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Article

A Methodology to Infer Crop Yield Response to Climate Variability and Change Using Long-Term Observations

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Abstract: A new methodology to extract crop yield response to climate variability and change from long-term crop yield observations is presented in this study. In contrast to the existing first-difference approach (FDA), the proposed methodology considers that the difference in value between crop yields of two consecutive years reflects necessarily the contributions of climate and management conditions, especially at large spatial scales where both conditions may vary significantly from one year to the next. Our approach was applied to remove the effect of non-climatic factors on crop yield and, hence, to isolate the effect of the observed climate change between 1961 and 2006 on three widely crops grown in three Mediterranean countries—namely wheat, corn and potato—using national-level crop yield observations' time-series. Obtained results show that the proposed methodology provides us with a ground basis to improve substantially our understanding of crop yield response to climate change at a scale that is relevant to large-scale estimations of agricultural production and to food security analyses; and therefore to reduce uncertainties in estimations of potential climate change effects on agricultural production. Furthermore, a comparison of outputs of our methodology and FDA outputs yielded a difference in terms of maize production in Egypt, for example, that exceeds the production of some neighbouring countries.

Keywords: crop yield; climate change; new methodology; reducing uncertainties

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1. Introduction

Crop yield response to climate change has received major attention for about three decades now, which is easily justified by the critical ramifications that such a response could have on global food security, human health and worldwide socio-economic stability [1–4]. The critical importance of understanding crop yield response to climate change triggered the development of numerous crop models varying from simple statistical to complex process based schemes that simulate mechanistically key physical and physiological processes involved in crop growth and development (e.g., [5,6]). However, despite the tremendous progress made so far in crop modelling science, existing crop models are still suffering serious shortcomings [7–9]. It has been shown for instance that crop models are still unable to reliably reproduce some critical processes governing crop growth and yield, such as CO_2 fertilization and crop rotation effects on yield [10,11]. Effects of climate extremes on plant growth and development, and on crop yield are also still poorly represented in current crop models [12,13]. Consequently, the important deficiencies that are still associated with their simulations contribute greatly to the large uncertainties in estimates of climate change effects on crop production.

To reduce these uncertainties, the use of statistical models has been suggested [14], especially at broad spatial scales because of their flexibility and usefulness at such scales at which climate change projections are also usually available and most reliable. Though there is reasonable justification supporting that argument, there is a common general belief that it is preferable to use process-based crop models at any scale, especially when the predictions are made under changing environmental conditions [13]. Process-based models can, indeed, account for some important physiological processes and their interactions that could affect crop yield such as plant acclimation to CO_2 and temperature [15,16], while statistical models cannot. Thus, that sound common belief implicitly suggests that efforts to reduce uncertainties in estimations of large scale crop production under changing environmental conditions must focus on those made by process-based crop models as a priority. To carry-out such an objective, one may consider the following actions:

i. Carefully analyse available long-term observations of crop yields in order to infer the most likely crop yield response to climate variability and change;
ii. Use the inferred response to test and calibrate crop models under current conditions.

Current conditions in point (ii) refer to relatively long periods over which significant changes in climate conditions have been detected already, as further discussed in Section 3.1. Preferably furthermore, the spatial scale of the analysed observations (point (i)) should be compatible as much as possible with the scale of application of the inferred crop yield response. This is because one may argue, for example, that the crop yield response to climate change that could be extracted from observations made at a farm level would hardly reflect regional or national level conditions where soil, climate and grown cultivars among other conditions may vary from one region to the other. Consequently, that extracted farm-level response may not be ideal to test and calibrate a model that is intended to be used for large scale estimations.

This study where the ultimate goal is to contribute to the improvement of large scale estimations of climate change effects on crop production emphasizes on the investigation of the abovementioned point (i). To satisfy the spatial-scale requirement discussed in the previous paragraph, time-series of national-level crop yield observations were used. These observations that cover the 1961–2006 period were analysed and a methodology to extract the contribution of climate change to crop yield trends throughout long periods, such as the 46 years' time interval of our study, is suggested, analysed and discussed.

2. Method

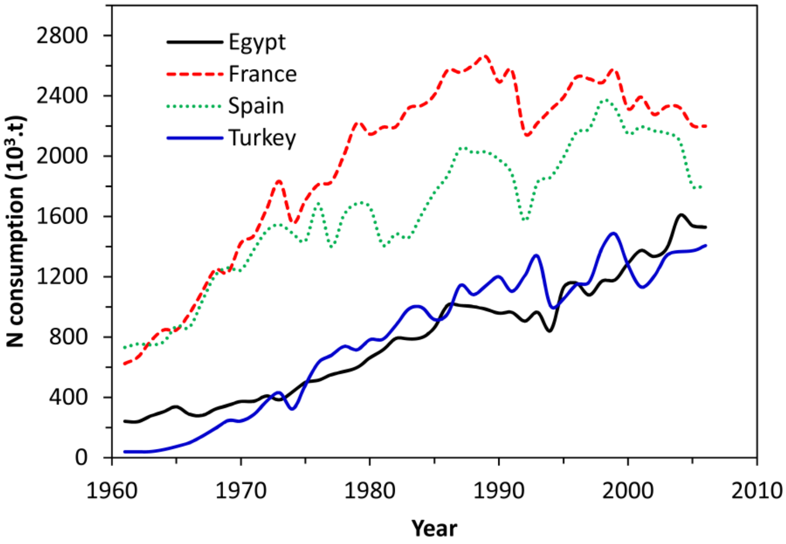
2.1. Approach and Formulations

The main objective of this study is to infer the observed crop yield response to climate variability and change from long-term crop yield observations, especially at a scale that is relevant to large-scale estimations of climate change impacts on crop production and food security. National level crop yield datasets of the Food and Agricultural Organization (FAO; see Section 2.2) that were used in this study are a concrete example of such observations. Because crop yield is generally influenced by climatic and non-climatic factors, a simple methodology was developed to split between the contributions of each of these factors to the observed crop yield evolution so that the effect of the climate component on crop yield could be extracted and analysed.

