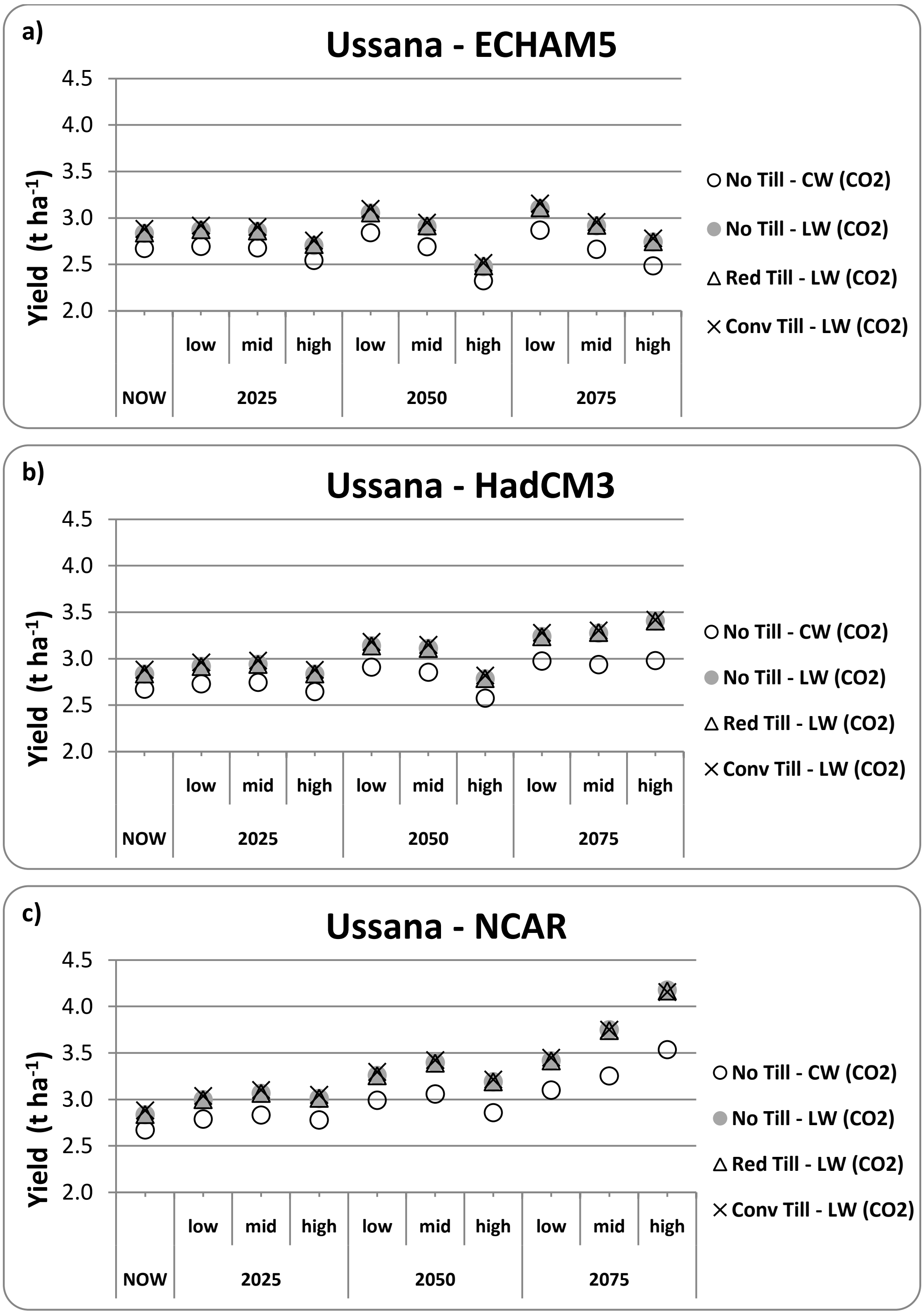


Fig. 51 - Grain yields (t ha^{-1}) from current to future periods, with projected CO_2 air concentrations, with ECHAM5 (a), HadCM3 (b) and NCAR (c) GCMs and three climate scenarios (low, mid and high) for each agronomic management at Ussana.

Benatzu

In table 25 the statistical analyses related to climate change impacts on grain yields (t ha^{-1}) at Benatzu are shown.

No significant interactions between agronomic practices and scenarios were observed for all GCMs. Therefore, it is assumed that there are similar behaviours of the agronomic techniques for each climate scenario considered, and then the effect of the agronomic practices are considered separately and independently from the scenarios for each GCM.

As already made for Ussana, in this paragraph will be described trends linked to different scenarios, whereas the response of agronomic managements in different scenarios will be shown in the paragraph dedicated to the adaptation strategies.

There is a significant tendency to a reduction of productions both in ECHAM5 and HadCM3 scenarios taking into account the only *indirect effect* of CO_2. Lower reductions of grain yield are expected for scenarios based on NCAR (Tab. 25 and Fig. 52).

As seen in Ussana, there is a trend in yields reductions. They tend to rise from 2025 towards the 2075 and from low to high scenarios. These trends are evident either in table 25 than in figure 52, where are represented yields for each GCM.

As can be seen in figure 52, differences between low, mid and high scenarios rise from 2025 to 2075 for all GCMs (especially for ECHAM5 and HadCM3). The highest decrease in yield is expected for ECHAM5-based scenarios, that may reach a reduction of 35% (3.07 compared to 4.78 t ha^{-1}) in 2075 considering the high scenario.

Reductions in yields due to the *indirect effect* of CO_2 are already significant in the 2025 for mid and high scenarios: in these climate conditions yields are lower than 4.48 t ha^{-1} and 4.58 t ha^{-1} for ECHAM5 and HadCM3 respectively (Tab. 25). In the NCAR-based scenarios these reductions are very slighter respect to the others GCMs: with NCAR-scenarios decreases in yields are significant only for 2050 for high and for mid and high scenarios in 2075 (Tab. 25). The explanation of this behaviour, which is similar to that observed for Ussana, has to be sought in the different projected precipitations between the GCMs as explained in previous paragraph.

Tab. 25 - Comparison of grain yield (t ha^{-1}) for current and future periods simulated with different practice, GCMs, climate scenarios at Benatzu site.

		ECHAM5		**HadCM3**		**NCAR**		**ALL GCMs**	
		CC effect only	**CC + CO_2 effect**	**CC effect only**	**CC + CO_2 effect**	**CC effect only**	**CC + CO_2 effect**	**CC effect only**	**CC + CO_2 effect**
Agronomic Practice (A)		***	***	***	***	***	***	***	***
	Conventional Till. LW	4.33 a	4.92 a	4.55 a	5.15 a	4.79 a	5.41 a	4.53 a	5.18 a
	Reduced Till. LW	4.23 a	4.84 ab	4.48 ab	5.12 a	4.72 ab	5.39 a	4.45 b	5.14 a
	NO-Till. LW	4.25 a	4.79 b	4.46 b	5.02 b	4.68 b	5.26 b	4.44 b	5.03 b
	NO-Till. CW	3.92 b	4.44 c	4.12 c	4.65 c	4.31 c	4.87 c	4.09 c	4.66 c
Scenario (B)		***	***	***	**	**	**	***	***
NOW		**4.78 a**	**4.78 c**	**4.78 a**	**4.78 cd**	**4.78 a**	**4.78 f**	**4.78 a**	**4.78 def**
2025	**low**	4.62 ab	4.82 bc	4.67 ab	4.88 c	4.72 a	4.93 ef	4.67 ab	4.88 de
	mid	4.48 bc	4.80 c	4.58 b	4.89 bc	4.68 ab	4.99 e	4.58 bc	4.89 d
	high	4.38 c	4.63 cd	4.51 bc	4.76 cd	4.66 ab	4.92 ef	4.51 c	4.77 ef
2050	**low**	4.49 bc	5.02 ab	4.59 b	5.12 a	4.68 ab	5.22 cd	4.59 bc	5.12 bc
	mid	4.12 d	4.82 bc	4.36 c	5.07 ab	4.60 abc	5.31 c	4.36 d	5.07 c
	high	3.81 e	4.31 e	4.17 d	4.67 d	4.51 bc	5.02 de	4.16 e	4.67 f
2075	**low**	4.37 c	5.07 a	4.51 bc	5.22 a	4.66 ab	5.37 c	4.51 c	5.22 ab
	mid	3.72 e	4.78 c	4.11 d	5.19 a	4.51 bc	5.63 b	4.11 e	5.20 ab
	high	3.07 f	4.45 de	3.74 e	5.25 a	4.46 c	6.15 a	3.76 f	5.28 a
Interaction (A) x (B)		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	CV (%)	*21.1*	*19.7*	*17.3*	*16.4*	*17.7*	*17.1*	*19.5*	*18.7*

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001;**
means in columns followed by different letters are significantly different at p=0.05 according to Tukey's test.

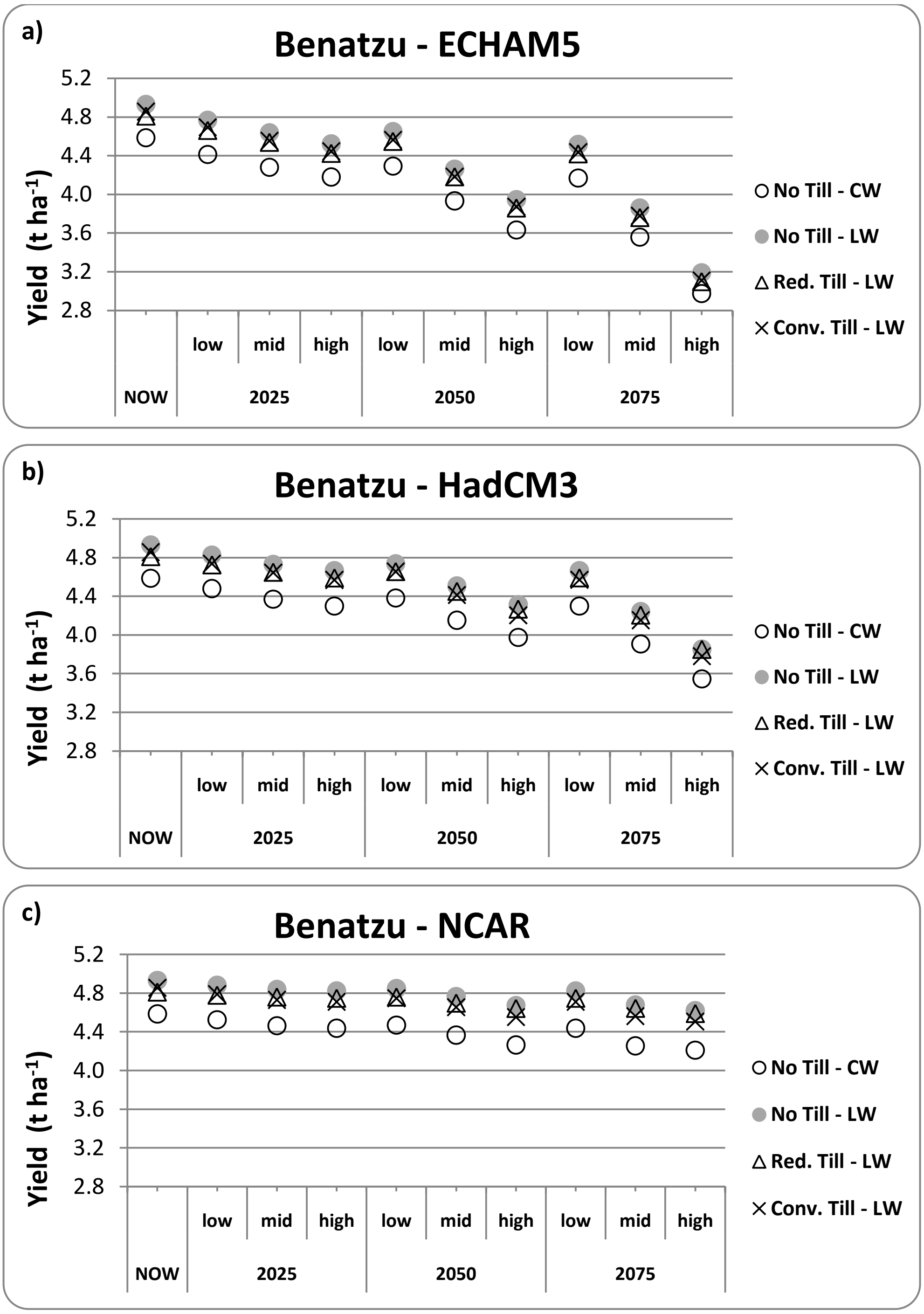


Fig. 52 - Grain yields (t ha^{-1}) from current to future periods, with current CO$_2$ concentration (380 ppm), with ECHAM5 (a), HadCM3 (b) and NCAR (c) GCMs and three climate scenarios (low, mid and high) for each agronomic management at Benatzu.

Statistical analysis performed for all GCMs together, shows mean yields and trends similar to scenarios based on HadCM3 (Tab. 25).

The combined effects of CO$_2$ atmospheric concentration between scenarios are very different. NCAR-based scenarios are more optimistic when compared to scenarios based on the other two GCMs considered (Tab. 25 and Fig. 53).

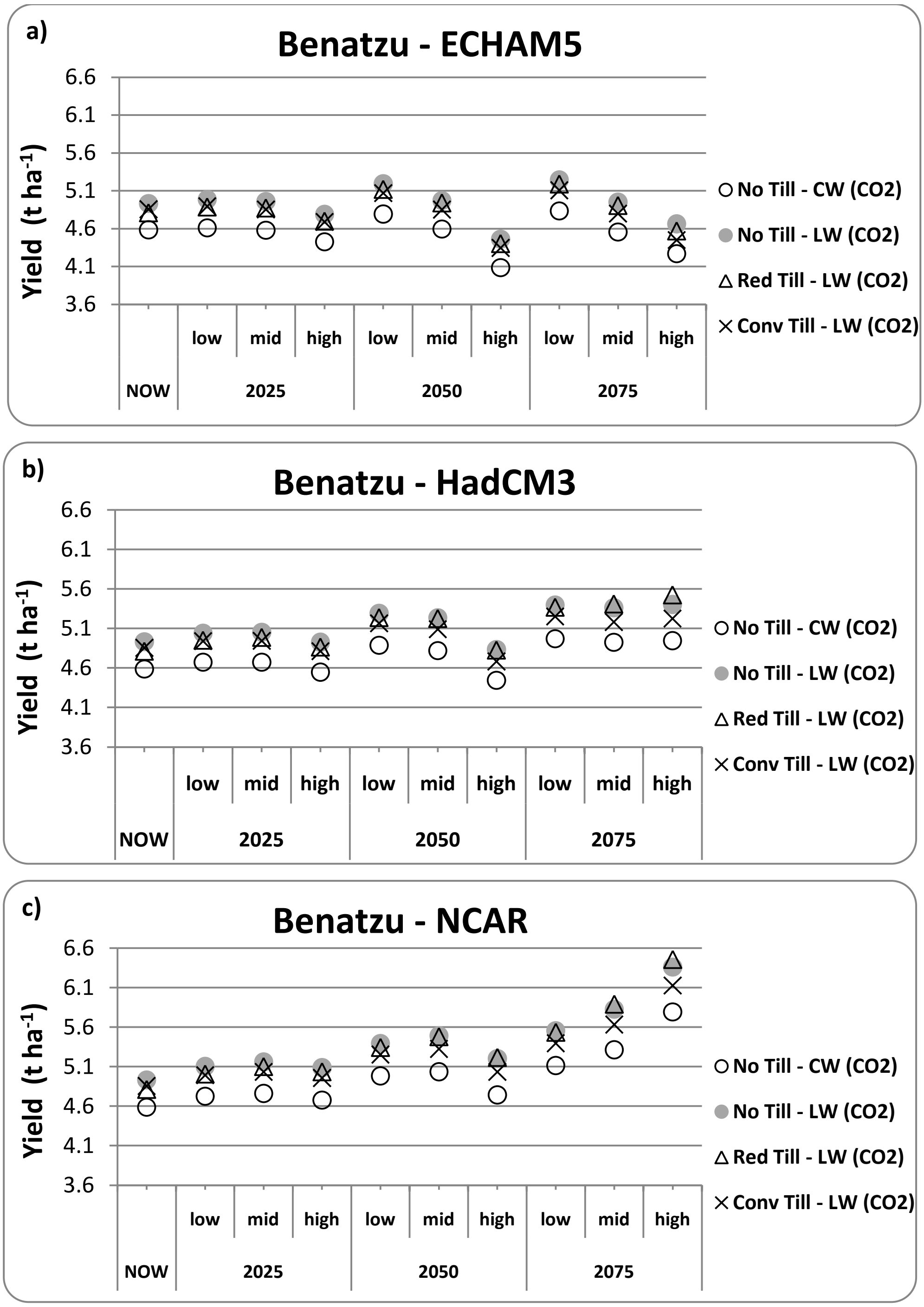


Fig. 53 - Grain yields (t ha^{-1}) from current to future periods, with projected CO$_2$ concentrations, with ECHAM5 (a), HadCM3 (b) and NCAR (c) GCMs and three climate scenarios (low, mid and high) for each agronomic management at Benatzu.

The projected yields for NCAR scenarios are higher compared to those obtained in current climate already in the 2025 considering an intermediate scenario. Starting from the 2050 towards 2075 yields are higher compared to current period for all scenarios considered. The highest value of yield (6.15 t ha^{-1}) is forecast considering the high scenario, with a yield increase of 28% respect to current climate conditions (Tab. 25 and

Fig. 53). These increases in production are probably due to more rainfall projected by NCAR respect to the others GCMs, and to the high CO_2 atmospheric concentration (705 ppm) considered for the high scenario in 2075.

The production trends of durum wheat on ECHAM5-based scenarios are clearly lower respect to NCAR scenarios (Fig. 53).

Yields projected using ECHAM5 scenarios in 2025 are not different from current climate, whereas are higher low scenarios either in 2050 and 2075 (5.02 an 5.07 t ha^{-1} respectively). Yields go further down for high scenarios either in 2050 and 2075 (Tab. 25). Despite the high CO_2 concentration (555 and 705 ppm respectively) expected for the high scenarios, the worse climate conditions respect to current climate cause lower yields.

Yields projected using HadCM3 scenarios are not significantly different between current climate and scenarios in 2025. Nevertheless, starting from 2050, simulated yields both in 2050 and 2075 are expected to be higher compared with the current climate except for the mid scenario in 2050 (Tab. 25).

As seen for Ussana, yield trends for all GCMs together, are very similar to those observed with HadCM3 scenarios. The highest projected yield increases, both considering HadCM3 scenarios and also all GCMs together, are near 10% (5.20 compared to 4.78 t ha^{-1}) in 2075 respect to current climate (Tab. 25).

The results obtained in Benatzu are very similar to those obtained for Ussana. It seems to indicate that climate change scenarios considered, on average, may not result in significant reductions in yield. On the contrary, results obtained in this study seem to indicate the possibility of obtaining higher yields for the *direct effect* of CO_2 that, for the crop growth model used, is able to compensate the decrease due to *indirect* CO_2 effect.

4.3.5. Adaptation strategies evaluation

In this paragraph will be described the statistical analyses of results obtained for adaptation strategies.

First of all, some considerations about conservation tillage and rotation as adaptation strategies will be exposed. Then will be shown the results of changes in planting date and after results of simulations implying genetic improvement, for each site separately.

The adaptation strategies were evaluated considering the four agronomic managements, the three GCMs selected, and only the intermediate climate scenarios for the three periods.

In graphs are presented mean values of yields and anthesis results whereas statistical analyses are reported in tables.

As already stated in the previous paragraph, since the two experimental sites are distant about 1 km from each other, no difference were observed for anthesis between Ussana and Benatzu.

4.3.5.1. Conservation tillage and rotations

The evaluation of the agronomic techniques considered as adaptation strategies can be made considering the climate change impacts on yields already show in tables 23-24 and in figures 50, 51, 52 and 53 in previous paragraphs. No significant interactions between agronomic managements and climate change scenarios were observed. These results indicate a similar behaviours of the agronomic practices for each climatic scenario and permit to consider independently the effect of the managements from climatic scenarios. The application of different tillage practices did not induce significant influences on yields both at Ussana and at Benatzu. The differences between expected yields simulated by the crop growth model do not differ from those observed in experimental trials conducted in the time span 2004-2009. Moreover in these trials was not observed even a significant interaction year × tillage (Tab. 7 and 9) as observed with crop model between tillage and scenarios (Tab. 23 and 24).

Conventional tillage with legumes as previous crop could be the highest yielding management for all scenarios considered. The differences between yields for different tillage practices are almost always no significant. At Ussana, when statistical differences in yields are detected, they have no appreciable practical significance being lower than 0.05 t ha^{-1} (Tab. 23). At Benatzu differences were larger respect to Ussana reaching values of 0.15 t ha^{-1} between conventional and no tillage with the same previous crop (Tab. 24). Graphs collected in figures 50-53 confirm that are expected similar trends between tillage practices. The same tables and figures highlight the beneficial effect of the precession with legumes that can be observed for no tillage management respect to the continuous wheat crops practice: yields obtained with continuous wheat crops are always lower compared to yields obtained with legumes as previous crop. Considering the combined effect of CO_2, the yield differences between these two types of rotation seem to widen from the current climate to future scenarios, especially for NCAR and HadCM3 scenarios (Fig. 51 and Fig. 53) confirming the beneficial effect of legumes as previous crop for durum wheat.

In order to evaluate the effects of different agronomic managements considered, in figures 54 and 55 the percent changes in yields for all scenarios respect to current period for Ussana are showed.

