World Bank - Morocco study on the impact of climate change on the agricultural sector

Impact of climate change on agricultural yields in Morocco

Impact des changements climatiques sur les rendements agricoles au Maroc

أثر تغير المناخ على المحاصيل الزراعية في المغرب

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Preamble – Préambule المحاصيل

The present document is an interim report on climate change impacts on crop yields in Morocco. It is part of a larger study led by the World Bank and the Government of Morocco on climate change and agriculture. The yield component was coordinated by FAO with INRA and DMN as the main national partners. The comprehensive final report is under preparation by the World Bank. The structure of this document is as follows: after the present preamble, a summary of the study on yields is given, with some background about climate change scenarios, in three languages (English on page 3, French and Arabic). Although the body of this document is written in English, the reader will find a detailed summary and the legends of figures and tables provided in French and Arabic as well, immediately after the table of contents that follows the summaries (page 23).

Ce document est un rapport provisoire décrivant l'impact des changements climatiques sur les rendements agricoles au Maroc. Il s'agit d'une contribution, coordonnée par la FAO, à une étude plus globale de la Banque Mondiale et du Gouvernement du Maroc sur le changement climatique et l'agriculture. Les principaux partenaires nationaux sont l'INRA et la DMN. Le rapport complet et final est en préparation à la Banque Mondiale. La structure du présent document est la suivante : après le préambule, un résumé de l'étude sur les rendements est fourni, avec quelques données générales sur les scénarios de changements climatiques, en trois langues (anglais, français à la page 9, et arabe). Bien que le corps du document soit rédigé en anglais, le lecteur trouvera un résumé détaillé ainsi que la traduction des légendes des figures et des tableaux en français et en arabe, immédiatement après la table des matières qui suit les résumés (page 26).

تعتبر هذه الوثيقة تقريرا مؤقتا لتأثير التغيرات المناخية على المحاصيل الزراعية بالمغرب؛ وهو جزء من دراسة أكبر لتغير المناخ والزراعة يُشرف عليها كل من البنك الدولي والحكومة المغربية. أُنجز هذا العمل بتنسيق من طرف منظمة الأمم المتحدة للتغذية والزراعة (FAO) مع أهم الشركاء الوطنيين وهم المعهد الوطني للبحث الزراعي (INRA) و المديرية الوطنية للأرصاد الجوية (DMN). بعد هذه الديباجة، يحتوي هذا التقرير على ملخص بثلاث لغات (الإنجليزية والفرنسية والعربية) مع بعض المعطيات العامة حول سيناريوهات تغير المناخ. ورغم كون هذا التقرير قد حُرر باللغة الإنجليزية فإمكان القارئ أن يعود إلى ملخص تفصيلي مع ترجمة لعناوين الجداول والأشكال باللغتين العربية والفرنسية.

Summary

Impact of climate change on agricultural yields in Morocco

Possible climate scenarios

All climate projections point at the development of more arid conditions in the Mediterranean region. Climatologists calculate projections from atmospheric models which transform assumptions of greenhouse gas emissions (in particular, CO_2) into climate projections. The models are simplified and easily managed representations of the Earth's atmosphere calculated on a global scale, using atmospheric grid-boxes of 250 km x 250 km. Climate projections are based on representations of the world as it might be to the year 2100. The Intergovernmental Panel on Climate Change (IPCC) refers to these representations of the future as *scenarios*, which lead, each one, to very different trajectories for worldwide greenhouse gas emissions. It should however be well understood that the scenarios are neither predictions nor forecasts. The scenarios are families of possible futures; they cover the range of atmospheric conditions which will result from our policy choices, ranging from drastic measures for emissions reduction which would follow rapid adoption of renewable energy, to an acceleration of fossil fuels use, in particular in developing countries.

Anticipating crisis situations

The Ministry of Agriculture, Rural Development and Fisheries (MPAM) and the World Bank (WB), in collaboration with the National Institute for Agricultural Research (INRA), the Food and Agriculture Organization of the United Nations (FAO) and the National Meteorology Authority (DMN) together undertook an original exploratory study to quantify the impact of climate change on Moroccan agriculture by the end of the 21st century. The objective of MPAM and WB is to determine the economic and political options for adapting Moroccan agriculture vis-à-vis climate change so that Morocco is not caught unawares by possible crisis situations. This study is operationally organized in 5 phases: 1) future climate projections at the level of Morocco; 2) impact on agricultural yields; 3) impact on water resources; 4) economic impact and 5) public policy options for adapting to climate change.

In this report, we present some results of the second phase of this study. The results presented here are purely descriptive in the sense that they do not endeavour to propose solutions, at this stage of the study, for adapting to climate change.

Downscaling global climate projections to Morocco level

During the first phase, the study undertook to statistically downscale climate projections, established by the IPCC, from grid-boxes of 250 km x 250 km at the global level, to a fine enough size (about one hundred square km[1]) compatible with the scale of the principal agro-ecological zones of Morocco (Figure I). Let us recall that the agro-ecological zones established by the Ministry of Agriculture, Rural Development and Fisheries are: *Favourable*, *Intermediate*, *Unfavourable-East*, *Unfavourable-South*, *Mountain* and *Saharan*. (Indicated in French by: *Favorable, Intermédiaire, Défavorable-Oriental, Défavorable-Sud, Montagne et Saharien*).

[1] This corresponds to grid-boxes of 10 km per side.

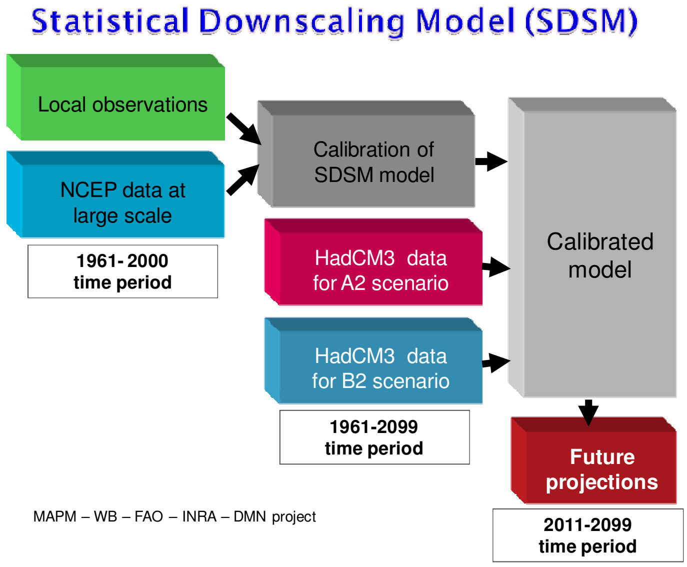
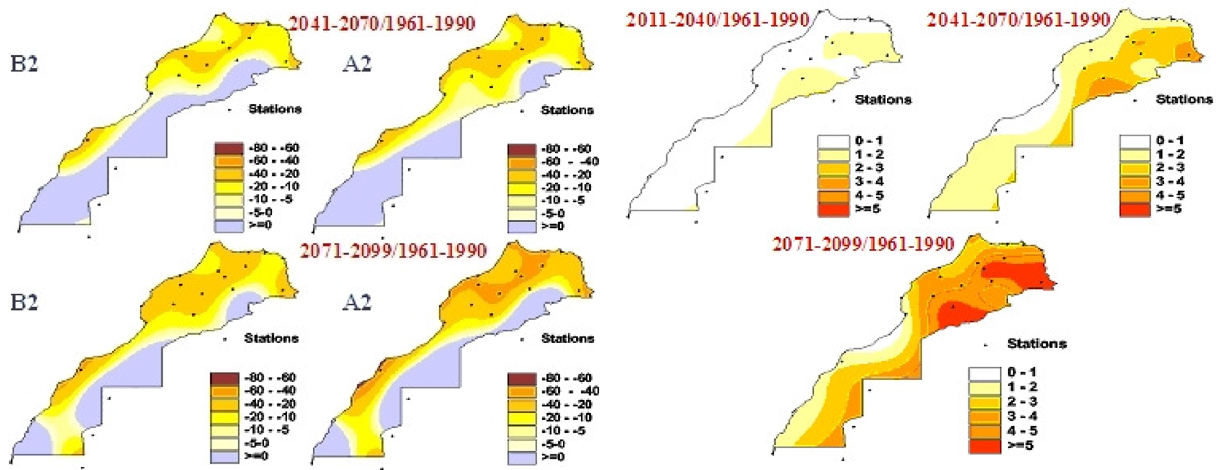


Figure I: Downscaling procedure to local level of large-scale climate projections (250 km grid-boxes). NCEP, National Centre for Environmental Prediction, SDSM, Statistical Downscaling Model, HadCM3 model of the United Kingdom's Met Office Hadley Centre. (Source: Wilby, personal communication: slide presented at the WB/MAPM, FAO, INRA, DMN workshop in Rabat on 26 May 2008.)

Figures IIa and IIb: main climate projections for Morocco



Precipitation anomalies (A2 and B2 scenarios): compared with the period 1961-1990, the decrease in precipitation will affect the entire country, especially by 2071-2099. According to the most pessimistic scenario, annual rainfall will drop about 20% from now to 2050 and by 40% by 2080, except for the *Saharan* zone where the decrease will be 16% in 2080. The decrease in precipitation will be more pronounced according to pessimistic scenario A2. It is during the autumn and spring that the decrease in rainfall will be felt, i.e. during the periods when peaks of rainfall are normally recorded. (Source: Babqiqi, personal communication: slide presented at the WB/MAPM, FAO, INRA, DMN workshop in Rabat on 26 May 2008.)

Temperature anomalies (A2 scenario): increases will occur throughout the entire country. According to scenario A2, warming will approach 3℃ from now until 2080 for the 6 agro-ecological zones of Morocco and will reach 5℃ in the *Unfavourable-East* and *Mountain* zones. This increase in temperature will involve an increase in evapotranspiration (the sum of soil water evaporation and plant water transpiration) of about 20% from now until 2050 and 40% by 2080, except for the *Saharan* zone (9% in 2080).
(Source: Babqiqi, personal communication: slide presented at the WB/MAPM, FAO, INRA, DMN workshop in Rabat on 26 May 2008.)

Representing climate change as impacts on agricultural production

In the second phase, climate projections (see Figure II), downscaled to the level of agro-ecological zones, were converted into agricultural yield projections. This aspect of the study is the subject of this report. About fifty rainfed and irrigated crops, in the six agro-ecological zones, for two climate scenarios A2 and B2 and for four time horizons: 2000 (current period, covering 1979 to 2006), 2030 (from 2011 to 2040), 2050 (from 2041 to 2070) and 2080 (from 2071 to 2099) were studied.

The methodology consisted in developing, for each crop and each agro-ecological zone, a **yield function** which is in fact an agro-climatic model which empirically links agricultural yields to the previously spatialised soil water balance countrywide. The technology trend observed on the level of agro-ecological zones, as well as the fertilizing effect of atmospheric CO_2 on the crops, were both taken into account in the yield functions. Finally, future yields are obtained by applying future climate conditions (HadCM3 model and the two emission scenarios: A2 and B2) to the yield functions thus established. The scenarios are described in the table below.

Scenario A2	Scenario B2
This is a pessimistic scenario which describes a world where global population is rapidly increasing, with strong economic growth based on polluting technologies in a world that has become more protectionist with increasing disparities between North and South. There is continued use of fossil fuels and uneven regional economic growth.	This is an optimistic scenario which describes a world where the focus is on local solutions, from the point of view of economic, social and environmental viability. The world population increases in a continuous way, but at a slower rate than in A2. There are intermediate levels of economic development and technological advances are slower and more varied.

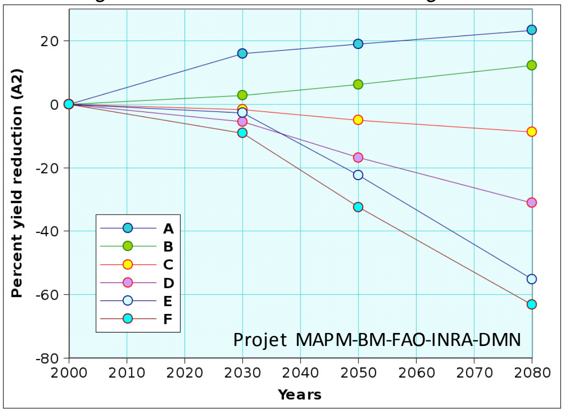
Climate change impact on agricultural production

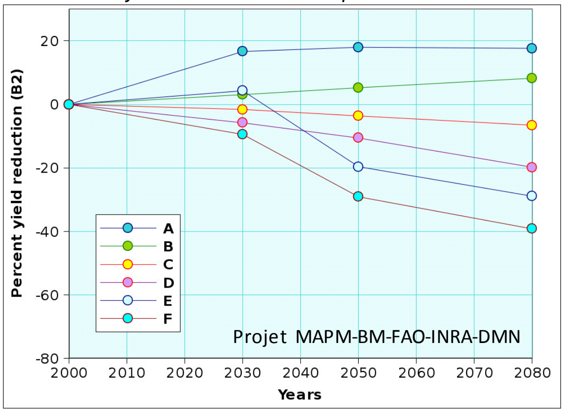
Climate projections on Morocco show gradually increasing aridity because of reduced rainfall and higher temperatures. It is necessary to keep in mind that climate models best predict averages rather than extreme values. This means that if aridity increases, on average, as predicted, there can nonetheless be certain years, sporadically, that will be very rainy. Increased aridity will thus have negative effects on agricultural yields, especially from 2030 onwards. All crops will not be equally vulnerable to climate change. In Figure III, one can note that rainfed crops (non-irrigated) will be particularly affected by climate change.

Figure III illustrates six typical projected behaviours of future crop yields, identified by the letters from A to F. A indicates some rare crops (all irrigated) that will undergo an improvement of their yields, while those in category F will suffer a severe drop in yields. Table 3.02 in the main report (page 67) indicates how individual crops are likely to be affected, by assigning each of them one the letters A through F for each of the main agroecological zones.

If irrigation water continues to be available in sufficient quantities, irrigated crop yields will continue to increase in spite of climate change. It is suggested that the increase in temperature, coupled with irrigation sufficient to satisfy crop water needs, will further the growth of cultivated plants and thus increase harvests of most crops. However, even in the event of increased aridity of the Moroccan climate, the availability of irrigation water is an assumption which still remains to be verified. Generally speaking, agricultural yields will remain more or less stable up to 2030, then will drop rather quickly beyond this date, more markedly in the case of scenario A2 than in that of scenario B2. All the agro-ecological zones will not be affected in the same way by climate change. The *Favourable* and *Intermediate* agro-ecological zones will be most vulnerable to climate change.

Figures IIIa and IIIb: Percent yield reduction, according to scenarios A2 and B2, by 2100. Adaptation due to current technology trend is not taken into account here. The crops are gathered into "impact groups" shown as A to F which can be characterized as follows:
A: *irrigated maize and irrigated seasonal vegetables* - B: *irrigated fruits and vegetables* - C: *fodder crops and vegetables* - D: *rainfed cereals and legumes* - E: *rainfed wheat and barley* - F: *Other rainfed crops.*





Impacts lessened by technology trend

When one studies increasing agricultural yields due to climate change, while taking into account the technology trend achieved in Morocco, one realizes that negative impacts are lessened. Technology trend is taken here in its broadest sense, including genetic improvement of crop plants, use of fertilizers and pesticides, mechanization, ploughing techniques, etc.

For soft wheat and durum wheat, for example, agricultural statistics of 1979 to 2006 show an increase in yields which was, on average, 0.02 tons/Ha and per year at the national level. In particular, this progress is the fruit of a significant effort provided by agronomic research (INRA) to create productive and drought and disease resistant varieties, in spite of climate risks. In experimental stations, the yield increase can go up to 0.05 tons/Ha and per year for the INRA's new varieties of soft wheat. In Figure IV, one can see the impact of climate change, without technology trend in red and with technology trend in green, for non-irrigated durum wheat at the national level. In scenario A2, without technology trend, durum wheat would have an ever-decreasing yield whereas the technology trend can partly offset the impact, at least until 2050. In the more favourable scenario B2, technology trend can compensate for the impact of climate change even until 2100. For barley, for example, technology trend was nil because, for a certain number of reasons, barley was relegated to marginal agricultural zones, thus affecting its yield. The shift between the green (with technology trend) and red (without technology trend) lines shows the adaptation of agriculture to future climate change. The most striking technology trend is found, for example, for the following crops: tomato, alfalfa, banana, potato or fodder.

Figure IVa and IVb: Impact of climate change on rainfed durum wheat yield in Morocco. IVa: moderate impacts until 2030 and severe beyond, according to scenario A2; **IVb**: moderate impact until 2030, and controlled beyond, according to scenario B2.

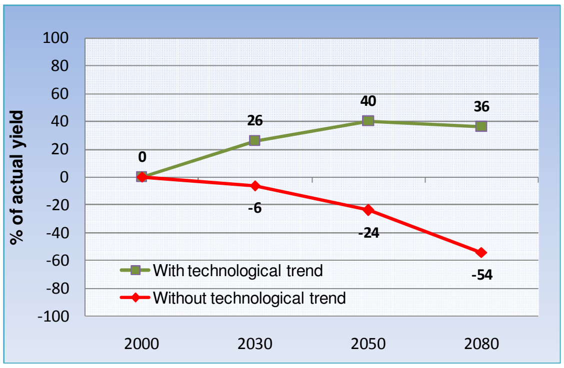


Figure IVa

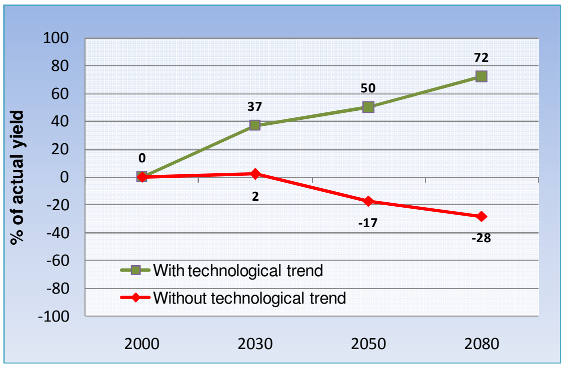


Figure IVb

Uncertainties concerning impact

Climate projections are based on physical models which are better at forecasting mean values of rainfall and temperature than their extremes. It follows that the impacts forecasted for the future represent averages of values which can sometimes strongly fluctuate from one year to another. However, yield projections differ very little between scenarios A2 and B2 until 2030[2]. Beyond this date, and until 2100, a huge disparity exists between the scenarios because of uncertainties related to the quantities of greenhouse gases which will be actually emitted into the atmosphere, the dynamics[3] of the agricultural sector, and Moroccan agriculture's adaptive capacity.

For this reason, impact estimates are reliable until 2030 and plausible beyond that date. However, the amplitude of expected long-term climate change is such that a reversal of trend is not very probable. These agricultural production impact forecasts are largely dependant on the climate models developed by climatologists and are only valid for the current conditions of Moroccan agriculture. In other words, changes to the current production systems due to changes in water management, land-use, varieties and crop mix will affect farmers' adaptation capacity can modify the impact forecasts. It should be clearly understood that one tries to model complex relationships between agricultural yields and future scenarios. Uncertainties related to impact projections are mainly due to our difficulty to imagine the world of tomorrow, the imperfections of climate models, downscaling techniques as to the statistical errors inherent in the baseline statistical data. Be that as it may, the expected average yield variations by agro-ecological zone are given in Table 3.02 of the main report, which summarises the impact estimates by crop and agro-ecological zone, referring to the yield impact profiles (A through F) defined in figure III.

Conclusions

The pooling of the efforts and expertise of national (MAPM, INRA and DMN) and international (WB and FAO) institutions made it possible to overcome operational and methodological difficulties and, especially, to ensure "quality control" in all the analysis phases of this study.

[2] Rather logically, the differences between scenarios are less pronounced for irrigated crops than for rainfed crops.

[3] We include in this term the various trends currently observed in Morocco, which address economic, environmental and other expectations.

The impact estimates of climate change on agricultural production are plausible over the next 20 years. For the more remote future, the magnitude of forecasted climate change is such that a reversal of trends is, nonetheless, not very probable. This study points out that technology trend (agricultural yield improvements in arid and semi-arid conditions), irrigation (water management at the level of agricultural plot, catchment area and region) and land use according to its agricultural function are significant keys for adapting to climate change.

Résumé

IMPACT DES CHANGEMENTS CLIMATIQUES SUR LES RENDEMENTS AGRICOLES AU MAROC

Les scénarios climatiques possibles

Toutes les projections climatiques convergent vers l'avènement d'un climat plus aride dans la région méditerranéenne. Les projections sont calculées par les climatologues à partir de modèles atmosphériques qui transforment des hypothèses d'émissions de gaz à effet de serre (notamment, le CO_2) en projections climatiques. Les modèles sont en fait des représentations simplifiées et manipulables de l'atmosphère terrestre calculées à l'échelle planétaire, sur des mailles atmosphériques de l'ordre de 250 km de côté. Les projections climatiques se basent sur des représentations de ce que pourrait être le monde jusque l'an 2100. Les experts du Groupe d'Experts Intergouvernemental sur l'Evolution du Climat (GIEC) ont appelé *scénarios* ces représentations du futur, qui conduisent chacun à des trajectoires d'émissions mondiales de gaz à effet de serre très différentes. Il faut cependant bien comprendre que les scénarios ne sont ni des prédictions ni des prévisions. Les scénarios sont des familles de futurs possibles; ils couvrent l'éventail des conditions atmosphériques qui résulteront de nos choix de société, allant de mesures drastiques de réductions d'émissions qui découlent de l'adoption rapide d'énergies renouvelables à une accélération de l'utilisation des carburants fossiles, notamment dans les pays en voie de développement.

Anticiper les situations de crise

Le Ministère de l'Agriculture, du Développement Rural et de la Pêche Maritime (MPAM) et la Banque Mondiale (BM), en collaboration avec l'Institut National de la Recherche Agronomique (INRA), l'Organisation des Nations Unies pour l'Alimentation et l'Agriculture (FAO) et la Direction de la Météorologie Nationale (DMN) ont entrepris ensemble une étude prospective originale pour quantifier les impacts des changements climatiques sur notre agriculture d'ici à la fin du 21ème siècle. L'objectif du MAPM et de la BM est de déterminer les options économiques et politiques d'adaptation de notre agriculture face aux changements climatiques pour faire en sorte que notre pays ne soit pas pris de court par des situations éventuelles de crise. Cette étude a été organisée de façon opérationnelle en 5 phases: (1) les projections climatiques futures à l'échelle du pays; (2) les impacts sur les rendements agricoles; (3) les impacts sur les ressources en eau; (4) les impacts économiques; (5) les options politiques d'adaptation aux changements climatiques.

Nous présentons ici quelques résultats de la deuxième phase de cette étude. Les résultats donnés sont purement descriptifs en ce sens qu'ils n'ont pas l'ambition de proposer, à ce stade de l'étude, des solutions d'adaptation aux changements climatiques.

Ramener les projections climatiques planétaires à l'échelle du Maroc

Durant la première phase, l'étude a entrepris de réduire statistiquement l'échelle spatiale des projections climatiques, établies par le GIEC sur des mailles de 250 km x 250 km au niveau planétaire, à une grandeur assez fine (de l'ordre de la centaine de km carrés [iv]) qui puisse être compatible avec l'échelle spatiale des principales zones agro-écologiques du Maroc (Figure I). Rappelons que les zones agro-écologiques établies par le Ministère de l'Agriculture, du Développement Rural et de la Pêche Maritime sont les *Favorable*, *Intermédiaire*, *Défavorable Oriental*, *Défavorable Sud*, *Montagne* et *Saharien*.

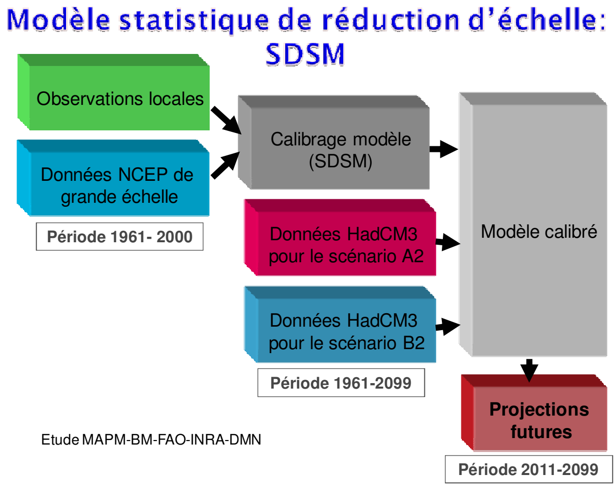
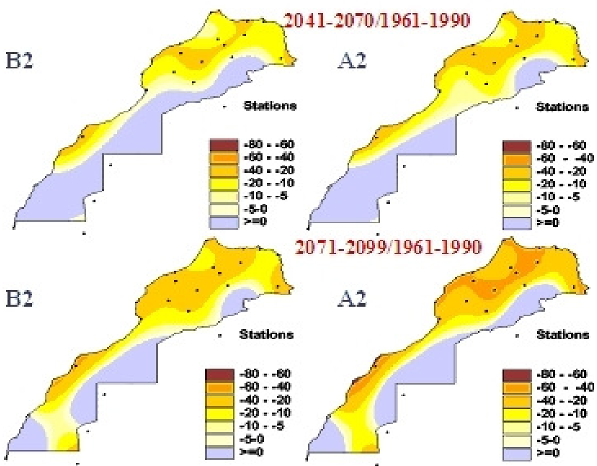
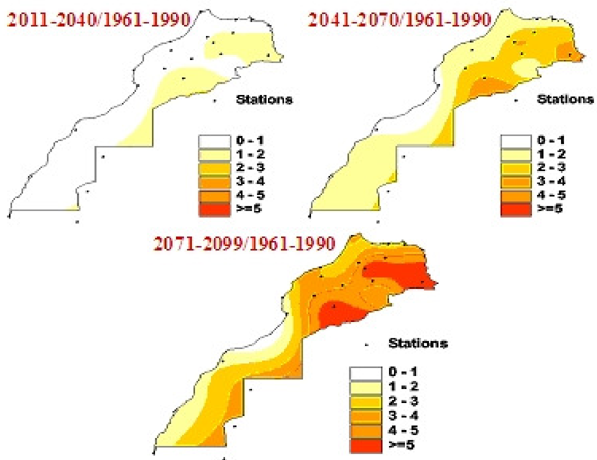


Figure I: Procédure de réduction à l'échelle locale des projections climatiques à grande échelle (mailles de 300km). NCEP, National Centre for Environmental Prediction (Centre National de Prévision Environnementale), SDSM, Statistical Downscaling Model (Modèle statistique de réduction d'échelle), HadCM3, modèle M3 du Centre Hadley du Service Météorologique Britannique.
(Source : communication de Wilby : diapositive présentée à Rabat le 26 Mai 2008 lors de l'atelier WB/MAPM, FAO, INRA, DMN.)