The starting point in our methodology is the first-difference approach (hereafter referred to as FDA), that was suggested by [17] and used in various studies to assess the effect of climate change on crop production in various part of the world (e.g., [17–22]). FDA assumes that the trend of the first-difference crop yield time-series (*i.e.*, constructed time-series using the difference in crop yield from one year to the next), reflects exclusively the effect of climate. FDA assumes indeed that non-climatic factors, such as crop management, change slowly from one year to the next so that the crop yield first-differences eliminate the influence of these factors on the constructed time-series. Here, we believe that such an assumption and its reliability is questionable. In fact, at large spatial scales, for example (e.g., national or continental), where farming policies and orientations among regions may vary considerably, that assumption becomes particularly weak and even not valid because factors that influence crop production, such as fertilizer applications and crop chemical treatments, may vary substantially from one year to the next (e.g., [23]; see also Figure 1). Furthermore, it is well known that non-linearity characterizes the effect of climate and crop management interactions on crop yield variations (e.g., [24–27]). A small change in crop management may lead to an important change in crop yield. Consequently, crop-climate trend analyses based on FDA will undoubtedly lead to unwarranted conclusions about the crop yield response to climate change, especially at large spatial scales.

Thus, it is obvious that the trend of the crop yield first-difference time-series reflects crop yield response to climate variability only when factors other than climate (*i.e.*, fertilization, technology, *etc.*), that influence crop yield do not vary or vary very little. As an illustration, the fertilization effect of the annual increase of atmospheric CO_2 (less than 2 ppm) on crop yield, which is very small from one year to the next [11,28], can be easily removed by FDA. In the extreme case where climate conditions do not vary, the crop yield first-differences reflect exclusively the effect of non-climatic factors. In all other intermediate cases, where both climatic and non-climatic factors influence crop yield significantly, it becomes difficult to distinguish the contribution of each of these factors to crop yield variability given the complex interactions between crop growing conditions and the non-linear crop yield response to these interactions. Hereafter, we describe our methodology to separate between climatic and non-climatic contributions to crop yield trends.

Figure 1. Temporal evolution of total nitrogen (N) consumption in four Mediterranean countries. It is shown that in all countries, important interannual variations in N consumption may occur (see Section 2.1 for more details).



At any time (year), crop yield (y) can be expressed as the sum of management and climate contributions, as follows:

$$y = y_c + y_m \tag{1}$$

where y_c and y_m are the climate and crop management (including technology and any other non-climatic factor) induced crop yields, respectively.

The temporal variation of y can then be expressed as:

$$\frac{dy}{dt} = \frac{dy_c}{dt} + \frac{dy_m}{dt} \tag{2}$$

Because y_m depends exclusively upon crop management variations, Equation (2) can be further expressed as follows:

$$\frac{dy}{dt} = \frac{dy_c}{dt} + \left(\frac{\partial y_m}{\partial m}\right)_c \frac{dm}{dt} \tag{3}$$

or

$$\frac{dy}{dt} = \frac{dy_c}{dt} + \left(\frac{\partial y}{\partial m}\right)_c \frac{dm}{dt} \tag{4}$$

Though Equations (3) and (4) are strictly identical, the use of Equation (4) is, hereafter, preferred to Equation (3) because crop yield data are usually available only in y form. The two equations are identical for the following reason:

$$\left(\frac{\partial y}{\partial m}\right)_c = \left(\frac{\partial y_m}{\partial m}\right)_c \text{ because } \begin{cases} \left(\frac{\partial y}{\partial m}\right)_c = \left(\frac{\partial y_c}{\partial m}\right)_c + \left(\frac{\partial y_m}{\partial m}\right)_c ;\ because\ y = y_c + y_m\ (Equation\ 1) \\ and \\ \left(\frac{\partial y_c}{\partial m}\right)_c = 0 \end{cases}$$

y_c is indeed the climate-induced crop yield, which is independent from crop management.

The subscript *c* outside the brackets refers to constant climate (see below for more details). In order to avoid any potential confusion in what follows, it is very important to note that according to the differential calculus [29], constant climate conditions are required to compute the second term of the right side of Equations (2–6) (management contribution), while constant management conditions are required to compute the first term of the right hand side of the same equations (climate contribution). In this study, the climate contribution is obtained by subtracting the calculated management contribution from the total yield (left hand side of Equations (2–6)).

Equation (4) can be further expressed as:

$$\frac{dy}{dt} = \frac{dy_c}{dt} + a_m \frac{dm}{dt} \tag{5}$$

Leading to the following more simplified expression:

$$\Delta y = \Delta y_c + \ a_m \Delta m \tag{6}$$

where a_m $\left(=\left(\frac{\partial y}{\partial m}\right)_c\right)$ is the crop yield variation as a function of crop management. $\Delta m,\ \Delta y\ and\ \Delta y_c$ are the annual variation of crop management, total crop yield and climate-induced crop yield first-differences, respectively.

Yearly time-step computation of the second term of the right hand side of Equation (6) and subtraction of its value from Δy will provide us with estimates of Δy_c, which represents the core objective of this study. The obtained Δy_c time-series represents indeed the crop yield response to climate change.