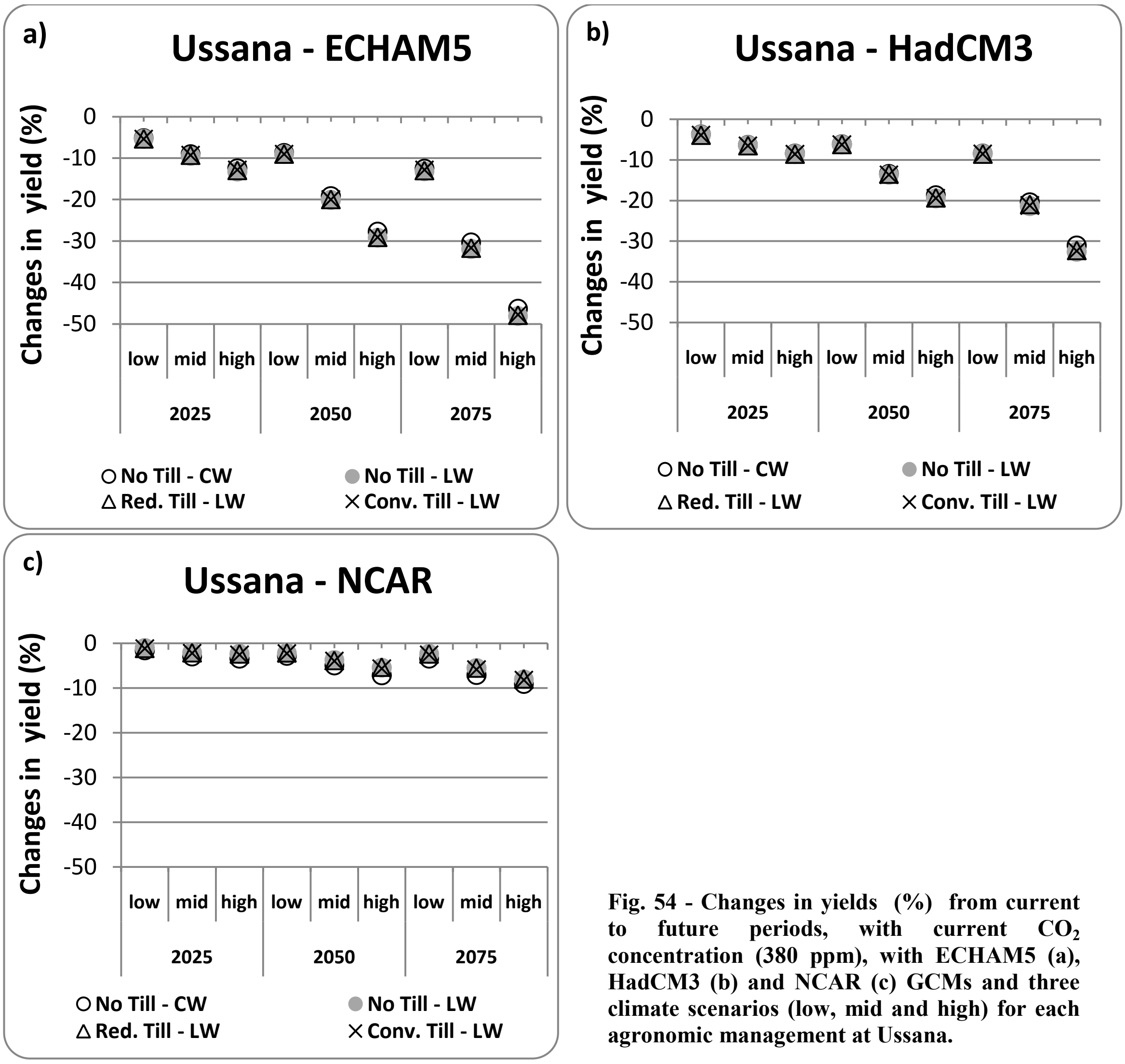


Fig. 54 - Changes in yields (%) from current to future periods, with current CO_2 concentration (380 ppm), with ECHAM5 (a), HadCM3 (b) and NCAR (c) GCMs and three climate scenarios (low, mid and high) for each agronomic management at Ussana.

No difference in yield between management, considering the only indirect effect of increased CO_2 concentration, was observed (Fig. 54). On the other hand, considering the combined effect of CO_2 concentration, rotations with legumes seem to promote more favourable changes in yields for durum wheat especially for the more optimistic scenarios (e.g., for NCAR and HadCM3) (Fig. 55). These results suggest that at Ussana the practice of alternating wheat and legumes can give the best results in more favourable climatic conditions, while under less favourable conditions for the development and growth of durum wheat the beneficial effects of these practices are reduced.

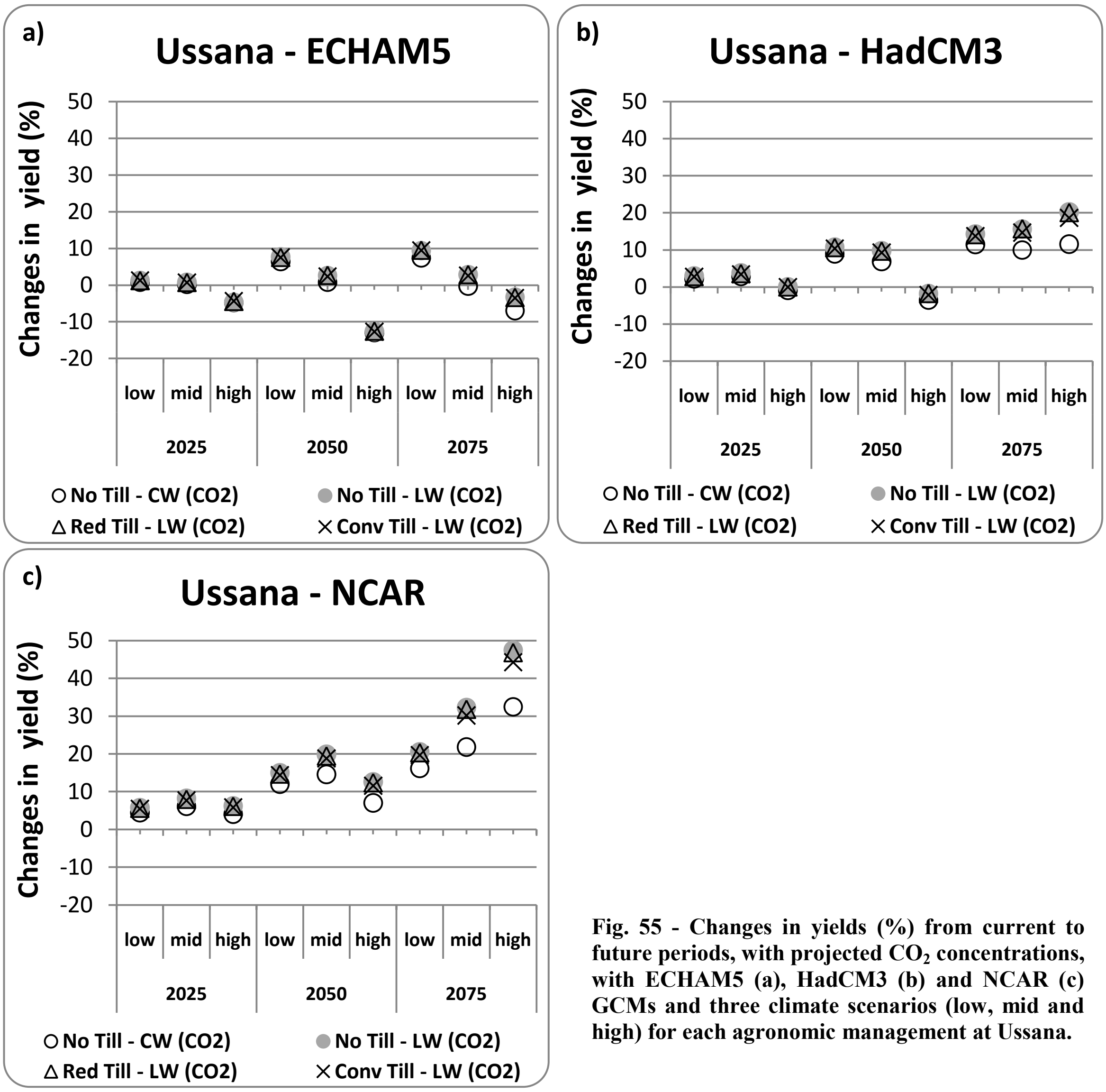
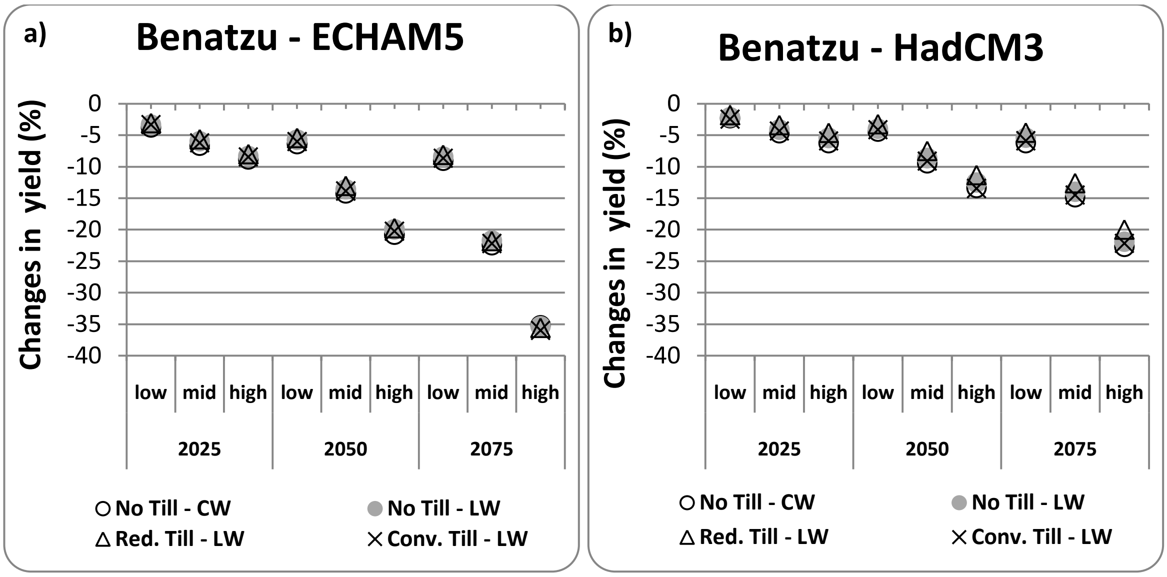


Fig. 55 - Changes in yields (%) from current to future periods, with projected CO_2 concentrations, with ECHAM5 (a), HadCM3 (b) and NCAR (c) GCMs and three climate scenarios (low, mid and high) for each agronomic management at Ussana.

In figures 56 and 57 the percent changes in yields for all scenarios respect to current climate for Benatzu are showed. Taking into account the only indirect effect of increased CO_2 concentration, no differences in yield changes between management were observed (Fig. 56).



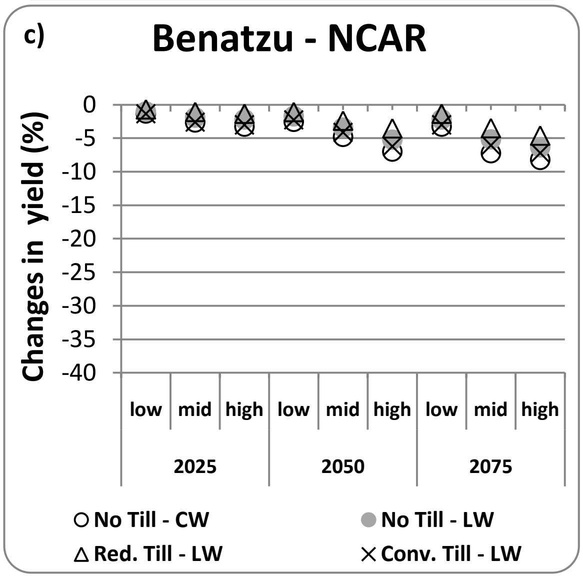


Fig. 56 - Changes in yields (%) from current to future periods, with current CO_2 concentration (380 ppm), with ECHAM5 (a), HadCM3 (b) and NCAR (c) GCMs and three climate scenarios (low, mid and high) for each agronomic management at Benatzu.

The same considerations are valid for the combined effect of increased CO_2 concentration at Benatzu site: although rotations with legumes provide higher yields compared to continuous wheat crops (Tab. 24 and Fig. 53) changes in yields are similar for all managements considered, even if it appears that the reduced tillage management with legumes as previous crop tends to benefit whenever applied with more favourable conditions for development and growth of wheat (Fig. 57). These results suggest a different behaviour of these practices between the two sites.

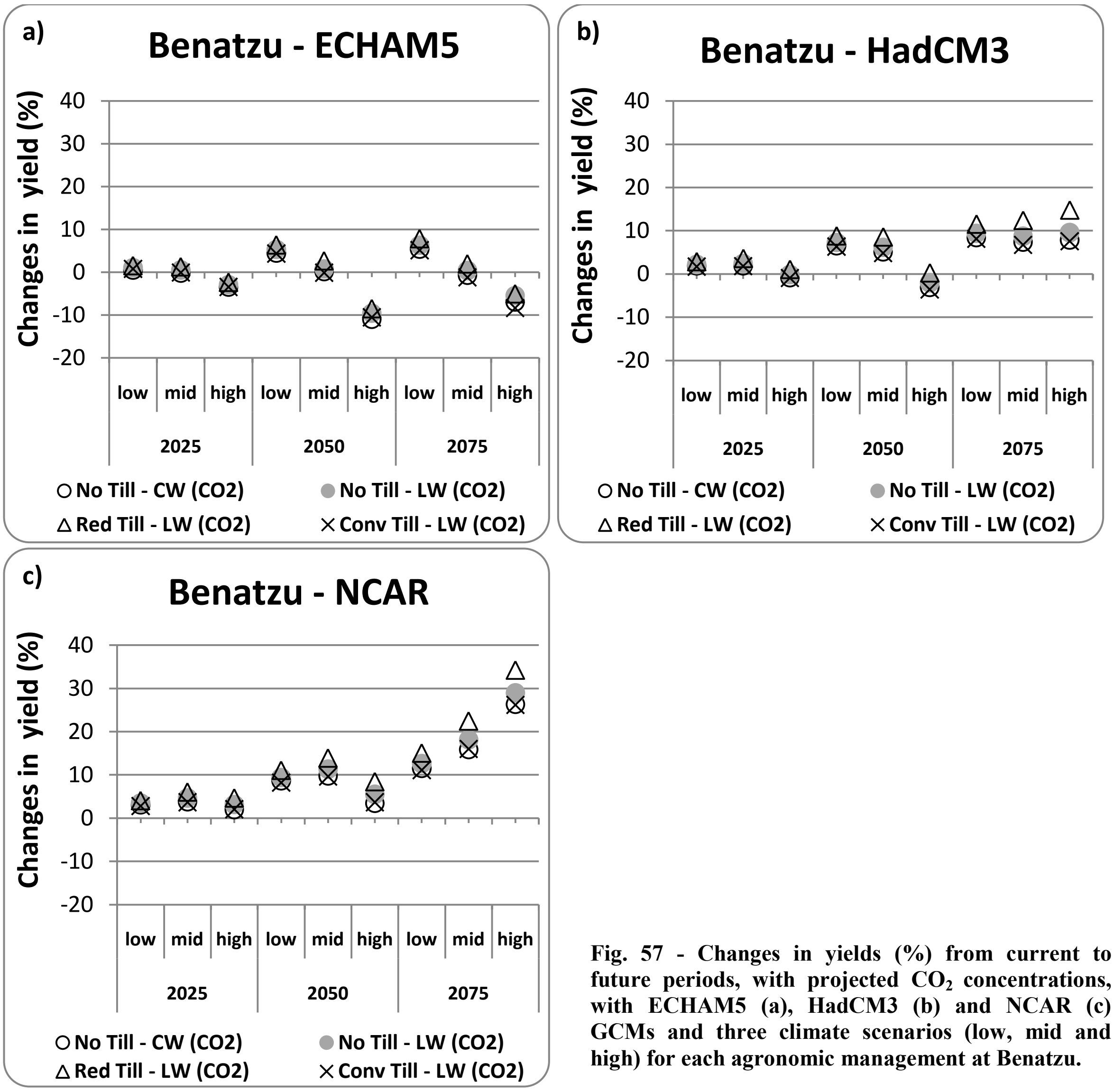


Fig. 57 - Changes in yields (%) from current to future periods, with projected CO_2 concentrations, with ECHAM5 (a), HadCM3 (b) and NCAR (c) GCMs and three climate scenarios (low, mid and high) for each agronomic management at Benatzu.

4.3.5.2. Variation in planting date

Starting from the ordinary planting date, for each treatment and site, the 99-year crop model for the all climate scenarios with mid climate scenarios and the corresponding values of CO_2 were run. The treatments applied in this experiment were 4 planting dates: the ordinary date, two early dates (-20 days and -40 days) and one later date (+20 days).

Impacts on anthesis

In table 26 are shown results of the anthesis appearance, expressed in days after planting (DAP), considering the effect of the planting date variation.

A general shortening of the crop cycle, from the current period to the future has been observed for all climate scenarios. The advance and delay of sowing date, result in a lengthening and shortening of the crop cycle in question. These changes for the current climate are lower when compared to the variation of planting date applied: + 35.9 and + 17.6 days for early sowing of -40 and -20 day respectively, and -16.6 days for delayed sowing of 20 days. The shortening of crop cycle tends to be more evident from current climate to 2075 and are more pronounced for NCAR scenarios respect to others (Tab. 26 and Fig. 58). This is probably due to the higher increases of minimum and maximum air temperatures projected by NCAR that promote a shortening of crop cycle.

Tab. 26 - Comparison of anthesis' appearance (DAP) for different planting dates, considering current and future periods for the three GCMs and mid scenario. Simulations were performed considering the ordinary date, two early dates (-20 days and -40 days) and one later date (+20 days).

		ECHAM5	**HadCM3**	**NCAR**	**ALL GCMs**
Scenario		***	***	***	***
NOW		126.0 a	126.0 a	126.0 a	126.0 a
2025		123.4 b	123.4 b	123.0 b	123.3 b
2050		120.4 c	120.8 c	119.9 c	120.4 c
2075		118.0 d	118.1 d	116.7 d	117.6 d
Planting date		***	***	***	***
- 40 days		148.4 a	148.4 a	147.7 a	147.3 a
- 20 days		130.3 b	130.3 b	129.6 b	129.2 b
ordinary		112.7 c	113.0 c	112.3 c	111.8 c
+ 20 days		96.4 d	96.6 d	96.0 d	95.6 d
Scenario × planting date		***	***	***	***
NOW	**- 40 days**	152.7 a	152.7 a	152.7 a	152.7 a
	- 20 days	134.4 e	134.4 e	134.4 e	134.4 e
	ordinary	**116.8 i**	**116.8 i**	**116.8 i**	**116.8 i**
	+ 20 days	100.2 m	100.2 m	100.2 m	100.2 m
2025	**- 40 days**	149.9 b	149.9 b	149.4 b	149.7 b
	- 20 days	131.6 f	131.6 f	131.2 f	131.5 f
	ordinary	114.3 j	114.2 j	113.8 j	114.1 j
	+ 20 days	97.8 n	97.8 n	97.4 n	97.7 n
2050	**- 40 days**	147.0 c	147.1 c	146.1 c	146.7 c
	- 20 days	128.9 g	129.0 g	128.1 g	128.7 g
	ordinary	110.8 k	111.8 k	110.8 k	111.1 k
	+ 20 days	94.7 o	95.5 o	94.7 o	95.0 o
2075	**- 40 days**	144.0 d	144.1 d	142.7 d	143.6 d
	- 20 days	126.1 h	126.2 h	124.7 h	125.7 h
	ordinary	109.0 l	109.1 l	107.8 l	108.6 l
	+ 20 days	93.1 p	93.1 p	91.8 p	92.6 p
C.V.		*2.4*	*2.4*	*2.4*	*2.5*

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001;**
means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

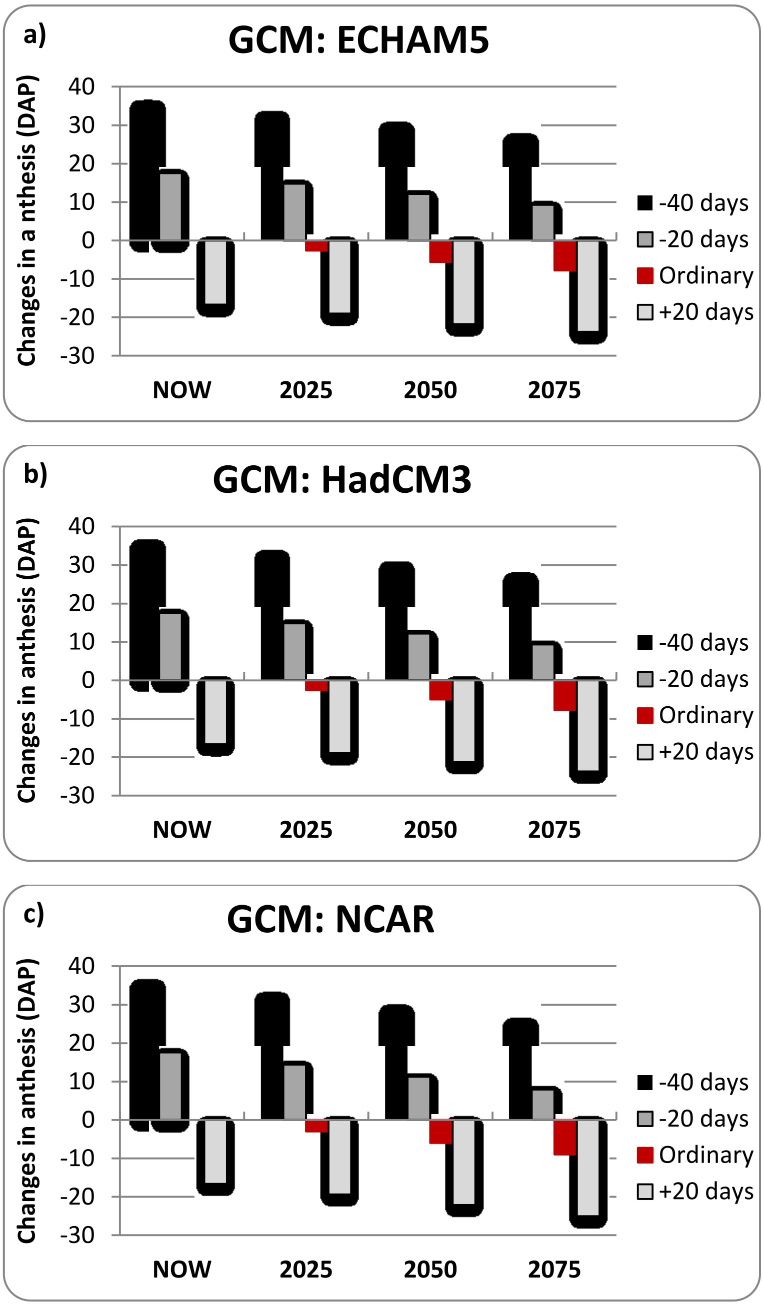


Fig. 58 – Changes in anthesis (DAP) from current to future periods respect to the ordinary planting date considering HadCM3 (a), ECHAM5 (b) and NCAR (c) GCMs and mid scenarios. Treatments considered are the ordinary planting date, two early dates (-20 days and -40 days) and one later date (+20 days).