Figures IIa et Iib : principales projections climatiques pour le Maroc



Anomalie des précipitations (scénarios A2 et B2): par rapport à la période 1961-1990, la baisse des précipitations va concerner tout le pays, surtout à l'horizon 2071-2099. Selon le scénario le plus pessimiste, la pluviométrie annuelle baissera de l'ordre de 20% d'ici 2050 et de 40% à l'horizon 2080, à l'exception de la zone *Saharienne* où la baisse sera de 16% en 2080.
La baisse de précipitations sera plus importante selon le scénario pessimiste A2. C'est au cours de l'automne et du printemps que la baisse pluviométrique se fera sentir, c'est-à-dire durant les périodes au cours desquelles on enregistre normalement des pics de pluviométrie.
(source: Babqiqi, diapositive présentée au WB/MAPM, FAO, INRA, atelier DMN à Rabat le 26 Mai 2008.)



Anomalie de la température moyenne (scénario A2) : de la même manière que pour les précipitations, les augmentations des températures vont affecter tout le pays.
Selon le scénario A2, le réchauffement avoisinera 3°C d'ici 2080 pour les 6 zones agro-écologiques du Maroc et atteindra 5°C dans les zones "Défavorable Orientale" et "Montagneuse". Cette augmentation de température entraînera une augmentation de l'évapotranspiration (somme de l'évaporation des sols et de la transpiration des plantes) de l'ordre de 20% d'ici 2050 et 40% à l'horizon 2080, à l'exception de la zone *Saharienne* (9% en 2080).

(source: Babqiqi, diapositive présentée au WB/MAPM, FAO, INRA, atelier DMN à Rabat le 26 Mai 2008.)

[iv] Ceci correspond à des mailles de 10 km de côté.

Traduire les changements climatiques en impacts sur la production agricole

Dans la deuxième phase, les projections climatiques (voir figure II) réduites à l'échelle des zones agro-écologiques ont été traduites en projections de rendements agricoles. C'est cet aspect de l'étude qui fait l'objet du présent rapport. Une cinquantaine de cultures pluviales et irriguées, dans les six zones agro-écologiques, pour deux scénarios climatiques A2 et B2 et à quatre horizons de temps : 2000 (période actuelle, couvrant de 1979 à 2006), 2030 (de 2011 à 2040), 2050 (de 2041 à 2070) et 2080 (de 2071 à 2099) ont été étudiées.

La méthodologie a consisté à développer, pour chaque culture et pour chacune des zones agro-écologiques, **une fonction de rendement** qui est en fait un modèle agroclimatique qui lie empiriquement les rendements agricoles au bilan hydrique préalablement spatialisé sur l'ensemble du pays. Le progrès technologique observé au niveau des zones agro-écologiques ainsi que l'effet fertilisant du CO_2 atmosphérique sur les cultures ont été tous deux pris en compte dans les fonctions de rendement. Finalement, les rendements futurs sont obtenus en appliquant les conditions climatiques futures (modèle HadCM3 et deux scénarios d'émissions A2 et B2) aux fonctions de rendement ainsi établies. Les scénarios sont décrits dans l'encadré ci-dessous.

Scénario A2	**Scénario B2**
Il s'agit d'un scénario pessimiste qui décrit un monde où la population mondiale est en rapide augmentation, avec une croissance économique forte qui repose sur des technologies polluantes dans un monde devenu plus protectionniste avec des inégalités croissantes entre le Nord et le Sud. Recours persistant aux énergies fossiles, croissance économique inégale selon les régions.	Il s'agit d'un scénario optimiste qui décrit un monde où l'accent est placé sur des solutions locales, dans un sens de viabilité économique, sociale et environnementale. La population mondiale s'accroît de manière continue mais à un rythme plus faible que dans A2. Il y a des niveaux intermédiaires de développement économique et l'évolution technologique est moins rapide et plus diverse.

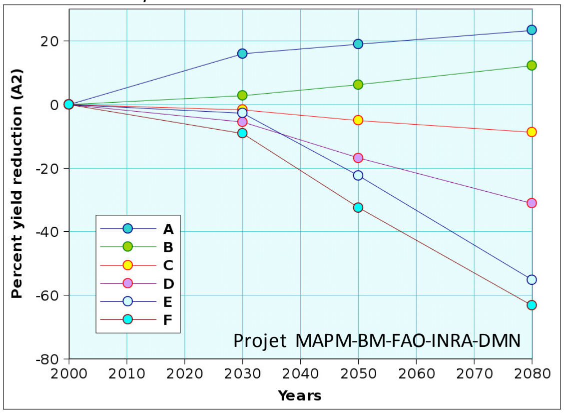
Les impacts des changements climatiques sur les productions agricoles

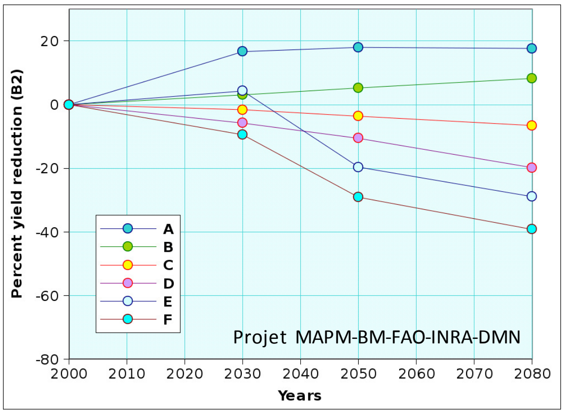
Les projections climatiques sur le Maroc indiquent que l'aridité va progressivement augmenter en raison de la diminution de la pluviométrie et de l'augmentation de la température. Il faut garder à l'esprit que les modèles climatiques prédisent mieux les moyennes que les valeurs extrêmes. Cela veut dire que, si en moyenne l'aridité va augmenter, certaines années peuvent malgré tout être sporadiquement très pluvieuses. L'augmentation de l'aridité va donc avoir des répercussions négatives sur les rendements agricoles surtout à partir de 2030. Toutes les cultures ne seront pas aussi vulnérables aux changements climatiques. Dans la figure ci-dessous, on peut remarquer que les cultures pluviales (non irriguées) seront particulièrement affectées par les changements climatiques.

La Figure III illustre six comportements typiques des rendements futurs, identifiés par les lettres de A à F. A indique les quelques rares cultures (toutes irriguées) qui verront une augmentation de leurs rendements, tandis que celles de la catégorie F subiront des pertes de rendements sévères. Le Tableau 3.02 du corps du rapport (page 67) donne le détail de la catégorie d'impact (A à F) à laquelle appartiennent les diverses cultures, par zone agroécologique.

Dans l'hypothèse où l'eau d'irrigation continuera à être disponible en quantités suffisantes, la plupart des cultures irriguées continueront à voir leurs rendements augmenter malgré les changements climatiques. On suppose que l'augmentation de température, couplée à une irrigation qui assure les besoins des cultures, favorisera la croissance des plantes cultivées et donc augmentera les récolte de la plupart des cultures. Cependant, la disponibilité en eau d'irrigation, surtout en cas d'augmentation de l'aridité du climat marocain, est une hypothèse qui reste encore à vérifier. De manière générale, les rendements agricoles resteront plus ou moins stables jusqu'à l'horizon 2030, puis baisseront assez rapidement au-delà de cette date, de façon plus marquée dans le cas du scénario A2 que dans celui du scénario B2. Toutes les zones agro-écologiques ne seront pas affectées de la même manière par les changements climatiques. Les zones agro-écologiques "*Favorable*" et "*Intermédiaire*" seront les plus vulnérables aux changements climatiques.

Figures IIIa et IIIb : Pourcentage de réduction des rendements agricoles selon les scénarios A2 et B2, jusqu'à l'horizon 2100. L'adaptation par le progrès technologique actuel n'est pas prise en compte ici. Les cultures sont rassemblées en "groupes d'impact" A à F qui peuvent être caractérisés comme suit :
A: *Légumineuses irriguées et fourrages* - B: *Arboriculture fruitière irriguée et cultures légumières* - C: *Fourrages et cultures légumières* - D: *Céréales pluviales et légumineuses* - E : *Céréales d'automne pluviales* - F: *Autres cultures pluviales*.





Les impacts réduits par le progrès technologique

Lorsque l'on étudie la progression des rendements agricoles avec les changements climatiques, mais en tenant compte du progrès technologique réalisé au Maroc, on se rend compte que les impacts négatifs sont moindres. Le progrès technologique est pris ici dans son sens le plus large, comprenant l'amélioration génétique des plantes cultivées, l'utilisation des fertilisants et pesticides, la mécanisation, les techniques de labour, etc.

Par exemple, les statistiques agricoles de 1979 à 2006 montrent, pour le blé tendre et le blé dur, une augmentation des rendements qui a été, en moyenne, de 0,02 tonnes/Ha et par an au niveau national. En particulier, ce progrès est le fruit d'un effort important fourni par la recherche agronomique (INRA) pour créer des variétés, productives et résistantes à la sécheresse et aux maladies, en dépit des aléas climatiques. En stations expérimentales, le gain de rendement peut aller jusque 0,05 tonnes/Ha et par an pour les nouvelles variétés de blé tendre de l'INRA. Dans la figure IV ci-dessous, on peut voir les impacts des changements climatiques sans progrès technologique en rouge et avec progrès technologique en vert pour le blé dur non irrigué au niveau national. Dans le scénario A2, sans progrès technologique, le rendement du blé dur irait toujours en diminuant alors que l'impact peut être compensé en partie par le progrès technologique, tout au moins jusqu'en 2050. Dans le scénario B2 plus favorable, le progrès technologique peut compenser l'impact des changements climatiques même jusqu'en 2100.

Figures IVa et Figure IVb : Impacts des changements climatiques sur le rendement du blé dur pluvial au Maroc. IVa : impacts modérés jusqu'en 2030 et sévères au-delà, selon le scénario A2 ; **IVb** : impacts modérés jusqu'en 2030, et maîtrisés au-delà, selon le scénario B2.

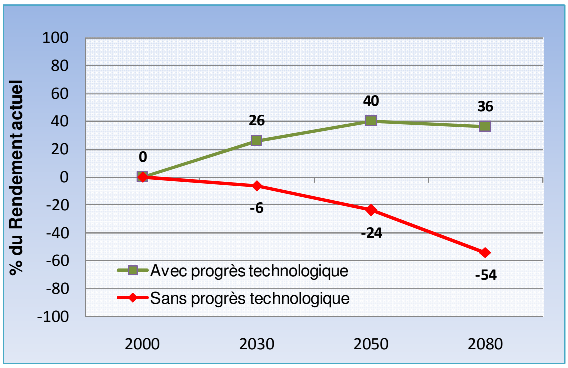


Figure Iva

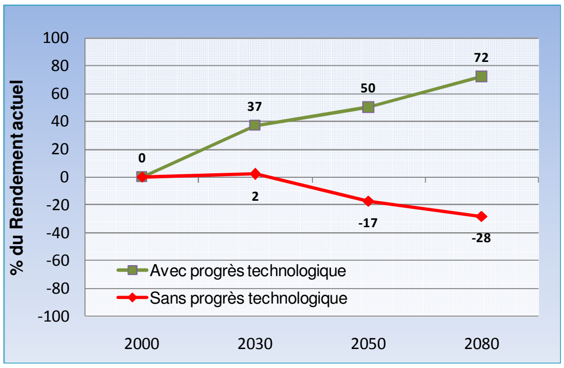


Figure IVb

Pour l'orge par exemple, le progrès technologique a été nul car, pour un certain nombre de raisons, l'orge a été reléguée vers les zones agricoles marginales affectant ainsi son rendement. Le décalage entre la ligne en vert (avec progrès technologique) et en rouge (sans progrès technologique) qui indique l'adaptation de l'agriculture aux changements climatiques futurs. Le progrès technologique le plus spectaculaire se retrouve, par exemple, pour la tomate, la luzerne, la banane, la pomme de terre ou les fourrages.

Les incertitudes concernant les impacts

Les modèles physiques sur lesquels reposent les projections climatiques prévoient mieux les valeurs moyennes de pluie et de température que leurs extrêmes. Il en découle, que les impacts prévus dans le futur représentent des moyennes de valeurs qui peuvent parfois fluctuer fortement d'une année à l'autre. Les projections de rendements diffèrent toutefois très peu entre les scénarios A2 et B2 jusqu'en 2030[v]. Au-delà de cette date, et jusqu'en 2100, des divergences énormes existent entre les scénarios en raison des incertitudes liées aux quantités de gaz à effet de serre qui seront réellement émises dans l'atmosphère, de la dynamique[vi] du secteur agricole et de la capacité d'adaptation de l'agriculture marocaine.

Pour cette raison, les estimations d'impact sont fiables jusqu'en 2030 et vraisemblables au-delà. Cependant, l'amplitude des changements climatiques attendus à long terme est telle qu'un renversement de tendance est peu probable. Ces prévisions d'impact sur les productions agricoles sont largement tributaires des modèles climatiques développés par les climatologues et ne sont valables que pour les conditions actuelles de l'agriculture marocaine. En d'autres termes, des altérations des systèmes de production actuels tels que la gestion de l'eau, l'affectation des terres, l'amélioration variétale, les cultures existantes ou l'adaptation des agriculteurs aux changements climatiques peuvent modifier les prévisions d'impact. Il faut bien comprendre que l'on essaye de modéliser des relations complexes entre les rendements agricoles et des scénarios futurs. Les incertitudes liées aux projections d'impacts sont principalement dues à notre difficulté à imaginer le monde de demain, aux imperfections des modèles climatiques, aux techniques de réduction d'échelle ainsi qu'aux erreurs statistiques inhérentes aux données statistiques qui ont servi de référence. Quoi qu'il en soit, les variations présumées des rendements moyens par zone agro-écologique sont données par le Tableau 3.02 du rapport principal, qui reprend les estimations d'impact par culture et par zone agro-écologique en utilisant les catégories d'impact (A à F) définies dans

[v] Assez logiquement, les différences entre scénarios sont plus faibles pour les cultures irriguées que pour les cultures pluviales.

[vi] Nous incluons dans ce terme les diverses tendances actuellement observées au Maroc, qui répondent à des logiques économique, environnementale, etc.

la figure III.

Conclusion

La mise en commun des efforts et de l'expertise d'institutions nationales (MAPM, INRA et DMN) et internationales (BM et FAO) a permis de lever des difficultés opérationnelles et méthodologiques et, surtout, d'assurer un "contrôle de qualité" dans toutes les phases d'analyse de cette étude.

Les estimations d'impact des changements climatiques sur les productions agricoles sont plausibles sur les 20 prochaines années. Pour le futur plus lointain, l'amplitude des changements climatiques prévus est telle qu'un renversement des tendances est cependant peu probable. Il ressort de cette étude que le progrès technologique (amélioration des rendements agricoles en conditions arides et semi-arides), l'irrigation (gestion de l'eau au niveau de la parcelle agricole, du bassin versant et de la région) et l'utilisation des terres selon leur vocation agricole sont des clés importantes d'adaptation aux changements climatiques.

ملخص

أثر تغير المناخ على المحاصيل الزراعية في المغرب

السيناريوهات المناخية الممكنة

تجتمع كل التوقعات المناخية في منطقة البحر الأبيض المتوسط على هيمنة المناخ القاحلي. ويعتمد خبراء المناخ في دراستهم لهذه التوقعات على نماذج للغلاف الجوي قادرة على تحويل افتراضات انبعاثات غازات الاحتباس الحراري (بما في ذلك ثاني أكسيد الكربون) إلى توقعات مناخية. وتعتبر هذه النماذج تمثلات مبسطة ومتمكن منها للغلاف الجوي يسهل حسابها على المستوى العالمي من خلال عيون مربعة تبلغ جوانبها 250 كلم، بحيث تصبح التوقعات المناخية صورة تقريبية لما يمكن أن يصير إليه العالم حتى عام 2100. ولهذا أطلق خبراء من الفريق الحكومي الدولي المعني بتغير المناخ(GIEC)، مفهوم السيناريوهات على التمثلات المستقبلية (فهي ليست بتكهنات ولا تنبؤات مستقبلية) الناجمة عن انبعاثات جد مختلفة للغازات المؤدية للاحتباس الحراري. هذه السيناريوهات الممكنة في لمستقبل تعبر عن الظروف الجوية الناتجة عن خياراتنا المجتمعية، بدءا من اتخاذ إجراءات جذرية للتخفيض من الانبعاثات الغازية إلى التسريع من استعمال الطاقات الوقود الأحفوري، وخاصة في البلدان النامية.

استباق الأزمات

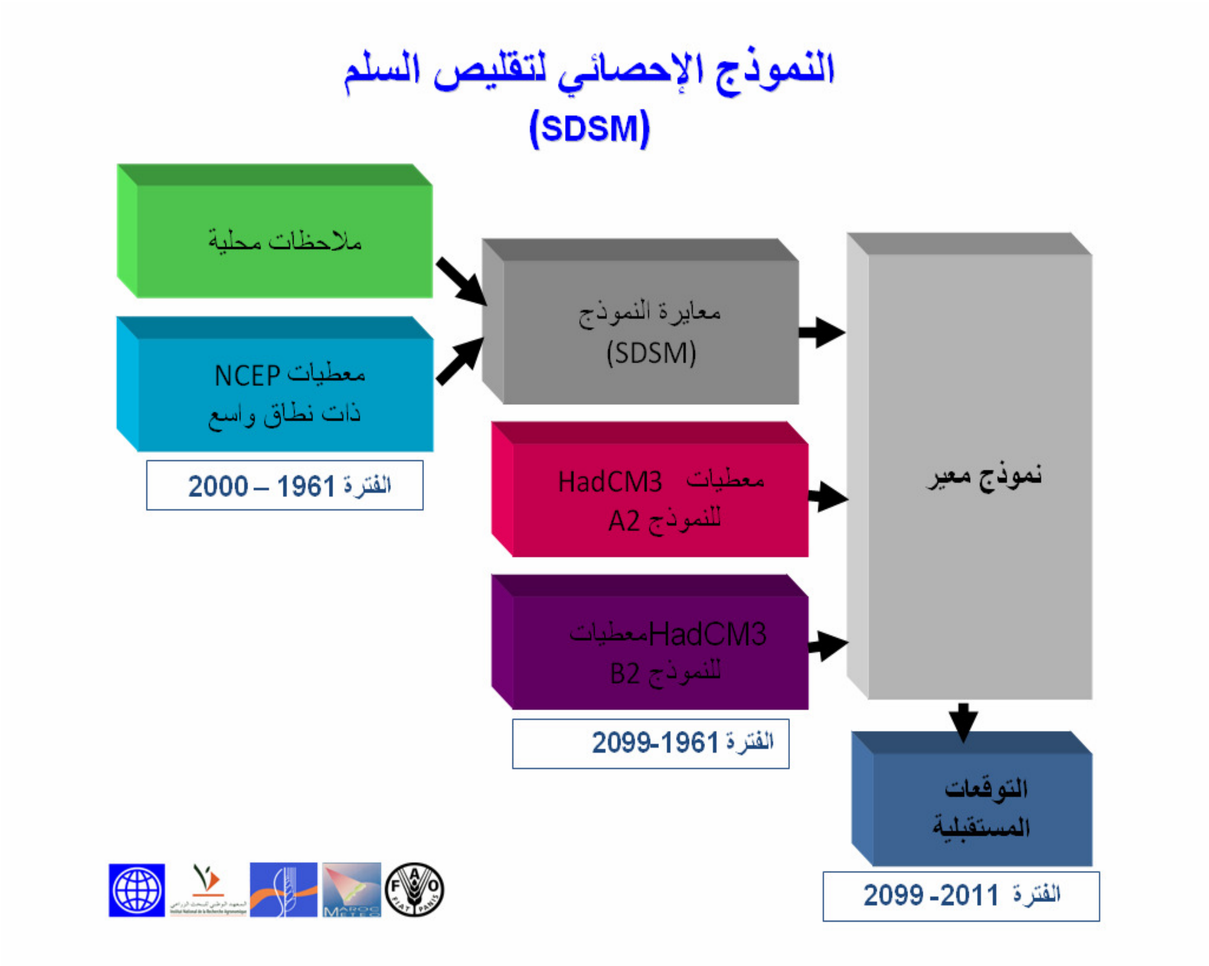
قام كل من وزارة الفلاحة والتنمية القروية والصيد البحري (MPAMA) والبنك الدولي بالتعاون مع المعهد الوطني للبحث الزراعي (INRA) و ومنظمة الأمم المتحدة للتغذية والزراعة (FAO) و مديرية الوطنية للأرصاد الجوية (DMN) بدراسة نوعية ومستقبلية لتحديد آثار تغير المناخ على زراعتنا إلى نهاية القرن الحالي و إيجاد الخيارات السياسية والاقتصادية لتكييف الزراعة الوطنية مع تغيرات المناخ و تجنب الأزمات المحتملة. تنقسم هذه الدراسة إلى 5 مراحل: 1) التوقعات المستقبلية للمناخ بالمملكة، 2) التأثيرات على المحاصيل الزراعية، 3) التأثيرات على مصادر المياه، (4) الآثار الاقتصادية 5) الخيارات السياسية للتكيف مع تغير المناخ.

ونقدم هنا بعض نتائج المرحلة الثانية من هذه الدراسة. النتائج المعروضة هنا وصفية بحتة لا تهدف، في هذه المرحلة من دراسة، لعرض الحلول الملائمة للتكيف مع تغير المناخ.

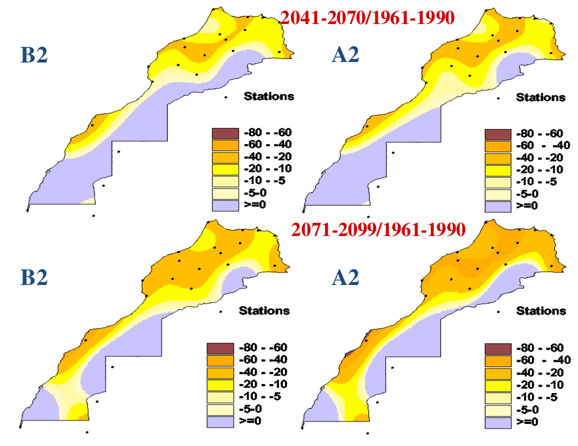
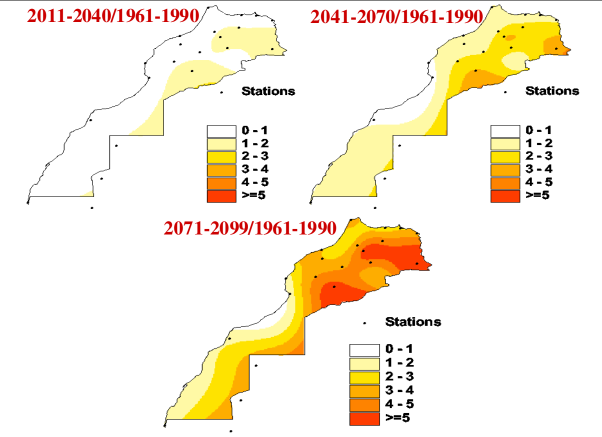
تركيز التوقعات المناخية العالمية على المستوى الوطني

تمحورت الدراسة خلال المرحلة الأولى حول تقليص إحصائي لمساحة التوقعات المناخية المعتمدة على الصعيد العالمي لدى الفريق الحكومي الدولي (GIEC) من 250 × 250 كلم² إلى مساحة أصغر (من فئة 100 كلم²) توافق مساحات أهم المناطق الزراعية-البيئية بالمغرب (الشكل 1). و نذكر هنا بأن وزارة الفلاحة والتنمية القروية والصيد البحري قد حددت المناطق الزراعية البيئية على الشكل التالي: المنطقة الملائمة، المنطقة المتوسطة، منطقة الشرق الضعيفة، منطقة الجنوب الضعيفة، المنطقة الجبلية والصحراء.

الشكل 1 : إجراءات لتقليص النطاق المتسع للتوقعات المناخية (عيون من حجم 300 كلم) إلى نطاق محلي. المركز الوطني للتنبؤات البيئية (NCEP)، النموذج الإحصائي لتقليص النطاق (SDSM)، النموذجي CM3 لمركز هادلي البريطاني للأرصاد الجوية (HadCM3).