As shown in Equation (4), the computation of the management term a_m requires constant climate conditions because, as explained above, a_m depends exclusively upon management practices as it represents the variation of crop yield that is inherent to the sole variation of crop managements. While in reality climate vary from one year to the next, such a requirement implies in practice that a relationship between crop yield and crop management over a given time interval can be used to compute a_m only under the condition where climate does not show any statistically significant change. To satisfy this condition, our approach was then:

To select a sub-period within the 1961–2006 time interval during which the change in climate was statistically not significant. Such a period could be either continuous or discontinuous in time;

i. To use crop yield and management observations over the selected sub-period to derive a relationship that statistically links interannual crop yield and crop management variations; and
ii. To apply the obtained relationship between crop yield and management to the entire period of study (*i.e.*, 1961–2006), since that relationship satisfies the climate constant conditions and is time independent.

To avoid any possible confusion, we strongly remind here that the “statistically constant climate condition” mentioned above apply only for the computation of the management term a_m, and does not mean that the climate is considered as “constant” for the whole study.

Moreover, because agricultural practices may involve various types of management, the crop management term in Equation (6) can be further expanded to include different individual management contributions, such as crop fertilization, irrigation, pesticide application, and genotype improvement. More specifically, the management term could be expressed as follows:

$$a_m \Delta m = a_F \Delta F + a_I \Delta I + a_G \Delta G +, \dots, + a_X \Delta X \tag{7}$$

where *F*, *I*, *G* and *X* refer to fertilizer application, irrigation, genotype improvement, and any other potential management practices including technological improvements, respectively.

The form of Equation (7) stems from the fact that crop yield has a climate component and one or more management components (fertilization, irrigation, *etc.*). For simplification, in fact, only one management term was represented in Equation (2) (a generic term). By incorporating various management components that contribute to the final crop yield in Equation (2) and following the same mathematical development shown in Equations (3–6), we obtain Equation (7). Hence, each specific term a_x that reflects the contribution of each individual crop management practice to crop yield can be calculated as follows:

$$a_X = \left(\frac{\partial y}{\partial X}\right)_c \tag{8}$$

Equation (7) attempts to capture the effect of various management practices on crop yield. Its applicability depends obviously upon the availability of sufficient observations related to each individual management practice. In fact, it could be used whether data time-series describing the effect of one or more individual managements on crop yield are available or not; as it is illustrated below in our case studies.

2.2. Data

Three different crops widely cultivated in three Mediterranean countries were selected for our analyses: maize in Egypt, wheat in Greece and potato in Morocco. National level crop yield observations between 1961 and 2006 [30]; and Climate Research Unit (CRU—version TS3) gridded monthly climate data at 0.5° for the same period [31] were used. For each country, our use of the climatic data was restricted to the cultivated areas as documented in [32,33].

To ideally extract the climate-induced crop yield trend using our approach, it is preferable to use observations of yearly variation of each crop management practice relatively to each crop and each country. To our best knowledge, however, such national-level observations do not exist yet, neither for a period as long as the period of our study (46 years), nor for a shorter period. Alternatively, we used the best available observations on crop management that are relevant to our study. These management observations, shown in Figure 2a,b along with crop yield observations (Figure 2c), include total fertilizer consumption (TFC) data as provided by the international fertilizer association [34], and national-scale estimates of total irrigated agricultural lands (TIL) given in [35]. Though not ideal to reach the best possible accuracy when splitting between climate and management contributions to crop yield trends, TFC and TIL data represent an acceptable alternative, considering that the rate of annual changes in these two variables at the national level reflects the annual changes in crop production. A consideration that is strongly supported by the high and statistically significant (95% confidence limit) correlation between annual changes in crop yield and each of the two variables (Figure 3a–c). Interestingly, furthermore, a literature review shows that some other authors have also used national-level fertilizer applications to analyse national-level crop yield evolution (e.g., [36]—for cereal crops in Poland; [37]—for various crops in Brazil).

Figure 2. Temporal evolution of total fertilizer consumption (**a**), irrigated cropland (**b**), and crop yield (**c**); between 1961 and 2006 in Egypt, Greece and Morocco. Crop yield refers to maize and wheat crops (primary *y*-axis) in Egypt and Greece, respectively; and to potato crop in Morocco (secondary *y*-axis).