Impacts on yields

Ussana

Yields (t ha^{-1}) obtained in simulations of planting date effects considering the four agronomic managements and all mid climate scenarios at Ussana are reported in table 27-28 and in figure 59.

Tab. 27 - Comparison of yields (t ha^{-1}) considering planting dates and agronomic managements from current to future periods for the three GCMs and mid scenario at Ussana. Simulations were performed taking into account the ordinary date, two early dates (-20 days and -40 days) and a later date (+20 days).

		ECHAM5	HadCM3	NCAR	ALL GCMs
Scenario (a)		***	***	***	***
	NOW	2.87 b	2.87 d	2.87 d	2.87 d
	2025	2.85 b	2.93 c	3.03 c	2.94 c
	2050	3.06 a	3.04 b	3.27 b	3.12 b
	2075	2.83 b	3.13 a	3.54 a	3.17 a
Planting date (b)		***	***	***	***
	- 40 days	3.22 a	3.35 a	3.56 a	3.39 a
	- 20 days	3.16 b	3.30 a	3.48 b	3.33 b
	ordinary	2.95 c	2.99 b	3.19 c	3.09 c
	+ 20 days	2.29 d	2.33 c	2.47 d	2.40 d
Management (c)		***	***	***	***
	Conventional Till. LW	3.00 a	3.10 a	3.30 a	3.17 a
	Reduced Till. LW	3.01 a	3.10 a	3.29 a	3.17 a
	NO-Till. LW	3.01 a	3.10 a	3.30 a	3.17 a
	NO-Till. CW	2.60 b	2.67 b	2.81 b	2.72 b
Interaction a × b		***	***	**	***
NOW	**- 40 days**	3.31 ab	3.31 a-c	3.31 de	3.31 b-e
	- 20 days	3.21 a-d	3.21 cd	3.21 e	3.21 e
	ordinary	2.80 e	2.80 e	2.80 g	2.80 f
	+ 20 days	2.15 g	2.15 h	2.15 j	2.15 h
2025	**- 40 days**	3.26 a-c	3.33 a-c	3.44 cd	3.34 cd
	- 20 days	3.16 a-d	3.24 bc	3.34 de	3.25 de
	ordinary	2.82 e	2.90 e	3.01 f	2.91 f
	+ 20 days	2.18 g	2.25 gh	2.33 i	2.25 h
2050	**- 40 days**	3.20 a-d	3.37 ab	3.62 b	3.40 a-c
	- 20 days	3.16 b-d	3.34 a-c	3.57 bc	3.35 bc
	ordinary	3.32 a	3.06 d	3.32 de	3.23 e
	+ 20 days	2.56 f	2.38 fg	2.56 h	2.50 g
2075	**- 40 days**	3.11 cd	3.39 ab	3.88 a	3.46 a
	- 20 days	3.10 d	3.41 a	3.81 a	3.44 ab
	ordinary	2.87 e	3.21 cd	3.63 b	3.24 e
	+ 20 days	2.26 g	2.52 f	2.83 g	2.54 g
Interaction a × c		n.s.	n.s.	n.s.	n.s.
Interaction b × c		***	***	***	***
Interaction a × b × c		n.s.	n.s.	n.s.	n.s.
C.V.		*22.3*	*20.9*	*20.9*	*22.0*

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001;**

means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

In the first four rows of table 27 mean grain yields from current climate to scenarios related to 2075 are shown. The highest yields will be obtained in 2050 for ECHAM5-based scenarios whereas, for the others GCMs, grow from current period to 2075. The shift in advance of planting date involves slight yield increases: these are higher for NCAR-based scenarios respect to the others. Tillage practices do not seem to determine differences in yields, whereas continuous wheat crops cause relevant decreases. As seen for climate change impacts, no interactions were observed between scenarios and managements, whereas significant interaction scenario × planting date ($p \leq 0.001$) and planting date × management were observed ($p \leq 0.001$) (Tab. 27). The scenario × planting date interaction observed in ECHAM5-based scenarios can be explained by significant higher yields simulated in 2050 with the ordinary planting date respect to higher yields simulated with an advance in planting date in others scenarios based on the same GCM. On the contrary, yields projected by the others GCMs are higher for the early plantings respect to the ordinary date but, this trend weakens passing from the current period to the future (Tab. 27).

In table 28 and figure 59 more detailed information about yields simulated with different agronomic management combinations are shown.

Tab. 28 - Comparison of yields (t ha^{-1}) considering planting date × agronomic management interaction for the three GCMs and mid scenario at Ussana. Simulations were performed taking into account the ordinary date, two early dates (-20 days and -40 days) and one later date (+20 days).

		ECHAM5	HadCM3	NCAR	ALL GCMs
Planting date × management		***	***	***	***
- 40 days	**Conv. Till. LW**	3.41 a	3.56 a	3.78 a	3.60 a
	Red. Till. LW	3.41 a	3.55 a	3.77 a	3.59 a
	NO-Till. LW	3.37 a	3.50 a	3.72 ab	3.55 ab
	NO-Till. CW	2.70 c	2.80 c	2.98 d	2.83 d
- 20 days	**Conv. Till. LW**	3.29 a	3.45 a	3.65 ab	3.49 b
	Red. Till. LW	3.29 a	3.45 a	3.64 ab	3.49 b
	NO-Till. LW	3.27 a	3.42 a	3.61 b	3.46 b
	NO-Till. CW	2.77 c	2.88 c	3.01 d	2.90 d
ordinary	**Conv. Till. LW**	3.00 b	3.04 b	3.26 c	3.15 c
	Red. Till. LW	3.00 b	3.04 b	3.26 c	3.15 c
	NO-Till. LW	3.04 b	3.08 b	3.29 c	3.19 c
	NO-Till. CW	2.76 c	2.80 c	2.95 d	2.88 d
+ 20 days	**Conv. Till. LW**	2.31 d	2.35 d	2.50 e	2.43 e
	Red. Till. LW	2.32 d	2.36 d	2.50 e	2.43 e
	NO-Till. LW	2.37 d	2.41 d	2.56 e	2.49 e
	NO-Till. CW	2.15 e	2.18 e	2.31 f	2.26 f

n.s., *, **, * = not significant, significant respectively at $p \leq 0.05$, $p \leq 0.01$, $p \leq 0.001$;**
means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

The results of simulations seem to indicate a trend towards increases of yields for agronomic practices that include rotation with legumes. This trend is more evident for scenarios based on NCAR and HadCM3. Trend observed for no-tillage management with continuous wheat crops are different: with this management yields are similar or lower than those obtained with the ordinary planting date (Tab. 28 and Fig. 59).

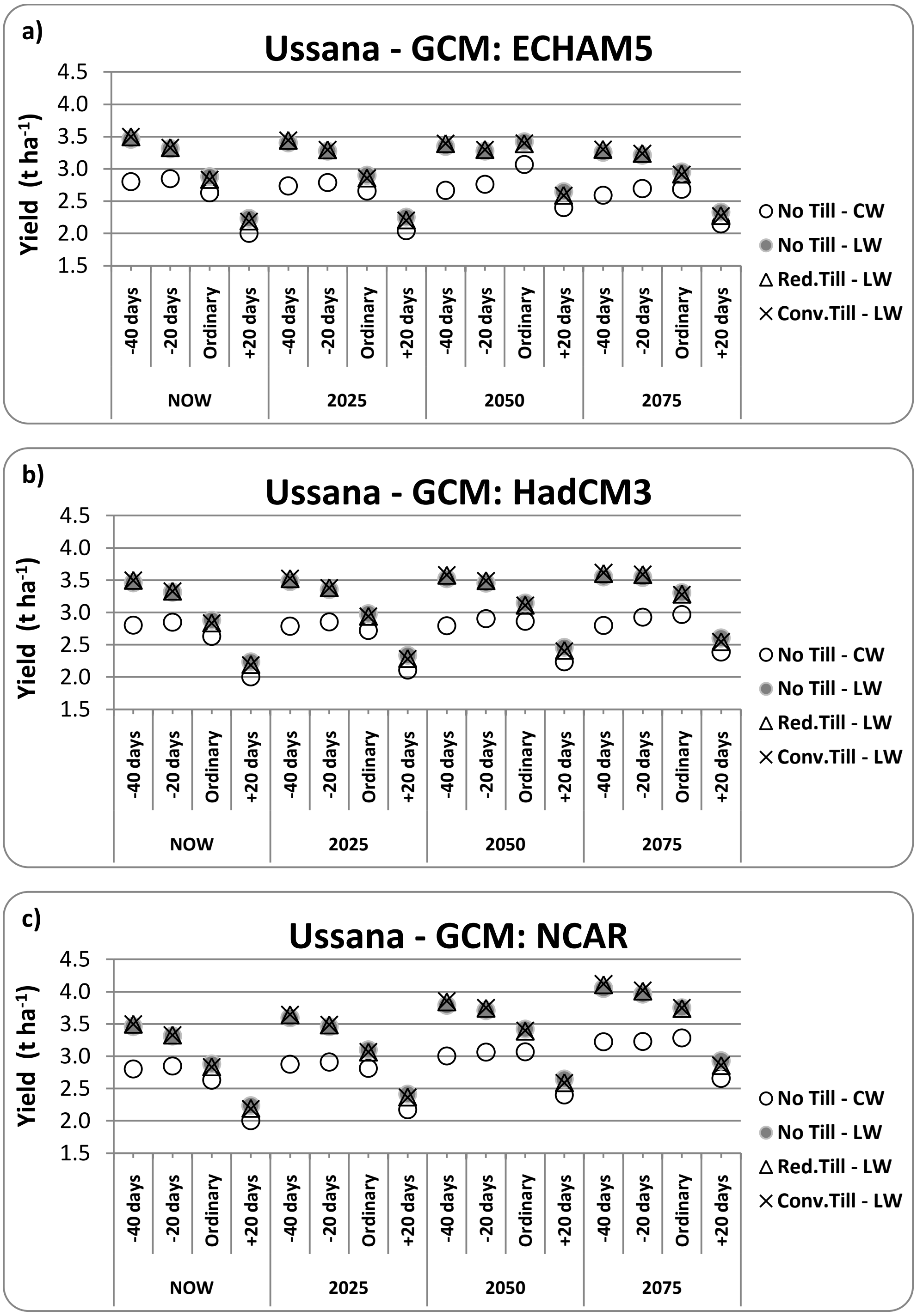


Fig. 59 - Yields (t ha^{-1}) from current to future periods considering HadCM3 (a), ECHAM5 (b) and NCAR (c) GCMs and mid scenarios at Ussana. Treatments considered are the ordinary planting date, two early dates (-20 days and -40 days) and one later date (+20 days) and agronomic managements.

Benatzu

Yields (t ha^{-1}) obtained in simulations of planting date variation considering the four agronomic managements and the intermediate climate scenarios at Benatzu are reported in table 29-30 and in figure 60.

Tab. 29 - Comparison of yields (t ha^{-1}) considering planting dates and agronomic managements from current to future periods for the three GCMs and mid scenario at Benatzu. Simulations were performed taking into account the ordinary date, two early dates (-20 days and -40 days) and a later date (+20 days).

		ECHAM5	HadCM3	NCAR	ALL GCMs
Scenario (a)		n.s.	***	***	***
NOW		4.55 a	4.55 d	4.55 d	4.55 d
2025		4.53 a	4.63 c	4.76 c	4.64 c
2050		4.57 a	4.78 b	5.09 b	4.81 b
2075		4.57 a	4.92 a	5.48 a	4.99 a
Planting date (b)		***	***	***	***
- 40 days		4.76 a	4.87 b	5.23 a	4.99 ab
- 20 days		4.74 a	4.88 b	5.16 a	4.95 b
ordinary		4.79 a	4.98 a	5.18 a	5.03 a
+ 20 days		3.93 b	4.13 c	4.30 b	4.18 c
Management (c)		***	***	***	***
Conventional Till. LW		4.71 a	4.87 a	5.13 a	4.95 a
Reduced Till. LW		4.68 ab	4.86 a	5.12 a	4.93 a
NO-Till. LW		4.62 b	4.78 b	5.03 b	4.85 b
NO-Till. CW		4.21 c	4.36 c	4.60 c	4.42 c
Interaction a × b		n.s.	***	n.s.	***
NOW	- 40 days	4.76 a	4.76 d	4.76 d	4.76 f
	- 20 days	4.82 a	4.82 cd	4.82 cd	4.82 d-f
	ordinary	4.78 a	4.78 d	4.78 cd	4.78 f
	+ 20 days	3.84 b	3.84 g	3.84 g	3.84 i
2025	- 40 days	4.72 a	4.80 cd	4.99 c	4.84 ef
	- 20 days	4.73 a	4.82 cd	4.95 cd	4.83 f
	ordinary	4.80 a	4.89 b-d	4.99 c	4.89 d-f
	+ 20 days	3.88 b	4.00 g	4.10 f	3.99 i
2050	- 40 days	4.75 a	4.90 b-d	5.35 b	5.00 b-d
	- 20 days	4.73 a	4.91 b-d	5.25 b	4.96 c-e
	ordinary	4.82 a	5.07 ab	5.31 b	5.07 bc
	+ 20 days	3.98 b	4.23 f	4.44 e	4.21 h
2075	- 40 days	4.80 a	5.04 ab	5.83 a	5.22 a
	- 20 days	4.69 a	4.98 bc	5.63 a	5.10 ab
	ordinary	4.78 a	5.19 a	5.63 a	5.20 a
	+ 20 days	4.02 b	4.47 e	4.83 cd	4.44 g
Interaction a × c		n.s.	n.s.	n.s.	n.s.
Interaction b × c		***	***	***	***
Interaction a × b × c		n.s.	n.s.	n.s.	n.s.
C.V.		*19.30*	*17.40*	*18.10*	*19.10*

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001;**
means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

In the first four rows of table 29 are shown mean yields from current period to 2075. Independently from agronomic management and planting date, the highest yields were obtained in 2075 scenario based on NCAR and HadCM3 scenarios whereas no difference in yields are expected for ECHAM5 scenarios. The advance of planting does not involve changes in yields for ECHAM5 and NCAR scenarios, while determines a slight reduction in HadCM3–based scenarios. Delay in sowing causes a decrease of grain yield for all scenarios considered. Continuous wheat crop with no-tillage management causes relevant decreases in yields compared to all managements coupled to rotation with legume crops. No-tillage practice causes slight reductions in yields compared to other tillage techniques: these yield reductions, that are always lower than 0.1 t·ha^{-1}, have a negligible practical significance. No interactions were observed between scenarios and managements while significant interaction scenario × planting date ($p \leq 0.001$) for HadCM3 scenarios and considering all scenarios together were observed. This significant interaction is probably due to a higher increase in yields observed for delayed sowing respect to others planting that is more noticeable passing from current period to 2075 (Tab. 29 and Fig. 60). These results indicate better conditions for delayed sowing in the future scenarios compared to current period at Benatzu site.

In table 30 and figure 60 are shown more detailed information about yields simulated with different agronomic management combinations to better understand the significant ($p \leq 0.001$) planting date × management interaction.

Tab. 30 - Comparison of yields (t·ha^{-1}) considering planting date × agronomic management interaction for the three GCMs and mid scenario at Benatzu. Simulations were performed taking into account the ordinary date, two early dates (-20 days and -40 days) and one later date (+20 days).

Planting date × management		***	***	***	***
- 40 days	**Conv. Till. LW**	4.98 ab	5.08 ab	5.45 ab	5.21 ab
	Red. Till. LW	5.05 a	5.16 a	5.52 a	5.29 a
	NO-Till. LW	4.79 bc	4.90 bc	5.26 bc	5.02 de
	NO-Till. CW	4.23 e	4.34 ef	4.69 de	4.45 g
- 20 days	**Conv. Till. LW**	4.93 a-c	5.07 a-c	5.35 a-c	5.14 b-d
	Red. Till. LW	5.02 a	5.18 a	5.46 ab	5.24 ab
	NO-Till. LW	4.74 c	4.87 c	5.16 c	4.95 e
	NO-Till. CW	4.28 e	4.41 e	4.67 de	4.47 g
ordinary	**Conv. Till. LW**	4.95 a-c	5.15 a	5.35 a-c	5.20 a-c
	Red. Till. LW	4.88 a-c	5.11 a	5.32 a-c	5.16 a-d
	NO-Till. LW	4.84 a-c	5.02 a-c	5.21 c	5.06 c-e
	NO-Till. CW	4.49 d	4.66 d	4.82 d	4.69 f
+ 20 days	**Conv. Till. LW**	3.99 fg	4.20 fg	4.36 fg	4.24 h
	Red. Till. LW	3.79 g	4.00 g	4.17 g	4.04 i
	NO-Till. LW	4.10 ef	4.31 ef	4.48 ef	4.35 gh
	NO-Till. CW	3.84 g	4.03 g	4.20 g	4.08 i

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001;**
means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

The results of model simulations seem to indicate a more stable yield for no-tillage technique coupled to rotations with legume crops: with no tillage technique are expected lower yields compared to yields obtainable with reduced tillage with early sowing while, for delayed sowing, no-tillage management is preferable (Tab. 30 and Fig. 60).

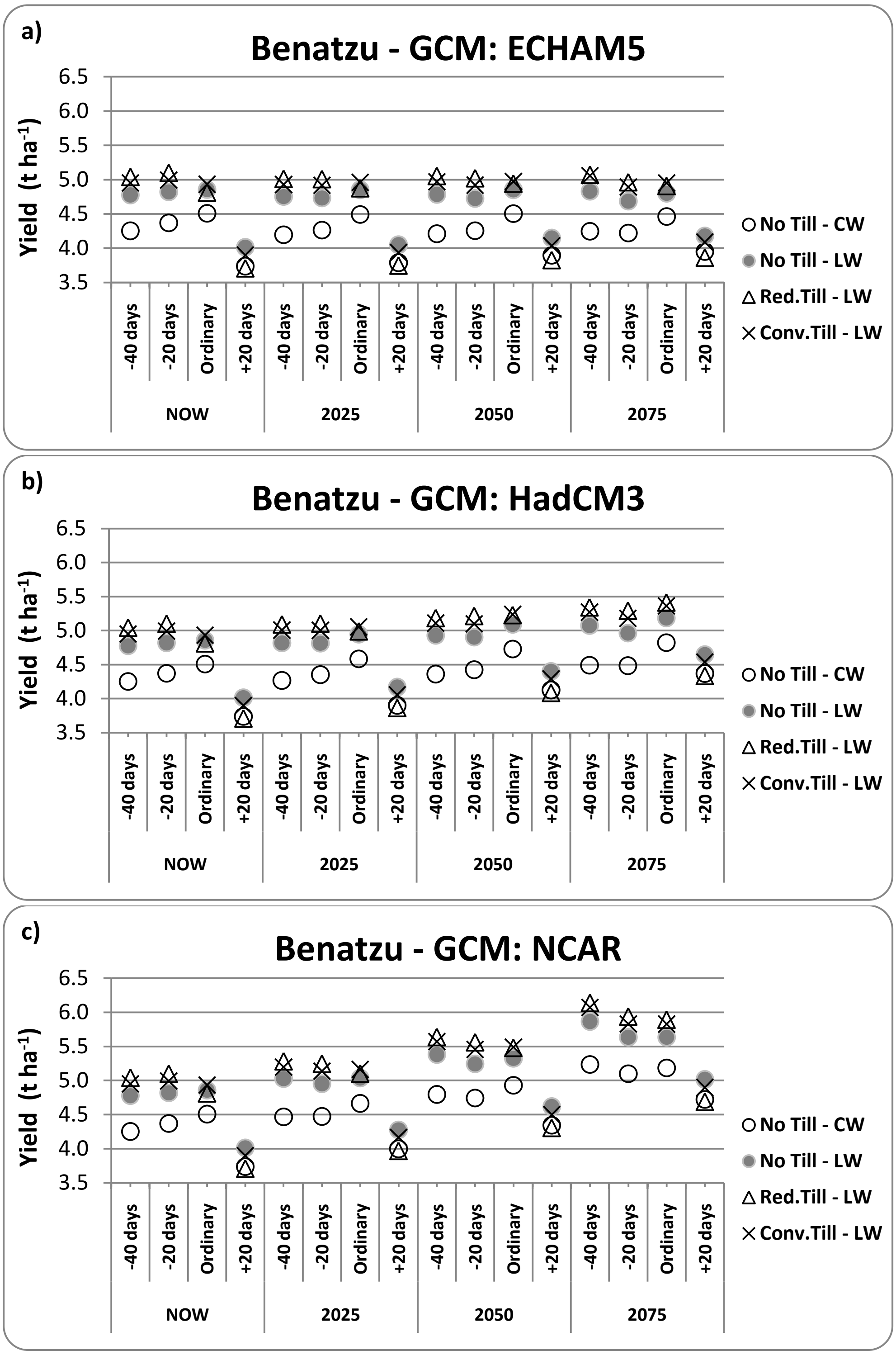


Fig. 60 - Yields (t ha^{-1}) from current to future periods considering HadCM3 (a), ECHAM5 (b) and NCAR (c) GCMs and mid scenarios at Benatzu. Treatments considered are the ordinary planting date, two early dates (-20 days and -40 days) and one later date (+20 days) and agronomic managements.

4.3.5.3. Simulations implying genetic improvement

In order to obtain two new virtual varieties, the first step followed to perform this experiment was to modify the genetic coefficient P1D already calibrated for the cultivar Simeto. The objective of this step was to obtain two new virtual varieties with the same characteristics of Simeto for the different length of cycle: a variety that under current conditions, reaches the stage of anthesis seven days prior compared to Simeto ("Early Simeto") and the other with delayed anthesis of 7 days ("Late Simeto"). In the following paragraphs will be shown the effects of the two virtual varieties compared to Simeto cultivar for anthesis and yield.

Impacts on anthesis

In table 31 are shown results relative to the appearance of the anthesis, expressed in days after planting (DAP), considering different cultivars: Simeto, "Early Simeto" and "Late Simeto".

In current climate the differences in DAP for anthesis are -7.1 days between Early Simeto and Simeto (109.7 compared to 116.8 days) and 6.9 between the latest and Late Simeto (116.8 compared to 123.7 days). Thus, the new synthetic varieties are calibrated properly for the goals of this experiment (Tab. 31).