الشكل 2 أ : أهم التوقعات المناخية بالمغرب

مفارقات في التساقطات المطرية (سيناريو A2 و B2)	مفارقات في درجة الحرارة المتوسطة (سيناريو A2)
	
بالمقارنة مع الفترة 1961- 1990، سيشمل التراجع في الأمطار سائر البلاد وخاصة في أفق 2071-2099. وفقا لأكثر السيناريوهات تشاؤما، فإن المعدل السنوي لهطول الأمطار سينخفض بنحو 20 ٪ بحلول عام 2050 و 40 ٪ بحلول العام 2080، باستثناء المنطقة صحراوية حيث سيكون الانخفاض بنسبة 16 ٪ في أفق 2080. يسجل السيناريو المتشائمA2 أكبر انخفاض في التساقطات. وسنشعر بهذا الانخفاض خلال فصلي الخريف والربيع، أي خلال فترات ذروة التساقطات.	كما هو الشأن بالنسبة للأمطار، فإن درجة حرارة الجو ستعرف ارتفاعا في جميع أنحاء البلاد. فمن خلال السيناريو A2 ، سيبلغ ارتفاع درجة الحرارة 3 درجات مئوية بحلول العام 2080 وذلك في المناطق الزراعية-البيئية الستة للمغرب ، وستصل إلى 5 درجة مئوية في المنطقة الجبلية وفي الشرق. وسينجم عن ارتفاع درجة الحرارة زيادة في نسبة التبخر (مجموع تبخر التربة وعرق النباتات) لتصل 20 ٪ بحلول عام 2050 و 40 ٪ بحلول العام 2080، باستثناء المنطقة الصحراوية حيث سيبلغ التبخر 9 ٪ في سنة 2080.

ترجمة تغير المناخ إلى آثار على الإنتاج الزراعي

في مرحلة ثانية ، ترجمت التوقعات المناخية (مخفضة إلى مستوى المناطق الزراعية-البيئية) إلى توقعات في الإنتاج الزراعي (أنظر الشكل 2). يعتبر هذا الجانب من الدراسة موضوع هذا التقرير، إذ تم الاهتمام بخمسين زراعة بعلية ومروية (مسقية) في ستة مناطق زراعية بيئية وفق سيناريوهين اثنين للمناخ A2 و B2 في أفق أربعة أزمنة : 2000 (الزمن الحالي المغطي للفترة 1979 إلى 2006)، 2030 (من 2011 حتى 2040)، 2050 (من 2041 حتى 2070) و 2080 (من 2071 حتى 2099).

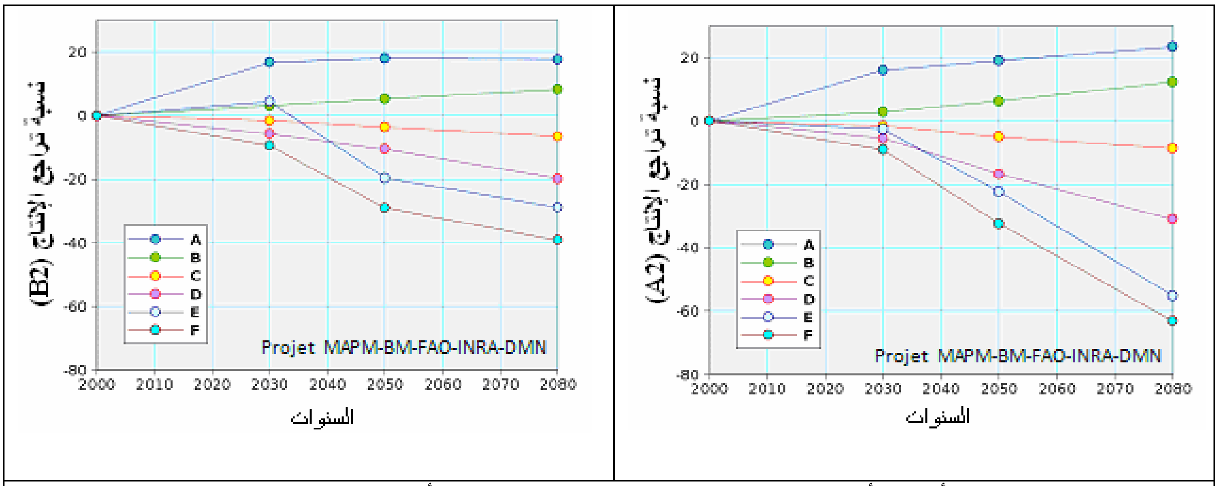
اعتمدت منهجية الدراسة على تطوير دالات للإنتاج خاصة بكل زراعة وفي كل مناطق الدراسة. تعتبر هذه الدوال نماذج زراعية- بيئية تربط نظريا الإنتاج الزراعي بالحصيلة المائية المتوقعة في كل البلاد. كما أخذ بعين الاعتبار، التقدم التكنولوجي الملحوظ في المناطق الزراعية البيئية وتأثير سماد ثاني أكسيد الكربون على المحاصيل. و يتم أخيرا التوصل إلى المحاصيل النهائية باستحضار الظروف المناخية المستقبلية (النموذج HadCM3 وسيناريو هي الانبعاثات الغازية A2 و B2) في دالات الإنتاج المنشئة. وفيما يلي وصف للسيناريوهين A2 و B2 :

سيناريو A2	سيناريو B2
هذا السيناريو متشاءم يصف العالم أكثر ديمغرافية (ارتفاع سريع لعدد السكان) مع نمو اقتصادي قوي مبني على التكنولوجيات المُلوثة في عالم أصبح أكثر حمائية مع تزايد الفوارق بين الشمال والجنوب. الاستمرار في استخدام الطاقة الحفورية ونمو اقتصادي غير متساو بين مناطق العالم.	هذا السيناريو المُتفائل يجعل من العالم أكثر تركيزا على الحلول المحلية رغبة في حيوية اقتصادية واجتماعية وبيئية، حيث سيعرف عدد سكان العالم تزايدا على نحو مستمر ولكن بمعدل أبطأ مما كان عليه في A2. التنمية الاقتصادية في مستوى متوسط والتطور التكنولوجي أبطأ ولكن أكثر تنوعا.

آثار تغير المناخ على الإنتاج الزراعي

تشير التوقعات المناخية بالمغرب إلى أن وثيرة الجفاف سترتفع تدريجيا بسبب انخفاض معدلات سقوط الأمطار وارتفاع درجة حرارة الجو. ينبغي أن نعلم على أن النماذج المناخية تتنبأ بشكل أفضل للمعدلات و القيم المتوسطة من تنبئها بالأرقام القصوى. وهذا يعني أنه إذا كان الجفاف الميزة العامة للسنوات القادمة، فإنه من الممكن لبعض السنوات أن تكون جد ممطرة. و سيؤثر ارتفاع معدل الجفاف سلبا على المحاصيل الزراعية وخاصة بعد عام 2030. كما أن الزراعات ستتفاوت في نسبة تكيفها مع تغير المناخ. ومن معاينة الشكل 3 الموالي، يمكن ملاحظة أن المحاصيل البعلية (غير المروية) ستعرف تأثيرا خاصا بتغير المناخ. أما بالمناطق المسقية ومع فرضية وفرة مياه الري، فإن مردود الزراعات المروية ستستمر في تسجيل الارتفاع رغم تغير المناخ نتيجة تحسن في النمو الناتج عن ارتفاع الحرارة ووفرة المياه. وتحتاج هذه الفرضية، فرضية وفرة مياه الري في ظروف ارتفاع وثيرة الجفاف، إلى إثبات أو تأكيد. يمكن القول بشكل عام، أن المحاصيل الزراعية ستعرف استقرارا في الإنتاج إلى حدود عام 2030 قبل أن تتراجع بشكل سريع وخصوصا في السيناريو A2 مقارنة بالسيناريو B2. كما أن المناطق الزراعية-البيئية لن تتأثر بنفس الدرجة من جراء تغير المناخ إذ أن المناطق الملائمة والمناطق المتوسطة ستكون أكثر تضررا.

الشكل 3: نسبة تراجع الإنتاج الزراعي حسب السيناريوهين A2 و B2 إلى غاية سنة 2100 بدون اعتبار تأقلم التقدم التكنولوجي الحالي.

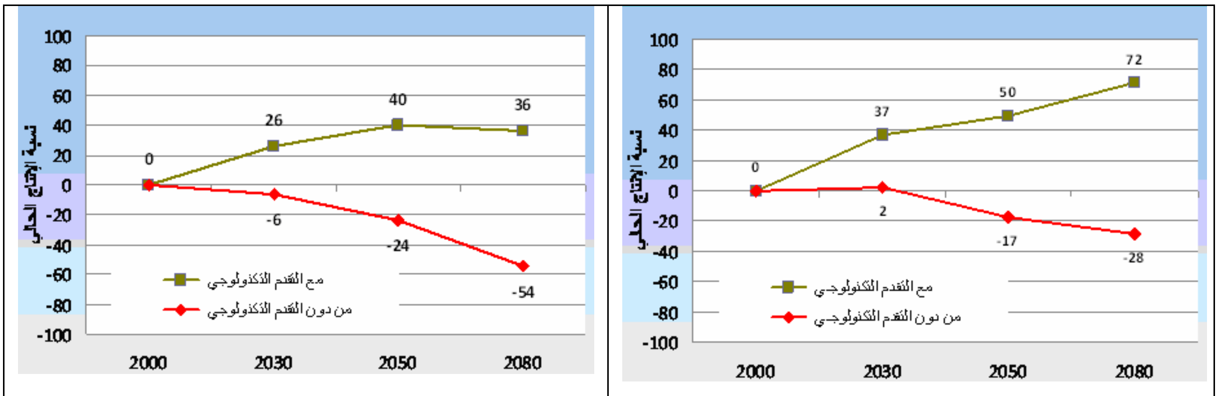


A: بقوليات مسقية والكلأ؛ B: أشجار مثمرة مسقية وخضروات؛ C: الكلأ والخضروات؛ D: حبوب القمح البعلية والبقوليات؛ E: حبوب قمح الخريف البعلية؛ F: زراعات بعلية أخرى.

التأثيرات المخفضة عن طريق التقدم التكنولوجي

في دراستنا لتفاعل الإنتاج الزراعي مع تغيرات المناخ مع اعتبار التقدم التكنولوجي الحاصل بالمغرب، نخلص إلى تراجع الآثار السلبية الناجمة عن ذلك. ونقصد بالتقدم التكنولوجي معناه الموسع و الذي يشمل التحسين الصفات الوراثية للنباتات المزروعة واستخدام الأسمدة والمبيدات الحشرية والميكنة وتقنيات الحرث ، الخ.
تشير الإحصاءات الزراعية، على سبيل المثال من 1979 إلى 2006، إلى زيادة سنوية في الإنتاج الوطني من القمح الصلب والطري بمعدل 0.2 قنطار في الهكتار. ويعزى هذا التقدم على وجه الخصوص إلى جهود البحث الزراعي (المعهد الوطني للبحث الزراعي) الرامية إلى استخراج أصناف منتجة ومقاومة للجفاف والأمراض رغم تغير الأحوال الجوية. أما بالمحطات التجريبية، فقد يصل التحسن السنوي لإنتاج الأصناف الجديدة من القمح الطري المستخرجة من طرف المعهد الوطني للبحث الزراعي، إلى 0.5 قنطار في الهكتار. في الشكل التالي، الخاص بالزراعات البعلية لأصناف من القمح الصلب بالمغرب، يمكن رؤية تأثيرات المناخ من دون التقدم التكنولوجي باللون الأحمر و مع التقدم التكنولوجي باللون الأخضر. ففي السيناريو A2 من دون التقدم التكنولوجي، يعرف إنتاج القمح الصلب تراجعا مستمرا يمكن تخفيفه بالتقدم التكنولوجي على الأقل حتى عام 2050. أما في السيناريو الأفضل B2 ، فبإمكان التقدم التكنولوجي التعويض عن تأثير تغير المناخ حتى حدود عام 2100. بالنسبة للشعير ، على سبيل المثال ، لم يكن للتقدم التكنولوجي أي أثر باعتبار أن هذه الزراعة (الشعير) ولعدة أسباب، تم إزاحتها إلى مناطق هامشية وضعيفة أثرت سلبا على المردودية. ويشير التفاوت بين الخط الأخضر (مع التقدم التكنولوجي) والأحمر (بدون التقدم التكنولوجي) إلى التكيف المستقبلي للفلاحة مع تغير المناخ. التقدم التكنولوجي الأكثر شدا للانتباه هو المسجل مثلا بالنسبة للطماطم والفصة والموز والبطاطس أو الزراعات الكلئية.

الشكل 4: آثار تغير المناخ على إنتاج القمح البعلي بالمغرب.



4b: آثار معتدلة حتى عام 2030 و متحكم فيها بعد ذلك وفق السيناريو B2 .	4a: تأثيرات معتدلة حتى عام 2030 وشديدة بعد ذلك وفق السيناريو 2

ضآلة الاحتمالات المرتبطة بالتأثيرات

تتنبأ النماذج الفيزيائية المعمول بها في التوقعات المناخية، بشكل أفضل لمعدلات التساقطات ولمتوسط درجات الحرارة من المستويات القصوى الممكنة. ويترتب على ذلك أن الآثار المتوقعة في المستقبل ما هي إلا معدلات يمكن في بعض الأحيان أن تعرف تغيرات قوية من سنة إلى أخرى. وإذ نسجل أن التوقعات المناخية لم تختلف إلا قليلا بين السيناريوهين A2 و B2 في أفق 2030[7]، فإن التباين يصبح كبيرا بعد ذلك إلى حدود سنة 2100 بسبب الشكوك المتعلقة بكميات غازات الاحتباس الحراري المنبعثة في الجو وكذلك بدينامكية القطاع الفلاحي[8] ثم بقدرة تكيف الفلاحة الوطنية.

[7] منطقيا، تبقى الاختلافات بين السيناريوهات ضعيفة بخصوص الزراعات المسقية مقارنة بالزراعات البعلية.
[8] بما في ذلك مختلف التوجهات الحالية الملاحظة بالمغرب والتي تستجيب للمنطق الاقتصادي والبيئي، الخ.

ولهذا السبب، فإن تقييمات الأثار صحيحة إلى حدود 2030 وتبقى نسبية بعد ذلك. أما فرضية تقلب التوجهات نتيجة آثار كبيرة في تغير المناخ على المدى البعيد، فهي ضعيفة الإحتمال. وترتبط توقعات الآثار على الإنتاج الزراعي بشكل كبير بالنماذج المناخية التي وضعها خبراء المناخ والتي لا تصح إلا في الظروف الحالية للفلاحة الوطنية. وبعبارة أخرى، فإن أي تغير في نظم الإنتاج الحالية - مثل تدبير المياه، واستخدام الأراضي، والتحسين الوراثي، والزراعات المعتمدة أو تكيف المزارعين مع تغير المناخ – يمكن أن ينجم عنه يؤثر في تقديرات الآثار المنتظرة. كما ينبغي استيعاب أن هذه المحاولات تسعى لوضع نماذج لعلاقات معقدة تربط الإنتاج الزراعي بالسيناريوهات المستقبلية. ضآلة الاحتمالات المرتبطة بتقدير الآثار راجعة بالأساس إلى الصعوبة التي نواجهها في تصور عالم الغد، وفي قصور النماذج المناخية، وفي تقنيات خفض النطاق وفي الأخطاء الإحصائية المحتملة في البيانات المعتمدة. وكيفما كان الحال، فإن الجدول 3.02 من التقرير الرئيسي يعرض التغيرات المفترضة لمعدلات المحاصيل في كل منطقة زراعية- بيئية ويشير إلى تقييمات الآثار لكل زراعة وفي كل منطقة وذلك باستعمال أصناف التأثير (من A إلى F) المذكورة في الشكل III.

خاتمة

مكنت الجهود والخبرات مجتمعة لكل من المؤسسات الوطنية (MAPM، INRA و DMN) و الدولية (البنك الدولي ومنظمة الأغذية والزراعة) من إزاحة الصعوبات العملية والمنهجية و ضمان "الجودة" في جميع مراحل هذه الدراسة. تعتبر تقييمات آثار تغير المناخ على الإنتاج الزراعي معقولة في العشرين سنة القادمة. أما على المدى البعيد، فإن حجم الكبير للتغيرات المناخية المنتظرة الغير عكسية تبقى غير محتملة. كما نستنتج من هذه الدراسة على أن أهم المفاتيح للتكيف مع تغير المناخ تتمثل في التقدم التكنولوجي (من تحسين للإنتاج الزراعي في بيئات الجافة وشبه الجافة) والري (من تدبير للمياه على مستوى الضيعة والمجال والمنطقة) واستعمال الأراضي وفق الإمكانات الفلاحية.

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Abstract

This study examines the impact of projected climate change on fifty major Moroccan crops (irrigated and rainfed) and six agro-ecological zones (AEZ: DEF-or, *Défavorable oriental; DEF-sud, Défavorable sud*; FAV, *Favorable*; INT: *Intermédiaire*; MONT: *Montagne* and SAH: *Saharien*). Two scenarios (conservative B2 and more extreme A2) are applied to the existing 240 unique AEZ x crop combinations[9]. It is stressed that the methodology describes impacts on current agriculture and that it includes only minor elements of spontaneous adaptation. Among others, no changes were assumed for the level of water control: rainfed crops continue to be grown under rainfed condition, and the same applies for irrigation. Therefore, "adaptations", like irrigating crops that are currently rainfed, were not envisaged in the simulations.

It is not possible to quantify the loss of reliability for the later parts of the 21st century. Due to the use of proven crop forecasting techniques, the reliability of the projected yield impacts is high for the near future, but the reliability decreases from the current period (baseline or "2000") to 2030, 2050 and 2080. However, due to the magnitude of some projected changes, it is unlikely that the sign of some changes will be reversed, even in the more distant future.

Six impact classes can be identified based on the projected effects of climate change on yield change. The classes are conventionally referred to as A (the most favourable one) to F (the least favourable). The yield changes are shown in the table below. Table 3.02 (page 67) indicates which class each crop and agroecological zone belong to.

Table 1: Percent yield change at different time horizons for the 6 impact classes.
This Table is a repetition of Table 3.01 (§ 3.1.1.,) where additional details are provided.

	Scenario A2			Scenario B2		
Class	2030	2050	2080	2030	2050	2080
A	16	19	23.33	16.67	18	17.67
B	2.8	6.27	12.26	3.07	5.25	8.25
C	-1.67	-5.03	-8.72	-1.59	-3.64	-6.56
D	-5.49	-16.77	-31.11	-5.81	-10.6	-19.81
E	-2.71	-22.36	-55.14	4.29	-19.64	-28.93
F	-9.12	-32.41	-63.24	-9.47	-29.12	-39.24

In class A, yields are projected to increase around 20 % (16.00 to 23.33) starting in 2030. Class A is group of agronomically and botanically unrelated crops: rainfed fodder crops in the DEF-or, irrigated maize in FAV and seasonal vegetables (irrigated) in FAV. They are all characterised by a rather high baseline water use of about 25,000 m³ water use per hectare and by a marked technology trend[10]. To achieve the yields projected if the technology trend is maintained throughout the century, water use increase will be 4-fold.

Class B is a very homogeneous group of irrigated fruits and vegetables that will benefit from climate change, with projected yield increases between 2.8 and 12.26%. Baseline water use is approximately 10,000 m³ per hectare. The class occurs all over the country and includes alfalfa, apples, early potatoes (seasonal potatoes come under C), greenhouse, industrial and

9 Sixty combinations do not occur, such as dates grown in the northernmost Mediterranean climates, or sugar beet cultivated in the south (SAHARA agro-ecological zone)

10 The technology trend is the increase of yields achieved over time due to the use of improved varieties, mechanization, better management, use of inputs, etc.

seasonal tomatoes, among others. It is a characteristic of group B that B2 conditions are less favourable than A2. If technology trend and CO_2 are taken into account, additional yield increases are projected to occur: in 2050, they roughly amount to 15% for CO_2 effects, while trend accounts for slightly more (about 20%); the corresponding water uses for 2080 grow by about 30% over current conditions.

Class C, where yields are projected to first remain stable then to decrease from 2030 onwards, includes mainly vegetables and fodder crops. Rainfed range lands occur always in this class and most of irrigated soft wheat. The probability of low yields[11] is usually comparable to current conditions, but increases to values between 15% and 20% in the FAV, indicating increasing climate risk. In this class, CO_2 effects are not well marked: they outbalance or just exceed negative effects in 2050. On the other hand, trend effects are well marked in both scenarios, and may reach or exceed + 50%. Baseline water use is comparable to class B, i.e. about 10,000 m^3 per hectare, but the water use associated with the trend projections are double towards the end of the century.

Class D includes mostly rainfed cereals (barley in the less favourable AEZs, maize) and legumes. It is the first where consistently negative impacts are projected to occur, and those effects tend to be more marked under A2 than under B2. The probability of low yields now reaches more than 30% in some agro-ecological zones (FAV, DEF-or). Trend and CO_2 play a comparable but minor role (in 2050), usually not exceeding a combined positive effect of about 10%. Average current water use is close to 5,000 m^3 per hectare and will need to double if the trend is continuing to 2080.

Class E includes essentially rainfed wheat and barley in FAV. Altogether its behaviour is similar to that of D until 2050, after which a sharp drop in yields occurs. The 2050 projection of the technology trend can exceed 100%, while CO_2 effects stay at a low 5 % impact. Current water use is close to 2500 m^3 per hectare; this is the first class where future water use is really crucial and a doubling of water supply is necessary by the end of the century.

In Class F, negative impacts on yields reach 10% already in 2030. The class includes several rainfed crops of major economic importance, for instance barley (rainfed) in some of the less favourable zones (DEF-sud, INT), olives in the DEF agro-ecological zones, rainfed sugar beet in FAV, as well as several legumes in various AEZs. The frequency of low yields is everywhere close to or above 20%, and reaches about 60% in DEF-OR and FAV for both scenarios. With few exceptions, the technology trend will be insufficient to compensate the yield losses due to climate change, especially under A2 projections. As in class E, average water use corresponds to 2500 m^3 per Ha. In this class, since yields do not increase, water consumption stays at the same level.

It is likely that the crops in classes E and F will particularly suffer, as even the extrapolation of yield trends does not compensate for climate conditioned yield drops. This includes (class E) barley in FAV, rainfed durum wheat in the DEF, FAV, INT, MONT agro-ecological zones and rainfed soft wheat in DEF-or, FAV, INT and MONT. In class F, we can list rainfed sugar beet in FAV and rainfed soft wheat in DEF-sud and SAH.

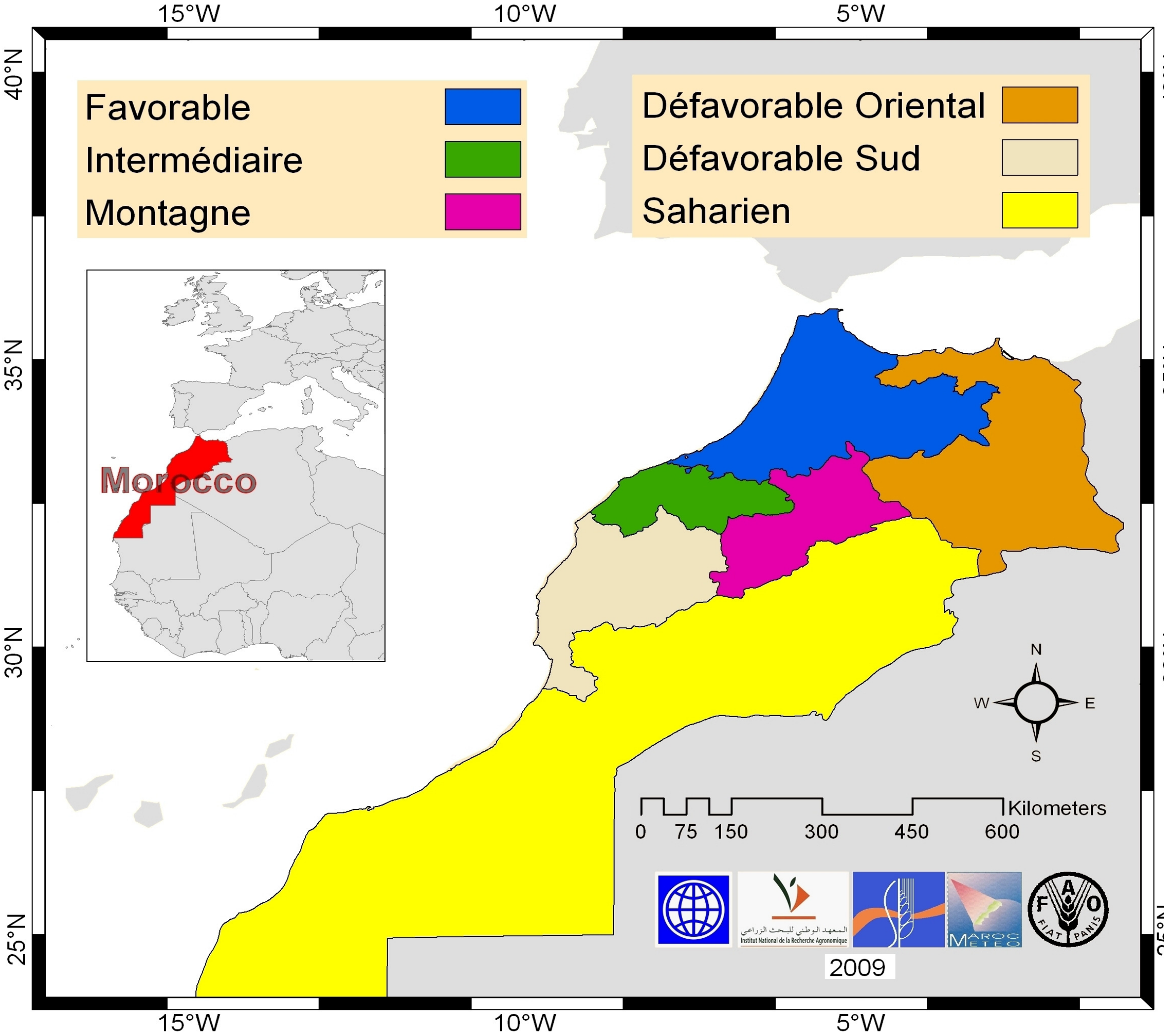
About 1500 crops defined by their ecophysiological requirements were also screened to assess if they may become more or less suitable in the various agro-ecological zones of Morocco. "New" crops of major economic importance such as Arabica coffee, Queensland nut (*Macadamia*) and Chinese cinnamon may become suitable under irrigated conditions in Morocco. The study also shows shifts in suitability of many woody and herbaceous species, indicating that the mix of species that currently characterises Moroccan agriculture is bound to undergo qualitative changes.