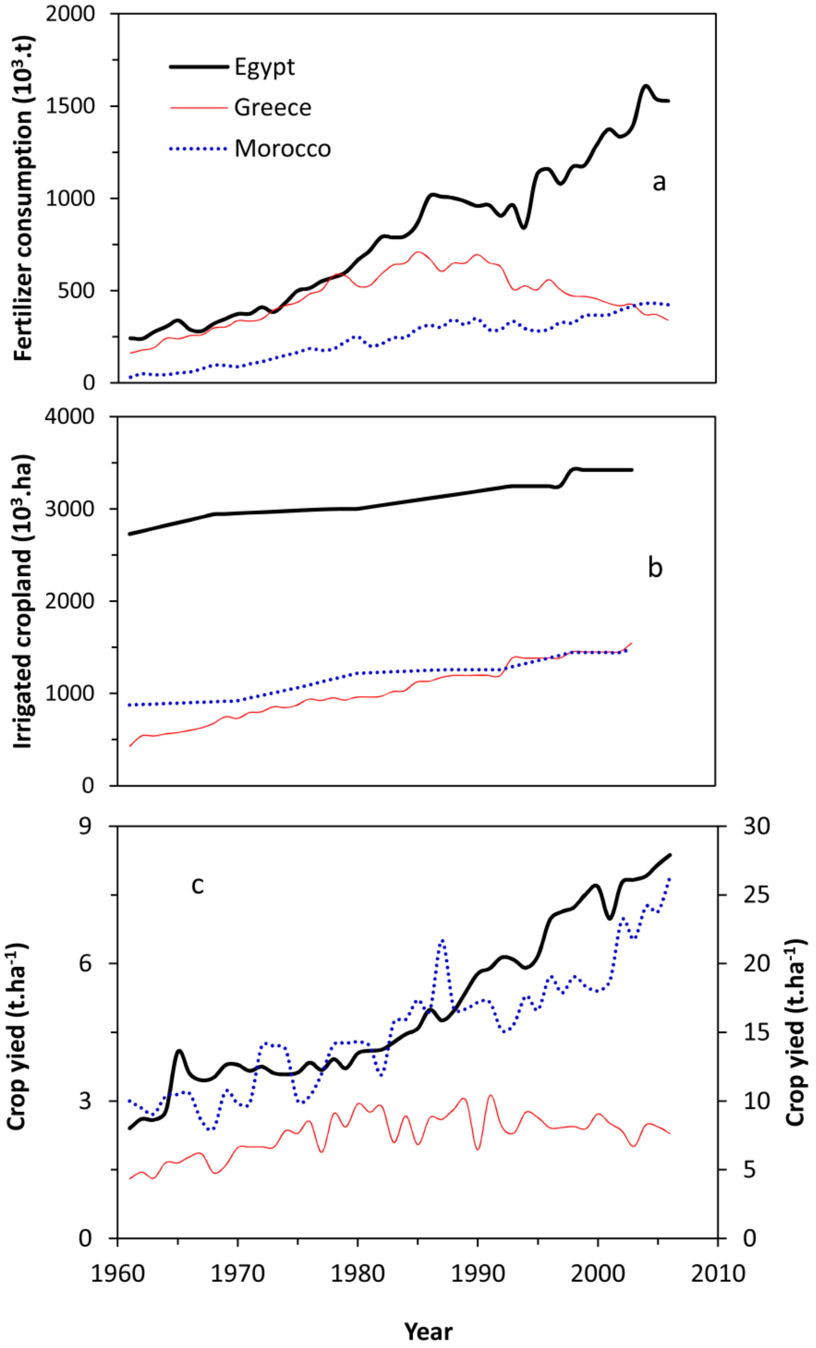
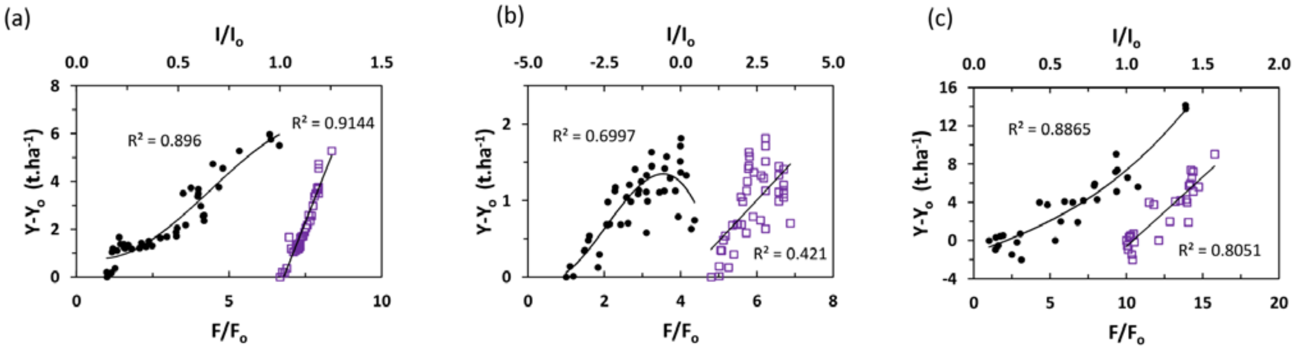


Figure 3. Variation of crop yield changes ($y - y_o$) as a function of total fertilizers consumption changes (F/F_o; filled circles—primary *x*-axis (bottom)), and as a function of irrigation changes (I/I_o, open squares—secondary *x*-axis (top)), for maize-Egypt (**a**), wheat-Greece (**b**) and potato-Morocco (**c**). The coefficient of determination (R^2) of the relationships between crop yield and each of the two variables is also shown. All the relationships are statistically significant at the 95% level ($p < 0.05$). The subscript "o" denotes initial values (*i.e.*, values at year 1961); while for the sake of a better visualization, $y - y_o = f(F/F_o)$ and $y - y_o = f(I/I_o)$ are illustrated instead of $y = f(F)$ and $y = f(I)$, respectively. The relationships $y - y_o = f(F/F_o)$ and $y = f(F)$, and $y - y_o = f(I/I_o)$ and $y = f(I)$ are indeed strictly similar.



It is worth noting that, like almost everywhere in the world, irrigation spread-out continuously throughout the last five decades in the three countries. Fertilizer consumption increased steadily until the mid-1980s and decreased thereafter in Greece, while it slightly decreased in Egypt and Morocco between the mid-1980s and the mid-1990s before it increases again (Figure 2a,b). Overall, crop yield trajectory has evolved in a similar way to TFC in the three countries (Figure 2a,c).

3. Results

3.1. Climate

Our climate trend analyses refer to the periods of May–September, October–June and August–March for maize, wheat and potato crops, respectively. These periods correspond roughly to the growing season of the selected crops in each of the three selected countries [38].

Annual variations of temperature and precipitation for the period of the study are shown in Figure 4a–d. In the three countries, temperature decreased from the early 1960s until the mid-1970s, but increased thereafter. The overall temperature increase (1961 through 2006) reached 0.64 °C, 0.35 °C and 1.15 °C in Egypt, Greece and Morocco, respectively (Figure 4a,b and Table 1). Since the mid-1970s, however, its increase was more substantial, reaching 1.2 °C (0.4 °C/decade), 1.4 °C (0.47 °C/decade) and 1.75 °C (0.58 °C/decade) in Egypt, Greece and Morocco, respectively. Such temperature changes since the mid-1970s are much larger than the observed 0.6 °C global temperature increase since 1950. They are even larger than the IPCC's projected 0.2 °C/decade increase for the next two to three decades [39]. Precipitation decreased in Greece (5%) and Morocco (30%), but increased in Egypt (9%). Several modelling studies have suggested that combined changes in temperature and precipitations that are comparable to the observed changes in the three studied countries could have important effects on yield of various crop species [11,40].