A general shortening of the crop cycle, from the current climate to the future scenarios has been observed for all GCMs: this trend is more pronounced for NCAR-based scenarios. This is probably due to the higher increases of minimum and maximum air temperatures projected by NCAR that promote a shortening of crop cycle compared to others scenarios.

The advance and delay respectively observed for Early Simeto and Late Simeto are bigger compared to that obtained with current climate: taking into account all GCMs together, differences amount are -7.8 days for Early Simeto and 7.5 days for Late Simeto respect to Simeto. Significant interactions scenario × variety have been observed. This can be explained with differences between varieties that extend starting from the current climate to future climate scenarios (Tab. 31 and Fig. 61).

Tab. 31 - Comparison of anthesis' appearance (DAP) for different varieties, considering current and future periods for the three GCMs and mid scenario. Simulations were performed considering three cultivar: Simeto, "Early Simeto" (Early) and "Late Simeto" (Late).

		ECHAM5	HadCM3	NCAR	ALL GCMs
Scenario		***	***	***	***
NOW		116.7 a	116.7 a	116.7 a	116.7 a
2025		114.2 b	114.2 b	113.7 b	114.0 b
2050		111.6 c	111.6 c	110.7 c	111.3 c
2075		108.9 d	109.0 d	107.6 d	108.5 d
Variety		***	***	***	***
Early		105.3 c	105.4 c	104.5 c	104.1 c
Simeto		113.0 b	113.0 b	112.3 b	111.9 b
Late		120.3 a	120.3 a	119.7 a	119.4 a
Scenario × variety		***	***	***	***
NOW	**Early**	109.7 g	109.7 g	109.7 h	109.7 g
	Simeto	**116.8** d	**116.8** d	**116.8** d	**116.8** d
	Late	123.7 a	123.7 a	123.7 a	123.7 a
2025	**Early**	106.8 h	106.8 h	106.3 j	106.7 i
	Simeto	114.3 e	114.2 e	113.8 f	114.1 e
	Late	121.4 b	121.4 b	121.0 b	121.2 b
2050	**Early**	103.9 i	103.9 i	102.8 k	103.5 j
	Simeto	111.7 f	111.8 f	110.8 g	111.4 f
	Late	119.1 c	119.1 c	118.4 c	118.9 c
2075	**Early**	100.9 j	100.9 j	99.2 l	100.3 k
	Simeto	109.1 g	109.1 g	107.8 i	108.7 h
	Late	116.8 d	116.9 d	115.8 e	116.5 d
	C.V.	*2.6*	*2.6*	*2.6*	*2.6*

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001;**
means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

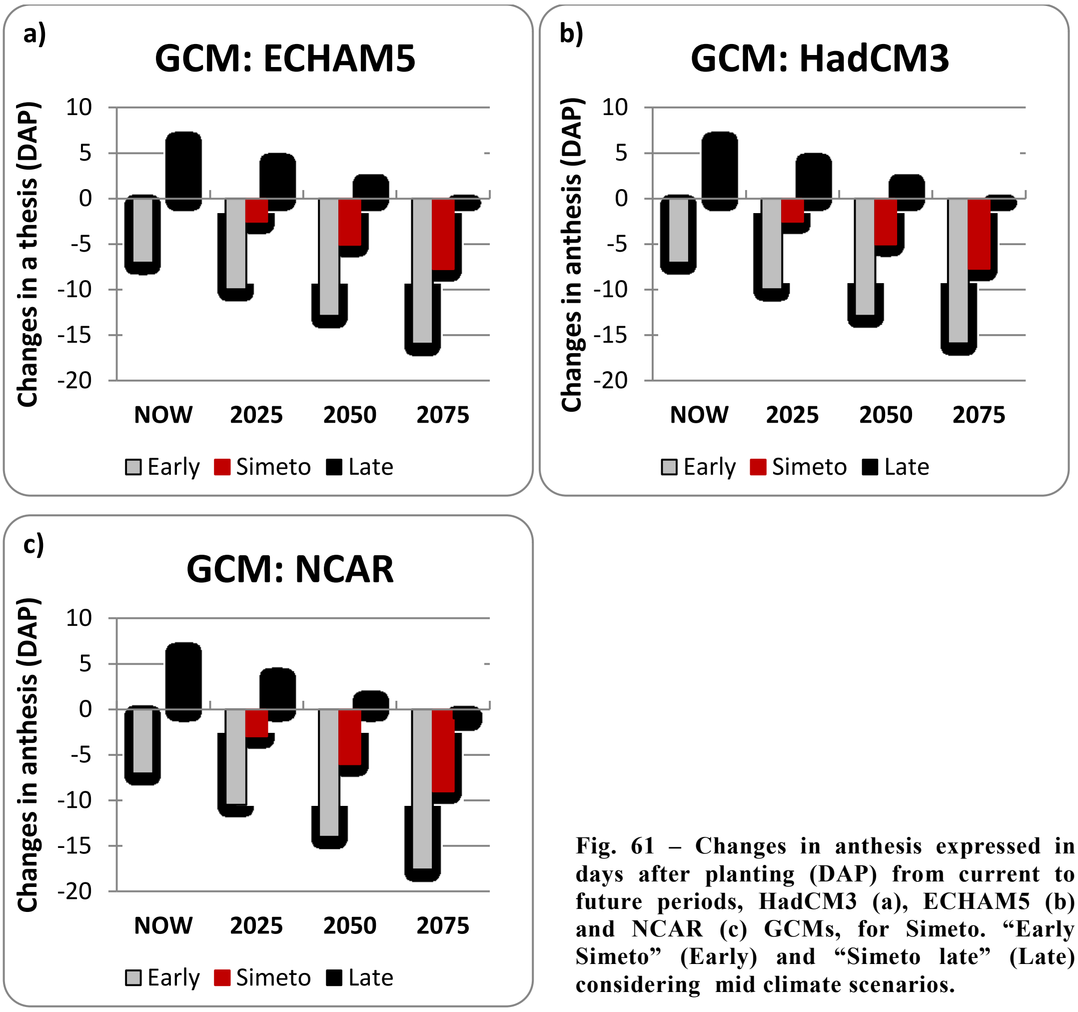


Fig. 61 – Changes in anthesis expressed in days after planting (DAP) from current to future periods, HadCM3 (a), ECHAM5 (b) and NCAR (c) GCMs, for Simeto. "Early Simeto" (Early) and "Simeto late" (Late) considering mid climate scenarios.

Impacts on yields

Ussana

Yields (t ha^{-1}) obtained in simulations of the three varieties with the four agronomic managements and all mid climate scenarios at Ussana are reported in table 32-33 and in figure 62.

In the first four rows of table 32 mean grain yields from current period to 2075 are shown. The highest yields will be obtained in 2050 and 2075 for ECHAM5-based scenarios respect to current climate. Yields simulated using scenarios based on HadCM3 and NCAR GCMs show a increasing trend from current climate to 2075: this are more pronounced for NCAR (Tab. 32).

Tab. 32 - Comparison of yields (t ha^{-1}) from current to future periods for the three GCMs and four agronomic managements with mid climate scenarios at Ussana. Simulations were performed for the three varieties: Simeto, "Early Simeto" (early) and "Late Simeto" (late).

		ECHAM5	HadCM3	NCAR	ALL GCMs
Scenario (a)		**	***	***	***
NOW		2.72 b	2.72 d	2.72 d	2.72 d
2025		2.74 ab	2.81 c	2.92 c	2.82 c
2050		2.79 a	2.96 b	3.21 b	2.99 b
2075		2.80 a	3.10 a	3.49 a	3.13 a
Variety (b)		***	***	***	***
Early		2.43 c	2.55 c	2.76 c	2.62 c
Simeto		2.84 b	2.99 b	3.19 b	3.05 b
Late		3.02 a	3.16 a	3.30 a	3.19 a
Management (c)		***	***	***	***
Conventional Till. LW		2.81 a	2.96 a	3.17 a	3.02 a
Reduced Till. LW		2.82 a	2.97 a	3.16 a	3.02 a
NO-Till. LW		2.85 a	2.99 a	3.19 a	3.05 a
NO-Till. CW		2.56 b	2.68 b	2.82 b	2.72 b
Interaction a × b		n.s	n.s	***	***
NOW	Early	2.35 e	2.35 g	2.35 g	2.35 g
	Simeto	2.80 c	2.80 e	2.80 e	2.80 de
	Late	3.01 ab	3.01 cd	3.01 d	3.01 c
2025	Early	2.39 de	2.45 g	2.56 f	2.47 f
	Simeto	2.82 c	2.90 de	3.01 d	2.91 c
	Late	3.01 ab	3.09 bc	3.18 c	3.09 b
2050	Early	2.46 de	2.62 f	2.89 de	2.66 g
	Simeto	2.87 bc	3.06 c	3.32 bc	3.08 e
	Late	3.04 a	3.22 ab	3.41 b	3.22 cd
2075	Early	2.51 d	2.78 e	3.24 c	2.84 e
	Simeto	2.87 bc	3.21 ab	3.63 a	3.24 ab
	Late	3.02 ab	3.32 a	3.60 a	3.31 a
Interaction a × c		n.s.	n.s.	n.s.	n.s.
Interaction b × c		*	**	***	***
Interaction a × b × c		n.s.	n.s.	n.s.	n.s.
C.V.		*24.0*	*21.9*	*21.5*	*23.0*

n.s., *, **, *** = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001;
means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

Significant (p≤0.001) yield differences between varieties have been observed for all GCMs. At Ussana, Late Simeto was the best variety for yield whereas Early Simeto was the worst. Tillage practices do not seem to determine differences in yields while continuous wheat crops with no-tillage techniques cause relevant decreases compared to other managements. No interactions were observed between scenarios and varieties for ECHAM5 and HadCM3 scenarios, while interactions are significant for NCAR scenarios.

In this last case the interactions could be explained in a better behaviour of Late Simeto compared to Simeto both in current climate and in 2025, while no differences in 2050 and 2075 have been observed. No interactions were observed between scenarios and managements (Tab. 32).

In table 33 and figure 62 more detailed information about yields simulated with different agronomic management combinations are shown.

Tab. 33 - Comparison of yields (t·ha^{-1}) considering variety × agronomic management interaction for the three GCMs and mid scenario at Ussana. Simulations were performed for the three varieties: Simeto, "Early Simeto" (early) and "Late Simeto" (late).

		ECHAM5	**HadCM3**	**NCAR**	**ALL GCMs**
Variety × management		*	**	***	***
Early	**Conv. Till. LW**	2.46 e	2.59 d	2.81 c	2.66 d
	Red. Till. LW	2.46 e	2.59 d	2.80 c	2.66 d
	NO-Till. LW	2.51 e	2.64 d	2.85 c	2.71 d
	NO-Till. CW	2.28 f	2.39 e	2.58 d	2.46 e
Simeto	**Conv. Till. LW**	2.88 bc	3.04 b	3.26 b	3.11 b
	Red. Till. LW	2.88 bc	3.04 b	3.26 b	3.11 b
	NO-Till. LW	2.92 b	3.08 b	3.29 ab	3.14 b
	NO-Till. CW	2.67 d	2.80 c	2.95 c	2.84 c
Late	**Conv. Till. LW**	3.11 a	3.26 a	3.43 a	3.30 a
	Red. Till. LW	3.11 a	3.26 a	3.43 a	3.30 a
	NO-Till. LW	3.12 a	3.26 a	3.42 a	3.30 a
	NO-Till. CW	2.74 cd	2.85 c	2.93 c	2.86 c

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001;**
means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

The significant interactions variety × management could be explained by the higher increases obtained, starting from Early Simeto towards Simeto taking into account conventional and reduced tillage compared to no-tillage. Thus the lengthening of the growing season favours conventional and reduced tillage compared to no-tillage practices. Moreover these trends are noticeable both for rotation with legumes and for continuous wheat crops (Tab. 33 and Fig. 62).

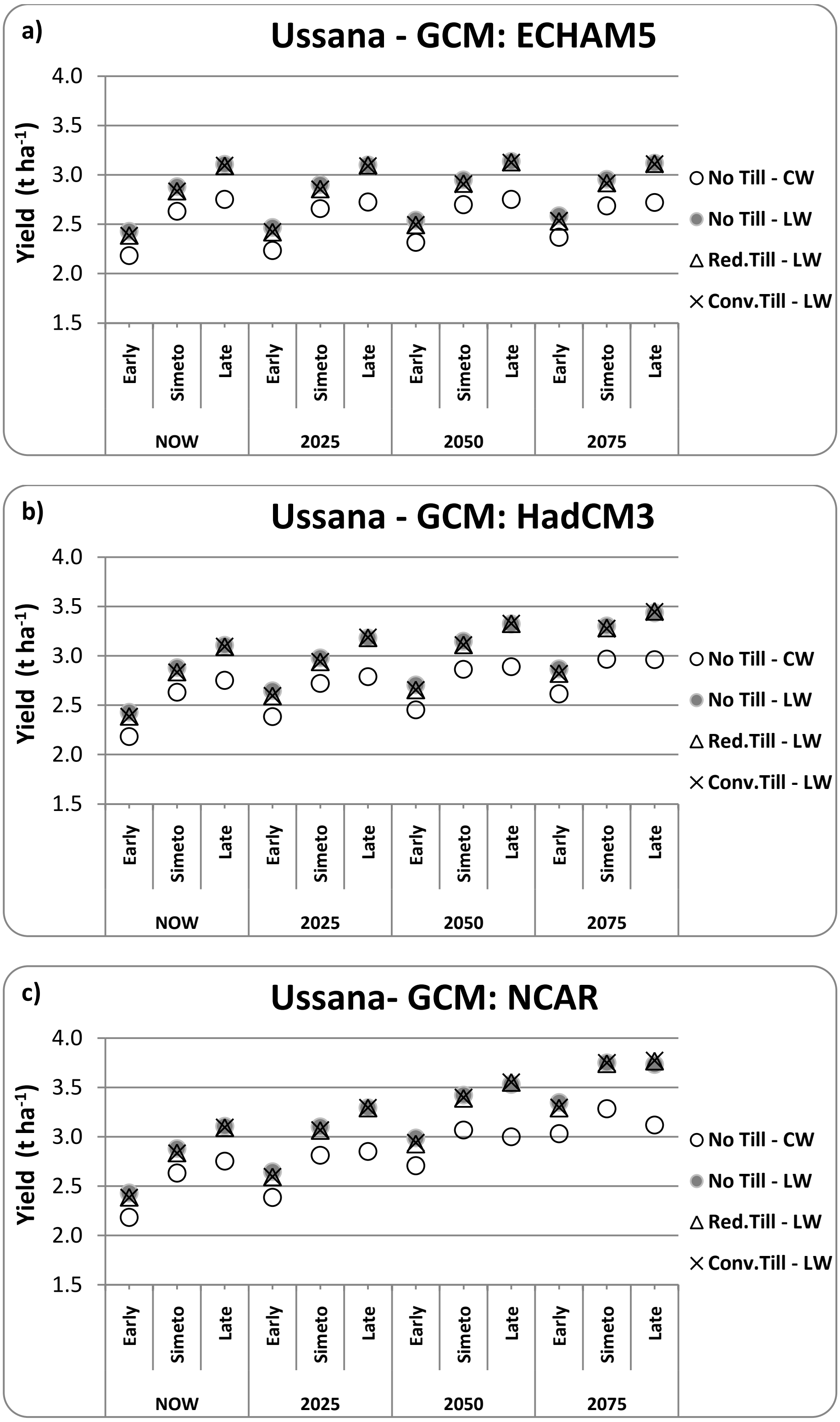


Fig. 62 - Yields (t ha^{-1}) from current to future periods considering HadCM3 (a), ECHAM5 (b) and NCAR (c) GCMs, for Simeto, "Early Simeto" (Early) and "Late Simeto" (Late) for each agronomic management and with mid climate scenarios at Ussana site.

Benatzu

Yields, expressed in t ha^{-1} and obtained in crop simulations for the three varieties with the four agronomic managements and all mid climate scenarios at Benatzu are reported in table 34-35 and in figure 63.

Tab. 34 - Comparison of yields (t ha^{-1}) from current to future periods for the three GCMsand and four agronomic managements with mid climate scenarios at Benatzu. Simulations are performed for three varieties: Simeto, "Early Simeto" (Early) and "Late Simeto" (Late).

		ECHAM5	HadCM3	NCAR	ALL GCMs
Scenario (a)		n.s.	***	***	***
NOW		4.56 a	4.56 d	4.56 d	4.56 d
2025		4.56 a	4.66 c	4.76 c	4.66 c
2050		4.61 a	4.83 b	5.08 b	4.84 b
2075		4.61 a	5.00 a	5.42 a	5.01 a
Variety (b)		***	***	***	***
Early		4.22 b	4.41 c	4.67 c	4.50 c
Simeto		4.79 a	4.98 a	5.18 a	5.03 a
Late		4.74 a	4.89 b	5.01 b	4.90 b
Management (c)		***	***	***	***
Conventional Till. LW		4.72 a	4.90 a	5.10 a	4.95 a
Reduced Till. LW		4.64 a	4.84 a	5.04 a	4.89 b
NO-Till. LW		4.66 a	4.83 a	5.03 a	4.88 b
NO-Till. CW		4.32 b	4.48 b	4.65 b	4.52 c
Interaction a × b		**	***	***	***
NOW	Early	4.10 c	4.10 e	4.10 g	4.10 g
	Simeto	4.78 a	4.78 c	4.78 e	4.78 d
	Late	4.79 a	4.79 c	4.79 e	4.79 d
2025	Early	4.17 bc	4.27 e	4.40 f	4.28 f
	Simeto	4.80 a	4.89 bc	4.99 cd	4.89 d
	Late	4.72 a	4.82 c	4.88 de	4.81 d
2050	Early	4.26 bc	4.51 d	4.85 de	4.54 e
	Simeto	4.82 a	5.07 ab	5.31 b	5.07 b
	Late	4.74 a	4.92 bc	5.07 c	4.91 cd
2075	Early	4.35 b	4.76 c	5.31 b	4.81 d
	Simeto	4.78 a	5.19 a	5.63 a	5.20 a
	Late	4.70 a	5.04 ab	5.32 b	5.02 bc
Interaction a × c		n.s.	n.s.	n.s.	n.s.
Interaction b × c		***	***	***	***
Interaction a × b × c		n.s.	n.s.	n.s.	n.s.
C.V.		*18.8*	*16.3*	*16.8*	*17.9*

n.s., *, **, * = not significant, significant respectively at p≤0.05, p≤0.01, p≤0.001;**
means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

Mean yields from current period to 2075 are shown in the first four rows of table 34. Yields simulated using scenarios based on HadCM3 and NCAR show an increasing trend from current climate towards the 2075: this is more pronounced for NCAR. No differences for ECHAM5-based scenarios were observed. Yields obtained in simulation related to Early Simeto are lower compared to other varieties for all scenarios. The highest expected yields by crop simulations were obtained with Simeto that is expected to be more productive than Late Simeto both in scenarios based on HadCM3 and NCAR (Tab. 34).

Tillage practices do not seem to determine differences in yields while continuous wheat crops coupled to no-tillage techniques cause relevant decreases compared to other managements. No significant interactions were observed between scenario and management. On the other hand significant interactions scenario × variety have been observed for all scenarios. The three varieties, in fact, respond differently to scenarios. This can be observed in all scenarios and is more noticeable for NCAR: in this case the Simeto cultivar is more productive in 2075 compared to Late Simeto whereas no difference was observed with current climate (Tab. 34).

The significant interactions variety × management observed for all scenarios are noticeable in table 35 and figure 63.

Tab. 35 – Yield ($t \cdot ha^{-1}$) comparison considering variety × agronomic management interaction for the three GCMs and mid scenario at Benatzu. Simulations were performed for the three varieties: Simeto, "Early Simeto" (Early) and "Late Simeto" (Late).

		ECHAM5	**HadCM3**	**NCAR**	**ALL GCMs**
Variety × management		***	***	***	***
Early	**Conv. Till. LW**	4.31 **c**	4.49 **c**	4.76 **de**	4.59 **de**
	Red. Till. LW	4.07 **d**	4.27 **d**	4.51 **f**	4.35 **g**
	NO-Till. LW	4.40 **c**	4.60 **c**	4.87 **cd**	4.69 **d**
	NO-Till. CW	4.10 **d**	4.28 **d**	4.53 **f**	4.37 **fg**
Simeto	**Conv. Till. LW**	4.95 **a**	5.15 **a**	5.35 **a**	5.20 **a**
	Red. Till. LW	4.88 **ab**	5.11 **a**	5.32 **a**	5.16 **ab**
	NO-Till. LW	4.84 **ab**	5.02 **ab**	5.21 **a**	5.06 **b**
	NO-Till. CW	4.49 **c**	4.66 **c**	4.82 **cd**	4.69 **d**
Late	**Conv. Till. LW**	4.90 **ab**	5.05 **ab**	5.18 **ab**	5.06 **b**
	Red. Till. LW	4.96 **a**	5.14 **a**	5.28 **a**	5.15 **ab**
	NO-Till. LW	4.75 **b**	4.89 **b**	5.01 **bc**	4.90 **c**
	NO-Till. CW	4.35 **c**	4.48 **c**	4.59 **ef**	4.49 **ef**

n.s., *, **, * = not significant, significant respectively at $p \leq 0.05$, $p \leq 0.01$, $p \leq 0.001$;**
means in columns followed by different letters are significantly different at p = 0.05 according to Tukey's test.

Simulations related to no-tillage practice coupled to rotation with legumes seem to respond better to early than late varieties respect to reduced and conventional tillage (Tab. 35 and Fig. 63). Thus the lengthening of the growing season favours conventional and reduced tillage compared to no-tillage practices. These differences are more noticeable taking into account the two no tillage managements: yields increases more with the rotation with legumes using later varieties whereas with continuous wheat crops yields obtained with Late Simeto are lower than Simeto (Tab. 35 and Fig. 63).