[11] Low yields are defined as yields so low that they occur only during one in ten years on average, under current conditions.

1. Introduction

The impact of climate change on agricultural yields constitutes the second step of the "World Bank - Kingdom of Morocco: Adaptation to climate change in the agriculture sector". It builds on climate change scenario data developed by Wilby (2008) and provides one the bases upon which "Impacts on Farming Systems" and "Economic impact assessments", will be based, leading eventually to "Policy adaptation options".

Figure 1.01: Major agro-ecological zones of Morocco. FAV: *Favorable*, INT: *Intermédiaire*; DEF-or: *Défavorable oriental*; DEF-sud: *Défavorable sud*; MONT: *Montagne* and SAH: *Saharien.*



This is a purely descriptive study in that it does not present any recommendations, apart from methodological ones. Instead, it attempts to describe in synthetic terms the large diversity of impacts that can be expected under the following conditions:

- Two climate scenarios (A2 and B2) that are part of the six families of scenarios adopted by IPCC starting with the Third Assessment Report (IPCC, 2000). B2 is based on a more “ecological” world and the projections are more conservative than those of A2;

- Six agro-ecological zones (AEZ) and the national level, i.e. standard zones used in defining prevailing agricultural and ecological conditions of Morocco (Figure 1.01). The AEZ are usually referred to simply as "zones". They include, from north to south and west to east: "*Favorable*" (including the areas from Tangier to Casablanca, abbreviated as FAV); east of FAV: "*Défavorable oriental*" (DEF-or); south of FAV: "*Intermédiaire*" (INT); east of FAV: "*Montagne*" (MONT); south of INT: "*Défavorable sud*" (DEF-sud) around Marrakech to just north of Agadir and, eventually, "*Saharien*" (SAH) including the remaining territory extending to the Mauritanian border in the south. National data were determined from AEZ data by weighting yields by the share of each AEZ in the respective crop's production;

- Four time horizons: each of the time horizons actually stands for a period of about 30 years centred on the conventional reference dates. They include the "current period" (or "baseline" or sometimes "2000", covering the years 1979-2006, for which crop statistics are available), 2030 (from 2011 to 2040), 2050 (2041-2070) and 2080 (2071-2099). Note that a statement like "yields will decrease from 2030" means that the 2030 average will decrease, but the decrease will probably start, on average, in the years from the beginning of the period, i.e. 2011;

- Fifty crops, including the main crops cultivated in Morocco, thus including the major agricultural export earners. The main categories of products are called "crop groups" or simply "groups" in this report (cereals, fodder crops, fruits...). The groups are described in Table 1.01. The selection of crops somehow reflects available statistics, both in terms of species covered, cultivation systems (irrigated or "bour", i.e. rainfed) and representativeness of the published data. For instance tomatoes grown in family gardens, no doubt a major source for local consumption, and non irrigated fruits, are not included. Some of the crops of major economic relevance (termed "pilot crops") are getting special attention. The list of crops included in this study is given in Table 1.01 below. Their distribution among AEZs is shown in Table 1.02.

The main questions answered in this report include the impacts of climate change on crop yields and their statistical distribution (risk patterns) as well as future water consumption - a key variable in semi-arid areas where most crops are irrigated -.

The approach adopted for assessing the impact of future climate on crop yields in Morocco is based on the worldwide experience of FAO in establishing and operating real time crop yield forecasting systems in a number of countries in a food security context (Gommes 2003; Gommes et al. 2009). The method is, therefore, well tested under real-world conditions and a variety of different climate conditions. In particular, the problems associated with up-scaling model data are avoided. The present study expanded existing software simulation tools to be able to process the extremely large amounts of data that constitute the basis of yield projections. The software that was developed is part of the outputs of the study. It is available upon request from *agromet@fao.org*.

Although there is no technique available to prove this point, the authors assume that the overall setting of Moroccan agriculture will remain relatively stable in the "short-term" (10 to 15 or 20 years, until about 2030). For the near future, yield projections are realistic and consistent with current agricultural statistics.

It remains that the study largely presents the impact of future climate on current agriculture. Spontaneous adaptation measures by farmers and as well as government-led adaptation policies may result in agricultural landscapes vastly different from the ones we know today. These dynamic aspects are not taken into consideration. However, even if crop mixes are likely to change, the impacts on individual crops as they are presented in this report will by and large remain valid. For the crops which display a marked technology trend, the trends were extrapolated, which may be interpreted as a form of adaptation. Each yield estimate is accompanied by an estimate of future water use.

Table 1.01: List of the fifty crops covered by this study. Pilot crops are bolded and prefixed with an asterisk. The suffix _rf indicates rainfed crops, while _irr stands for irrigated crops. _gh (used only once for tomatoes) identifies early crops grown in greenhouses.

Cereals	Fodder	Fruits	Legumes	Oil crops	Sugar crops	Vegetables
10	6	14	5	4	3	8
***Barley_rf**	Alfalfa_irr	Almond_rf	Bean_rf (Dry)	Groundnut_irr	***Sugar_beet_irr**	Niora_irr
Maize_irr	Barley_rf (Straw)	Apple_irr	Bean_rf (Dry_faba)	Olive_irr	***Sugar_beet_rf**	Potato_irr (Early)
Maize_rf	Fodder_crops_irr	Apricot_irr	Chickpea_rf	Olive_rf	Sugar_cane_irr	Potato_irr (seasonal)
Oats_rf	Fodder_crops_rf	Banana_irr	Lentil_rf	Sunflower_rf		***Tomato_gh (Early)**
Rice_irr	Rangeland_rf	***Citrus_irr**	Pea_rf (Dry)			Tomato_irr (Early)
Sorghum_rf	Vetch_rf (Orobe)	Dates_irr				***Tomato_irr (Industrial)**
***Wheat_irr (Durum)**		Fig_irr				***Tomato_irr (Seasonal)**
***Wheat_irr (Soft)**		Nut_irr				***Vegetables_irr**
***Wheat_rf (Durum)**		Peach_irr				**("Other Seasonal")**
***Wheat_rf (Soft)**		Pear_irr				
		Plum_irr				
		Pomegranate_irr				
		Vine_ir (Grape)				
		Vine_rf (Grape)				

Table 1.02: Distribution of crop groups among agro-ecological zones.

	DEF-orient	DEF-sud	FAV	INTERM	MONT	SAH	Sum
Cereals	7	7	10	9	7	7	47
Fodder crops	5	5	6	5	4	3	28
Fruits	13	14	13	12	10	12	74
Legumes	4	5	5	4	4	1	23
Oil crops	3	2	4	3	1	1	14
Sugar crops	2	1	3	1	0	0	7
Vegetables	8	8	8	7	8	8	47
Irrigated	27	27	29	24	20	24	151
Rainfed	15	15	20	17	14	8	89
Sum	42	42	49	41	34	32	240

It is stressed that the present study should not be taken beyond the specific limits for which it has been designed; in particular impacts should not be interpreted at a more detailed spatial scale than the six agro-ecological zones (AEZ). Since yield calibration was usually done with data at the AEZ scale, all statistics and trends that do not apply at that specific scale are at risk of being incorrect. A specific example that will be highlighted in later sections of this report is barley, which, in spite of obvious varietal improvements, does not display any technology trend at the AEZ scale, because the crop has been expanding more and more into marginal areas. A change in the context of the overall socio-economic setting and agricultural policies may alter this picture.

The simulations that lead to the results given in later sections of this report were usually run twenty times. It follows that most numeric values are averages of at least 20 values; for the "current" data and the 2030, 2050 and 2080 projections, variables were, in addition, averaged over the 30 years of the reference period, so that in the majority of cases, the individual data items are averages of at least 600 individual data items. There are about 240 unique combinations of crop and AEZ. For each of them, about 200 variables were eventually deemed worth recording. Such a volume of data cannot be described in details, and statistical clustering was used to identify the most significant patterns. The original output data are available[12].

All the results that will be presented are affected by uncertainties of various kinds[13]. Some of them are described in the report (§ 4.). The uncertainties stem from the imperfections of the analytical procedures, the statistical nature of some input data (essentially agricultural statistics and scenario projections), but also from the method adopted to present the analyses. As indicated above, we have analysed 240 combinations of crop and AEZ under different conditions. The analysis therefore includes a grouping of situations that are similar, but not identical. In addition, to simplify the presentation of results, many statements are not to be taken literally. For instance, the statement "the water requirements of rainfed grapevines in the DEF-or agro-ecological zone will increase by 17% - relative to current conditions - under scenario B2 in 2080" is given with the proviso that readers will keep the points above in mind.

12 ftp://ext-ftp.fao.org/SD/Reserved/Agromet/WB_FAO_morocco_CC_yield_impact/

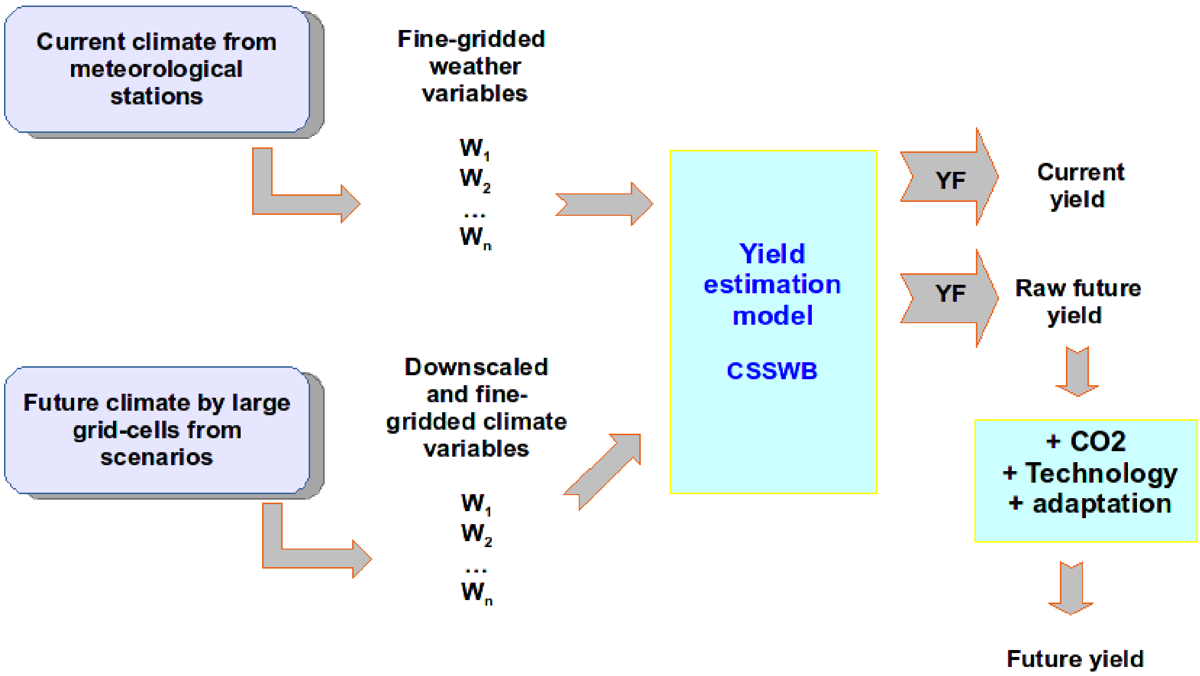
13 About eighty thousand individual crop impact data items (crop x agro-ecological zone x scenario x reference period z variable) are given in the summary files that underlie this report.

2. Methodology

2.1. Overview

The method consists in developing, for each of the crops covered by the present study a statistical function (known as Yield Function **YF**) that relates the current (historical) yields provided by agricultural statistics to prevailing climatic conditions[14] (Fig. 2.01). A simple model known as the Crop Specific Soil Water Balance (CSSWB) converts raw climate data into indicators (value-added variables) such as crop water stress and the amount of water actually available to crops in the root zone during the growing season.

Figure 2.01: General methodology and data flow into and from the Crop Specific Soil Water Balance (CSSWB) model; YF: yield function; $W_1 \ldots W_n$ are CSSWB input variables.



This could be expressed symbolically as

Current yield = YF (current_CSSWB_outputs)

Next to climate, a second major group of factors affecting yields are varietal improvement, the use of inputs such as fertiliser and pesticides, and the adoption of better management practices. They all contribute to the well-known technology trend that is present in most time series of yields.

Carbon dioxide (CO_2), the main anthropogenic greenhouse gas, in addition to its role in contributing to driving future climate through its warming potential, also plays a major part in photosynthesis. The main effect of increasing atmospheric CO_2 is a fertilisation effect, as

14 The yield functions are calibrated against detrended yield statistics, i.e. yields from which the trend component had been removed, leaving only the climate component.

CO_2 is currently limiting plant growth, accompanied by a more efficient use of soil water[15]. Therefore, future yields can be seen as resulting from several terms, as indicated in the equation below:

$$\textbf{Future yield} = \textbf{YF (future\_CSSWB\_outputs) * (1 + F(CO}_2\textbf{) * WSI) + Trend},$$

where ***future_CSSWB_outputs*** are the outputs of CSSWB obtained with scenario data, ***F(CO₂)*** is a factor depending on crop and future CO_2 concentrations, ***Trend*** is the projection of the current technology into a future (extrapolated) and ***WSI*** (0 to 100%, water satisfaction index) is a standard CCSWB output that varies from 0 to 1 and expresses the extent to which crop water requirements have been met (Frère and Popov, 1979).

2.2. Crop Specific Soil Water Balance (CSSWB)

The FAO CSSWB is a relatively coarse model that describes the water relations of a soil-plant-atmosphere system and puts out the variables (indicators, predictors) that will be used to estimate yields. Typical output variables include actual crop evapotranspiration (ETA) over certain crop growth phases (such as flowering), excess or deficit water, the above mentioned Water Satisfaction Index, and others. It is a very widely tested tool in and outside FAO (Rojas et al., 2005; Fischer et al., 2006) and is available under the names of AgroMetShell (AMS: software only) or CM Box[16] (package including training, data etc).

The main reason why a water balance provides value-added variables that are related with crop yields derives from the direct link between the water balance and the energy balance of crops. In fact, plants absorb solar energy for their photosynthesis. The radiant energy (light) is converted to chemical energy and to heat which, in turn, is used to evaporate water.

Although the mechanism is more complex (Gommes, 1998), there is a direct and linear relation between the amount of water (evapo)transpired and the amount of phosynthetates, provided water stress is not too severe, as has been known since the early work by he Wageningen school (De Wit et al., 1978) and innumerable studies since then. The linear relation holds across several orders of magnitudes of spatial scales (from leaf to plant to field to region) and provides the theoretical basis why most quantitative crop modelling resorts to evapotranspiration as the main crop simulation variable (actual examples for Morocco are shown below in the section on Water Use Efficiency, § 2.7.).

The CSSWB[17] is made "crop specific" through the use of crop specific coefficients (crop coefficients) which relate crop water demand to atmospheric evapotranspiration potential, cycle lengths and planting dates. Crops with similar crop coefficients were aggregated in the simulations, as for instance soft and durum wheat and barley, or maize, sunflower and sorghum.

The CSSWB is typically computed for point locations (typically meteorological stations, as in this study, or grid points; Table 2.01) at dekad[18] time step. Calculations start up to 10 dekads before

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15 Green-house growers sometimes artificially increase CO2 concentrations in greenhouses to increase yields and reduce water consumption (i.e. increase water use efficiency, measured in dry biomass accumulated per unit amount of water and radiant energy). See Bazzaz and Sombroek, 1996.

16 See http://www.fao.org/NR/climpag/pub/cm_box_4.pdf for an overview and additional links. Also refer to Bernardi and Gommes, 2006b.

17 A complete description is provided by Gommes, 1999.

18 A dekad is a ten-day period used in operational agrometeorology. The term derives from a WMO recommendation to distinguish dekads from decades. The dekad numbering starts in January (1-10 January, dekad 1) until December (21-31 December, dekad 36).

planting in order to ensure that realistic soil moisture values are used at the time of planting. At the end of each time step, soil moisture results from soil moisture at the beginning of the period plus water supply (rainfall and/or irrigation) less crop water requirements[19] (fig. 2.02). Soil is characterised by a water holding capacity (WHC[20]) that was assumed to be 100 mm throughout Morocco for this study. Water supply that exceeds WHC is lost through deep percolation and run-off.

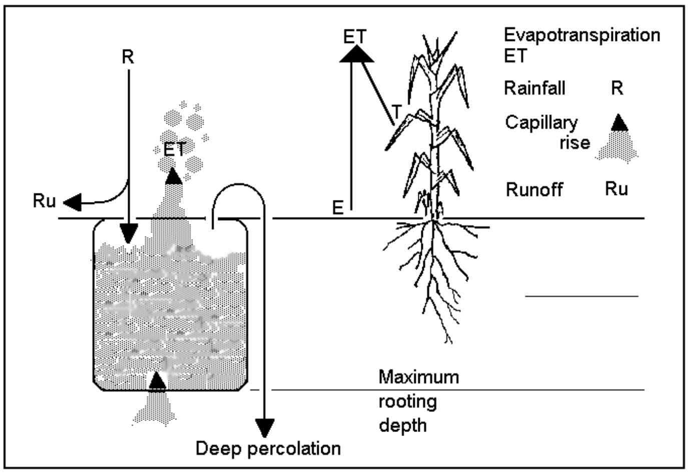


Figure 2.02: Schematic representation of a crop specific soil water balance. R: rainfall; Ru: run-off; E: soil water evaporation; T: plant water transpiration; ET: crop evapotranspiration, the sum of E and T. All variables are expressed in litres of water per m2 per day or dekad (10-day period), or mm. For this study, capillary rise of water from deeper layers was not taken into account. Illustration simplified from Gommes, 1999.

Crop water need and use are normally computed based on "reference crop evapotranspiration" (ET0 or Potential Evapotranspiration PET) using the standard equations proposed by Penman and subsequently modified by Monteith (Allen et al., 1998). The calculation of PET requires five meteorological variables: maximum temperature Tx, minimum temperature Tn, air humidity, wind speed and solar radiation. Unfortunately, the five variables are not available for future climate scenarios, so that a simplified method had to be designed in this study to estimate future PET based only on extreme temperatures Tx and Tn. This method is described hereafter as "pseudo-Penman PET" (details under § 2.4.).

Table 2.01: List of climatic stations. Refer to Annex 1 for additional details.

Agro-ecological Regions (AER) with main climatic stations
DEF-or: Oujda, Al Hoceima, Bouarfa
DEF-sud: Marrakech, Essaouira
FAV: Tangier, Taza, Meknes, Casablanca
INT: Settat
MONT: Beni Mellal, Middelt, Ifrane
SAH: Ouarzazate, Agadir, Laayoune
Mauritania: Bir Moghrein, Zouerate, Nouadhibou, Atar

Finally, actual crop water requirements depend on PET as well as crop stage and it is estimated, for each dekad of the crop cycle, by multiplying PET by the above-mentioned crop coefficient which depends on crop type and crop stage (phenology). This also assumes that crop phenology is known (especially planting dates and cycle lengths). In the current approach, cereal phenology is derived from rainfall and pseudo-Penman PET (See § 2.5), while it is assumed to be constant for other crops.

19 Provided sufficient water is available. If availability is less than requirement, crops undergo a stress.

20 The amount of water stored between the top layer and the maximum depth reached by the roots.

Water need (WN), requirement (WR) and use (WU)

While the terms above are often used interchangeably, this study adopts precise definitions that all apply at plant level (as opposed to the level of a whole irrigation system). Crops have a physiological need for water (water need, WN). The need is crop specific and depends on the evaporative power of the atmosphere (measured by PET): it is higher in dry climates than in wet ones. WR is the amount of water that should be provided to the crop in order to compensate for water deficits (difference between water supply and WN) as determined by the CSSWB. Water supply (WS) is the sum of irrigation and rainfall. For rainfed crops, supply usually differs from rainfall when rainfall is not regularly distributed over the growing cycle and part of it is lost by run-off or percolation. One way to express this is to say that WR is the amount needed to eliminate water stress and cancel interannual yield variability. WU is the amount of water that is actually available and evapotranspired. For a given location, two neighbouring fields will have different WU values (and different yields) if one is water stressed and the other is not. A fourth type of water requirement (the "EcoCrop water requirement") will be referred to below (see § 2.12.2. and § 3.5.1.).

As the simulations that are described in this report correspond to a very large number of calculations, a specific CSSWB software was developed (WABAL3). The software uses crop, soil and climate data as inputs. Since no data are available on irrigation water amounts, an "automatic irrigation" option was included: every time a crop undergoes a water stress, the programme adds just enough water to compensate for the stress.

2.3. Overall description of data flow

The description of the modelling procedure and the associated data flow is illustrated in Figure 2.03. To facilitate the description, five main flows are identified and indicated by yellow numbers on a blue field.

1. Based on a comprehensive set of current historical climate data (33+4 stations, 1961-2006), a method was developed to estimate crop water requirements using only the limited subset of variables available for the scenarios, i.e. maximum and minimum temperatures. The method will be referred to as "**pseudo-Penman potential evapotranspiration**." This is covered below in some detail under § 2.4.. The same data set was used to test pseudo-Penman potential evapotranspiration and to derive cycle lengths from rainfall and pseudo-Penman PET (§ 2.5.).

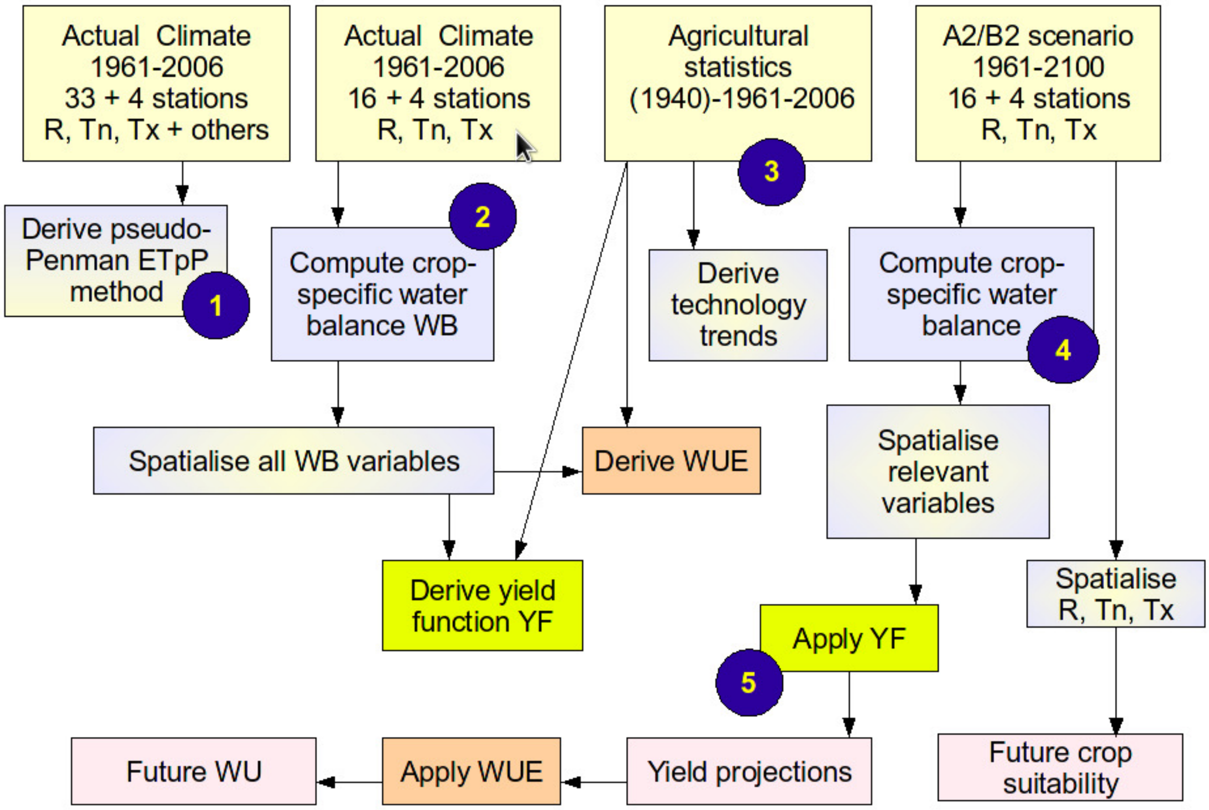
2. CSSWB is computed for current conditions for a limited subset of 16+4 stations, using only stations for which scenario data are available as well. The stations were selected to provide an acceptable coverage of the country[21] and the agro-ecological regions that are adopted in this study. The Mauritanian[22] stations were added to ensure spatial continuity over the whole Moroccan territory, including non-agricultural areas.

The complete list of CSSWB output variables is given in Annex 2.

21 In Morocco, the coverage of climatic stations in mountainous areas tends to be weak.

22 The authors wish to acknowledge the kind assistance of Dr. Gandega Yelli (Mauritanian Meteorological Service) in providing the data free of charge. An attempt was also made to include some Algerian stations, but this could not be accommodated in the limited budget of this study.

Figure 2.03: Overall data flow. R, Rainfall; Tn, minimum temperature; Tx, maximum temperature; ETpP, pseudo-Penman PET; WB, water balance; WU, water use; WUE, WU efficiency; YF, yield function.



