THE THERMAL EFFECT IN POTENTIAL YIELD OF WHEAT, DUE TO PROJECTED WARMING IN THE EASTERN MEDITERRANEAN AND THE MIDDLE EAST

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Abstract:

The region of the eastern Mediterranean and the Middle East (EMME) is characterized as a climate change "hot spot". The projected warming and drying of this region may have major consequences for both humans and natural ecosystems. One of the sectors that could be adversely impacted is agriculture. Its potential implications for food security are critical especially for this region with increasing population, limited adaptive capacity and geopolitical sensitivity. Climate change can affect agriculture directly through meteorological conditions that influence crop growth and yield. Wheat is the most widespread crop, cultivated worldwide.

The aim of this study is to explore the change in potential yield of wheat due to change of mean temperature and incoming solar radiation. At this stage we do not take in to account water availability or CO_2 fertilization (which a follow-up study will also address). The climate input is obtained from simulations by the PRECIS regional climate model (RCM) over the EMME domain at a 25 x 25 km resolution, driven by the A1B moderate emissions scenario for the 20th and 21st centuries. For the crop yield calculation we utilize part of Module II of the Agro-Ecological Zones (AEZ) methodology, developed by FAO and IIASA. In particular, we calculate the constraint-free crop yields, which reflect yield potentials with regard to temperature and radiation regimes derived from the RCM.

The results show that the change in temperature and solar radiation projected by PRECIS RCM leads to a decrease in potential wheat yield in the future, which confirms the overall expectations. We discuss these changes over specific sub-regions and time periods throughout the 21st century.

1 Introduction

The region of the eastern Mediterranean and the Middle East is the place of over 400 million inhabitants spread over an area with a 2000 km radius. After years of intense industrialization, rapid population growth and extensive land use changes the region has become a global climate change "hot spot".

The trends of the climate conditions documented by observations in the EMME indicate strong temperature increase and reduced precipitation during the 20th century [1]. This warming and drying is projected to intensify in the 21st century and may have major consequences for both humans and natural ecosystems [2]. One of the sectors that could be adversely impacted is agriculture and its potential implications for food security are critical for this region with increasing population, limited adaptive capacity and geopolitical sensitivity.

The EMME is characterized by high biodiversity, notably of plant species, related to the large gradients in topography, soil fertility and climate conditions. During the past eras the conversion of natural ecosystems into croplands and overgrazing have already strongly shaped the land cover. The EMME encompasses sub-regions that are very suitable for agriculture. Current climate conditions in the EMME allow for a large variety of crops, including C3 and C4 cereals, legumes and root crops [3, 2].

Wheat is counted among the “big three” cereal crops, with over 600 million tonnes annual harvest [4]. In 2009, 226 million hectares were sown to wheat; producing 685 million tonnes of grain yield of 3 tonnes/ha [5, 6]. Wheat is a cool season crop originating in the Fertile Crescent but now is widely spread around the world. It can be grown in a range of climates, from arctic and humid regions to tropical highlands and from sea level on the Dutch Polders to 4500m altitude. The growing conditions are very diverse, not only because of the widespread climatic regions and altitudes, but also because of the variability of soil types and crop management.

Wheat cultivars can be classified into winter and spring wheat. This usually refers to the season during which the crop is planted. Winter wheat is sown in autumn, while spring wheat is sown in autumn or spring.

Durum wheat (*Triticum tirgidum*) is known as the hardest type of winter wheat that currently exists. Durum is originated in the eastern Mediterranean and has been cultivated in this region for the last 12 thousand years [7]. Whilst farming has spread globally, a premium is set on durum wheat quality grown in the Mediterranean basin and this can account for up to 75% of the world total production [8]. The main environmental constraints limiting the production of durum wheat in this region are drought and temperature extremes with productivity ranging from 0-6 tonnes/ha [9].

Spring wheat, as mentioned above, can be defined as wheat which is sown in spring. This is not always the case. Spring wheat is also sown in autumn to over winter in regions with winter dominant rainfall and mild winter temperatures such as some arid and Mediterranean regions, as well as in the cool season of high lands in the tropics [6].

The effects of climate change on agriculture can be direct, by affecting the quantity and quality of crop production. The aim of this work is to highlight the thermal effect (driven by anthropogenic global warming) on potential yields of four types of wheat using the Agro-Ecological Zones (AEZ) methodology and regional climate projections simulated by the PRECIS RCM. The types of wheat that we are studying here are listed in table 1, where duration of growth cycle is shown. In addition, more information regarding the planting and harvesting dates are also shown. These crop calendars (table 1) are selected because of the fact that wheat is usually cultivated in the EMME region during this period of the year, the beginning of which also coincides with the start of the rainy season in this area. The length of the corresponding growth cycles is kept fixed in order to reveal the thermal effect only of the change in temperature and radiation.