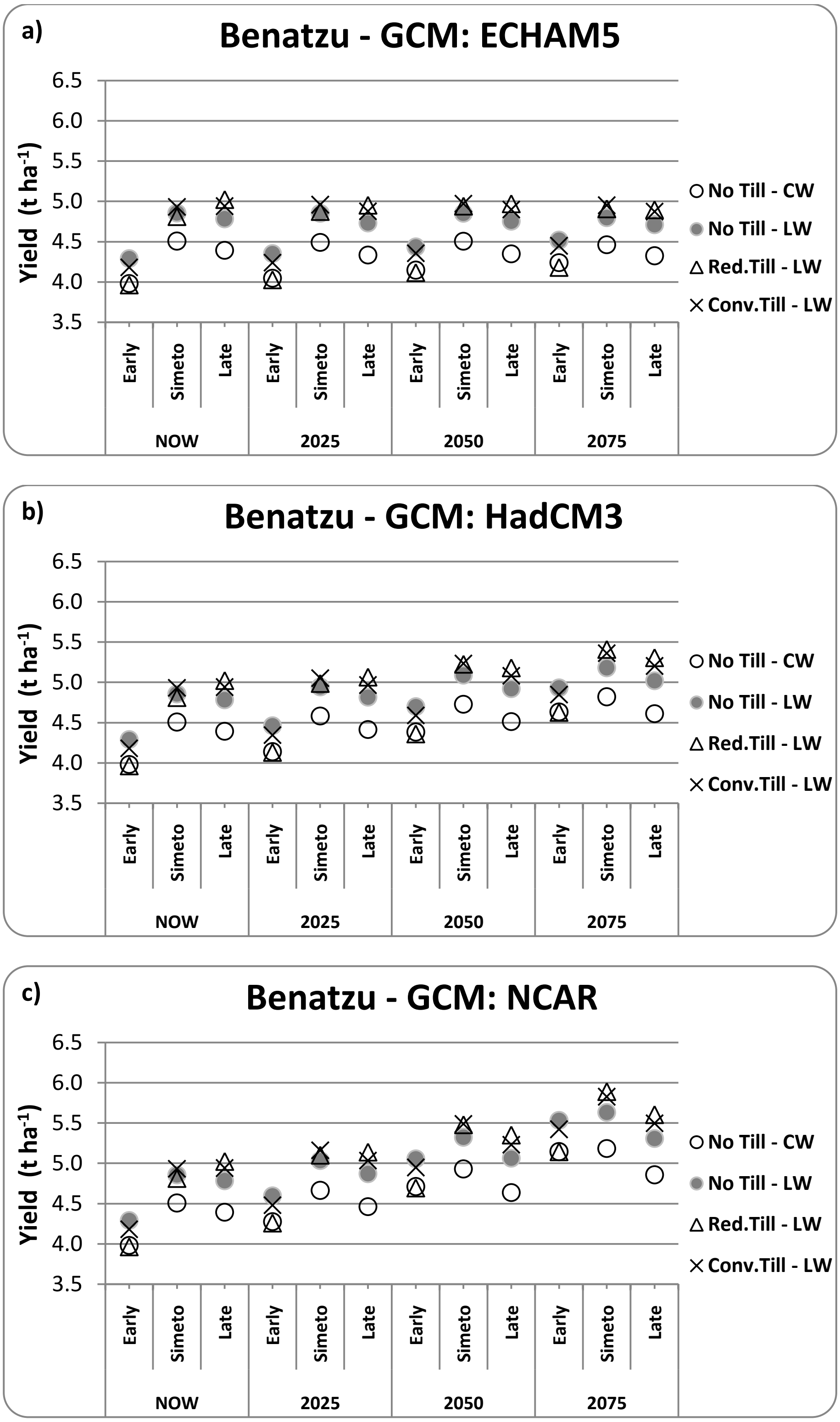


Fig. 63 - Yields (t ha^{-1}) from current to future periods considering HadCM3 (a), ECHAM5 (b) and NCAR (c) GCMs, for Simeto, "Early Simeto" (Early) and "Late Simeto" (Late) for each agronomic management and with mid climate scenarios at Benatzu.

5. DISCUSSION AND CONCLUSIONS

Agronomic section

The results obtained in five years of field experiments allow to express some explanations about tillage and rotations effects on durum wheat in a semiarid environmental conditions such as those of Southern Sardinia. Although five years of agronomic trials are sufficient to make the first assumptions regarding crop phenology and yields, both considering quality traits of production and quantity, a five-year period is not long enough for studying modifications on soil characteristics due to tillage and rotation. In fact, in general, a long term field experiments is necessary for studying changes in physical and chemical characteristics. For these reasons this study focuses on management effects on durum wheat phenology and yield.

Weather conditions normally, play an important role in crop growth and development of durum wheat. In our experimentation they caused low yields compared to the ordinary values. This was related to the fact that the weather during these five years of experiments was characterized by relatively drier conditions respect to the average climate conditions typical of this area. Weather significantly influenced development and growth of durum wheat and consequently, anthesis and yields: this is noticeable considering the significant effect of years observed in statistical analyses for numerous variables studied. Significant interactions observed for numerous variables between crop managements, and between crop management and years, makes difficult to interpret the results. Both in Ussana and Benatzu yields obtained with conservation tillage do not differ from conventional tillage. Similar results were obtained in other studies conducted in U.S. (Guy and Cox, 2002), in Mexico (Fischer *et al.,* 2002), Australia (Latta and O'Leary, 2003) and in Italy (Pisante and Basso, 2000; Carboni *et al., 2006;* De Vita *et al.,* 2007) on wheat. However, it should be considered that each experiment was carried out under different experimental conditions and type of conservation tillage. These vary greatly in different regions and so it is difficult to compare results obtained in all these studies (Van De Putte *et al.,* 2010). Moreover, tillage management must be considered with rotation. Yields obtained in Ussana and Benatzu confirm difficulties to interpret the effects of tillage and rotations together. Furthermore, the significant interaction tillage × precession observed at Ussana was not confirmed for Benatzu. At Ussana the reduced tillage management coupled to precession with legumes showed a beneficial effect that was more pronounced than for others tillage managements. This behaviour could be explained by a bigger concentration of legumes residues in reduced tillage that can increase the nutrients (especially nitrogen) available for wheat. With reduced tillage, in fact, the lower depth of tillage (about 15 cm) compared to moldboard ploughing (25-30 cm) involves a higher concentration of legume residues in the layer affected by tillage and then the beneficial effects of precession could be bigger than applying other tillage managements. On the contrary, with sod-seeding the residues of previous crop are partially buried and mineralized, thus the beneficial effects of legume residues could be lower. In Benatzu this effect was not observed. These different results are probably due to soil characteristic that play a role in durum wheat growth and yield: generally in Benatzu yields are higher than in Ussana because of the higher soil water capacity and a relatively high soil organic matter. This last characteristic, in average higher at Benatzu (2.1%) respect to Ussana, (1.3%), could have been covered the beneficial effect of buried residue legumes at Benatzu. The lower yields obtained in this last site in the driest years compared to Ussana is probably due to the different soil water retention curve: the water content in wilting point at Benatzu is higher than at Ussana. With extreme shortage of precipitation, and small amounts of water of soil, the water is more strongly retained in Benatzu than in Ussana, thus plants are advantaged in the latter site where can survive and grow better than in Benatzu.

In both sites, the precession with legumes had a significant beneficial effect on yields. These effects are also reinforced by the increased plant height and the higher spike density obtained in both sites that are good indexes of the better conditions for growing wheat. The better values of kernel protein content obtained together to the higher yields obtained in this experiment allow to confirm that the rotation with legumes is strongly recommended for durum wheat for these environments. These results are similar to those, reported by numerous studies (Giambalvo *et al.*, 1999; Berzsenyi *et al.*, 2000; Galantini *et al.*, 2000; Gan *et al.*, 2003). Moreover the significant interaction tillage × precession observed in Benatzu highlights the important positive effect of conventional tillage coupled to legumes precession.

Reduced and no-tillage practices had negative effects in some grain quality parameters: test weight was significant lower for conservation tillage in both sites, and at Benatzu, the no-tillage management causes lower values of test weight. These tendencies observed in Benatzu, but less pronounced in Ussana, do not agree with results of other studies carried out in Spain (López-Bellido *et al.,* 1998) and Italy (Giambalvo *et al.,* 1999;

De Vita *et al.*, 2007) where it has been observed the same or higher values of test weight. Results obtained in Benatzu contrasted with results observed by De Vita *et al.* (2007): on the contrary of this study, at Benatzu, taking into account the only continuous wheat management, the higher kernel protein content was obtained with the no-tillage technique compared to conventional tillage. This was observed also with respect to reduced tillage. Moreover, both in Ussana and Benatzu higher values of gluten index were observed for conventional tillage with respect to conservation tillage.

A final consideration deserves the impact of tillage and rotation practices on durum wheat development. In both sites, heading was influenced both by tillage and precession with higher influences observed for tillage, especially between conventional and no-tillage: with the last practice, an average of 3 days late for heading was observed compared to conventional tillage. This result could be explained as an adaptation response of durum wheat to dry environments, where plants tend to shorten phenological phases in order to complete their life cycle before occurring water stress. The conventional practice, probably, modified the water retention curve of soil and water availability for plants are lower compared to the water available when no-tillage practice is applied. Therefore, the shortening of the crop cycle observed for the conventional tillage can be explained by an earlier water stress, to which plants are subjected, compared no-tillage practice. In agreement with this result, Bescansa *et al.* (2006) observed that under drier conditions the long-term conservation tillage promotes higher soil water content. This was attributed to the higher presence of small pore-size and the higher soil organic matter content in untilled soils that caused a better water supply for plants.

The contradictory results of tillage studies over the world, sometimes in the same regions (Cantero-Martínez *et al.,* 2003; López and Arrùe, 1997) highlights the necessity to carry out experiments under different climate, soil and crop conditions to understand the best management for each region and to continue this experiment to verify effects of tillage and rotation both on yield and grain quality, and on soil characteristics in the long-term period.

Crop modelling section

The statistical analyses used to evaluate performance of the CSM-CERES-Wheat model confirm a good ability of this model in predicting development and growth of durum wheat in Mediterranean areas. Calibration and evaluation was already done in Sardinia (Dettori *et al.,* 2011) using a long term database from the same locations. However, this last work was made only considering some cultivars and using field experiments conducted according to the procedures of the Italian durum wheat network for cultivar evaluation that followed the ordinary management (conventional tillage). The attempt pursued in this work to calibrate the model to simulate tillage and rotation was partially reached as far as the simulation of the grain yield and anthesis. The latest improvements implemented in the beta version of DSSAT 4.5, that is still under development, respect to the previous model versions allowed to improve simulations of the processes involved in this work. Four of the six combinations of management considered in field experiments have been calibrated with satisfactory results for yields: conventional, reduced and no-tillage in rotation with legumes and no-tillage with continuous wheat. Both conventional and reduced tillage with continuous wheat were not satisfactorily calibrated because of the tendency of the model to overestimate yields. As observed in field experiments, no differences between tillage treatments were obtained in simulations with current climate. In this last case it is difficult to understand if no significant differences are related to good performances of the model or to low sensitivity of it. This last option, however, may be rejected by considering the different behavior observed for the no-tillage managements: significant differences between continuous wheat and legumes-wheat rotations observed in field experiments were successfully calibrated. Overestimates of yields observed with continuous wheat could be explained by the likely negative effects of diseases (especially rot roots) in field, that, is well known, are more frequent with continuous wheat than after rotation with legumes, and that the crop model used does not consider (Ghaffari *et al.*, 2002; Šť'astná *et al.*, 2002; Tubiello *et al.*, 2007b). Furthermore, the experiments carried out, started in 2003, were designed for agronomic purposes and some data used for the evaluation of the model (e.g. initial conditions at planting and detailed information about phenological stages) had to be estimated for the first years. As underlined by various studies, a more precise datasets, could sensibly improve the calibration of the model. This may be an issue of a future researches.

Climate change section

Climate

Independently from the wide scientific literature about climate change, analyses of climatic variable trends of the study site in the long term (1973-2009) were made. Air temperatures show significant increasing trends which are different for each season: these were significantly crescent for annual and seasonal (except for winter) minimum and maximum temperatures. Trends observed for T_{max} e T_{min} expressed in °C $decade^{-1}$ (respectively 0.78 and 0.34 °C $decade^{-1}$) are comparable with those reported in studies made by Jones and Moberg (2003) for surface air temperature variations: they reported an increasing trend of 0.43 °C $decade^{-1}$ in the time span 1977-2001 for the mean air temperature in Europe. No significant trends were observed for precipitations.

The methodological approach used in this thesis for assessing climate change impacts on durum wheat shows several strengths. The uncertainties linked to climate change projections, which depend on emission scenarios, climate sensitivity and GCM considered, were coped exploring a wide range of future scenarios with the aim to have a more likely crop impact assessment.

The pattern scaling technique applied allowed to explore uncertainties in the climate change patterns between GCMs but also uncertainties linked to emission scenarios and climate sensitivity. The strengths of this approach consisted in considering a wide range of variability in future climate projections: wide ranges of temperatures, precipitations and solar radiation, projected by the three GCMs considered with different emission scenarios and values of climate sensitivity. The main differences between climate change scenarios were observed in different patterns of rainfall due to the differences in CGMs. Scenarios based on NCAR-PCM provided the lowest decreases in precipitation (especially in spring) compared to the others scenarios. ECHAM5 foresees the highest pessimistic projections in decreasing of precipitations respect to current climate. Differences for temperatures between different GCM-based scenarios are lower respect to those observed for precipitations. The NCAR-based scenarios was the warmest considered.

The choice of reproducing weather series that represent future scenarios through a WG, was made to downscale information from GCMs at field scale, and to reproduce the local climate variability.

Moreover, the synthetic weather series obtained for each scenario, composed by 100 years, allow to obtain enough crop simulation outputs that can be used to made robust statistical analyses of climate change impacts. The validation of weather generator, performed comparing crop model output obtained between observed weather data versus outputs obtained with synthetic weather series (indirect validation) for current period, showed no statistical differences between means and so confirm that this tool, coupled to the crop growth models, provides outputs reliable for assessing climate change impacts on crops as already applied in other studies (Šť'astná *et al.,* 2002; Trnka *et al.,* 2004b; Trnka *et al.,* 2004b).

Climate change impacts evaluation

A general shortening of the crop cycle since the anthesis has been observed in moving from current climate towards future scenarios. The advancement in the anthesis stage occurrence depend on period, on GCM and on the combination of climate sensitivity with emission scenario considered. The shortening of this part of crop cycle rises from 2025 to 2075 and is more pronounced for scenarios based on NCAR that projected the warmest climate change scenarios. The combination of climate sensitivity and emission scenarios plays the main role in determining uncertainties linked to scenarios used for the same period. This causes wide differences in temperature and rain projections especially for 2075. The wide differences in temperatures projections, independently from the GCM considered, cause great differences in phenology: the appearance of anthesis reaches differences of 12 days between low and high scenarios.

Climate change impacts on yield were investigated considering also the direct and indirect effect of CO_2 air concentrations.

Simulations made in this study showed negative effects on yield linked to changed weather conditions due to indirect effect of CO_2 concentration (changes in meteorological variable values). Again, the climate sensitivity, coupled with the corresponding emission scenarios, plays the main role in determining reduction in yields. The uncertainties related to these reductions are very high and can reach 50% in 2075 for the high climate scenarios related to ECHAM5 GCM at Ussana, and 35% at Benatzu. These differences are lower considering low scenarios (14.8% and 8.6% at Ussana and Benatzu respectively). On the other hand, taking into account the NCAR GCM, yield reductions are lower respect to the other GCMs projections: 8.2% and 6.7% for high scenarios in 2075 at Ussana and Benatzu respectively, and 2.5 % both for Ussana and Benatzu for low scenarios for the same period. Taking into account all GCMs together and average yields, the maximum reduction in yields is equal to 29% at Ussana and 21% at Benatzu considering high climate scenario in 2075.

The direct and indirect combined effects of CO_2 atmospheric concentration, showed wide differences in projections between scenarios starting from a decrease of 12% at Ussana (10% at Benatzu) for ECHAM5 (high scenario) in 2050, to an increase of 43% at Ussana (28% at Benatzu with NCAR (high scenario) in 2075. Average yields of all climate change scenarios, yield changes vary from a reduction of 3% at Benatzu (1% at Ussana) in 2050 with high climate change scenario to an increase of 19% at Ussana (10% at Benatzu) in 2075 with high climate scenario.

These results highlight the importance of climate change scenarios used to study climate change impacts: in this work 3 GCMs and three climate sensitivity, coupled with the corresponding emission scenario, were used for each future period. The differences between the climate change scenarios are large and so yield projections are very different. On average, scenarios based on HadCM3 provided impacts similar to the average of all GCMs together. Even if the comparison with other climate change impact studies is strongly related to the GCMs, emission scenarios and crop model used, the results obtained in this work do not differ from the studies of Trnka *et al.* (2004b) in Czech Republic that used an analogue approach (seven GCMs and two emission scenarios), and that report a reduction in wheat yield ranging from 25.8% for the indirect effect of CO_2, and 8 and 25% for the CO_2 combined effect. Others authors (Brassard and Singh, 2008) that studied the effect of climate change using the CERES-Wheat model in seven regions of Canada obtained yield decreases in wheat that reach 40% without consider the CO_2 fertilization effect, whereas obtained yield increase of 42% considering the combined effect of CO_2. Lower yield variation was obtained by Bindi and Moriondo (2005) that used the CropSyst model to study the impact of a 2° C global temperature rise in the Mediterranean area: they obtained a prevalent decrease in cereal yields (23% in Morocco) without considering the direct effect of CO_2 and increases (reaching 19% in Turkey) considering the combined effect of CO_2. Similar results are obtained by Richter and Semenov (2005) in the UK using the Sirius model (Jamieson *et al.*, 1998) and HadCM2: they found yield increases between 15-23% in 2050.

These results highlight that in spite of a predicted reduction of precipitation, implying an increase of drought in the future, the positive direct effect of rising CO_2 is likely to be stronger than the effect of water shortage. There is a large discussion about the effect of CO_2 and the implementation of its effects on crop growth models (Long *et al.*, 2006; Tubiello *et al.*, 2007a). The CO_2 effect on plants is mainly made up of two aspects: i) the intensified photosynthesis activity and ii) the greater water use efficiency (WUE) due to a reduction in stomatal conductance and thus transpiration (Olesen and Bindi, 2002). In the CERES-Wheat model both of these effects are modelled: the augmented intensity of photosynthesis is modelled by the CO_2 modification factor, whereas the increases of WUE are modelled, in the transpiration module, by a function that considers the augmented stomatal resistance with the increasing of CO_2 air concentration.

To confirm the important role played by the CO_2 air concentration it is important to highlight that, in this work, the highest increased yield, simulated in 2075, is obtained for the high climate change scenarios in which a concentration of 705 ppm of CO_2 was found using the MAGICC/SCENGEN model.

Independently from uncertainties linked to modeling processes interested by elevated CO_2, plant physiologists and modelers converge in affirming that the effects of elevated CO_2 may be overestimated by models because of many limiting factors such as pests, weeds, nutrients and other competitions for resources, which are neither well understood at large scales, nor well implemented in the models (Tubiello *et al.*, 2007b).

Adaptation strategies assessment

The evaluation of tillage and rotation practices as adaptation strategies to cope with climate changes are restricted to the managements calibrated for the model: all tillage practices were coupled to rotation with legumes and no-tillage with continuous wheat. The different tillage practices did not induce significant influences on yields, both at Ussana and Benatzu, as observed in field experiments conducted in the time span 2004-2009. Yields obtained with continuous wheat are always lower respect to those obtained with rotation for all scenarios, and no significant interactions between agronomic techniques and scenarios were observed. These results indicate that there are not differences between tillage practices as adaptation strategies to cope with climate change, whereas continuous wheat crop are inadvisable in both sites, and especially at Ussana where projected increasing yields in 2075 are less favourable respect to rotation with legumes for no-tillage practices.

Early planting, respect to the ordinary date of sowing of field experiments, could provide better yields both with current climate and future scenarios at Ussana, whereas these advantages are noticeable at Benatzu only for NCAR scenarios. These results are consistent with Luo *et al.* (2009) that, in Australian conditions, individuate an early sowing of 2 weeks as effective adaptation strategy in dealing with the adverse effects of climate change, and partially with Savin *et al.* (1995) in Mexico for 24 years of observed weather, even though they observed strong interactions among sowing date, site, cultivar and year. Interactions with managements are observed also at Ussana and Benatzu: yield increases linked to early plantings can be obtained only for managements that include rotations with legumes, whereas the no-tillage with continuous wheat either not changes or provides yield decreases. On the other hand, planting carried out 20 days later respect to the ordinary dates caused decreasing of yields: in these conditions differences between managements tends to disappear. A general shortening of the crop cycle has been observed from the current period to the future for all climate scenarios. This trend increases from current towards future periods. The advance and delay of sowing date, caused a lengthening and shortening of the crop cycle respectively. These changes are more pronounced for scenarios based on NCAR respect to others climate change scenarios. This behaviour is explained by the higher increases in air temperatures projected by NCAR respect to the others GCMs that promote a shortening of crop cycle.

In this study, when the virtual cultivars with earlier (“Early Simeto”) and later (“Late Simeto”) anthesis are considered, the latest provided higher yields at Ussana both with current climate and with future climate change scenarios, even though the adavantages linked to “Late Simeto” tended to diminuish in the future. Managements including rotations with legumes take are more advantages. The worst agronomic management was the no-tillage practice coupled with continuous wheat. Similar results were obtained by Wang *et al.* (1992) in climate change impacts studies in Australia who observed that earlier maturing cultivars could have major yield decreases, and by Ludwig and Asseng (2010) in warming climates of Australia. More complex results were obtained at Benatzu where the best cultivar was the actual Simeto for future scenarios, whereas no difference from current climate were observed respect to “Late Simeto”. In this site, no-tillage practice coupled to rotation with legumes seems to respond better to early than late varieties respect to reduced and conventional tillage. Thus, the lengthening of the growing season favours conventional and reduced tillage. In these conditions, characterized by a soil with higher potential yields, differences among tillage practices tend to widen.

Simulations implying genetic improvement could be a useful tool (e.g. for breeders) because they could provide strategies to obtain improved cultivars adapted to produce in situations of climate change. This tool may be particularly useful to predict the behaviour of an early variety in climate change conditions. Considering time and cost involved in obtaining a new variety of durum wheat (about 8-10 years), this tool can be considered very effective. The same tool could provide also guidelines to breeders to study the interaction between virtual variety and alternative managements (e.g. N fertilization, irrigation, tillage etc.)

Conclusions

The approach used in this work permits to evaluate uncertainties linked to future climate scenarios and crop management options, such as tillage, rotation, planting date and cultivar choice. The CSM-CERES-Wheat model is able to count for the effect of the agronomic techniques and the main climate change conditions. Information on the impacts on yields due to i) the accelerated development and growth rate for rising temperatures; ii) the augmented intensity of photosynthesis and the increase of WUE due to increasing of CO_2 air concentration; iii) the shortage of water that limits several processes are reported

The results show a substantial no effect of tillage practices on yields, whereas rotations with legumes provide higher yields both considering field experiments and simulations with current and future climate scenarios. The positive effect of crop rotation provides also better grain quality characteristics (e.g kernel protein content). The crop growth model used in this study resulted more sensitive to climate scenarios than to crop managements and the uncertainties linked to climate scenarios, which are still too large especially for more distant future periods, causes estimates too variable and sometimes contradictory due to factors that have not been clarified yet (e.g. climate sensitivity, emission scenarios, CO_2 effects on plants).