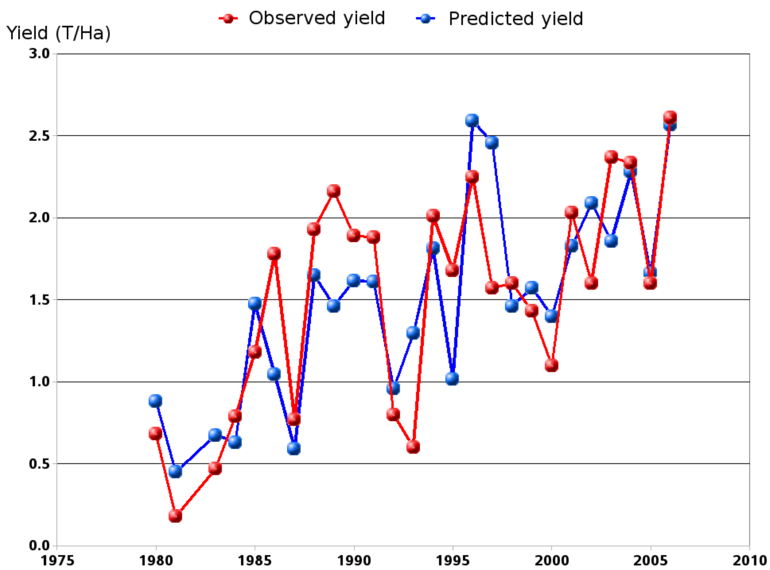


Figure 2.04: Sample comparison of agricultural yield (T/Ha, ordinate) obtained from statistics (red, observed yield) and from simulations (blue, predicted yield) for irrigated durum wheat in ORMVAs. Two variables (EXCf_irr, Smoist_cyc_irr) account for 62 % of variability and the technology trend is close to 20 Kg/Ha/year.

All the CSSWB output variables were spatialised to a 10 km grid (100 km² per grid cell), year by year, using the AURELHY methodology and averaged over the areas for which agricultural statistics are available, i.e., depending on the crop, the national level, the province or the ORMVA (Office Régional de Mise en Valeur Agricole). The AURELHY spatialisation method is described under § 2.10..

The specific purpose of the spatialisation is to bring climate data and agricultural statistics to the same spatial denominator. The averaged CSSWB output variables by administrative units and ORMVAs constitute a central dataset in the present study, as it was used to derive yield functions (YF, refer to § 2.6.) and water use efficiencies (WUE, details under § 2.7.). For most crops, especially the ones for which "good" statistical data are available, the quality of yield functions would be sufficient to use them for present day applications in crop forecasting, risk assessments, insurance and market planning. An example is shown in Figure 2.04. The example is not a particularly good one in statistical terms, as the coefficient of determination reaches only 0.62, while significantly higher values are obtained with some other crops. It is also stressed that, in this case, the data that were available for calibration of irrigated yields were obtained from ORMVA statistics.

3. In addition to their just mentioned use in the derivation of WUE and YF, agricultural statistics are also the basis for the determination of technology trends. The point is discussed with more detail under § 2.8.. The data used mostly refer to the period from 1961 to 2006, but for some crops, longer time series had to be resorted to, essentially because a recent drop in rainfall from the mid eighties has slowed down or occulted recent short-term trends.

4. Yield functions and technology trends applied to scenario data are the main ingredients of the yield projections. For the scenarios A2 and B2 data aggregated to dekad values, the CSSWB was run 20 times for each year between 1979 and 2099. For each year, all the variables that are used as yield predictors[23] are spatialised and averaged. The period 1979-2006 is then taken as the base line, the 600 values from 2011 to 2040 are averaged to yield the "2030", 2041 to 2070 provides "2050" and the 2071-2099 is taken to represent "2080". Note that, for the current period, the baseline yield differs from actual statistics conditions, as there are two values corresponding to scenarios A2 and B2, and because there are 20 replicates for each scenario, while agricultural statistics represent just one realisation. The fact that yields are available only for a limited number of years makes it very difficult to compare variability patterns between simulations and actual conditions. This specific point is discussed in sections 2.9. and 4.5..

5. Once yield projections have been obtained, they can be combined with WUE values to determine actual water use.

2.4. Pseudo-Penman potential evapotranspiration

The main reason why we had to derive a “pseudo-Penman” method is the absence of scenario projections for the variables required by the full Penman-Monteith method.

The evaporative water demand of the atmosphere is a physical variable that varies according to weather. There exist a number of methods, but many of them are valid only under specific circumstances or in specific locations (Choisnel et al., 1992, for a comparative study of methods). The most general method is the one originally developed by Penman, and subsequently refined by various authors. The current standard is considered to be the "FAO Penman-Monteith" (PM) equation described by Allen, R. G., L.S. Pereira, D. Raes, and M. Smith, 1998. Unfortunately, the PM equation requires several variables[24] that are not always available, particularly in climate change scenarios. It is thus necessary to develop a simpler

23 Only the variables used as predictors for the various crops were spatialised, as spatialisation is a time consuming process.

24 (temperature: maximum and minimum; solar energy or right sunshine hours; wind speed and air moisture).

method that requires only the two more common variables maximum temperature and minimum temperature (Tx and Tn) and the derived value $T_{avg} = (Tx+Tn)/2$.

Hargreave's evapotranspiration ET_H equation (see Choisnel et al., 1992)

$$ET_H = 0.0023\ R_a\ (T_{avg}+17.8)\ \sqrt{Tx - Tn}$$

uses Tx as a proxy for radiation, Tn as a proxy for air moisture while Tx - Tn are related to wind speed; Ra is the extraterrestrial solar radiation. Note that the thermal amplitude Tx - Tn appears under the square root sign. Since Tn indirectly estimates air moisture, the Hargreaves and Penman equations tend to differ in the most arid locations, i.e., in Morocco, there is a simple N-S and E-W gradient. It was also found that the ratio ET_{PEN}/ET_H departs from the zonal value along the sea (ocean). However, the ratio undergoes remarkably little seasonal variations (<5%), so that ET_{PEN}/ET_H could be spatialised and used for all ET calculations[25]. Fig. 2.05 illustrates the spatial variations of the ratio between ET_{PEN} and ET_H.

Figure 2.05: Spatial variations of the ratio between Penman-Monteith and Hargreaves estimations of evapotranspiration.

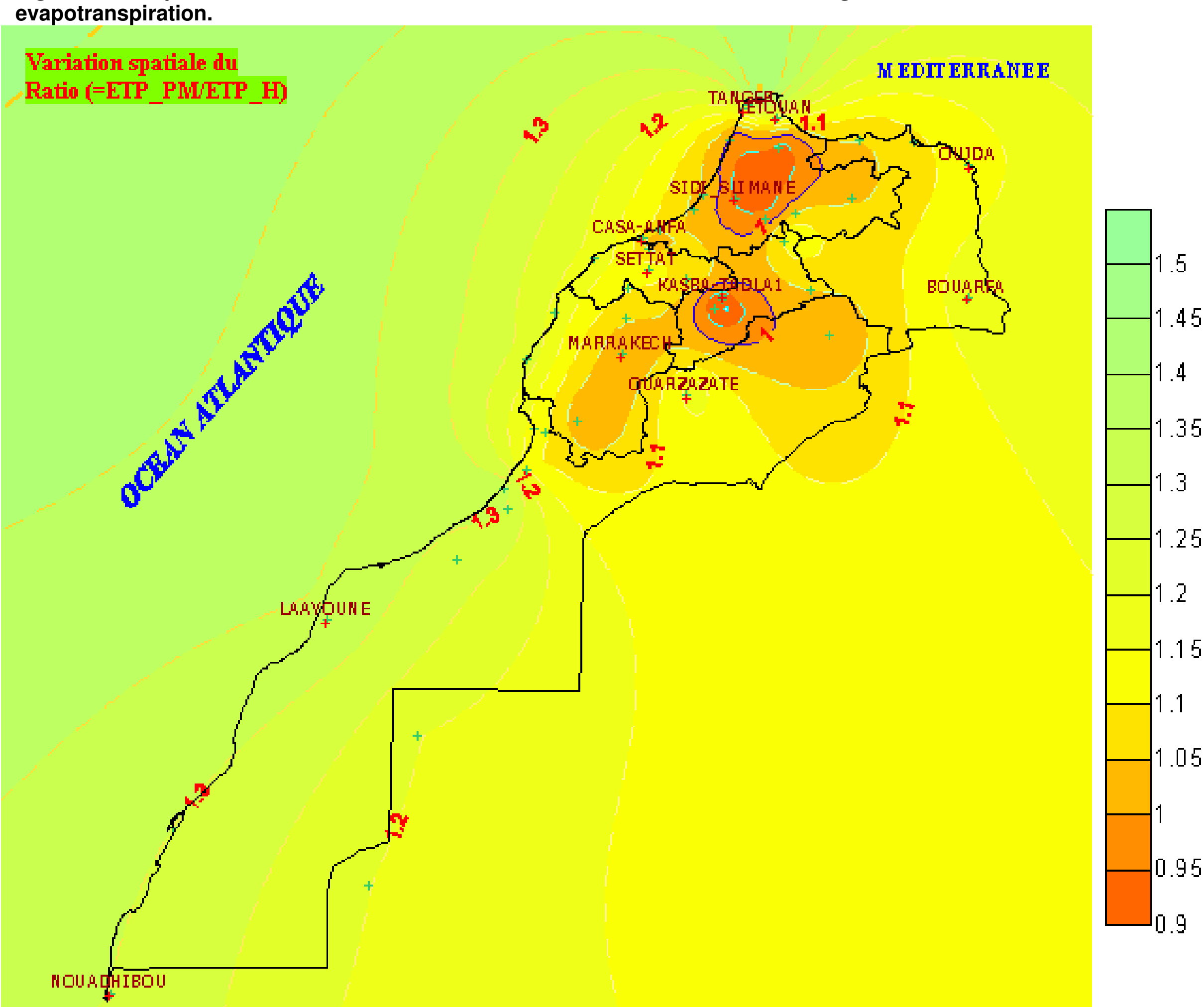
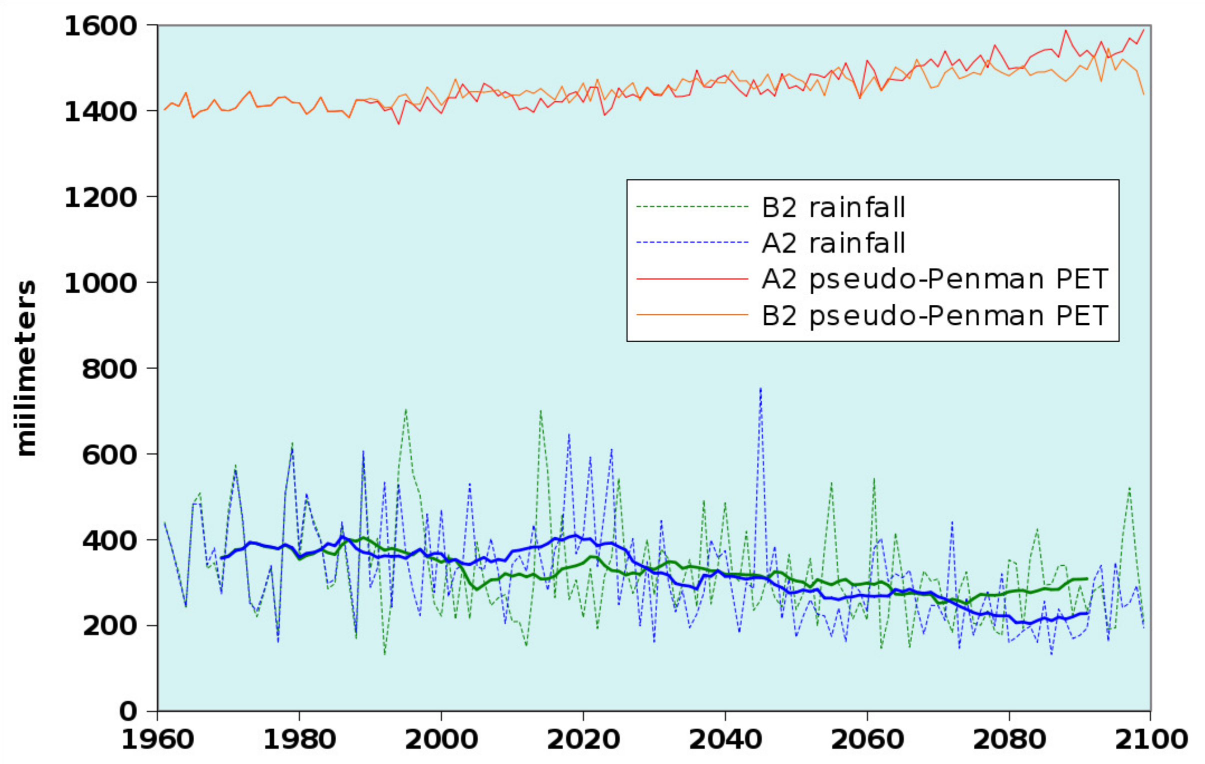


Figure 2.06 shows an example of rainfall and pseudo-Penman PET for the station of Settat, INT agro-ecological zone. The figure shows that PET is significantly less variable than rainfall and that the values for the scenarios A2 and B2 remain relatively similar until the end of the

25 The Penman-Monteith Vs. Hargreaves calibration is based on 40 Moroccan and 3 Mauritanian stations covering the period 1979-2005.

century, when A2 values tend to systematically exceed B2.

Figure 2.06: Annual totals of rainfall and pseudo-Penman PET in Settat between 1960 and 2100 according to the scenarios A2 and B2. The heavy lines on the rainfall curves represent 17-year moving averages.



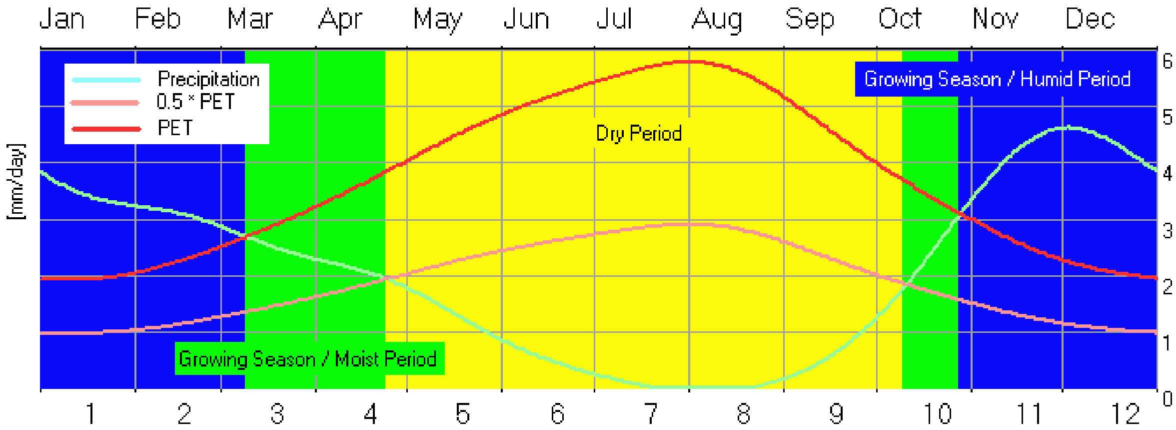
2.5. Phenology using Franquin's method

Franquin's method was resorted to as no systematic phenological observations are available for Morocco. The approach has become a classic method that was originally used in many FAO and WMO studies to derive rainfed growing period and their characteristics from climatic data (Cochemé and Franquin, 1967; FAO, 1978). It continues to be used in very diverse contexts today (e.g. Odekunle, 2004; Ilunga and Mugiraneza, 2006; De La Casa and Ovando, 2006; Djoulde Darman et al., 2008).

The approach is illustrated in figure Fig. 2.07. It was used, in the present study, for cereals only. For other crops, cycle lengths were kept at the current level since irrigation somehow protects phenology against qualitative climate change effects.

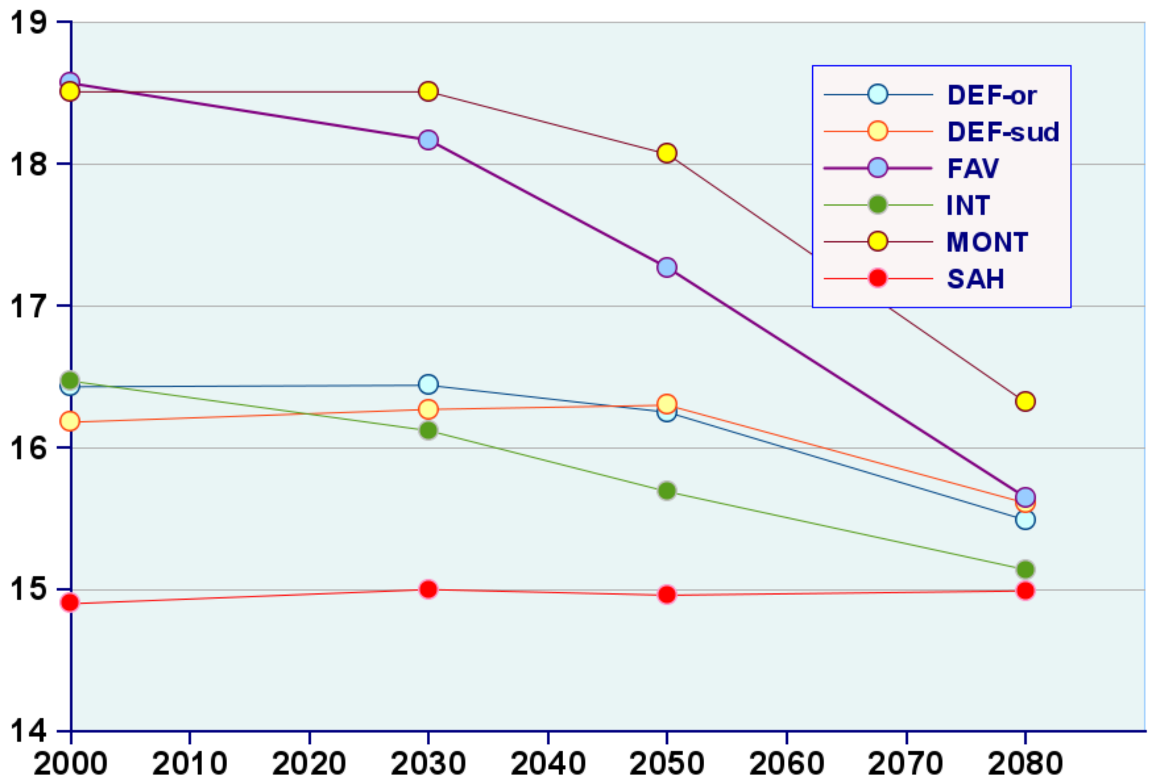
The rainfed growing season starts when Rainfall exceeds a given fraction Kc of PET, i.e. Kc=0.5 in the example illustrated in figure 2.06. The fraction is crop dependent and is related to the initial crop water need. In the example above, planting occurs on 10 October. The "intermediate period" (Rain < PET) gives way to the "humid period" on 28 October. The humid period ends on 8 March and the season itself on 23 April, for a total duration of the season of 196 days, just short of 20 dekads.

Figure 2.07: Determination of length of growing period (LGP) according to Franquin, using average input data. Ordinate: mm/day for rainfall, PET and 0.5PET. Blue: humid period when Rainfall exceeds PET; green: intermediate period with PET/2<rain<PET; yellow: dry period when Rain <PET/2. Abscissa: months, from January to December. The data correspond to the implementation of Franquin's method station of Tangier based on the data in New_LocClim (ftp://ext-ftp.fao.org/SD/Reserved/Agromet/New_LocClim/).



A specific software (PLDEK) was developed for the present project, which can be applied to average conditions (as above) but also to annual values. This is often difficult to achieve when rainfall variability in any given year results in several crossings of the PET and rainfall curves.

Figure 2.08: Changing wheat cycle lengths by agro-ecological zones.



2.6. Yield functions and their calibration

Different levels of significance are achieved for the yield functions, according to the crop, region and the amount of water control. In general, due to better agricultural statistics, Yield Functions are more reliable for the main crops, such as the main cereals.

Table 2.02: Main calibration variables for all crops according to AEZ. ETt_rain, total evapotranspiration (ET) under rainfed conditions; EXCf_rain, excess water at the time of flowering under rainfed conditions; EXCt_rain, excess water over the total cycle under rainfed conditions; r_cyc_rain, rainfall over the crop cycle; DEFh_rain, water deficit in the final part of the crop cycle, rainfed conditions; smoist_cyc_irr, average soil moisture over the crop cycle under irrigated conditions; smoist_cyc_rain, average soil moisture over the crop cycle under rainfed conditions; ETf_rain, ET at the time of flowering, rainfed conditions; EXCv_rain, excess water during the vegetative phase, rainfed conditions; r_cyc_irr, rainfall over the cycle, irrigated conditions; ETi_rain, ET during the initial phase, rainfed conditions; smoist_pres_irr, average pre-season soil moisture, irrigated conditions (before irrigation started).

	FAV	DEF		INT	MONT	SAH	n
		or	sud				
ETt_rain	2	4	3	2			11
EXCf_rain	5		3	2			10
EXCt_rain	2	1	4		3		10
r_cyc_rain	2	1	2	1	2	2	10
DEFh_rain	4		1		1	3	9
smoist_cyc_irr	1	3	2		1	2	9
smoist_cyc_rain	2	1	1	2		2	8
ETf_rain	5			2			7
EXCv_rain		1	2		2	2	7
r_cyc_irr		2		5			7
ETi_rain	1	2	1	1		1	6
smoist_pres_irr	2	3				1	6

When no statistical significance could be achieved at the regional level, the next level (national) was taken into account. On the contrary, for some irrigated crops, a lower level of aggregation (ORMVA) was adopted. For all crops that did not result in significant regressions, it was assumed that yield is proportional to the total amount of evapotranspiration accumulated over the crop growth cycle. This is equivalent to water use (WU). When no reference yield was available (as with range land), results are given in relative terms (current A2 and B2 WU values taken as 1).

A total of 43 different variables were actually used in the calibrations, although the total list include 49 (refer to annex 3 for a complete list of the variables). Twelve are shown in Table 2.02, i.e. the ones that occur most frequently, together with the AEZ where they are used. Note that all crops were simulated for rainfed and for irrigated conditions (i.e. automatic irrigation). This explains why several variables in Table 2.02 appear as both and _irr variant and a _rain variant.

Some calibration details are given for barley in Table 2.03. For barley straw yield, an important "crop" for which no statistics exist, an indirect approach was used, considering that grain represents 60% of the above-ground biomass under favourable conditions. The 60/40 ratio drops to 20/80 under bad conditions[26]. The quality of a season (good or bad) was based on the water satisfaction index (WSI). For a specific agro-ecological zone, WSI_{min} and WSI_{max} were extracted for the current period. Above WSI_{max}, straw = grain / 1.5 and below WSI_{min}, straw = grain x 4. Values were interpolated linearly between WSI_{min} and WSI_{max}.

Table 2.03: Coefficients of determination for barley as calibration (R2) and cross validation (Rp2), absolute and relative forecasting errors, and share of national production harvested in each of the AEZs during the 1980-2006 period.

AEZ	R^2	R_p^2	Error (T/ha)	Error (%)	% Prod.
FAV	0.9083***	0.8746***	0.13	15.7	22.8
DEF-or	0.6819***	0.5391***	0.17	23.3	13.5
DEF-sud	0.6537***	0.5384***	0.22	40.0	28.1
INT	0.7848***	0.7410***	0.20	31.8	20.5
MONT	0.4051***	0.3213**	0.33	39.3	9.4
SAH	0.7418***	0.6660***	0.16	24.4	5.7

, * Significance level 0.01 and 0.001, resp.

An overview of the strength of the regressions is shown in Table 2.04. The following typologies are not included because insufficient data were available to carry out a meaningful calibration: Barley_rf, Maize_rf, Oats_rf, Rice_rf, Citrus_rf, Chickpea_rf, Vetch_rf (bitter), Vegetables_rf, Bean_rf (Faba), Barley_irr, Oats_irr, Rice_irr, Chickpea_irr, Vetch_rf (Bitter), Tomato_irr (industrial). For the following crops, the calibration also included ORMVA data: wheat_rf (durum), wheat_rf (soft) and sugar beet.

26 Personal communication of Elcio Perpetuo Guimaraes, FAO.

Table 2.04: Significant coefficients of determination for yields of the main crops, by AEZ. _irr: irrigated; _rf: rainfed; _mix: mixed rf and irr; _gh: greenhouse; _of: open field. ND indicates that available data are insufficient to carry out a meaningful calibration, while NE means that calibration was not done, although it may be possible.