Figure 4. Annual variation of average temperature (**a**) and its anomalies (**b**) along with annual variation of total precipitation (**c**) and its anomalies (**d**), during the growing season between 1961 and 2006 in Egypt, Greece and Morocco. Temperature anomalies were calculated as the difference between current and average values, while precipitation anomalies were calculated as the ratio between current and average values. Precipitation anomalies are shown on the primary *y*-axis for Greece and Morocco, and on the secondary *y*-axis for Egypt.

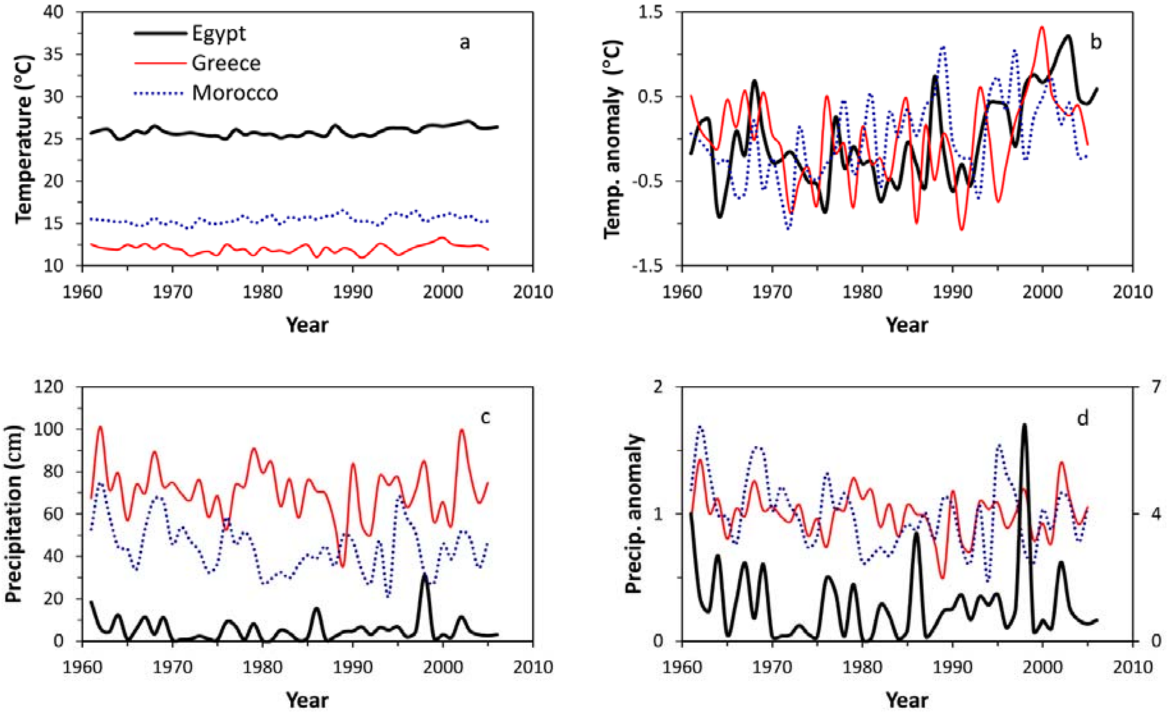


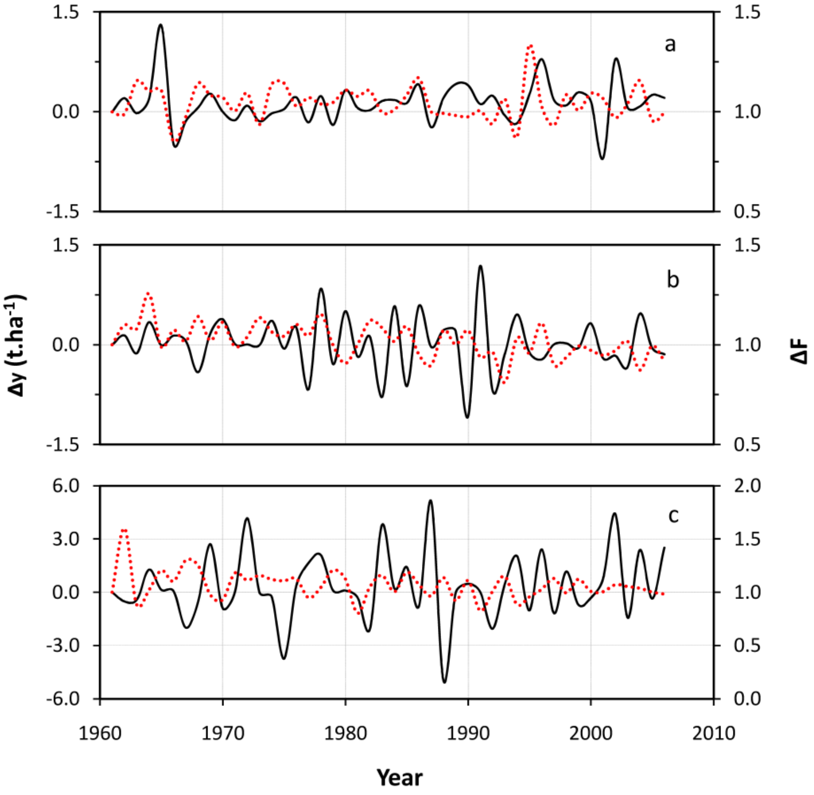
Table 1. Temperature and precipitation trends in the selected three countries, for the 1961–2006 and the 1971–2006 periods. *T*, *P* and *t* refer to temperature (°C), precipitation (cm) and time (year), respectively. p_1 and p_2 are the two-tailed *t*-test values for the 1961–2006 and the 1971–2006 periods, respectively. The relationship is statistically significant at the 95% confidence limit when *p* is lower than 0.05. While our study encompasses the period from 1961–2006 period, statistical analyses are given here as additional information for the 1971–2006 period also, where the trend in temperature change was more evident (see also Figure 4).