More efforts are necessary to improve our knowledge of the processes involved either in climate projections or in simulating crop growth. In general, the tillage effects on physical and chemical soil characteristics need to be better simulated.

The application of conservation tillage in this area, however, is to recommend for many reasons. Whether the results of this study confirm that the applicability of these techniques is beneficial in the current conditions and may be convenient in future climatic conditions, it is important to underline that conservation tillage can be considered an useful mitigation measures to cope with climate change (Johnson *et al.*, 2005; Hutchinson *et al.*, 2007). In fact, their application results in lower fossil-fuel uses and increases in carbon sequestration in the soil pool through less disturbance of soil organic matter (Follett, 2001; West and Marland, 2002).

The agricultural policy of the European Union, since 2003, with the *mid-term review* CAP reform, has fundamentally encouraged the adoption of these practices also for the social pressures on the farmer's community to reduce the environmental impact of agricultural processes. However, the adoption of conservation tillage practices by farmers, rather than being encouraged by these rising environmental concerns, will depend on its economic viability. This depends on the area where these practice are applied, but many studies (Stringi and Gianbalvo, 1999; Bonciarelli *et al.,* 2001; West and Marland, 2002; Carboni *et al.,* 2006) indicate that both reductions in fossil-fuel use and time needed for the cultivation result in a reduction of costs between 80-150 euro. These aspects together to Rural Development Plans approved in European Union, and especially plans approved in some regional administration in Italy (P.S.R., 2007), may encourage the adoption of conservation tillage and rotations with legumes. The changing economic and regulatory framework, and especially the economic subsidies aimed to these agronomic practices, may encourage the spread of conservation tillage in Europe as already happened in America and Australia because, as well as being environmentally sustainable, they seem to be economically feasible for farmers with clear overall benefit.

6. REFERENCES

Addiscott, T.M. and A.P. Whitmore. 1987. Computer simulation of changes in soil mineral nitrogen and crop nitrogen during autumn, winter and spring. The Journal of Agricultural Science, 109:141-157.

Alexandrov V., Eitzinger J., Cajic V., Oberforster M. 2002. Potential impact of climate change on selected agricultural crops in north-eastern Austria. Global Change Biology, 8(4): 372-389.

Alexandrov V. A. and Eitzinger J., 2005. The Potential Effect of Climate Change and Elevated Air Carbon Dioxide on Agricultural Crop Production in Central and Southeastern Europe. Journal Of Crop Improvement: 291-331.

Andales A., Batchelor W.D., Anderson C., Farnham D., Whigham, D.K., 2000. Incorporating tillage effects into a soybean model. Agricultural Systems, 66, 69-98.

Arshad, M., 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada. Soil and Tillage Research, 53, 41-47.

Bardossy A., and Plate E.J., 1992, Space-time model for daily rainfall using atmospheric circulation patterns, Water Resour. Res., 28(5), 1247–1259.

Bardossy A., Stehlik J., Caspary H., 2001. Generating of areal precipitation series in the upper Neckar catchment. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, 26(9): 683-687.

Basch G., 2009 No-Tillage worldwide. ECAF General Assembly –Helsinki 2009. Available on line at http://www.ecaf.org/docs/ecaf/no%20tillage%20worldwide.pdf

Bauer J., Herbst M., Huisman J., Weihermuller L., Vereecken H., 2008. Sensitivity of simulated soil heterotrophic respiration to temperature and moisture reduction functions. Geoderma, 145(1-2): 17-27.

Berzsenyi, Z., Győrffy, B., Lap, D. Q., 2000. Effect of crop rotation and fertilisation on maize and wheat yields and yield stability in a long-term experiment. European Journal of Agronomy, 13(2-3): 225-244.

Bescansa P., Imaz M.J., Virto I., Enrique A., Hoogmoed W.B., 2006. Soil water retention as affected by tillage and residue management in semiarid Spain. Soil and Tillage Research, 87: 19-27.

Bindi M. and Moriondo M., 2005. Impact of a 2° C global temperature rise on the Mediterranean region: Agriculture analysis assessment. In a report for WWF "Climate change impacts in the Mediterranean resulting from a 2°C global temperature rise".

Bonari E., Mazzoncini M., Di Bene C., Coli A., Petri M., 2005. Esperienze di semina su sodo del frumento in Italia. L'Informatore Agrario, 24: 33-36.

Bonciarelli F., Torquati B.M., Archetti R., 2001. Convenienza economica di lavorazioni ridotte del terreno. L'Informatore Agrario, 23: 41-47.

Boote K.J., Jones J.W., Hoogenboom G., Pickering N.B. 1998. The CROPGRO model for grain legumes. p. 99–108. In G.Y. Tsuji et al. (ed.) Understanding options for agricultural production. Kluwer Academic Publ., Dordrecht, the Netherlands.

Brandt S.A., 1992. Zero vs conventional tillage and their effects on crop yield and moisture. Canadian Journal of Plant Science 72: 679–688.

Brassard J. P., and Singh B., 2008. Impacts of climate change and CO_2 increase on agricultural production and adaptation options. Mitigation and Adaptation Strategies for Global Change 13: 241-265.

Brisson N., Gary C., Justes E., Roche R., Mary B., Ripoche D., Zimmer D., Sierra J., Bertuzzi P., Burger P., Bussière F., Cabidoche Y.M., Cellier P., Debaeke P., Gaudillère J.P., Hénault C., Maraux F., Seguin B., Sinoquet H., 2003. An overview of the crop model STICS. European Journal of Agronomy 18, 309–332.

Campbell C.A., Mcconkey B.G., Zentner R.P., Selles F., Curtin D., 1996. Long-term effects of tillage and crop rotations on soil organic C and total N in a clay soil in southwestern Saskatchewan. Canadian Journal of Soil Science, 76, 395-401.

Cantero-Martínez C., Angas P., Lampurlanés J., 2003. Growth, yield and water productivity of barley (Hordeum vulgare L.) affected by tillage and N fertilization in Mediterranean semiarid, rainfed conditions of Spain. Field Crops Research, 84(3), 341-357.

Carboni G., Virdis A., Musio F., 2006. Lavorazioni conservative per un grano duro migliore. L'Informatore Agrario, 44: 32-37.

Carter T.R., 2007. General guidelines on the use of scenario data for climate impact and adaptation assessment. Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA), 71 pp. Online at http://www.ipcc-data.org /guidelines/ TGICA_guidance_sdciaa_v2_final.pdf.

Chessa, P.A., Delitala, A., 1997. Il Clima della Sardegna. SAR, Sassari, Note Tecniche. Available online at http://www.sar.sardegna.it/pubblicazioni/notetecniche/nota2/index.asp.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L.Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr and P. Whetton, 2007: Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental

Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Conant R., Easter M., Paustian K., Swan A., Williams, S. 2007. Impacts of periodic tillage on soil C stocks: A synthesis. Soil and Tillage Research, 95(1-2): 1-10.

Dadoun F.A., 1993. Modeling tillage effects on soil physical properties and maize (Zea mays L.) development and growth. Unpublished Ph.D. thesis, Michigan State University, MI.

D'Egidio, M.G., Mariani B.M., Nardi S., Novaro P., Cubadda R., 1990. Chemical and technological variables and their relationships: A predictive equation for pasta cooking quality. Cereal Chem 67: 275–281.

De Vita P., Di Paolo E., Fecondo G., Di Fonzo N., Pisante M., 2007. No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture content in southern Italy. Soil and Tillage Research, 92, 69-78.

Derpsch R. and Friedrich T., 2009. Development and Current Status of No-till Adoption in the World. Proceedings on CD, 18th Triennial Conference of the International Soil Tillage Research Organization (ISTRO), June 15-19, 2009, Izmir, Turkey. Available on line at http://www.fao.org/ag/ca/CA-Publications/ISTRO%202009.pdf.

Dettori M., 2006. Impatto degli scenari climatici e coltivazione del grano duro: individuazione di line guida nella selezione di genotipi di grano duro arido resistenti. Tesi di Dottorato, AA 2005-2006.

Dettori M., Cesaraccio C., Motroni A., Spano D., Duce P., 2011. Using CERES-Wheat to simulate durum wheat production and phenology in Southern Sardinia, Italy. Field Crops Research, 120, (1),: 179-188.

Díaz-Zorita M., Duarte G.A., Grove J., 2002. A review of no-till systems and soil management for sustainable crop production in the subhumid and semiarid Pampas of Argentina. Soil and Tillage Research, 65(1), 1-18.

DOE-Department of Energy, 2006. Carbon Sequestration. http://cdiac2.esd.ornl.gov/index.html. October 7, 2004.

Donatelli, M., Stockle, C.O., Ceotto, E., Rinaldi, M., 1997. Evaluation of CropSyst for cropping systems at two loca- tions of northern and southern Italy. European Journal of Agronomy, 6: 35–45.

Donatelli M., and Campbell G.S., 1998. A simple model to estimate global solar radiation. In: Proc. 5th ESA Congress, Nitra, Slovak Republic, 2: 133-134.

Donatelli M., Bellocchi G, and Fontana F., 2003. RadEst 3.00: software to estimate daily radiation data from commonly available meteorological variables. European Journal of Agronomy, 18: 363-367.

Dubrovský M., 1997. Creating daily weather series with use of the weather generator. Environmetrics 8: 409-424.

Dubrovský M., Buchtele J., Zalud Z., 2004. High-frequency and low-frequency variability in stochastic daily weather generator and its effect on agricultural and hydrologic modeling. Climatic Change 63: 145-179.

Dubrovský, M., Nemesova, I., Kalvova, J., 2005. Uncertainties in climate change scenarios for the Czech Republic. Climate Research 29, 139-156.

Dubrovský M. 2009. Linking the climate change scenarios and weather generators with agroclimatological models. Seminar in Sassari, May 25 – June 5, 2009.

Duce P., Arca A., Canu S., Spano D., Motroni A., 2004 Individuazione delle aree agricole e delle colture a forte rischio per variazioni climatiche. Proceedings of the workshop "Climagri - Cambiamenti Climatici e Agricoltura". Rome 2004.

Erkossa T., Stahr K., Gaiser, T., 2006. Soil tillage and crop productivity on a Vertisol in Ethiopian highlands. Soil and Tillage Research, 85(1-2), 200-211. FAO, 1990 - Guidelines for Soil Profile Description. 3rd eds. (rev.), 70 pp. Rome.

Faulkner, E.H., 1942. Plowman's Folly. University of Oklahoma Press, Norman, OK, 155 pp.

Fischer G., Shah M., Velthuizen H., Nachtergael F.O., 2001. Global agro-ecological assessment for agriculture in the 21st century. International Institute for Applies Systems Analysis. IIASA Publications, Vienna Austria.

Fischer R., Santiveri F., Vidal I., 2002. Crop rotation, tillage and crop residue management for wheat and maize in the sub-humid tropical highlands. I Wheat and legume performance. Field Crops Research, 79(2-3), 107-122.

Follett, R. F., 2001. Soil management concepts and carbon sequestration in cropland soils. Soil and Tillage Research, 61, 77-92.

Fox, D.G. 1981. Judging air quality model performance: a summary of the AMS workshop on dispersion models performance. Bulletin of the American Meteorological Society, 62: 599-609.

Galantini, J. A., Landriscini, M. R., Iglesias, J. O., Miglierina, A. M., and Rosell, R. A. (2000) The effects of crop rotation and fertilization on wheat productivity in the Pampean semiarid region of Argentina 2. Nutrient balance, yield and grain quality. Soil and Tillage Research, 53(2): 137-144.

Gan Y. T., Miller P. R., McConkey B. G., Zentner R. P., Stebenson F. C., McDonald C. L., 2003. Influence of Diverse Cropping Sequences on Durum Wheat Yield and Protein in the Semiarid Northern Great Plains. Agronomy Journal, 95: 245-252.

Ghaffari A., Cook H.F., Lee H.C., 2002. Climate change and winter wheat management: a modelling scenario for South-Eastern England. Climatic Change, 55: 509-533.

Giambalvo D., Stringi L., Frenda A.S., Di Miceli G., 1999. Effects of crop rotation and soil tillage techniques on wheat production anquality in a Sicilian hilly environment. Rivista di Agronomia, 33: 202-208.

Gilbert, R.O., 1987. Statistical methods for environmental pollution monitoring. Van Nostrand Reinhold , New York.

Gijsman A.J., Hoogenboom G., Parton W.J., Kerridge, P.C. 2002. Modifying DSSAT Crop Models for Low-Input Agricultural Systems Using a Soil Organic Matter – Residue Module from CENTURY. Agricultural Systems, 462-474.

Glantz M.H., Gommes R., Ramasamy S., 2009 Coping with a changing climate: considerations for adaptation and mitigation in agriculture. FAO Environment and Natural Resources Service Series, No. 15 – FAO, Rome.

Godwin, D.C., and C.A. Jones. 1991. Nitrogen dynamics in soil-plant systems. p. 287–321. In J. Hanks and J.T. Ritchie (ed.) Modeling plant and soil systems. Agron. Monogr. 31. ASA, CSSA, and SSSA, Madison, WI.

Godwin D.C. and Singh U., 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 55–77.

Govaerts B., Sayre K. D., Deckers J., 2005. Stable high yields with zero tillage and permanent bed planting? Field Crops Research, 94: 33-42.

Greenwood, D.J., J.J. Neeteson, A. Draycott. 1985. Response of potatoes to N fertilizer: dynamic model. Plant Soil, 85: 185-203.

Guereña, A., Ruiz-ramos M., Diaz-Ambrona C. H., Conde J. R., Minguez M. I., 2001. Assessment of Climate Change and Agriculture in Spain Using Climate Models. Agronomy Journal 93: 237-249.

Guy S. O. and Cox D. B., 2002. Reduced tillage increases residue groundcover in subsequent dry pea and winter wheat crops in the Palouse region of Idaho. Soil and tillage research, 66: 69-77.

Hao, X., 2001. Effect of minimum tillage and crop sequence on crop yield and quality under irrigation in a southern Alberta clay loam soil. Soil and Tillage Research, 59(1-2): 45-55.

Hernanz J.L., Lopez R., Navarrete L., Sanchez-Giron V., 2002. Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semiarid central Spain. Soil & Tillage Research, 66, 129-141.Holland, J. M., 2004. The environmental consequences of adopting conservation tillage in Europe : reviewing the evidence. Agriculture, Ecosystems and Environment, 103: 1-25.

Holland J., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agriculture, Ecosystems and Environment, 103(1): 1-25.

Hoogenboom G., 2000. Contribution of agrometeorology to the simulation of crop production and its applications. Agricultural and Forest Meteorology, 103: 137-157.

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Batchelor WD, Hunt LA, Boote KJ, Singh U, Uryasev O, Bowen WT, Gijsman AJ, du Toit AS, White JW, Tsuji GY, 2004. Decision Support System for Agrotechnology Transfer Version 4.0 [CD-ROM]. University of Hawaii, Honolulu.

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Hunt LA, Boote KJ, Singh U, Uryasev O, Lizaso JI, Gijsman AJ, White JW, Batchelor WD, Tsuji GY, 2009. Decision Support System for Agrotechnology Transfer Version 4.5 [CD-ROM]. University of Hawaii, Honolulu.

Huang G. B., Zhang R.Z., Li, G.D., Li L.L., Chan K.Y., Heenan, D. P., Chen W., Unkovich M.J., Robertson M. J., Cullis B.R., Bellotti W. D., 2008. Productivity and sustainability of a spring wheat – field pea rotation in a semi-arid environment under conventional and conservation tillage systems. Field Crops Research, 107: 43-55.

Hulme, M., Wigley, T.M.L., Barrow, E.M., Raper, S.C.B., Centella, A., Smith, S., Chipanshi, A.C., 2000. Using a climate scenario generator for vulnerability and adaptation assessments: MAGICC and SCENGEN Version 2.4 Workbook. Climatic Research Unit, Norwich.

Hutchinson J., Campbell C., Desjardins, R. 2007. Some perspectives on carbon sequestration in agriculture. Agricultural and Forest Meteorology, 142(2-4): 288-302.

ICC Standard 158: Gluten Index Method for Assessing Gluten Strength in Durum Wheat (Triticum durum). International Association for Cereal Science and Technology.

IPCC, 2000a. Land Use, Land-Use Change, and Forestry. A Special Report of the Intergovernmental Panel on Climate Change..Robert T. Watson, Ian R. Noble, Bert Bolin, N. H. Ravindranath, David J. Verardo and David J. Dokken (Eds.) Cambridge University Press, UK. pp 375.

IPCC, 2000b. Emissions Scenarios. Summary for Policymakers. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change. Available at http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf.

IPCC, 2001. Climate Change 2001: Working Group II: Impacts, Adaptation and Vulnerability.

IPCC, 2007a: AR4 Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007b: AR4 Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A.(eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC, 2007c. AR4 Summary for Policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 7-22.

IPCC, 2007d. AR4 - III Technical Summary. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC. T, B., Bashmakov, I., Bernstein, L., Bogner, J. E., Bosch, P. R., Dave, R., Davidson, O. R., Fisher, B. S., Gupta, S., Heij, G. J., Ribeiro, S. K., Kobayashi, S., Levine, M. D., Martino, D. L., Masera, O., Metz, B., Meyer, L. A., Najam, A., Nakicenovic, N., Roy, J., Sathaye, J., Schock, R., Shukla, P., Sims, R. E., Smith, P., Tirpak, D. A., Zhou, D., and Kingdom, U.

IPCC, 2009. What is a GCM? Available online at http://www.ipcc-data.org/ddc_gcm_guide.html.

ISTAT, 2010. Dati annuali sulle coltivazioni. Istat - Istituto nazionale di statistica. Available online at http://agri.istat.it.

Jamieson P.D., Semenov M.A, Brooking I.R., Francis G.S., 1998. Sirius: a mechanistic model of wheat response to environmental variation. European Journal of Agronomy, 8(3-4): 161-179.

Jenkinson, D.S., J.H. Rayner. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Science. 123: 298-305.

Johnson J., Reicosky D., Allmaras R., Sauer T., Venterea R., Dell, C. 2005. Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil and Tillage Research, 83(1): 73-94.

Jones C.A., Dyke P.T.,Williams J.R., Kiniry J.R., Benson V.W., Griggs R.H., 1991. EPIC: an operational model for evaluation of agricultural sustainability. Agricultural Systems 37, 341–350.

Jones P.D. and Moberg A., 2003. Hemispheric and Large-Scale Surface Air Temperature Variations: An Extensive Revision and an Update to 2001. Journal of Climate, 16: 206-223.

Jones, J. W., Hoogenboom G., Porter C. H., Boote K. J., Batchelor W. D. Hunt L. A., Wilkens P. W., Singh U., Gijsman A. J. and Ritchie J. T., 2003. The DSSAT cropping system model. European Journal of Agronomy, Vol., 18pp, 235-265.

Jones J.W., Boote K.J., Hoogenboom G., 2007. Computer Simulation of Crop Growth and Management Responses. Summer Course 2007 June 11-15, June 22 July 23-27.

Jørgensen S.E., Kamp-Nielsen L., Christensen T., Windolf-Nielsen J., Westergaard. B., 1986. Validation of a prognosis based upon a eutrophication model. Ecol. Model., 35: 165-182.

Keating B.A., Carberry P.S., Hammer G.L., Probert M.E., Robertson M.J., Holzworth D., Huth N.I., Hargreaves J.N.G., Meinke H., Hochman Z., McLean G., Verburg K., Snow V., Dimes J.P., Silburn M., Wang E., Brown S., Bristow K.L., Asseng S., Chapman S., McCown R.L., Freebairn D.M., Smith C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. European Journal of Agronomy 18: 267–288.

Knight S.M., 2004. Plough, minimal till or direct drill?—Establishment method and production efficiency. In: Anon. (Eds.), HGCA Conference 2004: Managing Soil and Roots for Profitable Production. London, Home Grown Cereals Authority.

Lal, R., 1997. Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO_2-enrichment. Soil and Tillage Research, 43, 81-107.

Lal R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science (New York, N.Y.), 304: 1623-1627.

Lal, R., Reicosky, D., Hanson, J., 2007a. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil and Tillage Research, 93: 1-12.

Lal, R., Follett R. F., Stewart B. A. and Kimble, J. M. 2007b. Soil Carbon Sequestration To Mitigate Climate Change and Advance Food Security. Soil Science, 172(12): 943-956.

Latta J. and O'Leary G.J., 2003. Long-term comparison of rotation and fallow tillage systems of wheat in Australia. Field Crops Research, 83, 173-190.

Le Treut H., Somerville R., U. Cubasch, Ding Y., Mauritzen C., Mokssit A., Peterson T., Prather M., 2007: Historical Overview of Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Loague, K., and Green R.E. 1991. Statistical and graphical methods for evaluating solute transport models: overview and application. Journal of Contaminant Hydrology, 7: 51-73.

Long S.P., Ainsworth E.A., Rogers A., Ort D.R., 2004. Rising atmospheric carbon dioxide: plants FACE the future. Annual review of plant biology, 55: 591-628.

Long, S.P., Ainsworth E.A., Leakey A.D.B., Nösberger J., Ort D.R., 2006. Food for thought: lower-than-expected crop yield stimulation with rising CO2 concentrations. Science (New York, N.Y.) 312, no. 5782: 1918-21.

Lopez Fando C. and Pardo M.T., 2009. Changes in soil chemical characteristics with different tillage practices in a semi-arid environment. Soil and Tillage Research, 104: 278-284.

López M. and Arrùe J., 1997. Growth, yield and water use efficiency of winter barley in response to conservation tillage in a semi-arid region of Spain. Soil and Tillage Research, 44(1-2): 35-54.

Lopez-Bellido L. and Lopez-Bellido R.J., 2001. Efficiency of nitrogen in wheat under Mediterranean conditions: effect of tillage, crop rotation and N fertilization. Field Crops Research, 71(1): 31-46.

López-Bellido L., Fuentes M., Castillo J.E., Lopez-Garrido F.J., 1998. Effects of tillage, crop rotation and nitrogen fertilization on wheat-grain quality grown under rainfed Mediterranean conditions. Field Crops Research, 57(3): 265-276.