Table 1. Crops growing cycle, duration and calendar

Crop type	Growth cycle (L) [Nr of days]	Sowing date	Harvesting date
Winter (durum) wheat	180	1st November	30th April
Spring wheat	150	15th November	15th April
Subtropical cultivar of wheat	150	15th November	15th April
Tropical highland cultivar of wheat	100	10th December	22nd March

2 Data and Methodology

Calculations of potential yields of wheat are made using the first step of biomass and yield calculation model of Agro-Ecological Zones methodology developed by FAO and IIASA[1] [10, 11].
This calculates the constrained-free crop yields, which reflect yield potentials with regard to temperature and radiation regimes prevailing in the respective grid cells and are based on the eco-physiological model developed by Kassam [12].[1]

2.1 Data

The biomass model requires as climatic input mean temperature and incoming short-wave solar radiation data. These are obtained from simulations made by PRECIS (Providing REgional Climates for Impacts Studies) regional climate model. The RCM uses the same formulation of the climate system as its parent global model HadCM3 [13], which provided lateral boundary conditions from a simulation driven by the intermediate A1B scenario, based on the IPCC Special Report on Emissions Scenarios (SRES) [14].

PRECIS was run from 1950 to 2099 over a domain covering the EMME region at a horizontal resolution of 0.22° (~25 km) and 19 vertical levels. The domain boundaries are 22-44°N and 13-55°E latitude. The results from the simulation presented here have already been evaluated extensively and used in EMME climate change impact studies and assessments [15, 2, 16].

The data used here are daily timeseries divided into four periods of time representing the recent past, current and future climate conditions. Baseline (BL) period used as control period is 1961-1990, first period (P1) is 2011-2040, second period (P2) is 2041-2070 and third period (P3) is 2071-2099.

2.2 Methodology

Firstly, we applied a thermal suitability test. This test is performed using the temperature profile requirements, crop-specific rules that take into account crop growth cycle duration in different classes of mean daily temperatures. Temperature profiles are defined in terms of two times 9 classes of "temperature ranges" (denoted with "L" in Table 1) for days with average temperatures <5°C, -5-0 °C, … , 25-30°C and >30°C (at 5°C intervals) in combination with distinguishing increasing (a) and decreasing(b) temperature trends within the growth cycle.

Potential crop calendars (table 1) of each grid box of the domain are tested for the match of crop temperature profile requirements and prevailing temperature profiles. Temperature profile conditions are tested against optimum and sub-optimum requirements of wheat (table 2).

The calculation done here is for rain-fed conditions, because we consider only the growth cycle (L). When the conditions are satisfied the grid box is considered suitable for cultivation of wheat, if not then the grid-boxes are marked as non-suitable.

The suitability test is applied on each grid-box of the domain for all 4 periods of time, in which the climatic data is divided into. Further potential yield calculations are made only for suitable grid boxes.

[1] http://webarchive.iiasa.ac.at/Research/LUC/GAEZv3.0/

The potential yield of each crop is affected by the intensity of input and management assumed to be applied. In the EMME region intermediate level of input is the most appropriate choice. This is defined as: the farming system is partly market oriented. Production for subsistence plus commercial sale is a management objective. Production is based on improved varieties, on manual labor based on hand tools and/or animal traction and some mechanization. It is of medium intenseness, with some fertilizer application and chemical pest disease and weed control, adequate fallows and some conservation measures.

Table 2. Optimum and sub-optimum conditions for wheat [11]

Crop	Sub-optimum conditions	Optimum conditions
Winter (Durum) wheat	L6a < 0.667 * Lb	L6a < 0.5 * Lb
	L2a + L2b < 0.333*Lb	L2a + L2b < 0.333*Lb
	L1 = 0	L1 = 0
	L2b+L3b+L4b+L5b < 0.5*Lb	L2b+L3b+L4b+L5b< 0.5*Lb
	L3b+L4b+L5b+L6b > La	L3b+L4b+L5b+L6b > La
Spring wheat	L6a < 0.500*L	L6a < 0.375*L
	L6b = 0	L6b = 0
	L6a+L5a > 0.0835*L	L6a+L5a > 0.167*L
	L2a+L2b < 0.333*L	L2a+L2b < 0.333*L
	L1 = 0	L1 = 0
	L2b+L3b+L4b+L5b < 0.500*L	L2b+L3b+L4b+L5b < 0.500*L
Wheat (subtropical cultivar)	L6a < 0.500*L	L6a < 0.333*L
	L6b = 0	L6b = 0
	L6+L5+L4 > 0.167*L	L6+L5+L4 > 0.333*L
	L2a+L2b < 0.400*L	L2a+L2b < 0.333*L
	L1 = 0	L1 = 0
Wheat (tropical cultivar)	L6a < 0.333*L	L6a < 0.167*L
	L6+L5+L4 > 0.167*L	L6+L5+L4 > 0.333*L
	L2a+L2b < 0.400*L	L2a+L2b < 0.333*L
	L1 = 0	L1 = 0