	1961–2006	**1971–2006**	p_1/p_2
Egypt	$T = 0.014t - 6.56$	$T = 0.026t - 30.28$	9e4/~0
	$P = 0.017t - 24.26$	$P = 0.024t - 37.86$	0.62/0.64
Greece	$T = 0.0075t + 0.55$	$T = 0.03t - 44.36$	0.17/~0
	$P = -0.0684t + 194.13$	$P = -0.011t + 79.5$	0.51/0.94
Morocco	$T = 0.025t - 31.33$	$T = 0.038t - 58.31$	0/0
	$P = -0.233t + 496.7$	$P = -0.169t + 369.43$	0.025/0.22

3.2. Crop Yield

To further expand our argument on the limitation of FDA to isolate the effect of climate (and climate change) on crop yield (see Section 2.1), we compared year to year variations of crop yield and TFC (Figure 5a–c). Although very brief, this comparison suggests an interdependence between the variations of the two variables though not always evident. Such an interdependence is sometimes obvious, when both variables vary in the same direction at the same time (e.g., Figure 5a around year 1970), and sometimes lagged when a variation in crop yield corresponds to a similar variation of TFC during the previous year (e.g., Figure 5b around year 1994). That "time-lag" in variation could be at least partly explained by the climatic conditions that prevail during the year of fertilizer applications. During dry years for example, a portion of applied fertilizers remains in the soil after crop harvest and get used by crops during the following year, leading to an abnormal enhancement of yield. In some years, however, crop yield and TFC vary in opposite directions (e.g., Figure 5b,c around year 1967), likely reflecting stronger crop yield response to factors other than fertilization (e.g., extreme climate conditions, plant diseases, *etc.*).

Figure 5. Year to year changes in crop yield (Δ*y*; solid line) and in total fertilizer consumption (Δ*F*; dotted line). For a better visualisation, Δ*y* and Δ*F* are expressed as the difference and the ratio between values of two consecutive years, respectively. Panels (**a**), (**b**) and (**c**) refer to maize-Egypt, wheat-Greece and potato-Morocco, respectively.



In our case studies, as illustrated in Figure 3a–c, crop yield changes as a function of fertilizer changes is best explained by a third order polynomial expression:

$$y = \alpha F^3 + \beta F^2 + \gamma F + \delta + \varepsilon(t) \tag{9}$$

where α, β, γ and δ are the best fit parameters for each location and crop (Table 2). ε(t) is the residual error. We remind that such a relationship (or any other statistical relationship) must be obtained for a period of time (continuous or discontinuous) where, in statistical terms, climate does not change significantly (see Section 2.1). Moreover, it is worthwhile mentioning that it is not necessary to always use a third order polynomial expression to express the relationship between crop yield and any crop management practice. For instance, a linear relationship (first order polynomial expression) might be enough if it gives satisfactory results.

Table 2. Statistical relationships between crop yield and crop managements (fertilizer and Irrigation applications) for the three case studies. *y*, *F* and *I* refer to crop yield, total fertilizer consumption and irrigation, respectively (see text for details). *y* expresses the crop yield difference between any given year and the initial year (*i.e.*, year 1961), while *F* and *I* is the ratio of fertilizer consumption and Irrigation, respectively, between any given year and the initial year. R is the correlation coefficient and *p* is the two-tailed *t*-test value. The relationship is statistically significant at the 95% confidence limit when *p* is lower than 0.05.

	y* = *f(F,I)	**R^2**	***p***
Maize—Egypt	$y = -0.0304F^3 + 0.4003F^2 - 0.5656F + 0.9769$	0.90	<0.05
Wheat—Greece	$y = -0.1027F^3 + 0.6308F^2 - 0.6045F + 0.1372$	0.70	<0.05
Potato—Morocco	$y = (-0.0166F^3 + 0.3029F^2 - 0.9418F) + (28.3442I^3 - 100.1485I^2 + 120.412I) - 48.1972$	0.89	~0

The first order derivation of Equation (9) with respect to *F* yields:

$$\frac{\partial y}{\partial F} = 3\alpha F^2 + 2\beta F + \gamma \tag{10}$$

Equation (10) represents the expression needed to compute the term a_m in Equation (6), or more specifically, the term a_F in Equation (7).

In cases where sufficient data to constraint crop yield variations with more than one single management practice do exist, Equation (9) could be expanded to include other variables. For instance, assuming that we want to link crop yield variation to both fertilization and irrigation variations, as it is shown below in one of our case studies (see also Table 2), a relationship that expresses crop yield as a function of these two variables must be used. In our case study, the relationship that gives the best-fit is expressed as follow:

$$y = (\alpha_F F^3 + \beta_F F^2 + \gamma_F F + \delta_F) + (\alpha_I I^3 + \beta_I I^2 + \gamma_I I + \delta_I) + \varepsilon'(t) \tag{11}$$

The subscripts *F* and *I* refer to the best-fit parameters for fertilization and irrigation, respectively. The first order derivations of Equation (11) with respect to *F* and *I* yield, respectively:

$$\frac{\partial y}{\partial F} = 3\alpha_F F^2 + 2\beta_F F + \gamma_F \tag{12}$$

$$\frac{\partial y}{\partial I} = 3\alpha_I I^2 + 2\beta_I I + \gamma_I \tag{13}$$

Equations (12) and (13) allow for the computation of a_F and a_I terms in Equation (7), respectively.