López-Bellido L., López-Bellido R.J., Castillo J. E., López-Bellido, F.J., 2000. Effects of tillage, crop rotation and nitrogen fertilization on wheat-grain quality grown under rainfed Mediterranean conditions. Agronomy Journal, 92, 1054-1063.

Ludwig F. and Asseng, S., 2010. Potential benefits of early vigor and changes in phenology in wheat to adapt to warmer and drier climates. Agricultural Systems, 103(3): 127-136.

Luo Q., Bellotti W., Williams M., Wang E., 2009. Adaptation to climate change of wheat growing in South Australia: Analysis of management and breeding strategies. Agriculture, Ecosystems and Environment, 129: 261-267.

Lyon D.J., Stroup W.W., Brown R.E., 1998. Crop production and soil water storage in long-term winter wheat ± fallow tillage experiments. Soil & Tillage Research, 49, 19-27.

Mcconkey B.G., Liang B.C., Campbell C.A., Curtin D., Moulin A., Brandt S.A., Lafond G.P., 2003. Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils. Soil and Tillage Research, 74: 81-90.

McCown RL, Hammer GL, Hargreaves JNG, Holzworth DP, Freebairn DM, 1996. APSIM: a novel software system for model development, model testing, and simulation in agricultural systems research. Agricultural Systems 50: 255–271.

McDonald G.K., 1989. The contribution of nitrogen fertilizer to the nitrogen nutrition of rainfed wheat (Triticum aestivum) crops in Australia: a review. Australian Journal of. Experimental Agriculture 29: 455–481.

Mearns L.O., Rosenzweig C., Goldberg R. 1997. Mean and variance change in climate scenarios: Methods, agricultural applications, and measures of uncertainty. Climatic Change, 35: 367-396.

Mereu V., 2009. Climate change impact on durum wheat in Sardinia. PhD thesis, AA 2008-2009.

Mielke L.N. and Wilhelm W.W., 1998. Comparisons of soil physical characteristics in long-term tillage winter wheat-fallow tillage experiments. Soil and Tillage Research, 49: 29-35.

Mitchell, J.F.B., Manabe, S., Meleshko, V., Tokioka, T., 1990. Equilibrium climate change and its implications for the future. In: Houghton JT, Jenkins GJ, Ephraums JJ (eds) Climate change: the IPCC scientific assessment. report prepared by Working Group I. Cambridge University Press, Cambridge, p 131–164.

Monteith, J.L. 1977. Climate and the efficiency of crop production in Britain. Philos. Trans. R. Soc. London, Ser. B 281: 277–294.

Mrabet R., 2000. Differential response of wheat to tillage management systems in a semiarid area of Morocco. Field Crops Research, 66.

Murphy, J.M. 1999. An evaluation of statistical and dynamical techniques for downscaling local climate. Journal of Climate, 12: 2256-2284.

Nangia V., Mobin-ud-Din A., Du J, Changrong Y., Hoogenboom G., Xurong M., Wenqing H., Shuang L., Qin L., 2008. Modeling the effects of conservation agriculture on land and water productivity of rainfed maize in the Yellow River Basin, China. In Proceedings of the Workshop on Increasing the Productivity and Sustainability of Rainfed Cropping Systems of Poor, Smallholder Farmers, Tamale, Ghana, 22-25 September 2008.

Olesen, J., and Bindi, M. 2002. Consequences of climate change for European agricultural productivity, land use and policy. European Journal of Agronomy, 16(4): 239-262.

Ortiz, R., Sayre, K.D., Govaerts, B., Gupta, R., Subbarao, G.V., Ban, T., Hodson, D., Dixon, J.M., 2008. Climate change: Can wheat beat the heat? Agriculture, Ecosystems and Environment, 126: 46-58.

P.S.R., 2007. Programma di sviluppo rurale 2007-2013 Reg. (CE) n. 1698/2005. Assessorato dell'Agricoltura e Riforma Agro Pastorale della Regione Autonoma della Sardegna.

Parry, M.L., O.F. Canziani, J.P. Palutikof and Co-authors 2007: Technical Summary. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution ofWorking Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 23-78.

Parton W.J, Stewart J.W.B., Cole C.V., 1988. Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5: 109–131.

Payne R.W., Murray D.A., Harding S.A., Baird D.B., Soutar, D.M., 2009. GenStat for Windows (12th Edition) Introduction. VSN International, Hemel Hempstead.

Pickering N.B., Hansen J.W., Wells C.M., Chan V.K., Godwin D.C., 1994. WeatherMan: A utility for managing and generating daily weather data. Agronomy Journal, 86: 332-337.

Pisante M. andBasso F., 2000. Influence of tillage systems on yield and quality of durum wheat in Southern Italy. In: Royo C., Nachit M.M., Di Fonzo N., Araus J.L. EDS.. Durum wheat improvement in the Mediterranean region: New challenges. p. 549-554, Zaragoza.

Porter C.H., Jones J.W., Adiku S., Gijsman A. J., Gargiulo O.. Naab J. B., 2009. Modeling organic carbon and carbon-mediated soil processes in DSSAT v4.5. Operational Research - An International Journal (ORIJ).

Porter C., Jones J.W., Braga R., 2000. An approach for modular crop model development. International Consortium for Agricultural Systems Applications, Honolulu, HI, p 13. Available online at http://icasa.net/modular/index.html.

Porter J.R., Semenov M.A., 1999. Climate variability and crop yields in Europe. Nature 400: 724.

Racsko P., Szeidl L. Semenov M.A. 1991. A serial approach to local stochastic weather models. Ecological Modelling 57: 27-41.

Rezzoug W., Gabrielle B., Suleiman A., Benabdeli K., 2008. Application and evaluation of the DSSAT-wheat in the Tiaret region of Algeria. African Journal of Agricultural Research, 3(4): 284-296.

Richardson C.W. 1981. Stochastic simulation of daily precipitation, temperature and solar radiation. Water Resources Research 17: 182-190.

Richter, G., and Semenov, M., 2005. Modelling impacts of climate change on wheat yields in England and Wales: assessing drought risks. Agricultural Systems, 84(1): 77-97.

Riha S.J., Wilks D.S., Simoens, P., 1996. Impact of temperature and precipitation variability on crop model predictions. Climatic Change, 32(3): 293-311.

Rinaldi M., 2004. Water availability at sowing and nitrogen management of durum wheat: a seasonal analysis with the CERES-Wheat model. Field Crops Research, 89(1): 27-37.

Ritchie, J.T. and Otter, S., 1985. Description and performance of CERES-Wheat: a user-oriented wheat yield model. In: ARS Wheat Yield Project. ARS-38. Natl Tech Info Serv, Springfield, Missouri, pp. 159_/175.

Ritchie J.T., 1998. Soil water balance and plant water stress. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 41-54.

Ritchie, J.T., Singh, U., Godwin, D.C., Bowen, W.T., 1998. Cereal growth, development and yield. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 79-98.

Ritchie, J.T. and Godwin D.C., 2000. CERES Wheat 2.0. Unpublished book available online at http://nowlin.css.msu.edu/wheat_book/.

Ritchie, J.T., Porter, C.H., Judge, J., Jones, J.W., Suleiman, A.A., 2009. Extension of an Existing Model for Soil Water Evaporation and Redistribution under High Water Content Conditions. Soil Science Society of America Journal 73: 792-801.

Rosenzweig C., Iglesias A., Yang X.B., Epstein P.R., Chivian E., 2001. Climate change and extreme weather events. Implications for food production, plant diseases, and pests. Global Change and Human Health, Volume 2, n. 2: 90-104.

Rosenzweig C., Strzepek K.M., Major D.C., Iglesias A., Yates D.N., McCluskey A., Hillel D., 2004. Water resources for agriculture in a changing climate: international case studies. Global Environ Change 14: 345–360.

Rosenzweig C. and Tubiello F.N., 2007. Adaptation and mitigation strategies in agriculture: an analysis of potential synergies. Mitig Adapt Strat Glob Change 12:855–873.

Salmi T., Määttä A., Anttila P., Ruoho-Airola T., Amnell T., Laitos I.. 2002. Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann-Kendall Test and Sen's Slope Estimates -The Excel Template Application Makesens, Meteorologiska Institutet, Finnish Meteorological Institute, Helsinki available online at http://www.fmi.fi/organization/contacts_25.html.

Sanchez-Giron V., Serrano A., Hernanz J.L., Navarrete L., 2004. Economic assessment of three long-term tillage systems for rainfed cereal and legume production in semiarid central Spain. Soil and Tillage Research, 78(1): 35-44.

Santer B.D., Wigley T.M.L., SchlesingerM.E. MitchellJ.F.B., 1990: Developing Climate Scenarios from Equilibrium GCM Results. Max-Planck-Institut für Meteorologie Report No. 47, Hamburg, Germany, 29 pp.

Savin R. E., Satorre H., Hall A.J., Slafer G.A., 1995. Assessing strategies for wheat cropping in the monsoonal climate of the Pampas using the CERES-Wheat simulation model. Field Crops Research 42: no. 2-3: 81-91.

Schaeffer, D.L. 1980. A model evaluation methodology applicable to environmental assessment models. Ecol. Model., 8: 275-295.

Seligman, N.C. and H. Van Keulen. 1981. PAPRAN: A simulation model of annual pasture production limited by rainfall and nitrogen. p. 192–221. In M.J. Frissel and J.A.Van Veen (ed.) Simulation of nitrogen behaviour of soil–plant systems. Centrum voor Landbouwpublikaties en Landbouwdocumentatie (PUDOC), Wageningen, the Netherlands.

Semenov M., 2008. Simulation of extreme weather events by a stochastic weather generator. Climate Research, 35: 203-212.

Semenov M.A., and Porter J.R., 1995. Climatic variability and the modelling of crop yields. Agricultural and Forest Meteorology 73: 265-283.

Semenov M. and Barrow E., 1997. Use of a stochastic weather generator in the development of climate change scenarios. Climatic Change, 35: 397-414.

Semenov, M.A., Brooks, R.J., Barrow, E.M. and Richardson, C.W. 1998. Comparison of WGEN and LARS-WG stochastic weather generators for diverse climates. Climate Research 10: 95-107.

Smith P., Smith J., Powlson D., Mcgill W., Arah J., Chertov O., Coleman K., Franko U., Frolking S., Jenkinson D.S., Jensen L.S., Kelly R.H., Klein-Gunnewiek H., Komarov A.S., Li C., Molina J.A.E., Mueller T., Parton W.J., Thornley J.H.M. Whitmore A.P., 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma, 81(1-2): 153-225.

Soil Survey Staff, 1999. Soil Taxonomy - A Basic System of Soil Classification for Making and Interpreting Soil Surveys. 2nd Edition USDA-Natural Resources Conservation Service, Washington, DC, 871 pp.

Sombrero A. and de Benito A., 2010. Carbon accumulation in soil. Ten-year study of conservation tillage and crop rotation in a semi-arid area of Castile-Leon, Spain. Soil and Tillage Research, 107(2): 64-70.

Sommer R., Wall P. C., Govaerts B. 2007. Model-based assessment of maize cropping under conventional and conservation agriculture in highland Mexico. Soil and Tillage Research, 94: 83-100.

Šťastná M., Trnka M., Křen J., Dubrovský M., Žalud Z., 2002. Evaluation of the CERES models in different production regions of the Czech Republic. ROSTLINNÁ VÝROBA 48: 125-132.

Stockle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Europ. J. Agronomy, 18: 289-307.

Stringi L. and Gianbalvo, D., 1999. Agronomic, energetic and economic aspects of different cropping systems in a Sicilian hilly environment. Rivista di Agronomia, 33: 191-201.

Thomas G., Dalal R., Standley, J., 2007- No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. Soil and Tillage Research, 94(2): 295-304.

Thomas R.J., 2008. Opportunities to reduce the vulnerability of dryland farmers in Central and West Asia and North Africa to climate change. *Agriculture, Ecosystems & Environment* 126, no. 1-2: 36-45.

Trnka M., Dubrovský M., Žalud Z., 2004a. Climate Change Impacts and Adaptation Strategies in Spring Barley Production in the Czech Republic. Climatic Change, 64(1/2): 227-255.

Trnka M., Dubrovský M., Semerádová D., Žalud, Z., 2004b. Projections of uncertainties in climate change scenarios into expected winter wheat yields. Theoretical and Applied Climatology, 77(3-4): 229-249.

Tsuji GY, Uehara G, Balas S, 1994. Decision Support System for Agrotechnology Transfer (DSSAT) Version 3. University of Hawaii, Honolulu.

Tubiello, F.N., Donatelli, M., Rosenzweig, C., Stockle, C. O., 2000 Effects of climate change and elevated CO_2 on cropping systems: Model predictions at two Italian locations, European Journal of Agronomy , 13: 179-189.

Tubiello, F.N. and Ewert, F., 2002. Simulating the effects of elevated CO_2 on crops: approaches and applications for climate change. European Journal of Agronomy, 18: 57-74.

Tubiello F.N., Jagtap S., Rosenzweig C., Goldberg R., Jones J.W., 2002. Effects of climate change on US crop production from the National Assessment. Simulation results using two different GCM scenarios. Part I: Wheat, Potato, Corn, and Citrus, Climate Res 20 (3): 259–270.

Tubiello, F.N., Amthor, J.S., Boote, K.J., Donatelli, M., Easterling, W., Fischer G., Gifford R. M., Howden M., Reilly J., Rosenzweig C., 2007a. Crop response to elevated CO_2 and world food supply A comment on " Food for Thought . . ." by Long et al ., Science 312 : 1918 – 1921 , 2006. Europ. J. Agronomy, 26, 215-223.

Tubiello F.N., Soussana J.F., Howden S.M., 2007b. Crop and pasture response to climate change. Proceedings of the National Academy of Sciences of the United States of America, 104(50), 19686-90.

Tubiello, F.N. and Rosenzweig C., 2008. Developing climate change impact metrics for agriculture. The Integral Assessment Journal Bridging Sciences & Policy. Vol.8, Iss.1, pp.165-184.

USDA-NRCSa available online at Htpp://soils.cals.uidaho.edu/soilorders/Inceptisols.jpg

USDA-NRCSb available online at Htpp://soils.cals.uidaho.edu/soilorders/Alfisols.jpg

Van den Putte A., Govers G., Diels J., Gillijns K., Demuzere M., 2010. Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture. European Journal of Agronomy, 33(3): 231-241.

Van Ittersum M.K., Leffelaar P.A., Keulen H.V., Kropff M.J., 2003. On approaches and applications of the Wageningen crop models. European Journal of Agronomy, 18: 201-234.

von Storch H., Zorita E., Cubasch, U., 1993. Downscaling of global climate change estimates to regional scales: An application to Iberian rainfall in wintertime. Journal of Climate, 6: 1161-1171.

W.M.O., 2007. Climate information for adaptation and development needs. World Meteorological Organization, water, climate, water. WMO-no 1025.

Wallach, 2006. Evaluating crop models. In Working with Dynamic Crop Models. Evaluation, Analysis, Parameterization, and Applications. Edited by Wallach D., Makowsky D., Jones J.W. 447 pp.

Wang Y. P., Handoko J., and Rimmington, G. M., 1992. Sensitivity of wheat growth to increased air temperature for different scenarios of ambient CO2 concentration and rainfall in Victoria, Australia - a simulation study. Climate Research, 2: 131-149.

Wei X., Declan C., Erda L., Yinlong X., Hui J., Jinhe J., Ian H., Yan L., 2009. Future cereal production in China: The interaction of climate change, water availability and socio-economic scenarios. Global Environmental Change 19, no. 1: 34-44.

West, T.O. and Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agriculture, Ecosystems and Environment, 91, 217-232.

White J.W., Jones J.W., Porter C.H., Mcmaster G.S., Sommer, R., 2009. Issues of spatial and temporal scale in modeling the effects of field operations on soil properties. Operational Research - An International Journal (ORIJ).

Wilby R.L., Dawson C., Barrow E., 2002. SDSM — a decision support tool for the assessment of regional climate change impacts. Environmental Modelling & Software, 17, 147-159.

Wilby R.L., Charles S.P., Zorita E., Timbal B., Whetton P., Mearns L.O., 2004. Guidelines for Use of Climate Scenarios Developed from Statistical Downscaling Methods. Analysis, (August), 1-27. Available online at www.ipcc-data.org/guidelines/dgm_no2_v1_09_2004.pdf.

Wilby R.L., Troni J., Biot Y., Tedd L., Hewitson B.C., Smith D.M. Sutton R.T., 2009. A review of climate risk information for adaptation and development planning. International Journal of Climatology, 29: 1193-1215.

Willmott C.J., 1981. On the validation of models. Bull. Phys Geogr 2:184-194.

Willmott C.J., 1982. Some comments on the evaluation of model performance. Bull. Am. Meteorol. Soc. 63: 1309-1313.

Wright A.L., Dou F., Hons F.M., 2007. Soil organic C and N distribution for wheat cropping systems after 20 years of conservation tillage in central Texas. Agriculture, Ecosystems & Environment., 121: 376-382.

Zalud Z., and Dubrovský M., 2002. Modelling climate change impacts on maize growth and development in the Czech Republic. Theoretical and Applied Climatology, 72(1-2): 85-102.

T_{MAX}

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Winter	Spring	Summer	Autumn
1973	14.7	13.6	14.9	17.8	23.6	27.7	31.5	30.8	27.9	23.5	18.6	15.6	21.7	14.4	23.1	30.1	19.2
1974	15.6	15.0	16.8	17.4	22.8	27.3	28.8	30.5	27.0	19.3	17.4	15.2	21.1	15.8	22.5	28.8	17.3
1975	15.5	14.5	15.5	19.1	22.5	26.7	31.0	30.1	28.5	23.3	18.0	16.2	21.8	15.2	22.8	29.8	19.2
1976	14.3	15.0	16.5	17.2	22.7	27.4	30.2	29.2	25.9	22.8	16.9	15.8	21.2	15.3	22.5	28.4	18.5
1977	15.6	17.7	19.0	20.1	24.1	28.1	31.9	30.5	28.1	25.2	19.8	17.0	23.1	17.4	24.1	30.2	20.7
1978	14.4	15.8	17.9	17.9	22.1	27.5	30.4	31.5	28.8	23.3	18.5	17.2	22.2	16.0	22.5	30.2	19.7
1979	15.2	16.2	18.0	18.3	23.9	29.5	31.8	31.3	27.5	24.1	18.2	16.7	22.6	16.5	23.9	30.2	19.7
1980	15.4	16.6	17.7	18.4	22.4	28.6	30.2	33.1	30.0	24.3	19.8	13.8	22.6	16.6	23.1	31.1	19.3
1981	13.3	14.2	18.5	20.7	24.1	29.6	29.9	32.9	30.1	25.5	19.3	17.3	23.0	15.3	24.8	30.9	20.7
1982	16.5	15.6	16.8	21.0	24.7	31.4	35.1	33.0	29.1	24.3	19.2	15.9	23.6	16.3	25.7	32.4	19.8
1983	15.2	14.2	17.1	21.1	25.2	29.9	35.4	32.5	29.0	24.3	19.9	16.2	23.4	15.5	25.4	32.3	20.1
1984	14.9	13.9	16.2	19.3	22.9	27.7	32.4	31.7	28.1	23.7	21.1	15.8	22.3	15.0	23.3	30.7	20.2
1985	9.6	13.8	13.1	19.3	22.3	27.9	31.2	29.7	28.1	24.5	18.0	17.4	21.3	12.1	23.2	29.7	19.9
1986	12.8	14.1	16.5	18.4	28.2	26.3	30.4	32.9	29.3	24.5	17.8	14.8	22.2	14.5	24.3	30.9	19.0
1987	13.9	14.9	15.1	20.0	22.0	26.9	31.6	33.5	32.7	26.7	18.8	17.3	22.8	14.7	23.0	32.6	20.9
1988	15.3	14.1	15.5	20.7	25.7	28.9	33.5	32.6	28.2	26.3	18.8	14.5	22.9	15.0	25.1	31.4	19.9
1989	14.9	16.2	19.7	19.0	24.4	29.1	33.4	33.6	27.9	23.6	19.3	18.2	23.3	16.9	24.2	31.7	20.4
1990	15.4	18.4	18.6	18.8	23.7	28.6	31.6	31.2	29.3	25.1	17.6	13.0	22.6	17.5	23.7	30.7	18.6
1991	14.6	14.1	17.8	17.3	21.2	28.0	32.4	32.4	28.9	22.3	17.0	13.7	21.7	15.5	22.2	31.3	17.6
1992	14.5	14.4	15.8	19.5	25.4	26.9	31.1	33.0	28.6	22.1	19.3	15.4	22.2	14.9	23.9	30.9	19.0
1993	14.0	13.0	14.8	19.1	24.4	29.6	31.1	33.2	28.1	23.6	17.1	15.0	22.0	14.0	24.4	30.8	18.5
1994	13.3	14.3	19.2	17.7	26.8	29.4	34.1	35.5	29.1	24.2	20.3	16.1	23.4	15.6	24.6	32.9	20.2
1995	12.3	14.3	15.6	18.2	24.9	28.7	34.0	32.4	27.8	26.3	18.9	16.4	22.6	14.1	23.9	31.4	20.6
1996	16.6	13.4	16.3	20.6	25.5	30.3	33.9	34.4	27.0	23.3	20.3	15.9	23.2	15.4	25.5	31.8	19.8
1997	16.1	17.1	19.5	19.9	26.8	31.5	32.2	32.9	29.6	24.9	19.1	16.2	23.9	17.5	26.1	31.6	20.1
1998	16.4	17.1	17.7	21.0	25.1	32.0	34.1	34.1	28.5	23.9	17.6	14.7	23.5	17.1	26.1	32.2	18.7
1999	15.6	13.9	18.2	21.2	27.2	32.2	23.6	28.8	25.0	26.8	18.8	15.6	22.3	15.9	26.8	25.8	20.4
2000	14.1	16.1	18.6	22.0	28.0	29.5	32.0	35.6	30.4	23.7	19.9	17.8	24.0	16.3	26.5	32.7	20.5
2001	16.0	15.9	21.3	20.5	28.1	31.7	33.6	34.2	27.4	28.9	19.3	14.5	24.3	17.7	26.8	31.7	20.9
2002	15.0	16.7	20.0	20.8	25.0	32.0	33.0	32.0	28.2	24.6	20.2	16.9	23.7	17.2	25.9	31.1	20.6
2003	14.8	13.8	18.6	20.8	27.5	35.0	36.4	38.2	30.0	25.0	21.2	15.5	24.8	15.8	27.8	34.9	20.6
2004	14.4	16.1	16.5	19.3	22.8	30.5	31.5	33.8	29.7	27.6	18.8	16.2	23.1	15.6	24.2	31.7	20.9
2005	13.8	12.7	18.0	20.6	28.1	32.7	35.2	32.3	30.1	27.0	20.4	15.4	23.9	14.8	27.1	32.6	20.9
2006	15.3	16.1	18.8	24.4	30.5	32.3	37.2	32.3	29.6	27.3	23.0	18.8	25.5	16.7	29.1	33.0	23.0
2007	18.1	18.1	19.0	23.6	27.1	33.1	34.3	35.2	30.4	26.2	20.0	18.0	25.3	18.4	27.9	33.3	21.4
2008	19.6	18.4	18.5	23.7	27.5	31.2	35.1	35.1	30.4	25.9	19.9	18.0	25.3	18.8	27.5	33.5	21.3
2009	12.7	12.8	16.2	18.8	26.4	32.2	35.5	36.4	30.9	24.9	21.9	16.6	23.8	13.9	25.8	34.2	21.1
Mean	**14.9**	**15.2**	**17.4**	**19.8**	**25.0**	**29.7**	**32.4**	**32.8**	**28.8**	**24.7**	**19.2**	**16.1**	**23.0**	**15.8**	**24.8**	**31.3**	**20.0**
Max	**19.6**	**18.4**	**21.3**	**24.4**	**30.5**	**35.0**	**37.2**	**38.2**	**32.7**	**28.9**	**23.0**	**18.8**	**25.5**	**18.8**	**29.1**	**34.9**	**23.0**
Min	**9.6**	**12.7**	**13.1**	**17.2**	**21.2**	**26.3**	**23.6**	**28.8**	**25.0**	**19.3**	**16.9**	**13.0**	**21.1**	**12.1**	**22.2**	**25.8**	**17.3**
Median	**14.9**	**14.9**	**17.7**	**19.5**	**24.9**	**29.5**	**32.2**	**32.9**	**28.8**	**24.5**	**19.2**	**16.1**	**23.0**	**15.6**	**24.4**	**31.4**	**20.1**
St. Dev.	**1.7**	**1.6**	**1.7**	**1.8**	**2.2**	**2.1**	**2.5**	**2.0**	**1.4**	**1.8**	**1.4**	**1.3**	**1.1**	**1.4**	**1.8**	**1.7**	**1.1**