All equations of the biomass and yield calculation model (AEZ methodology) [11, 12] are transferred into a script in R[2] programming language in order to perform the needed calculations. More detailed description is presented in the following paragraphs.

The maximum rate of gross biomass production (b_{gm}) is related to the maximum net rate of CO_2 exchange of leaves P_m, which is dependent on temperature, the photosynthesis pathway of the crop and the level of atmospheric CO_2 concentration.

$$b_{gm} = F \times b_0 + (1 - F) b_c \quad (1)$$

where, F is the fraction of daytime and is related to the maximum active incoming short wave radiation on clear days (A_c or PAR) [17] and the incoming short-wave radiation (Rg) which was provided from PRECIS (both measured in [$cal\ cm^{-2}\ day^{-1}$]).

b_0 is the gross dry mater production rate of a standard crop for a given location and time of the year on a completely overcast day and

b_c is the gross dry mater production rate of a standard crop for a given location and time of the year on a perfectly clear day, both measured in $kg\ ha^{-1}\ day^{-1}$ [17].

A_c, b_0 and b_c are interpolated from Vega R. [18].

The net biomass production B_n for a crop of N days, where half of the maximum rate of net biomass (dry matter) production is the seasonal average rate of net biomass production, can be derived from:

[2] http://www.r-project.org/

$$B = \frac{0.36\ b_g \times L}{1/_N + 0.25 c_t} \quad (2)$$

where, b_{gm} is the maximum rate of gross biomass production and is calculated by (1),

L is the growth ratio of b_{gm} at actual LAI (Leaf Area Index) to b_{gm} at LAI of 5.

N is the length of normal growth cycle. c_t is the maintenance respiration, dependent on both crop and temperature.

Finally, potential yield (Y_p) is estimated from net biomass (B_n) using the equation:

$$Y_p = H_i \times B_n \quad (3)$$

where, H_i is the harvest index, i.e. proportion of the net biomass of a crop that is economically useful. All crop-specific input parameters needed for calculations are found in table 3.

Table 3. Crop-specific input parameters (*N*, *LAI* and *Hi* are taken from the model's input parameter list [11] and *L* is taken from [19]).

Crop	N[days]	LAI	L	Hi
Winter (Durum) wheat	180	4	0.91	0.35
Spring wheat	150	3.8	0.89	0.3
Wheat (subtropical cultivar)	150	4	0.91	0.33
Wheat (tropical cultivar)	100	2.7	0.732	0.28

3 Results

Projections of mean temperature and incoming short-wave radiation from PRECIS (A1B emissions scenario) divided into four periods of time (BL=1961-90, P1=2011-40, P2=2041-70 and P3=2071-99) are used here to calculate potential yield of four types of wheat in the EMME region. Figure 1 shows maps of changes in temperature (a) and solar radiation regimes (b) simulated for each future period compared to the baseline period (BL). The model projects an increase in temperature in the whole domain of 0.2-2.9 ºC (P1-BL), 1.1-4.7 ºC (P2-BL) and 2.1-6.2 ºC (P3-BL). Radiation in the north-western part of the region seems to have an increasing trend in the future unlike its eastern part where the trend is decreasing.

The whole domain is tested for suitability to grow each type of wheat, i.e., if optimum and sub-optimum conditions are satisfied. This is done by testing if temperature profile requirements and prevailing daily mean temperature regimes in each grid-box match. Only the subsequent suitable fields are used further for the potential yield calculations.