	FAV	DEF-or	DEF-sud	INT	MONT	SAH	NAT
Alfalfa_irr	0.299	0.659	0.441	0.000	ND	0.446	NE
Alfalfa_mix	NE	NE	NE	NE	NE	NE	0.408
Alfalfa_rf	0.913	0.769	0.702	0.000	0.000	0.326	ND
Barley_mix	0.908	0.682	0.654	0.785	0.405	0.742	NE
Bean_irr (Faba)	ND	ND	ND	ND	ND	ND	ND
Bean_mix (Faba)	0.820	0.334	0.459	0.422	0.736	0.745	NE
Chickpea_mix	0.000	ND	0.000	0.000	0.765	ND	NE
Citrus_irr	0.000	0.000	0.583	0.000	0.000	ND	0.500
Fodder_irr	0.349	0.755	0.000	0.000	0.000	0.000	NE
Fodder_mix	NE	NE	NE	NE	NE	NE	0.771
Fodder_rf	0.804	0.379	0.750	0.911	0.292	ND	ND
Groundnut_mix	0.229	ND	ND	0.229	ND	ND	0.229
Legumes_mix	0.619	0.410	0.577	0.639	0.517	0.706	NE
Lentil_irr	0.289	ND	ND	ND	ND	ND	ND
Lentil_mix	0.819	0.303	0.241	0.742	0.678	ND	NE
Lentil_rf	0.611	0.619	0.513	0.747	0.608	ND	NE
Maize_irr	0.449	ND	0.000	0.506	ND	0.183	ND
Maize_mix	0.125	0.024	0.461	0.497	0.011	0.085	NE
Niora_irr	ND	ND	ND	ND	ND	ND	0.000
Oats_mix	0.297	0.497	0.736	0.321	0.410	ND	NE
Olive_irr	0.000	0.336	0.385	0.828	n.a.	0.000	NE
Olive_mix	0.418	0.581	0.772	0.341	0.411	0.000	NE
Olive_rf	0.427	0.585	0.631	0.376	0.411	0.729	NE
Potato_irr (early)	ND	ND	ND	ND	ND	ND	0.345
Potato_irr (seasonal)	ND	ND	ND	ND	ND	ND	0.834
Sorghum_mix	0.000	ND	ND	0.000	ND	ND	NE
Sugarbeet_rf	0.214	ND	ND	ND	ND	ND	NE
Sugarcane_irr	0.187	ND	ND	ND	ND	ND	ND
Tomato_gh (early)	ND	ND	ND	ND	ND	ND	0.518
Tomato_gh_of (early) ***	ND	ND	ND	ND	ND	ND	0.826
Tomato_irr (industrial)	ND	ND	ND	ND	ND	ND	0.000
Tomato_irr (open field)	ND	ND	ND	ND	ND	ND	0.599
Tomato_irr (seasonal)	0.398	0.000	0.432	0.000	0.226	0.000	0.000
Vegetables_irr	0.637	0.467	0.000	0.000	0.245	0.211	ND
Vetch_mix (bitter)	0.480	ND	ND	ND	ND	ND	NE
Wheat_irr (durum)	ND	ND	ND	ND	ND	ND	0.623
Wheat_irr (soft)	ND	ND	ND	ND	ND	ND	0.376
Wheat_mix (durum)	0.911	0.693	0.671	0.761	0.507	0.498	0.498
Wheat_mix (soft)	0.916	0.299	0.714	0.800	0.683	0.658	0.474
Wheat_rf (durum)	ND	ND	ND	ND	ND	ND	0.850
Wheat_rf (soft)	ND	ND	ND	ND	ND	ND	0.639

2.7. Water use efficiencies (WUE)

2.7.1. Background

The specific reason why a fair amount of attention is given to WUE derives from the need to asses the additional water needs associated with the "technology trend" that affects many crops in Morocco. The trend is made up by a mix of varietal improvement, mechanization, "better" irrigations systems, increased use of inputs, probably use of information (e.g. weather and seasonal forecasts) and better farm management. The exact share of the factors that make up the trend is impossible to determine, among others because it has changed over time and according to regions[27].

The yield projections for 2030, 2050 and 2080 include several options, i.e. "current technology" (CTech, calibrated against recent detrended yield statistics), CTech plus technology trend (Ctech + Ttrend) and Ctech + Ttrend + CO_2 effects. CO_2 effects include CO_2 fertilization and improved water use efficiency due to stomatal control. The CO_2 effects are usually low or very low, essentially because they cannot express themselves due to water stress[28].

Together with the above-mentioned changes in cycle length (§ 2.5), the technology trend remains one of the most important indicators of what could be termed "adaptation to climate change". Other components of adaptation, e.g. changing cropping patterns, adoption of different irrigation methods etc. cannot be assessed when using static modelling as in the present study. While most crops will experience decreasing yields under Ctech conditions, the inclusion of Ttrend offsets the negative climate change impact in many cases. It is obvious that the yield that corresponds to Ctech + Ttrend will have to be paid for with water, and the crucial question is "how much water will be needed to achieve the Ctech + Ttrend yield?"

2.7.2. Method

Current raw[29] national yields are regressed against total actual evapotranspiration as computed using the WABAL programme. The procedure is illustrated in Figure 2.09a in the case of soft wheat, following the general approach based on the work of Albrizio & Steduto (2005), Steduto & Albrizio (2005), Sadras & Angus (2006), Steduto et al. (2007), Keller & Seckler (2008) and Jlibene et al. (2008). Note that, in the present study, yields are regional yields, while in all the other studies quoted the approach refers to data from experimental fields. It remains that the well know observation of the direct and mostly linear relation between water (evapo)transpiration and biomass accumulation (roughly: photosynthesis) is observed with our Moroccan regional data as well, which both confirms the soundness of the simple water balance methodology and provides an additional illustration of the fact that the direct link between transpiration and plant productivity holds across the scales from leave to plant to field (de Wit et al., 1978) and region as well (refer to § 2.2).

If, in figure 2.09a we express yield Y as

intercept + slope * ETT,

we can compute X0 as the ratio -intercept/slope of the regression line. The interpretation of X0 is probably dependent on the spatial scale: it is a measure of the amount of total

27 Some factors, e.g. mechanisation and inputs are available, but at an insufficient level of detail to be analysed meaningfully.

28 On the other hand, crops grown in greenhouses with artificially increased CO_2 and ample water and nutrient supply do display the effects.

29 Raw = with the trend included.

evapotranspiration (ETT) below which no yield is achieved. Rainfall necessarily equals or exceeds ETT, X0 is also a measure of the minimum amount of rainfall below which no rainfed crops can be grown. Note that X0 itself is a measure of the level of technology.

Figure 2.09a: Plot of national 1980-2006 rainfed soft wheat yield against total actual evapotranspiration ETT in mm; Figure 2.09b: Determination of average water use efficiency (WUE) as the slope of blue curve [0.00852514 tons/(Ha.mm)] and maximum ("best") WUE corresponding to the upper limit of observed points [0.0130012 tons/(Ha.mm)].

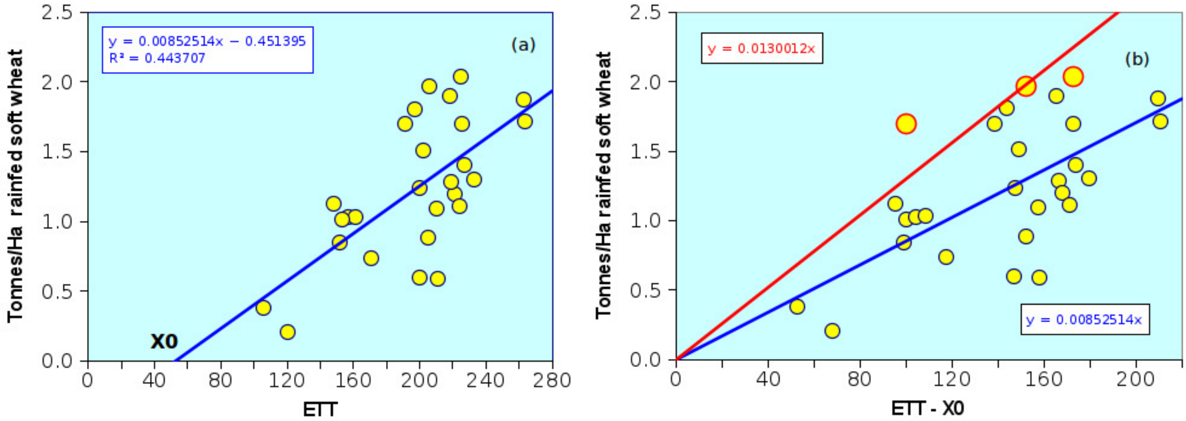


Figure 2.09a Figure 2.09b

In the next step (Figure 2.09b), yields are regressed against ETT - X0 and forced through the origin. This corresponds to the blue line in the figure and the slope measures WUE_{avg}[30] in Tons/(Ha.mm) and describes "average" conditions. To obtain the red curve, observations are subdivided into three groups separated by the 1st and second terciles, followed by the determination of the median ETT-X0 value in each group as well as the maximum Yield (red circles in Figure 2.09b). The regression line through the origin of the maximum yields against ETT - X0 provides the upper limit of water use efficiency (WUE_{max}) under current conditions in Morocco.

As indicated in the above-mentioned publications, WUE_{max} is very closely linked to the intimate mechanisms of photosynthesis and can legitimately be considered a crop constant that will not change significantly in the future with improved varieties. Of course, it is likely that WUE_{max} it itself scale and location dependent, but since it results from modelled crop evapotranspiration, it is very largely independent of non-crop factors, including the efficiency of irrigation systems. One of the potential ways in which breeding can affect WUE is through the harvest index, but it can be assumed that here too there are limits that cannot be exceeded to avoid lodging and other problems. An interesting case, but probably too far-fetched for the present study is the likely influence of higher CO_2 on biomass partitioning between root, shoot and leaves, and grain.

The procedure works well for all rainfed and most irrigated crops. For crops that can be rainfed or irrigated, we have used the rainfed crops' data to derive X0 and WUE_{max}. Similarly, "good results" are achieved for all crops that are always irrigated[31], with the exception of rice and Niora. For rice and Niora, where we find a near-independence between yield and ETT, the same procedure can still be applied if, instead of computing X0, we use the lowest observed ETT value as X0. The values that are achieved in this case are, for rice: X0=150.34, WUE_{avg}=0.0522696 Tons/(Ha.mm) and WUE_{max}=0.0908388 Tons/(Ha.mm) and for Niora: X0=99.53, WUE_{avg}=0.0676233 Tons/(Ha.mm) and WUE_{max}=0.108793 Tons/(Ha.mm).

30 Note that Tonnes/(Ha.mm) can easily be converted to the standard Kg/m3 by multiplying its numeric value by 100.

31 They include alfalfa, banana, tomato, ground nuts, vegetables, sugar cane, citrus, *rosaceae* except almond.

2.7.3. Estimated WUEavg and WUEmax for Morocco

The results are listed in Table 2.05, X0 values are actually meaningful only for rainfed crops, as actual evapotranspiration for irrigated crops is based on an “automatic irrigation” option of WABAL. The methodology to estimate actual WUE under non CTech conditions can use either WUE_{avg} (pessimistic) or by WUE_{max} (optimistic). It was eventually decided to adopt the "pessimistic" option and assume that water use is unlikely to be optimal, among others because irrigation systems are rarely optimal, even if water use can be optimised at plant level.

The final WU data have thus been estimated as

$$WU = yield/WUE_{avg} + X0.$$

In the specific case of barley, the same WUE_{avg} was adopted for grain and for straw.

Clearly, the fact whether the water needed to achieve projected yields will or will not be available is beyond the scope of this part of the study.

Table 2.05: Water use efficiencies (WUE) computed for Morocco based on national yield statistics and WABALestimated actual evapotranspiration. WUE is expressed in Kg/m3. The references in the last column are the following: a) Shatanawi et al., 2007; b) Algahriani, 2007; c) Karaa et al., 2007; d) Impa et al., 2005; e) Webber et al., 2007; f) Taley et al., 2003; g) Tang & Tann, 1977; h) Zwart & Bastiaanssen, 2004. Values (*) for rice, bananas and niora are taken from the literature. Values (**) for range land are arbitrary.

Crop	X0 (mm)	WUE average (Kg/m3)	WUE max. (Kg/m3)	WUE max/ avg	Reference values
Alfalfa	188	6.1	7.1	1.2	1.03(b)
Almond	49	0.7	0.8	1.1	
Apple	262	2.4	2.7	1.1	
Apricot	262	2.4	2.7	1.1	
Banana(*)				1.0	0.90(f),3.11(g)
Barley	22	0.5	0.8	1.6	0.96(b),1.59(f)
Barley(straw)	22	0.5	0.8	1.6	
Bean(dry)	65	0.4	0.7	1.5	0.38(e)
Bean(faba,dry)	55	0.7	1.4	2.0	
Chickpea	65	0.4	0.7	1.5	4.2(a)
Citrus	357	2.2	2.8	1.3	1.56(b)
Dates	823	0.2	1.1	4.3	
Fig	140	4.9	5.9	1.2	
Fodder(irrigated)	13	13.7	16.5	1.2	
Fodder(rainfed)	48	7.9	13.7	1.7	
Grapevine(irrigated)	446	1.9	7.2	3.8	3.02(b)
Grapevine(rainfed)	31	1.0	5.4	5.5	
Groundnut	608	0.9	1.2	1.4	1.58(f)
Lentil	3	0.5	1.1	2.4	
Maize(irrigated)	17	0.2	0.6	2.6	1.95(c),2.01(f),2.64(h)
Maize(rainfed)	17	0.2	0.6	2.6	1.95(c),2.01(f),2.64(h)
Niora	150	0.3	0.5	1.8	
Nut	409	0.7	1.0	1.4	
Oats	8	0.4	0.8	2.1	1.45(b)
Olive(irrigated)	19	0.5	0.7	1.5	0.80(b)
Olive(rainfed)	19	0.5	0.7	1.5	0.80(b)
Pea(dry)	65	0.4	0.7	1.5	
Peach	262	2.4	2.7	1.1	
Pear	262	2.4	2.7	1.1	
Plum	262	2.4	2.7	1.1	
Pomegranate	385	1.6	2.0	1.2	
Potato(early)	48	0.6	0.7	1.2	4.73(b)
Potato(seasonal)	48	0.6	0.7	1.2	4.73(b)
Rangeland(**)	100		0.0	1.0	
Rice	150	0.6	1.6	2.7	5.4(d),1.84(h)
Sorghum	9	0.4	0.4	1.0	0.97(b),4.58(f)
Sugarbeet(irrigated)	377	9.7	14.0	1.5	
Sugarbeet(rainfed)	377	9.7	14.0	1.5	
Sugarcane	79	24.5	32.7	1.3	4.61(f)
Sunflower	40	0.5	0.8	1.6	0.89(c),0.96(f)
Tomato(early,greenhouse)	369	9.2	11.4	1.2	3.54(b)
Tomato(early,openfield)	369	9.2	11.4	1.2	
Tomato(Industrial)	369	9.2	11.4	1.2	
Tomato(seasonal)	369	9.2	11.4	1.2	
Vegetables(seasonal)	150	0.3	0.5	1.8	7.1(b,onion),2.87(b,watermelon),7.94(f)
vetch(bitter)	65	0.4	0.7	1.5	
Wheat(durum,rainfed)	27	0.5	1.4	3.0	0.66(b),2.27(f),1.63(h)
Wheat(durum,irrigated)	27	0.5	1.4	3.0	0.66(b),2.27(f),1.63(h)
Wheat(soft,irrigated)	53	0.9	1.3	1.5	0.66(b),2.27(f),1.63(h)
Wheat(soft,rainfed)	53	0.9	1.3	1.5	0.66(b),2.27(f),1.63(h)

2.8. Technology trend

The spatial scale at which trends could be identified in agricultural statistics is given in Table 2.06. Whenever possible (i.e. whenever statistically significant), the trend corresponding to the agro-ecological zone was used. However, in some cases, mostly when the number of data points available in the agricultural statistics at the AEZ scale were insufficient to achieve significance, national trends were used.

Table 2.06: Trends identified in Moroccan crops by major crop group. Rosaceae stands for all the fruits trees related to apples (apples, pears) and plums (plum, apricot...). Regional trends are those identified at the level of agro-ecological zones.

CATEGORY	Regional trend	National trend	No significant trend	Insufficient data
Cereals	Maize (irrigated), Rice	Soft wheat, Durum wheat	Barley, Oat, Maize (rainfed), Sorghum	
Fodder crops	Other fodder crops (rainfed). Other fodder crops (irrigated)		Alfalfa	Rangeland
Fruit crops			Citrus, Vine (irrigated), Vine (Rainfed), Date	Rosaceae, Banana, Fig, Pomegranate, Nut
Legumes			Dry faba bean, Chickpea, Legumes (Dry bean, Dry pea), Bitter vetch	
Oil crops	Groundnut		Sunflower, Olive (irrigated), Olive (rainfed)	
Sugar crops	Sugar beet (rainfed),Sugar beet (irrigated)		Sugar cane	
Vegetables	All seasonal vegetables	Seasonal tomato, Seasonal potato, Early tomato (greenhouse). industral tomato, early potato	Early tomato (open field), niora	

2.9. Current and predicted yield variability patterns

2.9.1. Statistics adopted to assess future risk

For all crops covered by this study, all simulations have been carried out six hundred times for each scenario, six hundred being the product of twenty scenario runs and thirty years for each reference period (base-line or 2000, 2030, 2050 and 2080). As noted in section 4, there is no certainty that the scenario data are reliable enough to realistically predict the future statistical features of climate variability. There are some indications that they underestimate variability for the baseline period, and may do so for the projections as well.

In addition, as yields in semi-arid areas are very closely linked to rainfall, the statistical distribution of yields tends to follow the statistical distribution of rainfall, i.e. it exhibits mostly a marked positive skew[32]. As a result, the mean is not the "expected value" nor is it the "most probable" one and the standard deviation as a measure of dispersion is mostly meaningless.

32 A positive skew is characterised by many low values and a few high and very high ones. An extreme case is the J-shaped curve that is characteristic of rainfall in semi-arid and arid areas: most values are 0, with some extremely high ones.

We have therefore adopted the following parameters:

- low yield probability. Low yield is the yield which corresponds to frequency of exceedence of 90% under the baseline (current) conditions, i.e. a yield as bad as the "low" yield currently occurs only one year in ten. Low yield probability is the frequency of occurrence of "low yields" in the future. The percent change in low yields thus indicates by how much low yields will increase;
- the lowest decile (D1) and the highest decile (D9), as well as the interdecile range (D9-D1) are used to assess how yield dispersion and risk will change. Even if they are arguably the best parameters available for the current purpose, D1, D9 and D9-D1 remain imperfect statistics. This is because the frequency of zero yields will increase and therefore D1, D2, D3 etc. tend to take the same value, thereby taking much significance out of the low values, while D9 remains useful. The deficiencies of D1 naturally also apply to D9-D1.

2.9.2. A case study: does the adopted simulation procedure preserve current (1979-2006) frequency distributions of rainfall and barley yield?

Simulated rainfall shows bimodal distributions in FAV, INT and MONT zones. We have verified that the bimodality was present in the downscaled climate change scenarios at individual stations, and that it is not an artefact due to the AURELHY technique.

The rainfall distributions translate into bimodal distributions in simulated yield particularly for the INT and MONT zones. FAV zone yield is less affected by rainfall distribution.

In the specific case of barley, observed yield distributions (=current yields from agricultural statistics) for all zones can be considered as normal, but only one zone of simulated yield shows normal distribution (DEF-or). INT, DEF-sud and MONT zones show skewed yield distributions. The simulated yields in INT and DEF-sud exhibit a lognormal (i.e. skewed) distribution rather than a normal distribution. Comparisons are difficult as observed baseline-yields are very few, especially at the level of the AEZ, so that statistics are mostly ambiguous. On the other hand, 600 simulated yields provide much clearer information about distributions.

One of the problems with INT and DEF-sud is that there are negative values computed from the yield functions (18 and 45 out of 1120 values, respectively). The correlations for yield functions are good (R^2p=0.74 and 0.54 respectively) but their yield functions have the lowest negative intercepts.

In Table 2.07, we present mean, standard deviation, and skewness for all cases. Mean and standard deviations for observation and simulation agree well.

Clearly, given the limited number of observed yield data, the comparison with the simulations is not so easy.

We therefore resorted to using a longer yield time series (starting in 1940) to compare it with simulated yields. Interestingly, observed yield and rainfall (at national level) show bimodality too, although the bimodality in rainfall is much weaker than that of yield. Figure 2.10 provides a rough graphical comparison of rainfall over the barley crop growing cycle and simulated barley yields, while Figure 2.11 shows the statistical distribution of observed durum and barley yields at the national level.

Wheat yields, in particular, show a relative peak at zero yield values, as well as the second peak, which indicates a relative bimodality, even if the distribution can be deemed to be normal. The distribution for barley is definitely skewed (lognormal), even if no peak appears at the level of crop failures.

While the qualitative agreement between the statistical distributions of observed and simulated yield of one crop can hardly be regarded as a proof of a reliable methodology, it nevertheless indicates that yield projections are probably realistic, within the limits of the methodology.

Table 2.07: Test for normal and log-normal distribution of simulated and observed barley yields in six agro-ecological regions (Kolmogorov-Smirnov, Lilliefors and Jarque-Bera tests)

Orge (barley) 1979-2006 (baseline)	Average Yield (T/ ha)	Standard Deviation (T/ha)	Skewness	Normal Distribution	Lognormal Distribution	N	
Agroclimatic zone:	**FAVORABLE**						
Historical Observations	1.20	0.47	0.34	Y	Y	28	28years
Historical Simulation	1.43	0.55	0.26	N	N	1120	28years*20ensembles*2scenarios
Agroclimatic zone:	**INTERMEDIAIRE**						
Historical Observations	0.98	0.55	-0.01	Y	Y	28	28years
Historical Simulation	1.16	0.76	0.75	N	Y	1120	28years*20ensembles*2scenarios
Agroclimatic zone:	**Défavorable Sud**						
Historical Observations	0.76	0.41	0.26	Y	Y	28	28years
Historical Simulation	0.81	0.49	0.82	N	Y	1120	28years*20ensembles*2scenarios
Agroclimatic zone:	**Défavorable Oriental**						
Historical Observations	0.89	0.31	0.04	Y	Y	28	28years
Historical Simulation	0.92	0.19	-0.08	Y	N	1120	28years*20ensembles*2scenarios
Agroclimatic zone:	**Montagne**						
Historical Observations	1.04	0.45	0.19	Y	Y	28	28years
Historical Simulation	1.22	0.43	0.66	N	N	1120	28years*20ensembles*2scenarios
Agroclimatic zone:	**Saharien**						
Historical Observations	0.75	0.35	0.71	Y	Y	28	28years
Historical Simulation	0.81	0.24	0.31	N	N	1120	28years*20ensembles*2scenarios

Figure 2.10: Statistical distribution (absolute frequencies) of rainfall and barley for the INT agro-ecological zone over the baseline period.

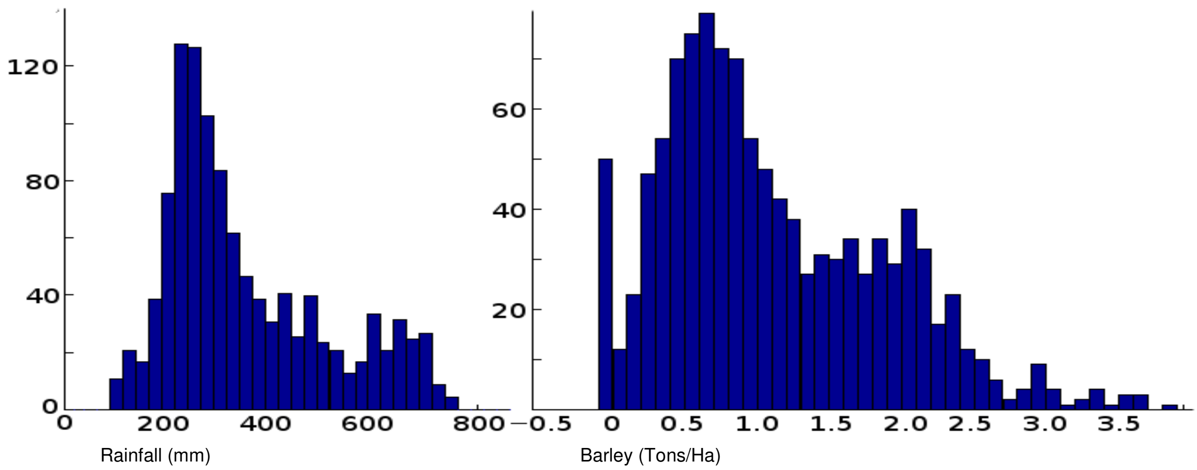
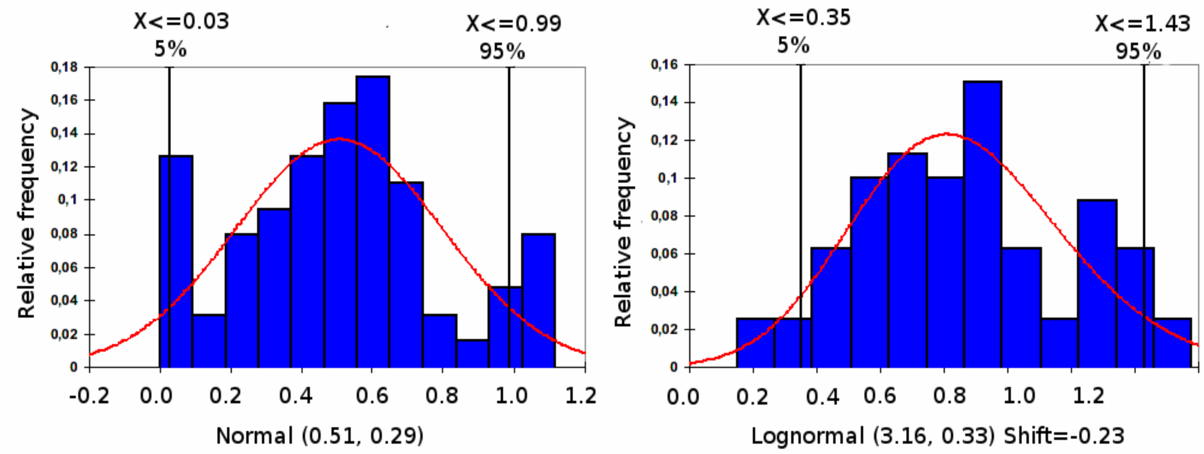


Figure 2.11: Statistical distribution (relative frequencies) of national durum wheat yields and barley yields.



Durum wheat yields (mm) Barley yields

2.10. AURELHY spatialisation method

AURELHY (Analysis using the Relief for Hydrometeorology) is a regionalisation (spatialisation) method originally developed by Bénichou and Le Breton (Bénichou and Le Breton, 1987) and widely used to create climate grids from point data in complex terrain. It is in wide use (e.g. Thomas and Herzfeld, 2003. Patriche, 2007) and a number of applications exist for Morocco, where the approach is well tested in crop forecasting, estimations of agroclimatic potential and land use mapping (Göbel et al., 1995; El Mourid et al., 1996; Arifi et al., 1999; Göbel et al., 1999a and 1999b).

All point data in this study were converted to a grid with 10 x 10 km cells (approx 0.1 degree) before they could be averaged over various spatial units (provinces, ORMVA[33], regions, national) for comparison purposes with agricultural statistics and the computation of yield projections. The number of grid points on land that were routinely processed amounts to 2,748,348.