T_{MIN}

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Winter	Spring	Summer	Autumn
1973	6.5	4.6	6.0	7.1	11.7	16.0	17.7	17.9	16.2	12.8	8.1	5.9	10.9	5.7	11.6	17.3	8.9
1974	6.1	5.9	7.6	8.5	11.2	14.5	16.1	16.9	15.5	9.6	8.0	5.4	10.5	6.5	11.4	16.2	7.7
1975	5.8	5.9	5.8	7.4	11.2	13.6	16.8	17.5	16.4	11.0	8.2	6.5	10.5	5.8	10.7	16.9	8.5
1976	4.9	6.0	5.9	8.3	12.4	14.4	17.0	17.0	14.5	12.6	8.0	6.5	10.6	5.6	11.7	16.2	9.0
1977	6.5	7.2	7.9	8.4	11.5	14.8	17.3	17.0	14.0	14.2	9.6	5.7	11.2	7.2	11.5	16.1	9.8
1978	4.1	6.9	7.7	8.6	10.8	14.3	15.5	16.3	14.2	10.4	6.4	7.6	10.3	6.2	11.2	15.4	8.1
1979	6.0	6.4	6.8	6.8	9.5	14.8	16.7	16.4	13.9	12.6	6.3	5.4	10.2	6.4	10.4	15.7	8.1
1980	4.8	5.4	6.0	6.7	9.5	13.3	14.6	17.1	15.1	10.9	8.7	3.4	9.6	5.4	9.8	15.6	7.7
1981	2.7	2.9	7.7	9.2	10.1	14.3	15.4	16.3	15.6	12.6	6.2	7.7	10.1	4.4	11.2	15.8	8.8
1982	6.2	5.6	5.2	7.2	11.0	16.6	19.0	17.8	17.2	12.4	9.5	5.3	11.1	5.7	11.6	18.0	9.1
1983	3.7	3.5	6.2	8.2	11.1	14.6	18.3	18.0	15.6	11.9	9.7	5.7	10.6	4.5	11.3	17.3	9.1
1984	4.5	3.9	5.5	6.4	10.0	13.7	16.7	17.0	14.3	11.7	9.4	5.8	9.9	4.6	10.1	16.0	9.0
1985	2.3	5.2	4.6	7.8	9.6	12.0	13.7	13.5	13.9	12.5	10.7	6.9	9.4	4.0	9.8	13.7	10.0
1986	5.7	4.9	5.8	8.9	14.4	13.6	16.4	19.0	16.3	14.0	9.7	6.2	11.3	5.5	12.3	17.2	10.0
1987	5.7	8.2	3.6	7.2	9.5	14.4	19.0	19.2	17.0	15.9	9.5	7.3	11.4	5.8	10.4	18.4	10.9
1988	5.6	2.4	5.0	9.6	14.0	15.3	18.9	18.0	14.6	12.7	6.2	3.1	10.5	4.3	13.0	17.2	7.3
1989	2.4	2.7	5.2	7.2	10.6	13.2	17.2	18.0	15.6	10.3	7.7	6.9	9.8	3.4	10.3	16.9	8.3
1990	3.2	7.1	6.0	8.2	11.7	13.8	16.6	17.7	16.5	15.3	8.1	4.0	10.7	5.4	11.2	17.0	9.1
1991	3.9	4.1	7.9	5.6	7.7	12.8	16.1	17.9	17.2	12.4	7.6	4.5	9.8	5.3	8.7	17.1	8.2
1992	3.5	2.2	6.5	6.2	11.0	13.5	16.0	17.9	14.9	13.2	9.5	6.2	10.1	4.1	10.2	16.3	9.6
1993	4.5	3.1	3.2	7.6	11.4	14.6	15.8	17.8	14.6	12.8	8.4	6.6	10.1	3.6	11.2	16.1	9.3
1994	5.3	4.1	5.2	6.9	11.4	14.0	18.1	19.9	18.7	14.2	11.4	6.5	11.3	4.9	10.8	18.9	10.7
1995	2.1	2.9	3.6	4.3	10.0	14.0	18.5	19.1	15.0	12.8	9.0	7.7	10.0	2.9	9.5	17.6	9.8
1996	8.0	4.4	6.5	9.2	11.6	14.9	17.0	18.8	15.4	12.1	9.9	6.8	11.2	6.3	11.9	17.1	9.6
1997	6.7	5.5	4.9	7.0	11.2	17.1	17.9	19.4	17.4	14.9	10.4	7.6	11.7	5.7	11.7	18.2	10.9
1998	4.5	4.6	5.1	8.1	11.6	15.7	18.4	18.8	16.6	12.1	6.6	4.7	10.6	4.7	11.8	17.9	7.8
1999	5.6	3.7	5.4	7.8	11.1	16.0	12.3	16.3	17.9	14.1	8.7	6.1	10.4	4.9	11.6	15.5	9.6
2000	2.1	4.5	5.6	8.8	13.6	15.7	18.3	18.6	15.7	13.8	10.0	7.8	11.2	4.1	12.7	17.5	10.5
2001	6.2	4.9	8.2	6.5	13.0	14.6	18.1	18.7	14.9	14.5	9.7	4.9	11.2	6.4	11.4	17.2	9.7
2002	3.3	5.2	7.0	8.1	11.1	15.7	18.4	19.2	15.6	12.2	9.7	6.7	11.1	5.1	11.7	17.7	9.6
2003	5.2	3.4	4.5	6.9	12.8	17.7	20.7	20.9	17.0	15.0	11.6	6.1	11.9	4.4	12.5	19.5	10.9
2004	5.7	6.7	6.1	9.3	10.2	15.1	18.0	18.8	16.7	14.8	9.6	7.2	11.5	6.2	11.5	17.8	10.5
2005	3.8	4.2	5.4	8.7	11.9	17.0	19.1	18.8	16.5	14.2	9.3	6.0	11.3	4.4	12.5	18.1	9.9
2006	4.7	5.2	6.9	9.6	12.7	16.6	20.9	19.1	17.0	15.2	10.3	7.9	12.2	5.6	13.0	19.0	11.1
2007	7.3	7.3	7.0	10.3	13.3	16.3	18.2	19.3	15.9	12.1	10.0	6.4	12.0	7.2	13.3	17.8	9.5
2008	5.3	4.0	7.0	8.6	14.0	16.3	18.9	19.3	15.8	12.1	9.9	6.2	11.5	5.4	13.0	18.0	9.4
2009	4.6	3.0	5.0	8.1	10.8	15.6	19.0	20.0	17.4	12.6	9.0	6.6	11.0	4.2	11.5	18.8	9.4
Mean	**4.8**	**4.8**	**5.9**	**7.8**	**11.4**	**14.9**	**17.4**	**18.1**	**15.9**	**12.9**	**8.9**	**6.2**	**10.8**	**5.2**	**11.4**	**17.1**	**9.3**
Max	**8.0**	**8.2**	**8.2**	**10.3**	**14.4**	**17.7**	**20.9**	**20.9**	**18.7**	**15.9**	**11.6**	**7.9**	**12.2**	**7.2**	**13.3**	**19.5**	**11.1**
Min	**2.1**	**2.2**	**3.2**	**4.3**	**7.7**	**12.0**	**12.3**	**13.5**	**13.9**	**9.6**	**6.2**	**3.1**	**9.4**	**2.9**	**8.7**	**13.7**	**7.3**
Median	**4.9**	**4.6**	**5.9**	**8.1**	**11.2**	**14.6**	**17.7**	**18.0**	**15.7**	**12.6**	**9.4**	**6.2**	**10.7**	**5.4**	**11.5**	**17.2**	**9.4**
St. Dev.	**1.5**	**1.5**	**1.2**	**1.2**	**1.4**	**1.3**	**1.8**	**1.4**	**1.2**	**1.5**	**1.4**	**1.2**	**0.7**	**1.0**	**1.1**	**1.2**	**1.0**

Rain

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**	**Winter**	**Spring**	**Summer**	**Autumn**
1973	81.0	19.0	30.0	12.0	0.0	0.0	0.0	0.0	16.0	32.0	2.0	36.0	228.0	130.0	12.0	16.0	70.0
1974	15.0	62.3	92.0	22.0	7.0	20.0	2.0	0.0	26.6	61.0	203.0	59.0	569.9	169.3	49.0	28.6	323.0
1975	4.0	95.0	55.0	12.0	37.0	2.0	0.0	2.0	1.0	66.0	71.0	35.0	380.0	154.0	51.0	3.0	172.0
1976	12.0	102.0	82.0	34.0	62.0	40.0	68.0	14.0	86.0	97.0	44.0	71.0	712.0	196.0	136.0	168.0	212.0
1977	82.0	11.0	2.0	40.0	11.0	57.0	2.0	41.0	13.0	88.0	11.0	9.0	367.0	95.0	108.0	56.0	108.0
1978	90.0	39.0	47.0	106.0	27.0	0.0	0.0	0.0	25.0	58.0	94.0	63.0	549.0	176.0	133.0	25.0	215.0
1979	47.0	138.0	61.0	98.0	17.0	8.0	8.0	0.0	41.0	28.0	21.0	46.0	513.0	246.0	123.0	49.0	95.0
1980	33.0	4.0	40.0	36.0	68.0	0.0	0.0	0.0	0.0	45.0	59.0	42.0	327.0	77.0	104.0	0.0	146.0
1981	100.8	177.1	0.8	9.5	4.1	0.0	0.0	2.5	7.7	2.7	29.4	133.6	468.2	278.7	13.6	10.2	165.7
1982	4.0	25.0	8.0	66.0	1.0	0.0	0.0	2.0	58.0	57.0	24.2	83.0	328.2	37.0	67.0	60.0	164.2
1983	0.0	27.0	29.0	3.0	4.0	3.0	1.0	7.0	58.6	35.0	15.0	14.0	196.6	56.0	10.0	66.6	64.0
1984	22.0	86.0	45.0	4.6	69.0	2.0	0.0	3.0	6.0	52.0	88.0	213.0	590.6	153.0	75.6	9.0	353.0
1985	96.0	24.2	175.6	37.0	28.0	0.0	0.0	0.0	36.0	44.0	99.0	25.0	564.8	295.8	65.0	36.0	168.0
1986	97.0	80.6	64.0	85.0	17.0	25.0	4.0	0.0	57.0	74.0	79.0	28.2	610.8	241.6	127.0	61.0	181.2
1987	56.0	41.0	18.0	1.0	31.4	16.8	0.0	0.4	0.0	40.0	88.0	33.0	325.6	115.0	49.2	0.4	161.0
1988	121.0	31.0	39.0	60.0	14.0	0.0	0.0	0.0	15.4	14.2	26.0	49.8	370.4	191.0	74.0	15.4	90.0
1989	41.8	32.2	21.2	72.2	16.6	8.8	6.8	4.6	64.4	7.2	54.2	49.4	379.4	95.2	97.6	75.8	110.8
1990	24.2	11.2	25.6	68.6	44.2	0.0	0.0	68.2	2.8	79.8	57.6	57.2	439.4	61.0	112.8	71.0	194.6
1991	16.4	74.4	23.2	11.8	0.0	11.8	5.6	5.0	73.4	81.8	72.0	4.0	379.4	114.0	23.6	84.0	157.8
1992	19.4	24.2	43.8	27.6	27.3	36.0	0.6	0.0	12.2	101.8	36.4	68.2	397.5	87.4	90.9	12.8	206.4
1993	13.2	86.2	41.0	42.6	89.8	3.0	0.0	1.2	57.6	72.2	126.2	52.8	585.8	140.4	135.4	58.8	251.2
1994	51.2	24.2	2.6	61.6	3.2	2.2	0.0	0.4	39.6	39.4	25.2	54.2	303.8	78.0	67.0	40.0	118.8
1995	15.6	0.8	26.4	43.6	12.4	7.2	2.8	20.2	78.2	0.4	97.6	70.4	375.6	42.8	63.2	101.2	168.4
1996	32.0	65.2	81.4	59.8	50.8	93.2	0.0	9.6	63.2	71.6	69.6	149.8	746.2	178.6	203.8	72.8	291.0
1997	90.2	33.0	7.6	27.0	21.0	3.8	0.0	17.6	51.8	65.4	165.2	54.6	537.2	130.8	51.8	69.4	285.2
1998	27.4	38.0	13.4	60.8	38.6	0.6	0.0	5.6	53.2	46.2	17.6	50.6	352.0	78.8	100.0	58.8	114.4
1999	38.8	17.4	61.6	23.4	17.0	9.6	2.0	0.0	44.8	18.4	126.7	53.4	413.1	117.8	50.0	46.8	198.5
2000	5.8	18.8	31.2	38.4	11.8	41.6	0.0	0.0	2.6	123.4	88.3	122.8	484.7	55.8	91.8	2.6	334.5
2001	49.6	33.2	11.4	20.0	21.4	0.0	0.0	0.0	0.0	0.0	27.8	17.4	180.8	94.2	41.4	0.0	45.2
2002	18.1	12.3	52.1	95.4	30.6	14.0	0.0	52.3	6.3	33.2	49.7	8.6	372.6	82.5	140.0	58.6	91.5
2003	68.9	100.5	19.8	13.5	8.3	7.3	0.0	0.0	24.0	69.3	63.2	72.0	446.8	189.2	29.1	24.0	204.5
2004	33.1	31.1	50.8	103.1	52.5	0.0	0.0	0.0	47.6	16.7	163.9	132.3	631.1	115.0	155.6	47.6	312.9
2005	22.8	66.8	28.0	75.8	11.4	21.2	0.0	11.0	14.0	5.0	76.0	50.6	382.6	117.6	108.4	25.0	131.6
2006	12.6	13.2	17.0	9.8	0.8	1.0	7.6	6.2	87.8	21.8	7.6	78.2	263.6	42.8	11.6	101.6	107.6
2007	18.6	42.2	56.6	77.2	25.8	3.6	1.0	0.4	13.4	20.2	34.8	10.4	304.2	117.4	106.6	14.8	65.4
2008	17.6	17.4	46.0	10.8	31.2	4.2	0.6	0.4	13.4	109.8	70.2	80.2	401.8	81.0	46.2	14.4	260.2
2009	88.4	46.2	41.4	109.0	6.0	2.6	0.0	0.0	128.8	34.6	39.8	23.0	519.8	176.0	117.6	128.8	97.4
Mean	**42.3**	**47.3**	**40.3**	**45.4**	**24.8**	**12.0**	**3.0**	**7.4**	**35.8**	**49.0**	**65.5**	**59.5**	**432.4**	**129.9**	**82.2**	**46.3**	**173.9**
Max	**121.0**	**177.1**	**175.6**	**109.0**	**89.8**	**93.2**	**68.0**	**68.2**	**128.8**	**123.4**	**203.0**	**213.0**	**746.2**	**295.8**	**203.8**	**168.0**	**353.0**
Min	**0.0**	**0.8**	**0.8**	**1.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**2.0**	**4.0**	**180.8**	**37.0**	**10.0**	**0.0**	**45.2**
Median	**32.0**	**33.0**	**39.0**	**38.4**	**17.0**	**3.6**	**0.0**	**0.4**	**26.6**	**45.0**	**59.0**	**52.8**	**397.5**	**117.4**	**75.6**	**46.8**	**165.7**
St. Dev.	**33.8**	**39.2**	**32.4**	**32.8**	**22.0**	**19.5**	**11.2**	**15.2**	**31.1**	**32.4**	**46.9**	**43.8**	**136.0**	**65.7**	**46.0**	**38.4**	**82.5**

Modeling groups	IPCC ID (label in figures)	Grid type/resolution/ model top	Deep convection scheme/modification	Downdrafts* SC/UC/Meso	Closure/ trigger	Flux correction
National Center for Atmospheric Research	CCSM3 (CCSM3)	Spectral T85-L26 2.2mb	Zhang and McFarlane (1995)	Y/N/N	CAPE	N
National Center for Atmospheric Research	PCM (PCM)	Spectral T42-L26 2.2mb	Zhang and McFarlane (1995)	Y/N/N	CAPE	N
Canadian Centre for Climate Modeling and Analysis	CGCM3.1-T47 (CGCM-T47)	Spectral T47-L32 1mb	Zhang and McFarlane (1995)	Y/N/N	CAPE	Heat, water
Canadian Centre for Climate Modeling and Analysis	CGCM3.1-T63 (CGCM-T63)	Spectral T63-L32 1mb	Zhang and McFarlane (1995)	Y/N/N	CAPE	Heat, water
LASG/Institute of Atmospheric Physics	FGOALS-g1.0 (IAP)	Gridpoint 64 × 32-L32 2 mb	Zhang and McFarlane (1995)	Y/N/N	CAPE	N
NASA Goddard Institute for Space Studies	GISS-AOM (GISS-AOM)	Gridpoint 90 × 60-L12	Russell et al. (1995)	N/N/N	CAPE	N
NASA Goddard Institute for Space Studies	GISS-ER (GISS-ER)	Gridpoint 72 × 46-L20 0.1 mb	Del Genio and Yao (1993)	Y/N/N	Cloud-base buoyancy	N
NASA Goddard Institute for Space Studies	GISS-EH (GISS-EH)	Gridpoint 72 × 46-L20 0.1 mb	Del Genio and Yao (1993)	Y/N/N	Cloud-base buoyancy	N
Hadley Centre for Climate Prediction and Research, Met Office	UKMO-HadCM3 (HadCM3)	Spectral T63-L18 4mb	Gregory and Rowntree (1990)	Y/N/N	Cloud-base buoyancy	N
Hadley Centre for Climate Prediction and Research, Met Office	UKMO-HadGEM1 (HadGEM1)	Spectral T63-L18 4mb	Gregory and Rowntree (1990)	Y/N/N	Cloud-base buoyancy	N
CSIRO Atmospheric Research	CSIRO Mk3.0 (CSIRO)	Spectral T63*L18 4mb	Gregory and Rowntree (1990)	Y/N/N	Cloud-base buoyancy	N
Meteorological Research Institute	MRI-CGCM2.3.2 (MRI)	Spectral T42-L30 0.4mb	Pan and Randall (1998)	Y/N/N	CAPE	Heat, water
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change	MIROC3.2–hires (MIROC-hires)	Spectral T106-L56	Pan and Randall (1998)/ Emori et al. (2001)	Y/N/N	CAPE/ relative humidity	N
Same as above	MIROC3.2-medres (MIROC-medres)	Spectral T42-L20 30 km	Pan and Randall (1998)/ Emori et al. (2001)	Y/N/N	CAPE/ relative humidity	N
NOAA/Geophysical Fluid Dynamics Laboratory	GFDL-CM2.0 (GFDL2.0)	Gridpoint 144×90-L24 3mb	Moorthi and Suarez (1992)/ Tokioka et al. (1988)	N/N/N	CAPE/ threshold	N
NOAA/Geophysical Fluid Dynamics Laboratory	GFDL-CM2.1 (GFDL2.1)	Gridpoint 144×90-L24 3mb	Moorthi and Suarez (1992)/ Tokioka et al. (1988)	N/N/N	CAPE/ threshold	N
Max Planck Institute for Meteorology	ECHAM5/MPI-OM (MPI)	Spectral T63-L31 10mb	Tiedtke (1989)/ Nordeng (1994)	Y/N/N	CAPE/ moisture convergence	N
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data Group	ECHO-G (ECHO-G)	Spectral T30-L19 10mb	Tiedtke (1989)/ Nordeng (1994)	Y/N/N	CAPE/ moisture convergence	Heat, water
Météo-France/Centre National de Recherches Météorologiques	CNRM-CM3 (CNRM)	Spectral T63-L45 0.05mb	Bougeault (1985)	N/N/N	Kuo	N
Bjerknes Centre for Climate Research	BCCR-BCM2.0 (BCCR)	Spectral T63-L31 10mb	Bougeault (1985)	N/N/N	Kuo	N
Institute for Numerical Mathematics	INM-CM3.0 (INM)	Gridpoint 72×45-L21	Betts (1986)	N/N/N	CAPE	Water
Institute Pierre Simon Laplace	IPSL-CM4 (IPSL)	Gridpoint 96×72-L19	Emanuel (1991)	Y/Y/N	CAPE	N

Fig. 64 - The principal GCMs considered by the IPCC in the AR4 (from http://journals.ametsoc.org/doi/full/10.1175/JCLI4272.1)

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