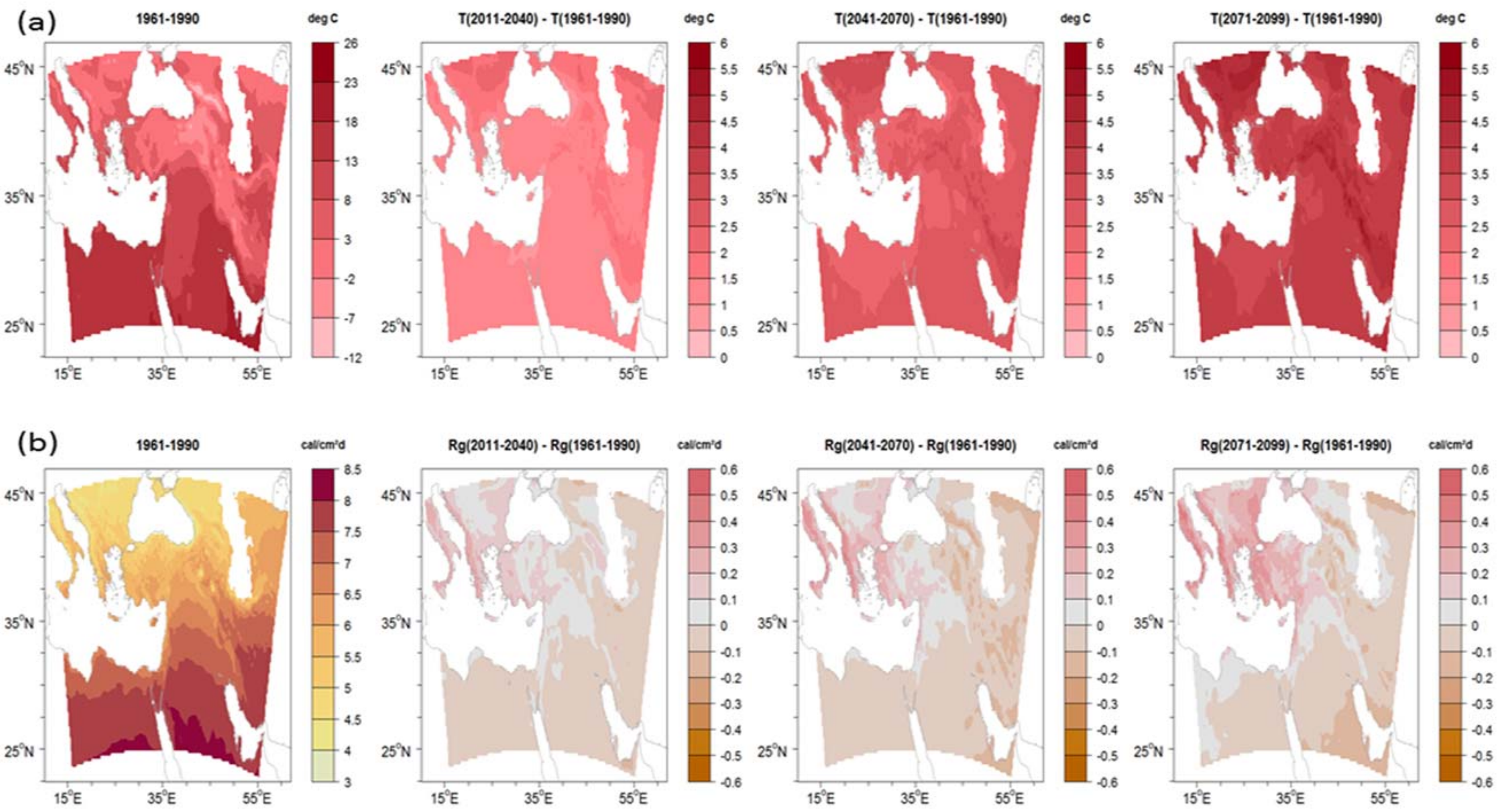

Fig.1. Changes in mean temperature (a) and incoming short-wave radiation (b), projections from PRECIS RCM, A1B emissions scenario.