The method's principle is as follows:

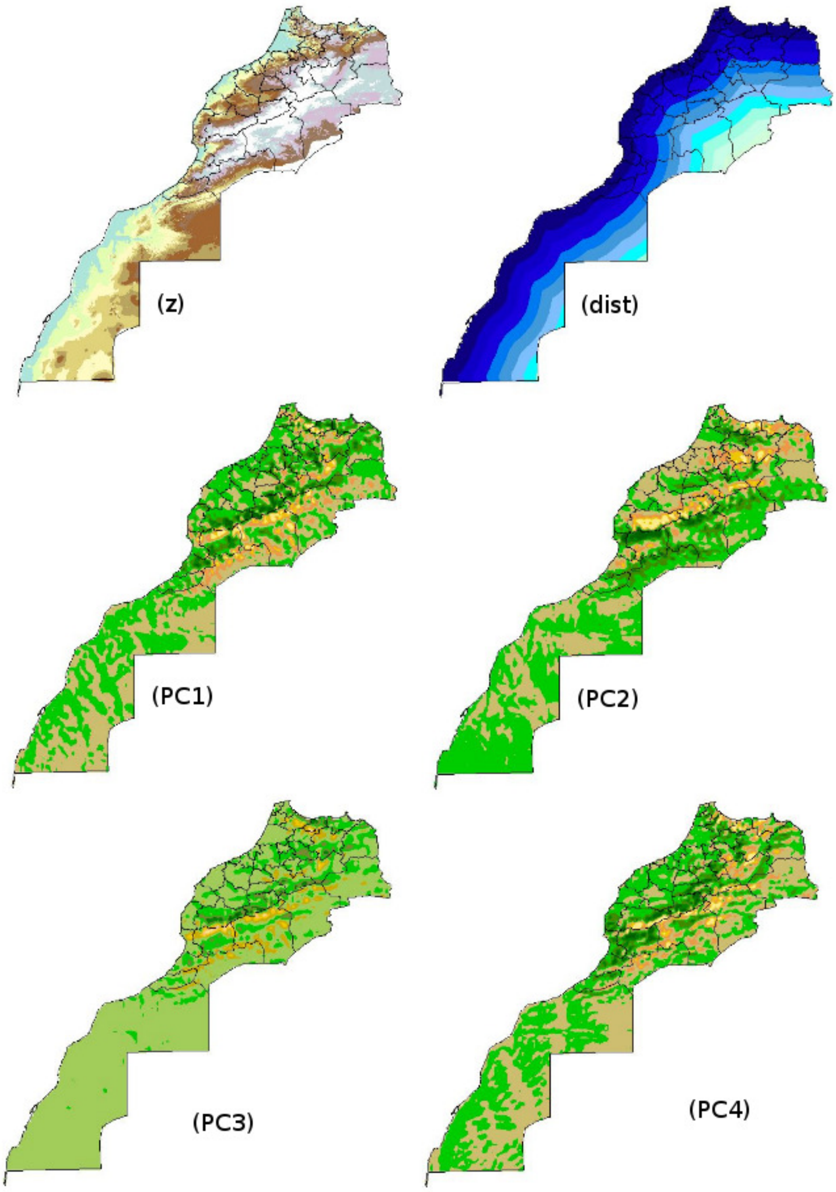
1. define a large number (40) of "landscape variables", and replace them with their first principle components[34] (PCs). The landscape variables correspond to the difference in elevation between each grid point and 40 points regularly distributed around the grid point (8 sectors and 5 distances from 6 to 26 km). For Morocco as a whole, the 10 first components account for 97.4% of the variance and 5 components explain 92.3%;
2. regress each of the water balance and climatic variables against the 5 PCs, longitude, latitude, altitude and distance from the closest sea. The same set of 9 variables has been used to spatialise all the variables. Six are illustrated in Figure 2.12;
3. compute residues and spatially interpolate them with a universal kriging algorithm to a resolution of 0.1 degree;
4. add original zonal and altitudinal component to spatialised residues to obtain final grids.

33 The corresponding polygons had to be prepared for this study, including those corresponding to the ORMVAs.

34 This needs to be done only once.

The automated procedure was developed by the current project.

Figure 2.12: Six of the nine spatialisation variables used in Morocco. (z), elevation; (dist), distance to the nearest sea or ocean; (PC1) to (PC4), the first four principal components.



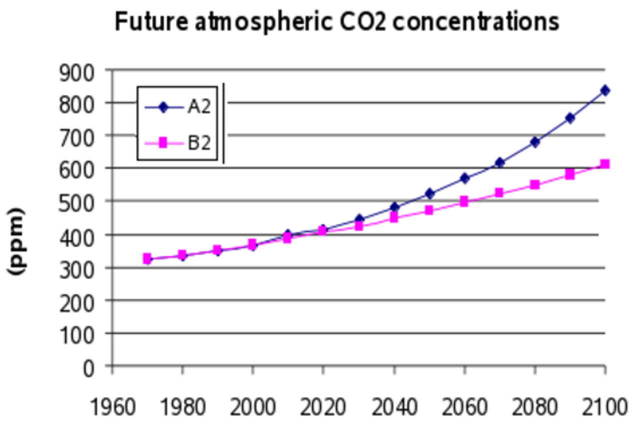
The spatial resolution of 0.1 degree (about 10 km) was adopted for the grids, as this provides a good compromise between computational load and spatial accuracy.

2.11. CO_2 fertilization

Nitrates, phosphates and some other ions (elements) are normally present in soil in low concentrations that limit plant growth. The purpose of soil fertilisation is to supply those elements at sufficiently high concentrations so that they are no longer limiting. Similarly, current CO_2 concentrations are so low that they limit plant growth[35]. In fact, as indicated in an earlier footnote, it has been the practice of vegetable producers to raise CO_2 concentrations in greenhouses up to 0.1% (1,000 ppmv) for such crops as citrus and especially vegetables (e.g. tomatoes) to increase yield while reducing water consumption and lighting costs (Fujisawa Hiroyuki et al., 2001; Gelder et al. ,2005).

Altogether, CO_2 effects are complex, because several mechanisms interact: a CO_2 fertilisation effect and an anti-transpiration effect, as well the interaction of CO_2 effects AND temperature. Those effects cannot be distinguished in practice for “real plants” at the scale at which the present study was conducted. For a short overview, refer to Bazzaz and Sombroek, 1996 and Sombroek and Gommes, 1996.

Figure 2.13: Projected CO_2 concentrations for scenarios A2 and B2 (left) **and "raw CO_2 correction factors" by major CO_2 assimilation pathway and CO_2 concentration** (ppmv).



ppm CO_2	C3	C4
330	1.00	1.00
440	1.11	1.05
550	1.19	1.08
660	1.25	1.10
770	1.30	1.12
880	1.33	1.13
990	1.36	1.14

Because of the disparity of experimental data, most studies (incl. the recent global study by Cline, 2007) just use standard CO_2 factors that depend on CO_2 concentration and major CO_2 assimilation pathway, i.e. C3 (all crops) and C4 (maize, sorghum, sugar cane), which leaves out only ananas, a crop not grown in Morocco. The CO_2 factors used in this study were taken from Tubiello et al. (2007) which were derived using crop simulation models. Although some studies point into another direction (Manderscheid and Weigel, 2007), we have assumed that the full positive CO_2 effects needs taking into account only when there is no water stress.

As mentioned (§ 2.1), our simulations include the computation of a “Water Satisfaction Index” (WSI) that varies from 0 (full water stress) to 1 (no water stress). We have assumed that the "raw" F(CO_2) factor mentioned in § 2.1. F(CO_2) has to be multiplied by WSI. This results in low CO_2 corrections for most rainfed crops and a “full CO_2 effect" that varies from 0 to WSI * F(CO_2).

35 Current average CO2 concentrations amount to 0.0385% by volume, or 385 ppmv.

2.12. EcoCrop suitability

2.12.1. Overview

EcoCrop 1 is a database on crop ecophysiology developed by FAO starting in the 1990s[36]. It contains ecophysiological limits for about 1710 plant species[37], including the most important climate and soil requirements (annual rainfall, temperature, soil salinity, soil pH, growth cycle length...), in addition to growth habit, uses etc.

Figure 2.14a: Suitability classes obtained by comparing annual rainfall and growing cycle temperature T with crop thresholds: temperatures below Tmin (and above Tmax) and rainfall R below Rmin (and above RMax) not allow the crop to be cultivated. Topmin,Topmax, Ropmin and Ropmax delimit the optimum suitability range (coded 30, green).
Figure 2.14b: The recoding of suitability classes into simpler codes (A, B, C, D, E) used to define suitability profiles (see text for details)

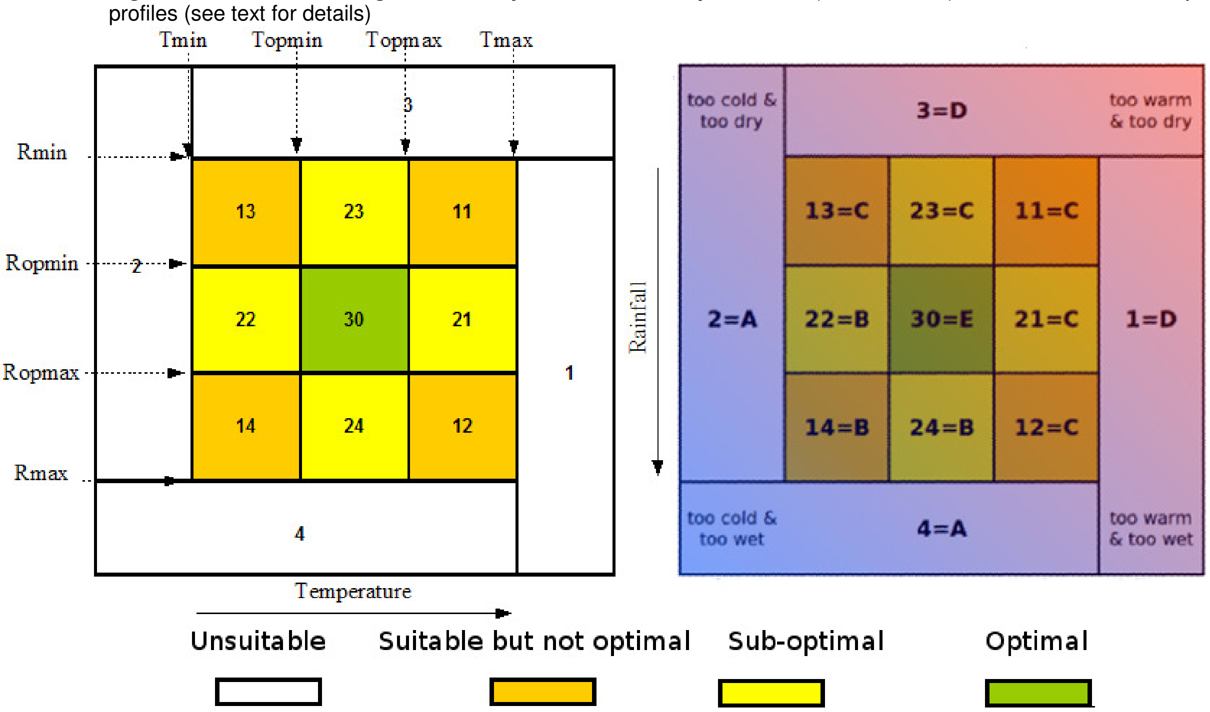


Figure 214a Figure 214b

EcoCrop was developed to permit the identification of plant species for defined uses and specific locations. To the authors' knowledge, the current study is the first application of EcoCrop to a climate change problem.

The general principle is to compare the scenario outputs with the climatic requirements of each crop of the database. If the scenario parameters fit into the required ranges of the crop, the crop is said to be suitable.

36 http://www.fao.org/ag/agl/agll/ecocrop.htm, http://ecocrop.fao.org/ecocrop/srv/en/home

37 In reality, the number of crops available is lower, as reference data are missing for some crops, and because we considered only crops with cycles between 90 and 365 days, resulting in an effective number of some crops of 1566.

We assessed the future crop suitability based on the crop cycle length and the climatic parameters (annual rainfall and temperature). Each crop is characterized by:

- Gmin, Gmax, the range of viable crop cycle length in days (see Table2.08)
- Tmin, Tmax, the range of viable average temperature during the crop growth cycle
- Topmin, Topmax, the range of optimal temperature during the crop growth cycle[38]
- Rmin, Rmax, the range of viable cumulated annual rainfall
- Ropmin, Ropmax, the range of optimal cumulated annual rainfall

Six typical crop cycles are defined according to crop type (Table 2.08).

Table 2.08: Crop cycle length adopted for the EcoCrop suitability study.

Period	Duration (Days)	Remark
March to May	90	Short cycle of spring Crops
March to June	120	Spring crops (seasonal vegetables)
Feb. to July	180	Long cycle of spring Crops
Oct. to May	240	Winter cereals
Feb. to Oct.	270	Most tree crops
Sept. to Sept.	360	Evergreen crops

The average temperatures are computed for each of the 6 cycles for both scenarios (A2 and B2) and for each period (current, 2030, 2050, 2080). The minimum temperature was taken as the average of the daily minimum temperatures during the crop cycle. The maximum temperature is the average of the daily maximum temperature during the crop cycle.

2.12.2. Suitability code and "suitability profile"

The 13 suitability classes are defined in Figure 2.14: "unsuitable" (1, 2, 3, 4) indicates that either temperature or rainfall are below or above their acceptable thresholds for the crop. "Suitable but not optimal" (11, 12, 13, 14) indicates that rainfall and temperature are within the acceptable range for the crop, but that none of them is optimal. "Sub-optimal" (21, 22, 23, 24) is used when either rainfall or temperature (only one of them) falls in the optimal range unsuitable. The code "30" (optimal class) is used when both rainfall and temperature fall within the optimum range for the crop.

The satisfaction of rainfall and temperature requirements is insufficient to assess the suitability code of a crop. The cycle length must be taken into account too. For each cycle (Table 2.07), the crop suitability was computed with regard to rainfall and temperature parameters for all crops and all the 6 cycles, yielding between 0 and 6 suitability codes, of which the maximum was recorded in the final database for the 4 periods and the six agro-ecological zones. Note that the suitability classes were selected with reference to the possibility to adapt the crops to climate. For instance, if for two different cycles (Table 2.07), the codes 13 and 12 were obtained, 13 (the maximum value) was retained: using irrigation, it is possible to move to class 22, after which the crop could be grown in a greenhouse, thereby switching from 22 to 30 (optimal).

For irrigated crops, we have optimistically considered that water supply was optimal, thus using only temperature as the limiting factor. It is also observed that we can define an

38 Note that in EcoCrop the temperatures are referred to the crop growth cycle, while rainfall is the annual value.

"EcoCrop water requirement" expressed in mm and defined as the difference between rainfall and Ropmin (Figure 2.14). Whenever rainfall > Ropmin, the "ecocrop water requirement" was set to 0. EcoCrop WR values tend to be higher than actual ecophysiological crop water requirements because we are referring here to a more geography-based definition: suitable rainfall ranges were determined by comparing crop distribution with rainfall in the areas where the crop growths either "marginally" or "optimally". The amount of water actually available for plant growth tends to be lower. In general Ropmin values are this relatively high. For instance, banana (*Musa acuminata x M. balbis*) has a Ropmin value of 1400 mm, when the crop actually is grown economically with less water. For durum wheat, Ropmin=500mm. If we compare this with the average WUE given in Table 2.04, the amount of water corresponds to 2.5 tons/Ha; for the best WUE, the water should be sufficient to obtain 7 tons/Ha.

Very different situations are sometimes grouped under the same suitability code. For example, the case where the climate is slightly too dry and too warm to be optimal and the case where the climate is slightly too wet and too cold are both “suitable but not optimal”. However, from an agronomic point of view, the two situations are rather different in terms of impacts. The suitability profiles described below somehow improve over this situation as they follow a trend from "too cold and too wet" to "too dry and too warm". There is no perfect qualitative coding system; nevertheless, the one presented below results from some experimenting and was adopted because it allows meaningful cross-comparisons between the simulations and the CSSWB approach and the EcoCrop method.

We defined the "suitability profile" using the right half of Figure 2.14 where the 13 suitability codes are recoded into a smaller number of conditions identified by letters from A (conditions to wet and cold) to D (warm and dry) and E (optimal). One letter is used for each of the current period, 2030, 2050 and 2080, so that a 4-letter code describes the overall behaviour of a plant for a given agro-ecological zone and scenario. For instance, rainfed durum wheat in DEF-sud is described as CCCD (scenario B2) and CCDD (scenario A2). The Irrigated durum profile is BBBB for both scenarios. Seasonal vegetables (irrigated) in MONT are coded as BBBB (A2) and BBEB (B2), indicating that conditions will be optimal for scenario B2 in 2050, but return to B in 2080.

3. Impacts

3.1. Impact of climate change on crops in Morocco at current technology level and without CO_2 effects

3.1.1. Definition of impact classes

As indicated above, the study identified 240 unique combinations of 50 crops and 6 AEZs. 60 combinations do not occur and were thus not taken into account. Since yields are by far the most significant variables, the synthetic description of the types of impact was derived using statistical clustering (grouping of similar situations) based on projected % change in yield for 2030, 2050 and 2080, for two scenarios. The resulting clusters of six classes (A to F) are sub-optimal[39] in statistical terms, but perform well with yields and water-related variables, without CO_2 fertilization and technology trend.

Overview of major impact groups

***Group A*:**
a small, heterogeneous group of agronomically unrelated irrigated crops that are projected to significantly benefit from climate change;

***Group B*:**
irrigated fruits and vegetables that will benefit from climate change;

***Group C*:**
fodder crops and vegetables that will suffer from climate change very moderately starting in the 2030s;

***Group D*:**
rainfed cereals and legumes undergoing a drop of yields of about 5% in 2050;

***Group E*:**
wheat and barley (both rainfed) whose yield drops will exceed 20% from 2050;

***Group F*:**
a group of rainfed winter crops that will undergo yield losses in excess of 30% by 2050; includes mainly cereals, legumes and oil crops.

The six impact classes (A to F) are illustrated in the figures and the table below (Table 3.01 and Figures 3.01a and 3.01b). They correspond to the current technology levels, i.e. they describe what is projected to happen to the current crops and cropping systems if they are subjected to the climatic conditions of the scenarios A2 and B2. The projections assume that crops will continue to be managed as today, in particular as regards the level of water control (i.e. rainfed crops remain rainfed and irrigated crops continue to be irrigated).

The impacts for all crops in all AEZs is given in Table 3.02. While the table answers questions about future yields of any crop in any AEZ, additional information is required to

39 14 principal components would be necessary to summarize 97% of the variance of the 240 x 103 variables matrix. The list of variables is given in Annex 2. There is nevertheless a good statistical agreement between the 6-class system presented here and the optimum 6-class classification, mainly because variables describing the water balance and yields are well correlated. The variables that create most difficulties are those related with deciles and interdecile intervals. This can be understood considering that, in the future, the frequency of zero yield values (= no harvest) increases and statistical distributions of yields tend to be distorted (i.e. lower deciles overlap). Variables based on deciles constitute a block poorly correlated variables, inside the group and with other variables.

understand the structure of the impact classes, which will be covered in more details in the subsequent sections, focusing on 2050 projections as the 2030 data depart relatively little from the baseline.

Table 3.01: Percent yield change at different time horizons for the 6 impact classes

	Scenario A2			Scenario B2		
Class	2030	2050	2080	2030	2050	2080
A	16	19	23.33	16.67	18	17.67
B	2.8	6.27	12.26	3.07	5.25	8.25
C	−1.67	−5.03	−8.72	−1.59	−3.64	−6.56
D	−5.49	−16.77	−31.11	−5.81	−10.6	−19.81
E	−2.71	−22.36	−55.14	4.29	−19.64	−28.93
F	−9.12	−32.41	−63.24	−9.47	−29.12	−39.24

Figures 3.01a and 3.01b: Percent yield reductions at different time horizons for the 6 impact classes.

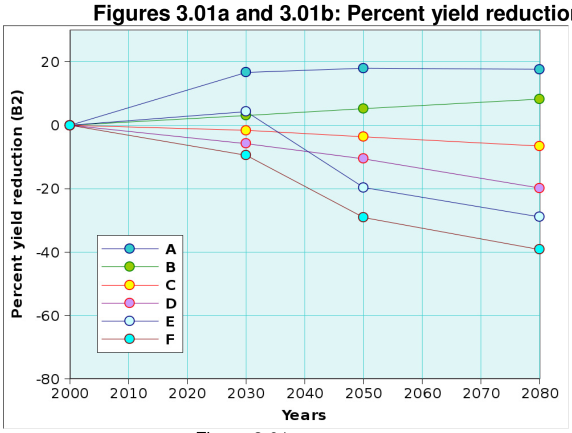


Figure 3.01a

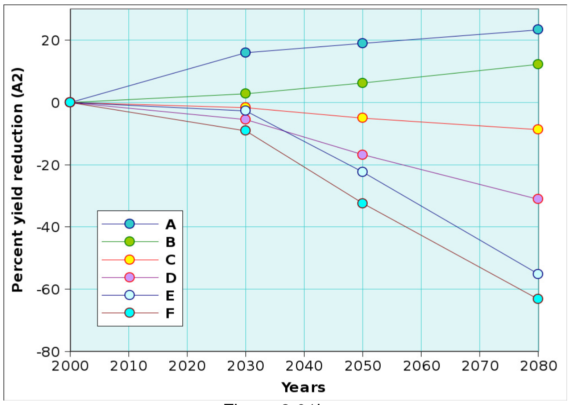


Figure 3.01b

By far the largest homogeneous crop group is the combination of fruits and vegetables in class B (Table 3.03), of which most are irrigated, which explains why yields are expected to increase. Class B crops are, in addition, well distributed among the AEZs, as already seen in Table 1.02 (Introduction). The second most coherent class is D, with mostly rainfed cereals and legumes. Distribution among ecological zones is less balanced than in fruits and vegetables as they occur mainly in the areas with Mediterranean climate in the north, i.e. FAV and INTERM.

Group A is the one with the lowest number of occurrences. It includes only irrigated crops that will benefit from increased temperature (fodder_crops in DEF-or, maize in FAV and seasonal vegetables). Altogether, class A does not really fit into the more logical B to F classes, as will be shown below.

Table 3.02: Overview of projected future yield changes (A to F impact classes) **without technology nor CO_2 effects** (current technology and CO_2 concentrations)

Crop	DEF-orient	DEF-sud	FAV	INTERM	MONT	SAH
Alfalfa_irr	B	B	B	B	B	B
Almond_rf	D	D	D	D	D	C
Apple_irr	B	B	B	B	B	B
Apricot_irr	B	B	B	B	B	B
Banana_irr	-	B	B	B	-	-
*Barley_rf	D	F	E	F	D	D
Barley_rf (Straw)	B	D	C	F	C	C
Bean_rf (Dry)	-	C	F	-	-	-
Bean_rf (Dry_faba)	C	D	E	F	D	F
Chickpea_rf	D	D	D	D	D	-
* Citrus_irr	C	C	B	C	B	C
Dates_irr	B	B	-	-	-	B
Fig_irr	B	B	B	B	B	B
Fodder_crops_irr	B	B	B	B	-	-
Fodder_crops_rf	A	E	E	E	C	-
Groundnut_irr	-	-	B	B	-	-
Lentil_rf	D	D	C	D	C	-
Maize_irr	D	B	A	D	-	B
Maize_rf	-	D	D	D	D	D
Niora_irr (Vegetable)	B	B	B	B	B	B
Nut_irr	B	B	B	-	B	B
Oats_rf	F	-	F	D	D	-
Olive_irr	F	D	B	-	-	B
Olive_rf	F	F	D	B	C	-
Peach_irr	B	B	B	B	B	B
Pea_rf (Dry)	D	C	F	F	D	-
Pear_irr	B	B	B	B	B	B
Plum_irr	B	B	B	B	B	B
Pomegranate_irr	B	B	B	B	B	B
Potato_irr (Early)	B	B	B	B	B	B
Potato_irr (seasonal)	C	D	C	C	D	D
Rangeland_rf	C	C	C	C	C	C
Rice_irr	-	-	B	-	-	-
Sorghum_rf	-	-	D	D	-	-
* Sugar_beet_irr	C	C	C	C	-	-
* Sugar_beet_rf	-	-	F	-	-	-
Sugar_cane_irr	B	-	B	-	-	-
Sunflower_rf	D	-	D	D	-	-
* Tomato_gh (Early)	B	B	B	B	B	B
Tomato_irr (Early)	D	C	C	C	D	D
* Tomato_irr (Industrial)	B	B	B	-	B	B
* Tomato_irr (Seasonal)	B	B	B	B	B	B
* Vegetables_irr (Seasonal)	C	C	A	B	B	B
Vetch_rf (bitter, orobe)	-	-	C	-	-	-
Vine_ir (Grape)	B	B	B	B	-	B
Vine_rf (Grape)	D	D	D	D	-	-
* Wheat_irr (Durum)	D	D	D	D	D	D
* Wheat_irr (Soft)	C	C	C	C	C	B
* Wheat_rf (Durum)	E	E	E	E	E	F
* Wheat_rf (Soft)	E	F	E	E	E	F

Table 3.03: Distribution of crop groups among impact classes. Note “irrigated" stands for “open field irrigation” so that “greenhouse tomatoes” are accounted under the rainfed crops in class B.

	A	B	C	D	E	F	Total
Cereals	1	4	5	20	10	7	47
Fodder	1	11	11	1	3	1	28
Fruit	0	60	5	9	0	0	74
Legumes	0	0	5	12	1	5	23
Oil crops	0	5	1	5	0	3	14
Sugar crop	0	2	4	0	0	1	7
Vegetables	1	32	8	6	0	0	47
irrigated	2	107	21	15	0	1	146
Rainfed	1	7	18	38	14	16	94
Total	3	114	39	53	14	17	240

Table 3.04: Percent change between baseline and 2050 of yield, water requirement and yield distribution patterns. Low yields are defined as yields that correspond to the lowest decile in the baseline period.