In the following subsections, we will use our approach to analyse the resulting crop yield trend after the removal of the effect of fertilizer applications for maize and wheat crops, grown in Egypt and Greece, respectively. In the last case study, namely potato crop grown in Morocco, we will firstly analyse the resulting crop yield trend after the removal of the effect of fertilizer applications. We will secondly illustrate how the same resulting trend evolves when we further remove the effect of an additional management practice (irrigation).

3.2.1. Maize—Egypt

The case of Egypt is particularly interesting because agriculture is fully dependent upon irrigation [35], which reduces the dependency of crop yield to fluctuations in climatic variables other than precipitation (mostly temperature), and to fluctuations in management practices other than irrigation (fertilization, pesticide application, *etc.*).

In this case, the best-fit relationship between crop yield and fertilization was obtained for a 41 year sub-period where changes in climate conditions (temperature and precipitation; the two climatic variables responsible for the largest variations in crop yields [41]) were statistically non-significant (see Section 2.1). That relationship (not shown but very similar to the one shown in Figure 3a; see Table 2) was applied thereafter to the entire period of the study (1961–2006), and was used to compute the term a_F in Equation (7). This allowed us to infer an approximation of the contribution of crop management to maize yield evolution throughout the entire period of study, and thus to isolate the effect of climate on the crop's yield trend.

Obtained results indicate that our methodology and FDA yielded different trends (Figure 6a and Table 3). Though both trends are statistically non-significant, some interesting strong dissimilarities must be noticed when analysing results of the two approaches. The first of these differences is related to the sign of the trends. While FDA yielded a positive trend, suggesting a positive crop yield response to the observed temperature increase, our approach yielded a negative trend (Table 3). In reality, the difference between the two trends could be more important if the effect of other crop management practices that influence crop yield, such as genotype improvements and changes in planting dates, were removed as well. The different trend signs may also lead to different physiological interpretations of the response of maize yield to climate change in Egypt in particular, and in the Eastern Mediterranean region in general. Since agriculture is fully irrigated in Egypt, a positive and a negative trend could be interpreted as resulting from a shift towards more and less optimal temperature growth conditions, respectively. Maize belongs in fact to the family of C4 crop species, whose optimal growth is physiologically met within the 25–35 °C temperature range [42]. Although much beyond the scope of this paper, one may suggest on one hand that the observed average temperature increase in Egypt during the study period (0.97 °C) is sufficiently low to not cause any noticeable shift in crop growing conditions (inside or outside the optimal range for maize growth). On the other hand, the increase in the frequency of extreme climatic events in the eastern Mediterranean region during the second half of the last century [8,43] could support the idea that the evolution of climatic conditions during the period of our study has had a negative impact on maize crop yield, which is in agreement with the obtained negative trend using our approach. Moreover, a study by [40] suggests also a negative response of maize yield in response to a 2 °C temperature increase in Egypt, which is in agreement with our approach's estimation.

Figure 6. Year to year changes in the climate-induced crop yield (Δy_c) obtained using the first-difference approach (dotted line), using our approach after the removal of the effect of crop fertilization on the temporal/annual crop yield evolution (black solid line), and using our approach after the removal of both effects of crop fertilization and irrigation (gray solid line; panel c only). Panels (**a**), (**b**) and (**c**) refer to maize-Egypt, wheat-Greece and potato-Morocco, respectively. Note that the black and the gray solid lines in panel c almost always overlap.

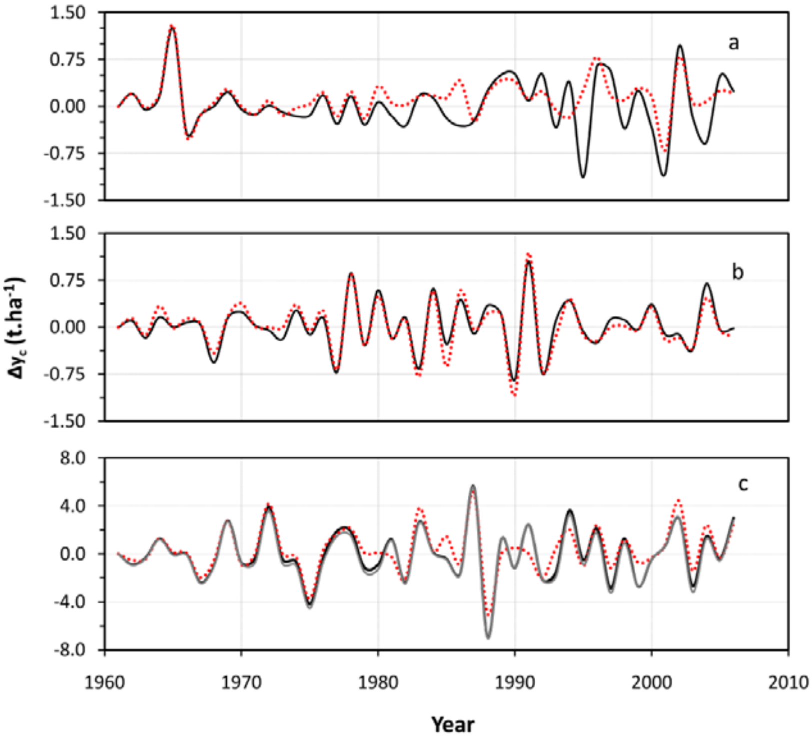


Table 3. Results of crop yield trend analyses. Year to year variation in the climate-induced crop yield, Δy_c (t.ha^1), is expressed as a function of time, *t* (in years). FDA refers to the first-difference approach, while *F* and *I* refer to fertilizers and irrigation applications (*i.e.*, when their effects on the temporal crop yield evolution were removed).