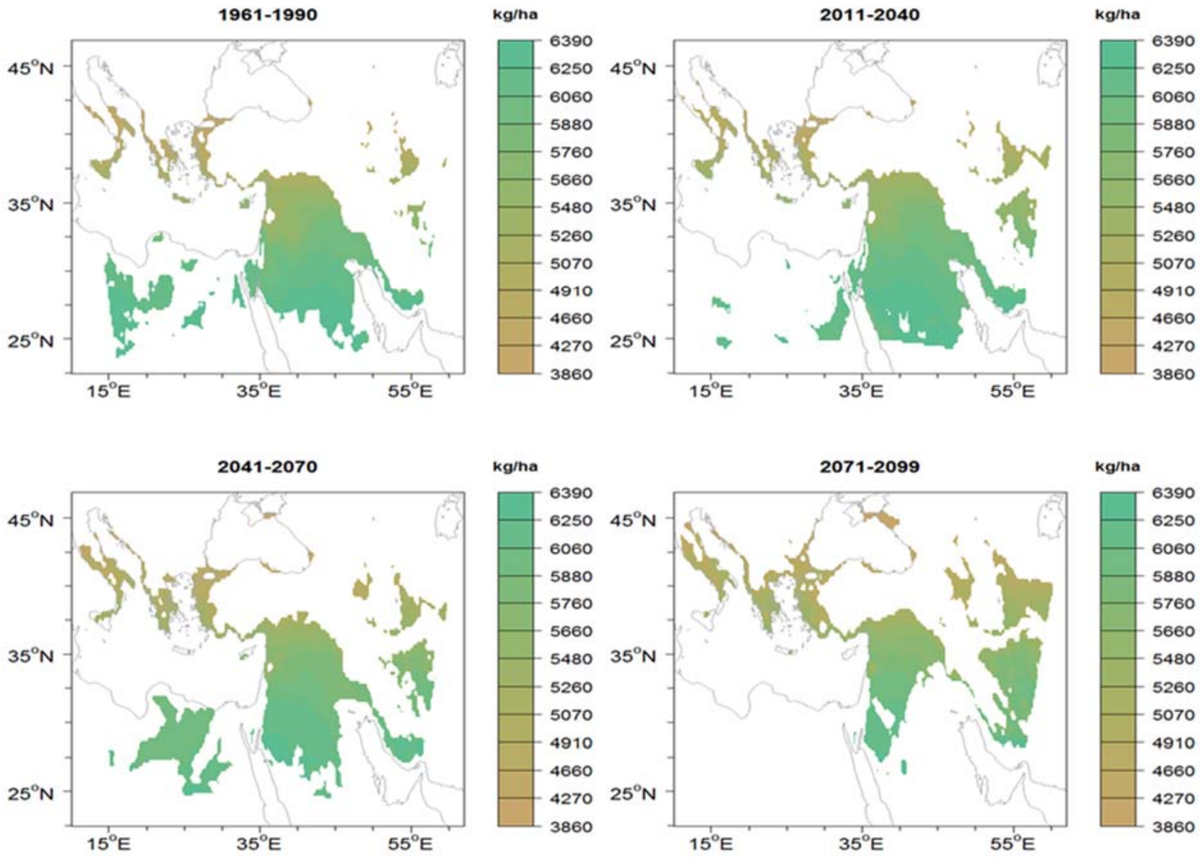

Fig.2. Calculated potential yield for durum wheat

Yield potentials of durum wheat in the EMME region are presented in figure 2 where results are presented only in the suitable grid-cells of the region. From this figure one can draw conclusions regarding two aspects. First, the change in suitability to cultivate durum in the future is shown. There is a shift towards the northern part of the region, which follows the trend of the agro-climatic zones. Higher temperatures simulated for the southern part of the domain lead to less suitable area to grow this specific crop, whereas higher temperatures projected for the northern part of this region, make it more suitable for cultivation.

Second aspect, is the change in potential yield in the future. The values calculated for the baseline period are compared with literature and are found within the limits of actual durum production. As mentioned above the actual durum production in our area of interest ranges from 0-6 tones/ha [9, 20]. Our calculations give results in the following ranges: BL= 4030-6500 kg/ha, P1= 4460-6442 kg/ha, P2= 3970-6440 kg/ha and P3= 4040-6390 kg/ha. The outcome of the potential yield projections is variable. Overall there is a tendency for diminishing suitable areas, with the northern Africa, Sicily, Crete and Cyprus becoming, according to the calculations, unsuitable by the end of the century. Areas in Iran are becoming suitable by 2071-2099. Interestingly, some areas that remain suitable throughout the 21st century (mainland Greece, western Turkey) exhibit an increase of potential yield.

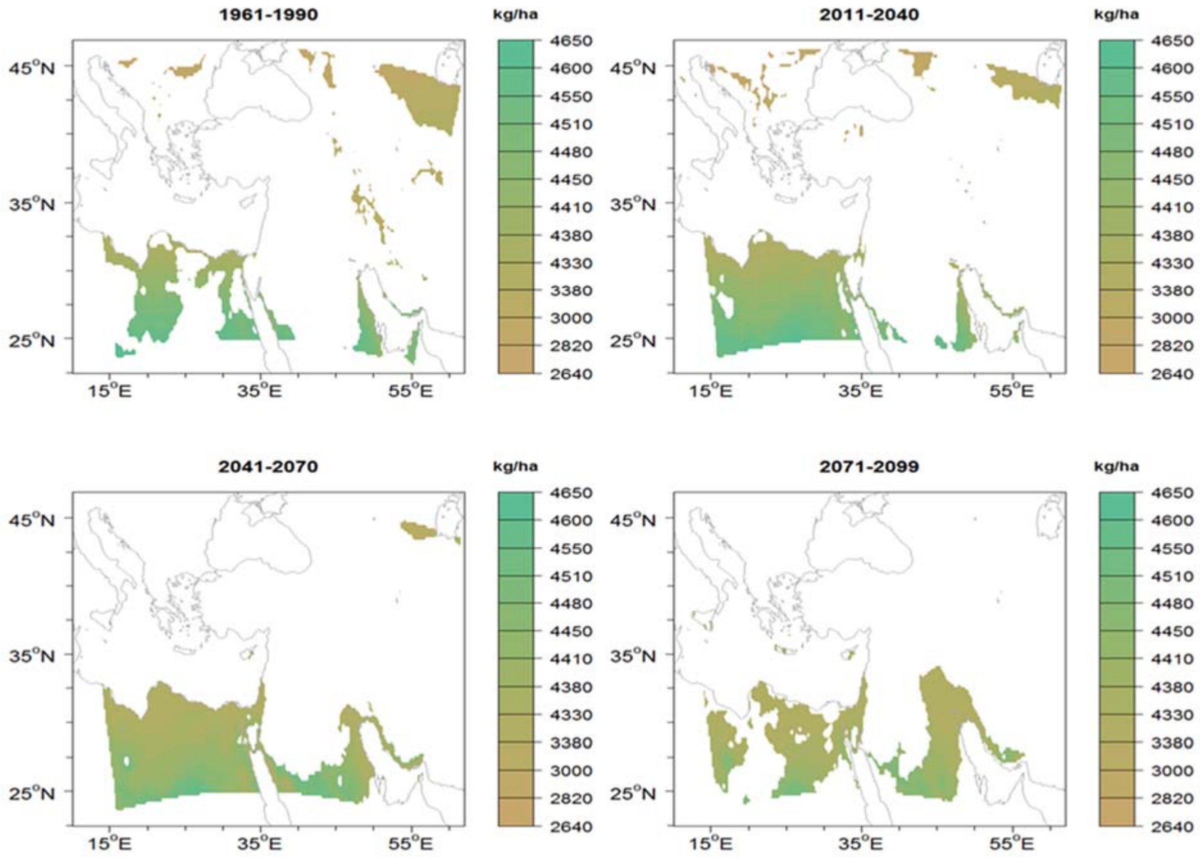

Fig. 3. Projected potential yield of spring wheat

Figure 3 shows the results after the suitability test and potential yield calculations for spring wheat. The (few) areas of the northern part of the domain that are suitable in the control period (BL=1961-1990) are decreasing as we move on to the future periods. This shows that higher temperatures and the change in solar radiation regimes that are projected for the future are not within the acceptable limits of climatic conditions needed to grow spring wheat. In contrast with this, the southern part of the domain becomes more suitable in the future and at the end of the century is projected, that areas which are suitable in the baseline period will not be in P3 (2071-2099).

Performed calculations for potential yield of spring wheat give the following ranges for each period of time that we are looking at: Yp(BL)= 2768 – 4633 kg/ha, Yp(P1)= 2645 – 4644 kg/ha, Yp(P2) = 3177 – 4580 kg/ha and Yp(P3) = 3029 – 4533 kg/ha. In general potential yield of spring wheat seems to be decreasing in the future. Some areas, as mentioned above, that are suitable in the period of 1961-1990 like parts of south Russia, Caucasus region, Iraq, Romania and Bulgaria will not be suitable in the future which means that yield may not attainable in these areas. Parts of some countries have potential yield that is increasing in the future. South-eastern part of Cyprus, southern part of Greece (Crete), southern part of Italy, Egypt, parts of Libya and parts of Saudi Arabia. The last three countries mentioned have also decreasing trends in potential yield as well as increasing in suitability.