Case Study	*Y = f(time)*
Maize—Egypt	
FDA	$\Delta y_c = 0.00245.t - 4.78$
Our approach	$\Delta y_c = -0.0011.t - 2.1423$
Wheat—Greece	
FDA	$\Delta y_c = -0.0026.t + 5.3028$
Our approach	$\Delta y_c = 0.0013.t - 2.5148$
Potato—Morocco	
FDA	$\Delta y_c = 0.0177.t - 34.8$
Our approach (effect of *F* removed)	$\Delta y_c = 0.0099.t - 19.531$
Our approach (effects of *F* & *I* removed)	$\Delta y_c = 0.0086.t - 17.162$

3.2.2. Wheat—Greece

The case of cultivated wheat in Greece is particularly interesting because wheat is a major crop grown in Eastern Europe [32]. Again, the two approaches resulted in opposite trajectories of the climate-induced wheat yield trend. FDA and our approach resulted in a negative and a positive trend, respectively (Table 3); suggesting a negative and a positive response of wheat yield to climate change, respectively.

In contrast to the estimated negative trend by FDA, our approach estimated a positive climate-induced crop yield trend, suggesting that the abrupt change in the TFC's trajectory around the mid-1980s (Figure 2a) has influenced negatively the overall yield trend (*i.e.*, the trend before the removal of the management effect). A negative influence that clearly exceeded the effect of climate on the crop's yield trend, yet it was overlooked by FDA. In absolute terms, indeed, the effect of management calculated as the difference between the two trend slopes shown in Table 3 was about three times larger than the effect of climate; We remind that our approach = FDA − management effect.

As discussed above in Section 2.2, although much caution should be made to not draw definitive conclusions about the accuracy of our approach's estimates, this case study shed light once again on the importance of splitting between the contributions of the various factors that influence crop growth and yield (climate, management, *etc.*), before estimating crop yield response to climate change using large-scale observations. Such an argument is moreover supported by [40]'s study, which predicted in agreement with our approach's estimation a positive wheat yield response to a 2 °C temperature increase in Greece.

3.2.3. Potato—Morocco

Potato is the major cultivated root crop in the Mediterranean region in general and in Morocco in particular [30]. In this case, both approaches yielded a positive climate induced crop yield trend (Table 3). As we may expect, however, the trend that resulted from FDA was stronger than the one that resulted from our approach; because the effect of crop fertilization on crop yield was removed in our approach. A further weakening of our approach's trend was obtained consequently to the removal of the effect of an additional management practice on crop yield, namely irrigation (Table 3). Moreover, the difference between FDA's slope and our approach's slope (when both soil fertilization and irrigation effects on yield were removed) is equivalent to an annual production of approximately 9,000 tons, which amount may appear negligible when compared to the average total annual production (14.6×10^6 tons). One may anticipate, however, that the difference between the two approaches, in terms of annual production, would have been much larger if the effect of all management practices on the crop's yield trend were eliminated, as well as for regions/countries where crop managements are more intense.

4. Discussion and Conclusion

The large uncertainties associated with the most recent estimations of future crop production provide salient evidence that much effort is still needed to unravel the complexity of crop response to environmental changes; hence, our attempt to enhance our understanding of crop yield response to climate change using long-term observations. Our approach consisted of using available national-level observations of crop yield and crop managements to extract the sole contribution of climate to crop yield trends throughout the 1961–2006 time period. A simple methodology was proposed to eliminate the contribution of any particular crop management practice to crop yield evolution whenever sufficient information on that practice is available. Though national-level data were used for its development, the proposed methodology is scale independent and is flexible in such a way that it can be used whether information about one or more crop management practices is available or not. In case where no data about crop management are available, it simplifies to the first-difference approach.

It is well recognized that a major source of uncertainty in crop model simulations is closely inherent to our incapacity to test the performance of these models under long-term changing conditions, under climate change conditions, and over spatial scales that are relevant to regional or national estimations. Now that long-term national scale observations of crop yield became available and since these observations extend over a time interval of several decades during which a statistically significant change in climate has been observed in several parts of the world, our methodology represents a tool to overcome the three abovementioned major crop model testing difficulties. It undoubtedly provides us with a new opportunity to better understand crop yield response to climate change, and thus to better calibrate and improve crop model simulations. Furthermore, by deriving the correct crop yield response to climate change, our approach could also help us build statistical relationships between crop yield and relevant climate variables to investigate potential impact of climate change on crop production at large spatial scales (regional, national, *etc.*).

Nonetheless, the accuracy of the proposed methodology is particularly dependent upon the accuracy of crop management information used to extract the climate-induced crop yield trend. In this study, for instance, we are much aware that it would have been preferable to use observations of fertilizer applications by crop and by country (see Section 2.2). Given that these observations do not exist yet, we have alternatively used observations of total fertilizer consumption by country which may had caused some biases in the resulting climate-induced crop yield trends presented in Table 3. This, obviously, stresses out the need for sustained efforts to enhance the scientific community access to more detailed and accurate observations about crop yield and all factors that contribute to its annual and decadal variations if we want to take seriously the issue of future food security.

Our results indicated that climate change-induced crop yield trends using our approach could be significantly different from the trends that would be obtained using the FDA approach, both in term of magnitude and sign. This is an important finding as that trend difference might have important ramifications in terms of production and food availability and, therefore, on any subsequent food security analyses. For the maize-Egypt case, for instance, the slope difference between the inferred yield trends by our approach and by FDA approach (0.00355 t/ha/year) is equivalent, when converted to annual production, to about 2,700 tons/year (calculated as the product of maize yield and total harvested area). Such an amount could be considered as negligible when compared with total maize production in Egypt or other important maize producer countries. It represents, nevertheless, more than the total annual production of some neighbouring countries that heavily rely on maize grain importation to satisfy their consumption needs [30], such as Algeria, Libya and Lebanon.

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Conflicts of Interest

The authors declare no conflict of interest.

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