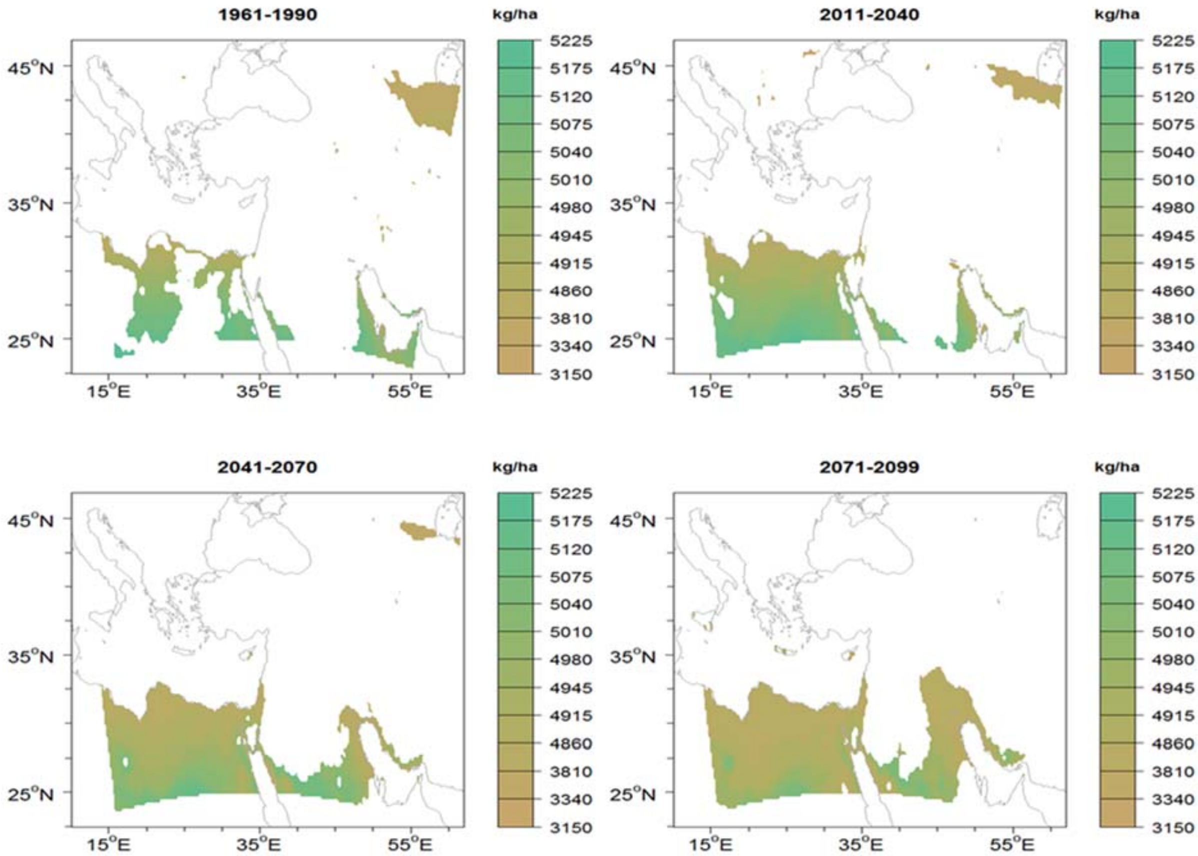

Fig. 4. Projected potential yield of subtropical cultivar of wheat

The overall picture of potential yield of the subtropical cultivar of wheat (Fig. 4) is very similar to the maps shown in figure 3 for spring wheat for suitability of growing these crops in the EMME region. Some areas lose their suitability by the end of the 21st century in the northern part of the domain. As expected, areas that are in the subtropical zones are more appropriate to grow the specific cultivar of wheat.

Numerical results of calculations made for potential yield are within the following ranges:
Yp(BL)=3290 – 5210 kg/ha, Yp(P1) = 3153 – 5223 kg/ha , Yp(P2) = 3573 – 5151 kg/ha and
Yp(P3) = 4342 – 5100 kg/ha. In comparison with results of spring wheat, potential yield of subtropical wheat gets higher values. Future projections show that changes in mean temperature and incoming short-wave radiation will lead in decreasing the yield potential for subtropical cultivar of wheat in this region.

Maps on figure 5 show potential crop yield for the region of eastern Mediterranean and Middle East for tropical highland cultivar of wheat. Climatic conditions projected by PRECIS RCM (temperature and radiation) allow the cultivation of this type of wheat in this area. Most of the parts of the model's domain, which are suitable in the control period, remain suitable in the future (part of Libya, Egypt, Iraq and Israel). Countries like Cyprus, Greece, Italy, Bulgaria, Romania, Turkey and Lebanon are projected to have more suitable climatic conditions to grow tropical cultivar of wheat in the future periods of time. By the end of the century most of the domain is marked as suitable for cultivation.

Potential yield for this type of wheat calculated are in the following ranges of values:
Yp(BL) = 1386 - 2478 kg/ha, Yp(P1) = 1428 – 2474 kg/ha, Yp(P2) = 1395 – 2465 kg/ha and Yp(P3) = 1345 – 2450kg/ha. Overall these values have decreasing trend. Some areas have increasing trend in potential yield in the future. These are northern Iraq, Iran, Cyprus, Turkey, eastern part of Greece and Crete and also southern Italy.

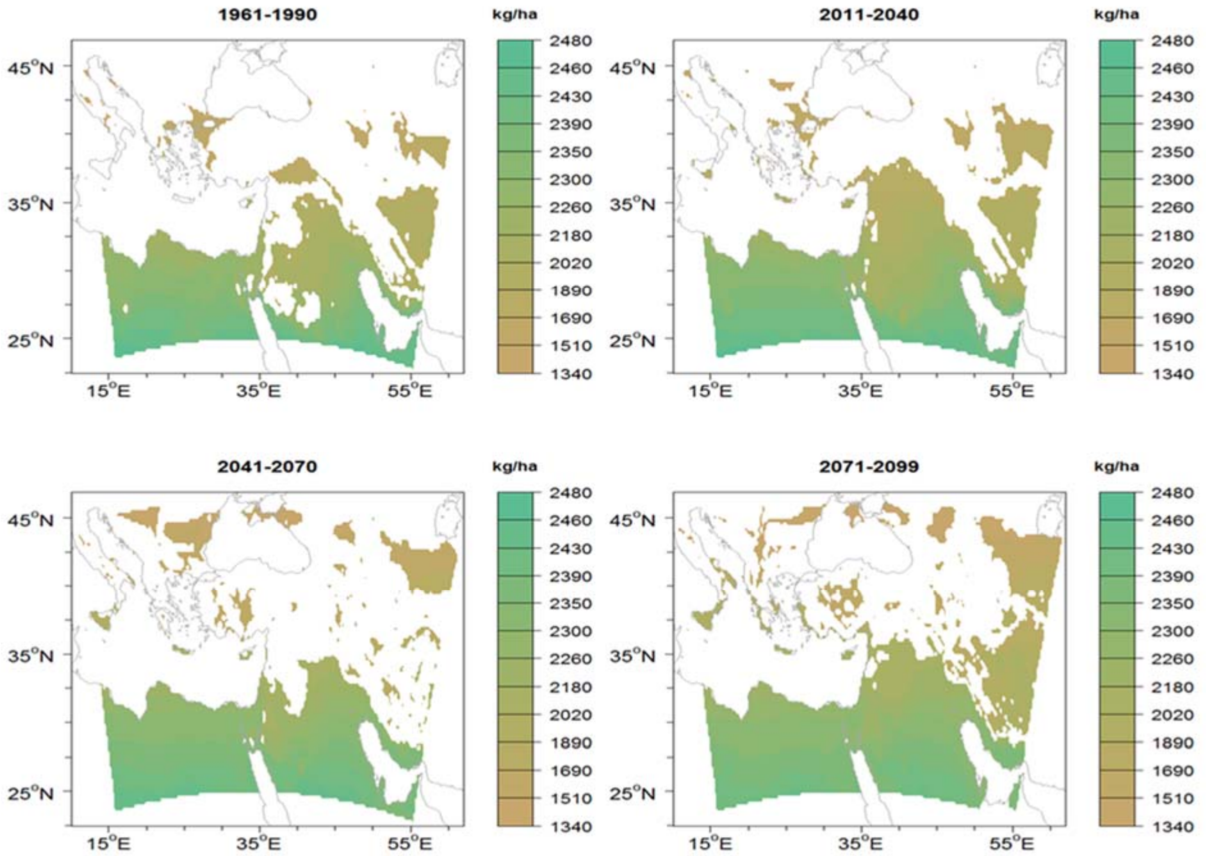

Fig 5. Potential yield calculated for tropical highland cultivar of wheat

4 Conclusions

Wheat is counted among the "top three" cereal crops, with over 600 million tons of annual harvest [4]. In this study we present projected changes on potential crop yields by taking into account changes in temperature and incoming solar radiation. Our work complements the GAEZ web portal developed and maintained by FAO and IIASA as it allows the use of any gridded climate dataset as input for the crop yield calculations. Crops studied in this paper are four types of wheat including winter (durum), spring, subtropical and tropical highland cultivars as classified by FAO and IIASA in the AEZ methodology.

Considering the thermal and light conditions simulated by PRECIS, durum and subtropical cultivar of wheat are the ones that give the highest values of potential yields and hence may be the favoured wheat cultivars in the EMME region. Calculations for potential yield of spring wheat also have high values, in contrast with the potential yield projected for tropical cultivar of wheat which has the lowest values of the four types in the region. Overall, the results of the calculations have a decreasing trend in all four types of wheat but in some particular areas a small increase is shown.

There is a loss of suitable areas for durum wheat in the southern parts of the EMME domain but also widening of the suitable areas at the eastern parts (Iran). This is not the case when studying the rest of the types of wheat. For those, most of the southern parts of the domain are more suitable. Northern part of the regions will lose their suitability to grow spring and subtropical wheat, but climatic conditions that are projected for the region will make this part of it more suitable to grow tropical cultivar of wheat.

Further work will incorporate water availability and CO_2 fertilization in the calculation of potential yield for a more complete assessment (thermally and water driven with CO_2 fertilization taken into account).

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