Scenario	Variable	Crop Group					
		A	B	C	D	E	F
A2	(1)	19.00	6.10	−4.89	−16.11	−22.36	−33.73
	(2)	16.33	12.09	13.03	13.28	16.43	16.20
	(3)	0.00	0.00	0.13	0.27	0.22	0.46
	(4)	96.67	13.66	2.95	−11.89	−35.07	−49.13
	(5)	−6.67	3.67	−8.63	−18.30	−15.64	−29.27
	(6)	−55.00	10.09	−22.66	−16.98	−5.71	−9.20
B2	(1)	18.00	5.21	−3.79	−10.40	−19.64	−30.20
	(2)	13.33	9.81	11.61	11.25	17.21	14.60
	(3)	0.00	0.01	0.11	0.19	0.18	0.43
	(4)	105.33	12.88	4.63	−5.36	−23.43	−42.07
	(5)	−8.33	2.64	−8.11	−11.27	−19.14	−28.80
	(6)	−57.00	−17.25	−23.37	−15.11	−15.43	−13.13

(1) % yield change
(2) % change in water requirements
(3) Low yields probability
(4) % change of 1st yield decile
(5) % change of 9th yield decile
(6) % change of yield interdecile

Table 3.04 lists yield, water requirements and yield distribution patterns in 2050, by crop groups and scenarios. As will be shown in Figure 3.02, the pattern of average percent yield change and water requirements is rather coherent between the scenarios, except in group A.

Table 3.04 shows that, for groups C to E risk will increase (with little difference between scenarios) and reach about 0.5 in group F, i.e., low yields[40] may happen every third year in class D and every second year in class F. Although their behaviour is “numerically coherent” between classes and scenarios, their interpretation is not straightforward, as mentioned above.

40 Low yields are defined as yields that correspond to the lowest decile in the baseline period.

As already mentioned in § 2.9., this is because the statistical distribution of yield in semi-arid areas is often J-shaped or, at least very asymmetric with a positive skew: some very high values in exceptional years, but otherwise an accumulation of occurrences at low yield values.

Altogether, the shrinking interdecile interval points at a relative decrease of the number of good years, and an accumulation of zero yields at the other end of the scale.

Figure 3.02 describes the relation between yield and water requirements across the classes. As can be noted, class A does not fit into the general and rather consistent pattern.

The graph is best read from right to left, starting with the two first points [5.21, 9.81] and [6.10, 12.09] that correspond to class B, scenarios B and A, respectively. They correspond to the mostly irrigated group of crops and indicate the direct proportional relation between yield and water consumption in non water-stressed crops: a 10 % increase in water consumption is associated with a roughly equivalent increase in yield. For the other classes, water use efficiency decreases from class C to F, indicating that even yield reductions due, for instance, to shrinking cycle lengths, have to be paid for by increased mounts of water resulting from increased water demands associated with higher temperatures.

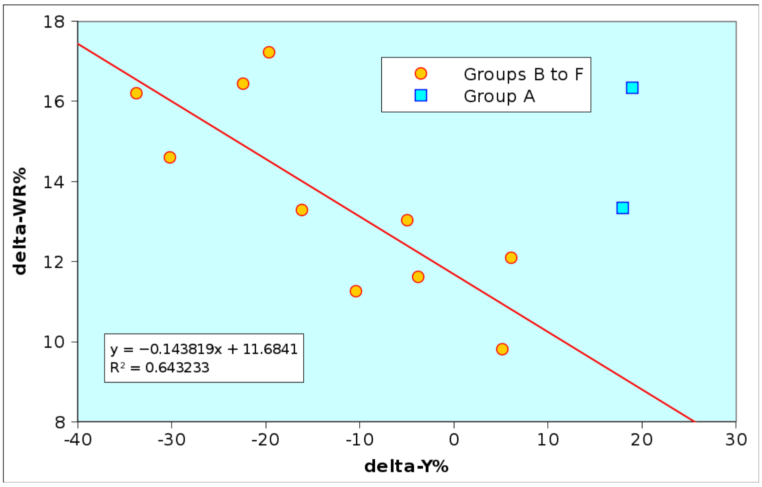
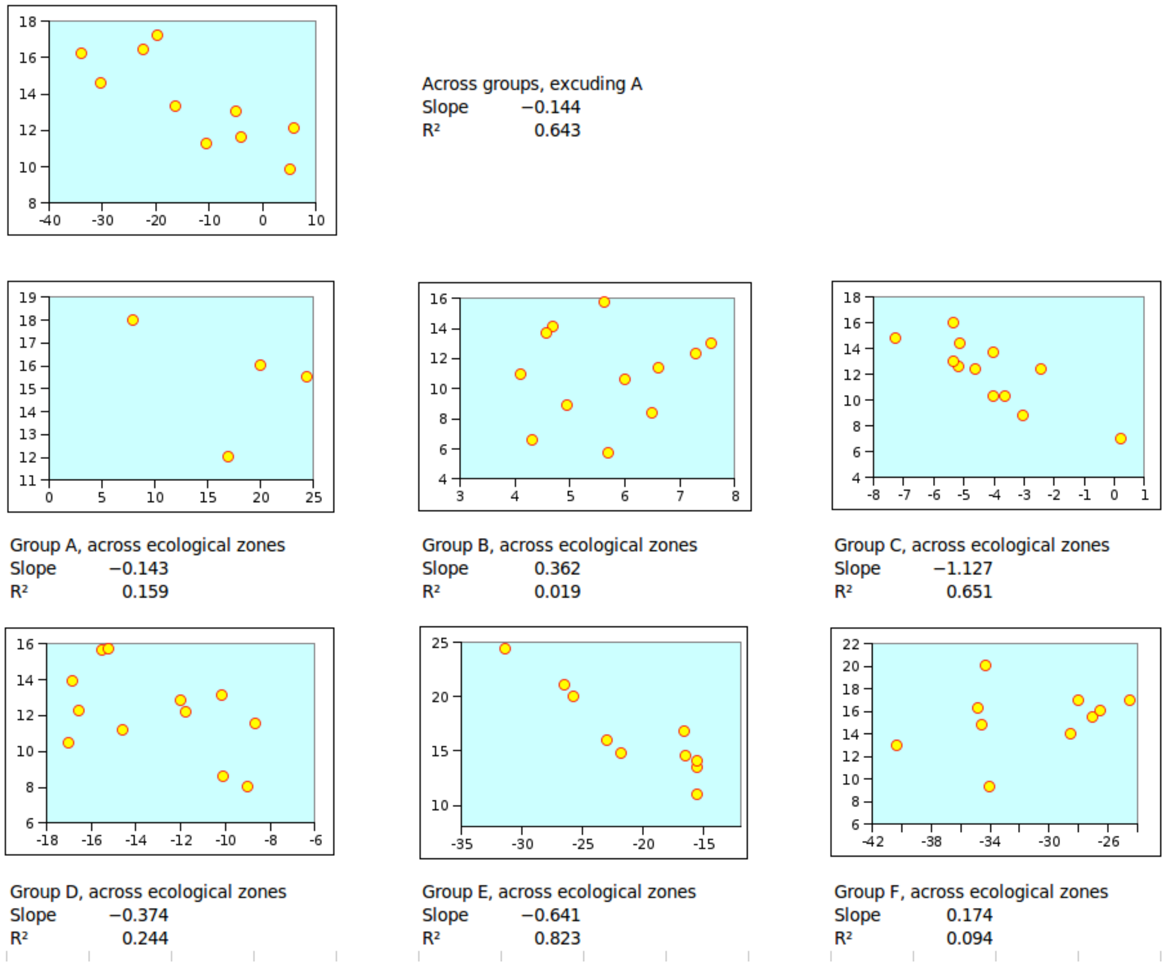


Figure 3.02: Relation between yield and water requirements (WR) across the classes for scenarios A2 and B2. Delta-Y% and Delta-WR% refer to percent change between 2000 and 2050.

Figure 3.03 illustrates the relation between yield change and water requirements change between now (baseline) and 2050 for the six climate change impact classes. Recall that water requirement (WR) is a measure of unsatisfied water need, i.e. a measure of water stress. Each point corresponds to a scenario and an AEZ. For instance, according to Table 3.02, class A occurs in DEF-or (rainfed fodder crops) and in FAV (irrigated maize and irrigated seasonal vegetables). The 4 points for class A in Figure 3.03 thus correspond to FAV and DEF-or, each for scenario A2 and B2. The point corresponding to FAV is the average of two crops. Figure 3.03 confirms that the definition of impact classes based on yield changes is meaningful as well from the point of view of crop water relations.

Groups C and E and, to some extent, group D and possibly group A illustrate a situation where low yield reductions between now and 2050 are accompanied by low reductions in water requirements. On the other hand, water requirements increase more in relative terms in the AEZs where yield reductions are highest. For class B, which includes mainly irrigated crops, and class F, there seems to be virtually a statistical independence between future yields and future water requirements.

Figure 3.03: relation between yield and water requirements (i.e. unsatisfied water needs) **for the six climate change impact classes between 2000 and 2050.** The abscissa indicates percent change of yields and the ordinate carries the percent change in water requirement. The top left figure is a repetition of Figure 3.02 for comparison purposes. Each point corresponds to a scenario and an AEZ.



3.1.2. Class A: low climate change impact crops

As mentioned repeatedly, class is very atypical Class A of botanically, agronomically and economically unrelated crops: irrigated maize and irrigated seasonal vegetables in FAV and rainfed fodder in DEF-or, as illustrated in the crop group and agro-ecological distribution given in Table 3.05, while Table 3.06 illustrates the major variables. It is described here mainly for the sake of completeness, and because class A differs too much from the other classes to be included in any of them. In particular, it would distort the rather coherent statistics of its nearest neighbour (class B) if combined with it.

As yields are projected to increase, the probability of low yields is basically 0. On the other hand, class A is probably the only one where the interdecile amplitude is meaningful or, at least, easy to interpret: for both scenarios, the range of yield values is expected to shrink.

Table 3.05: Distribution of crop groups among agro-ecological zones for impact class A.

	DEF-orient	DEF-sud	FAV	INTERM	MONT	SAH	Sum
Cereals	0	0	1	0	0	0	1
Fodder crops	1	0	0	0	0	0	1
Fruits	0	0	0	0	0	0	0
Legumes	0	0	0	0	0	0	0
Oil crops	0	0	0	0	0	0	0
Sugar crops	0	0	0	0	0	0	0
Vegetables	0	0	1	0	0	0	1
Irrigated	0	0	2	0	0	0	2
Rainfed	1	0	0	0	0	0	1
Sum	1	0	2	0	0	0	3

Table 3.06: Impact class A, percent change between baseline and 2050 of yield, water consumption and yield distribution patterns.

Scenario	Variable	Agroecological zone					
		DEF-or	DEF-sud	FAV	INTERM	MONT	SAH
A2	(1)	8.00	n.a.	24.50	n.a.	n.a.	n.a.
	(2)	18.00	n.a.	15.50	n.a.	n.a.	n.a.
	(3)	0.00	n.a.	0.00	n.a.	n.a.	n.a.
	(4)	23.00	n.a.	133.50	n.a.	n.a.	n.a.
	(5)	−8.00	n.a.	−6.00	n.a.	n.a.	n.a.
	(6)	−28.00	n.a.	−68.50	n.a.	n.a.	n.a.
B2	(1)	20.00	n.a.	17.00	n.a.	n.a.	n.a.
	(2)	16.00	n.a.	12.00	n.a.	n.a.	n.a.
	(3)	0.00	n.a.	0.00	n.a.	n.a.	n.a.
	(4)	37.00	n.a.	139.50	n.a.	n.a.	n.a.
	(5)	6.00	n.a.	−15.50	n.a.	n.a.	n.a.
	(6)	−16.00	n.a.	−77.50	n.a.	n.a.	n.a.

(1) % yield change
(2) % change in water requirements
(3) Low yields probability
(4) % change of 1st yield decile
(5) % change of 9th yield decile
(6) % change of yield interdecile

3.1.3. Class B: irrigated fruits and vegetables[41]

Class B is the class of irrigated fruits and vegetables, which occur country-wide, with a relative decrease only in the MONT agro-ecological zone. A number of crops are specific of this yield impact class, characterised by a modest yield increase, and a relative independence of yield and water requirement changes. In fact, only two rainfed crops appear in this class: straw from barley in DEF-orient and olives in INT. Irrigated olives fall into B only in FAV and SAH, while they tend to belong to the less favourable classes elsewhere. No legumes belong to this class.

[41] The names given to classes B, C. D and E are conventional. They describe the crops that are most typical for the class.

Table 3.07: Distribution of crop groups among agro-ecological zones for impact class B. Greenhouse tomatoes have been counted among "irrigated" crops.

	DEF-orient	DEF-sud	FAV	INTERM	MONT	SAH	Sum
Cereals	0	1	1	0	0	2	4
Fodder crops	3	2	2	2	1	1	11
Fruits	10	11	11	9	9	10	60
Legumes	0	0	0	0	0	0	0
Oil crops	0	0	2	2	0	1	5
Sugar crops	1	0	1	0	0	0	2
Vegetables	5	5	5	5	6	6	32
Irrigated	18	19	22	17	16	20	112
Rainfed	1	0	0	1	0	0	2
Sum	19	19	22	18	16	20	114

Table 3.08: Impact class B, percent change between baseline and 2050 of yield, water consumption and yield distribution patterns.

Scenario	Variable	Agroecological zone					
		DEF-or	DEF-sud	FAV	INTERM	MONT	SAH
A2	(1)	7.58	4.95	5.64	4.71	7.31	6.50
	(2)	13.00	8.89	15.73	14.12	12.31	8.35
	(3)	0.00	0.00	0.00	0.00	0.00	0.00
	(4)	15.79	12.74	10.23	11.53	17.50	15.90
	(5)	5.47	2.95	3.86	2.94	3.88	4.05
	(6)	10.68	9.26	21.68	30.82	−10.56	2.05
B2	(1)	6.63	4.32	4.59	4.12	6.00	5.70
	(2)	11.32	6.53	13.68	10.94	10.56	5.70
	(3)	0.00	0.00	0.01	0.01	0.01	0.00
	(4)	16.05	13.21	8.91	12.06	11.75	15.65
	(5)	4.16	2.26	3.05	1.65	2.25	1.95
	(6)	−23.84	−17.58	−3.50	−12.88	−22.38	−33.00

(1) % yield change
(2) % change in water requirements
(3) Low yields probability
(4) % change of 1st yield decile
(5) % change of 9th yield decile
(6) % change of yield interdecile

The crops that are always irrigated and that occur in B everywhere include the following: alfalfa, apples, apricot, figs, gapes, nuts, peaches, pears, plums, pomegranates, niora, early potatoes (seasonal potatoes come under C), greenhouse, industrial and seasonal tomatoes. Some of them (nuts, grapes, and industrial tomatoes) are not grown in all AEZs.

An interesting observation about this class is the difference of behaviour of the interdecile yield interval. B is the only class where there is a systematic difference between the scenarios, with A2 witnessing increased variability while B2 has negative values. This indicates, again, the somewhat artificial nature of this statistic when water supply is short. Altogether, B is the class with the lowest variability of yields over time, and also the class where the differences between scenarios are less marked, as practically only temperatures affects yields, even indirectly through their effect on cycle lengths.

3.1.4. Class C: fodder crops and vegetables

C is a class of modest decreases that will set in the late 2030s for both scenarios. The class occurs in all agro-ecological zones and includes both rainfed and irrigated crops. It is typically the class of fodder and vegetables, i.e. plants where the vegetative part is consumed, contrary to other classes where the harvested part is grain, tubers or fruits (Table 3.09). Rainfed range lands occur always in this class that is represented countrywide, with a minimum of occurrence in the SAH zone. Irrigated soft wheat also mostly occurs under C (it falls under B in SAH).

Not surprisingly, the largest yield decreases for the 2050 period occur in there FAV agro-ecological zone, where many C crops are rainfed (Table 3.10).

Table 3.09: Distribution of crop groups among agro-ecological zones for impact class C.

	DEF-orient	DEF-sud	FAV	INTERM	MONT	SAH	Sum
Cereals	1	1	1	1	1	0	5
Fodder crops	1	1	3	1	3	2	11
Fruits	1	1	0	1	0	2	5
Legumes	1	2	1	0	1	0	5
Oil crops	0	0	0	0	1	0	1
Sugar crops	1	1	1	1	0	0	4
Vegetables	2	2	2	2	0	0	8
Irrigated	5	5	4	5	1	1	21
Rainfed	2	3	4	1	5	3	18
Sum	7	8	8	6	6	4	39

Table 3.10: Impact class C, percent change between baseline and 2050 of yield, water consumption and yield distribution patterns.

Scenario	Variable	Agroecological zone					
		DEF-or	DEF-sud	FAV	INTERM	MONT	SAH
A2	(1)	-4.00	-3.63	-7.25	-5.33	-4.60	-4.00
	(2)	13.71	10.25	14.75	16.00	12.40	10.25
	(3)	0.06	0.09	0.19	0.14	0.16	0.11
	(4)	7.00	2.00	2.38	9.33	-4.20	-1.75
	(5)	-13.14	-6.00	-10.13	-10.00	-5.40	-5.00
	(6)	-42.86	-22.88	-15.75	-29.33	-7.20	-10.00
B2	(1)	-5.14	-3.00	-5.13	-5.33	-2.40	0.25
	(2)	12.57	8.75	14.38	13.00	12.40	7.00
	(3)	0.10	0.08	0.16	0.10	0.14	0.10
	(4)	4.14	5.25	6.50	10.67	-3.00	1.00
	(5)	-13.29	-8.38	-9.13	-10.50	-2.60	0.25
	(6)	-36.43	-27.63	-22.38	-35.33	-5.00	1.00

(1) % yield change
(2) % change in water requirements
(3) Low yields probability
(4) % change of 1st yield decile
(5) % change of 9th yield decile
(6) % change of yield interdecile

As already noted for class B, the differences between scenarios are low here as well. A difference with the previous class is that the probability of low yields now shows an increase that is usually between 10 and 20%. There is also a marked decrease of the frequency of high yields (between 10 and 50%), indicating a shifting of yield distributions towards the lower yield range.

3.1.5. Class D: rainfed cereals and legumes

Even if class D includes mostly rainfed cereals and legumes (38 crops out of 53), irrigated Durum wheat is one of the crops that always falls under this class. Almonds (rainfed), rainfed maize and rainfed chickpeas also belong here.

Table 3.01 indicates that yield decreases expected in 2030 are close to 5%, while in 2050 they amount to 10 % (B2) and 16 % (A2). It is interesting to compare these averages with the values listed in Table 3.12 for various agro-ecological zones. It appears, in fact, that the decreases are rather constant across agro-ecological zones.

The probability of low yields now reaches more than 30% in some agro-ecological zones (FAV, DEF-or). The shift towards low yields is confirmed in this class as well (Table 3.12), and more so under A2 conditions than under B2.

Table 3.11: Distribution of crop groups among agro-ecological zones for impact class D.

	DEF-orient	DEF-sud	FAV	INTERM	MONT	SAH	Sum
Cereals	3	2	3	5	4	3	20
Fodder crops	0	1	0	0	0	0	1
Fruits	2	2	2	2	1	0	9
Legumes	3	3	1	2	3	0	12
Oil crops	1	1	2	1	0	0	5
Sugar crops	0	0	0	0	0	0	0
Vegetables	1	1	0	0	2	2	6
Irrigated	3	3	1	2	3	3	15
Rainfed	7	7	7	8	7	2	38
Sum	10	10	8	10	10	5	53

Table 3.12: Impact class D, percent change between baseline and 2050 of yield, water consumption and yield distribution patterns.

Scenario	Variable	Agroecological zone					
		DEF-or	DEF-sud	FAV	INTERM	MONT	SAH
A2	(1)	−16.82	−17.00	−15.50	−15.18	−16.55	−14.60
	(2)	13.91	10.45	15.63	15.73	12.27	11.20
	(3)	0.35	0.25	0.32	0.23	0.21	0.26
	(4)	−18.45	−11.36	−19.25	−9.45	−9.64	2.20
	(5)	−16.36	−20.64	−15.13	−15.55	−20.55	−22.00
	(6)	−8.82	−24.45	4.25	−13.18	−26.64	−36.40
B2	(1)	−12.00	−10.09	−10.13	−11.73	−8.64	−9.00
	(2)	12.82	8.55	13.13	12.18	11.55	8.00
	(3)	0.26	0.19	0.24	0.15	0.15	0.16
	(4)	−12.00	−2.91	−9.25	−9.91	−0.73	9.20
	(5)	−11.36	−10.91	−9.38	−11.73	−10.27	−16.00
	(6)	−11.09	−15.27	−7.25	−14.73	−17.45	−31.80

(1) % yield change
(2) % change in water requirements
(3) Low yields probability
(4) % change of 1st yield decile
(5) % change of 9th yield decile
(6) % change of yield interdecile

3.1.6. Class E: rainfed wheat and barley

Class E is basically the rainfed wheat class with (rainfed) barley in zone FAV (Table 3.02 and Table 3.13). As such, it is one of most important crop groups for Morocco, both in economic and food security terms. Projected yield decreases (Table 3.14) are relatively similar for the two scenarios, but nowhere lower than 15 %.

DEF-sud and MONT will suffer least, but projected decreases are close to 30% in DEF-or and INT, where the probabilities of low yields will increase to about one year in 5. While the highest yields corresponding to the 9th decile will decrease relatively little (10 to 20 %), 1st decile low yields will drop significantly leading to a “compression” of the yield distribution at low values.

Table 3.13: Distribution of crop groups among agro-ecological zones for impact class E.

	DEF-orient	DEF-sud	FAV	INTERM	MONT	SAH	Sum
Cereals	2	1	3	2	2	0	10
Fodder crops	0	1	1	1	0	0	3
Fruits	0	0	0	0	0	0	0
Legumes	0	0	1	0	0	0	1
Oil crops	0	0	0	0	0	0	0
Sugar crops	0	0	0	0	0	0	0
Vegetables	0	0	0	0	0	0	0
Irrigated	0	0	0	0	0	0	0
Rainfed	2	2	5	3	2	0	14
Sum	2	2	5	3	2	0	14

Table 3.14: Impact class E, percent change between baseline and 2050 of yield, water consumption and yield distribution patterns.

Scenario	Variable	Agroecological zone					
		DEF-or	DEF-sud	FAV	INTERM	MONT	SAH
A2	(1)	−23.00	−16.50	−21.80	−31.33	−15.50	n.a
	(2)	16.00	14.50	14.80	24.33	11.00	n.a
	(3)	0.17	0.12	0.24	0.30	0.21	n.a
	(4)	−41.00	−19.50	−40.80	−31.67	−35.50	n.a
	(5)	−17.00	−14.00	−16.40	−17.00	−12.00	n.a
	(6)	−10.00	−11.00	−2.60	−9.33	1.50	n.a
B2	(1)	−26.50	−15.50	−16.60	−25.67	−15.50	n.a
	(2)	21.00	13.50	16.80	20.00	14.00	n.a
	(3)	0.19	0.08	0.15	0.29	0.20	n.a
	(4)	−40.50	26.00	−25.60	−33.33	−35.50	n.a
	(5)	−23.50	−23.50	−17.20	−24.33	−7.50	n.a
	(6)	−19.50	−29.00	−15.80	−18.33	7.50	n.a

(1) % yield change
(2) % change in water requirements
(3) Low yields probability
(4) % change of 1st yield decile
(5) % change of 9th yield decile
(6) % change of yield interdecile

3.1.7. Class F: high climate change impact crops

Class F is the most seriously affected by climate change (Table 3.16). It includes several crops of major economic relevance - almost all of them rainfed - that will undergo yield decreases between around 30 and 35 % in most agro-ecological zones, regardless of the scenarios. Water requirements increase between 15 and 20%.

Table 3.15: Distribution of crop groups among agro-ecological zones for impact class F.

	DEF-orient	DEF-sud	FAV	INTERM	MONT	SAH	Sum
Cereals	1	2	1	1	0	2	7
Fodder crops	0	0	0	1	0	0	1
Fruits	0	0	0	0	0	0	0
Legumes	0	0	2	2	0	1	5
Oil crops	2	1	0	0	0	0	3
Sugar crops	0	0	1	0	0	0	1
Vegetables	0	0	0	0	0	0	0
Irrigated	1	0	0	0	0	0	1
Rainfed	2	3	4	4	0	3	16
Sum	3	3	4	4	0	3	17

Table 3.16: Impact class F, percent change between baseline and 2050 of yield, water consumption and yield distribution patterns.

Scenario	Variable	Agroecological zone					
		DEF-or	DEF-sud	FAV	INTERM	MONT	SAH
A2	(1)	−27.00	−28.00	−34.50	−34.25	n.a.	−40.33
	(2)	15.50	17.00	14.75	20.00	n.a.	13.00
	(3)	0.74	0.17	0.57	0.34	n.a.	0.50
	(4)	−36.50	−40.00	−72.50	−63.50	n.a.	−13.33
	(5)	−22.50	−27.00	−23.75	−35.50	n.a.	−34.33
	(6)	9.00	−24.50	24.00	−27.25	n.a.	−31.33
B2	(1)	−28.50	−24.50	−34.75	−26.50	n.a.	−34.00
	(2)	14.00	17.00	16.25	16.00	n.a.	9.33
	(3)	0.79	0.13	0.61	0.22	n.a.	0.45
	(4)	−33.00	−14.00	−65.75	−56.00	n.a.	−16.67
	(5)	−26.50	−27.50	−25.25	−36.25	n.a.	−26.00
	(6)	−6.50	−29.50	16.50	−33.75	n.a.	−18.67

(1) % yield change
(2) % change in water requirements
(3) Low yields probability
(4) % change of 1st yield decile
(5) % change of 9th yield decile
(6) % change of yield interdecile

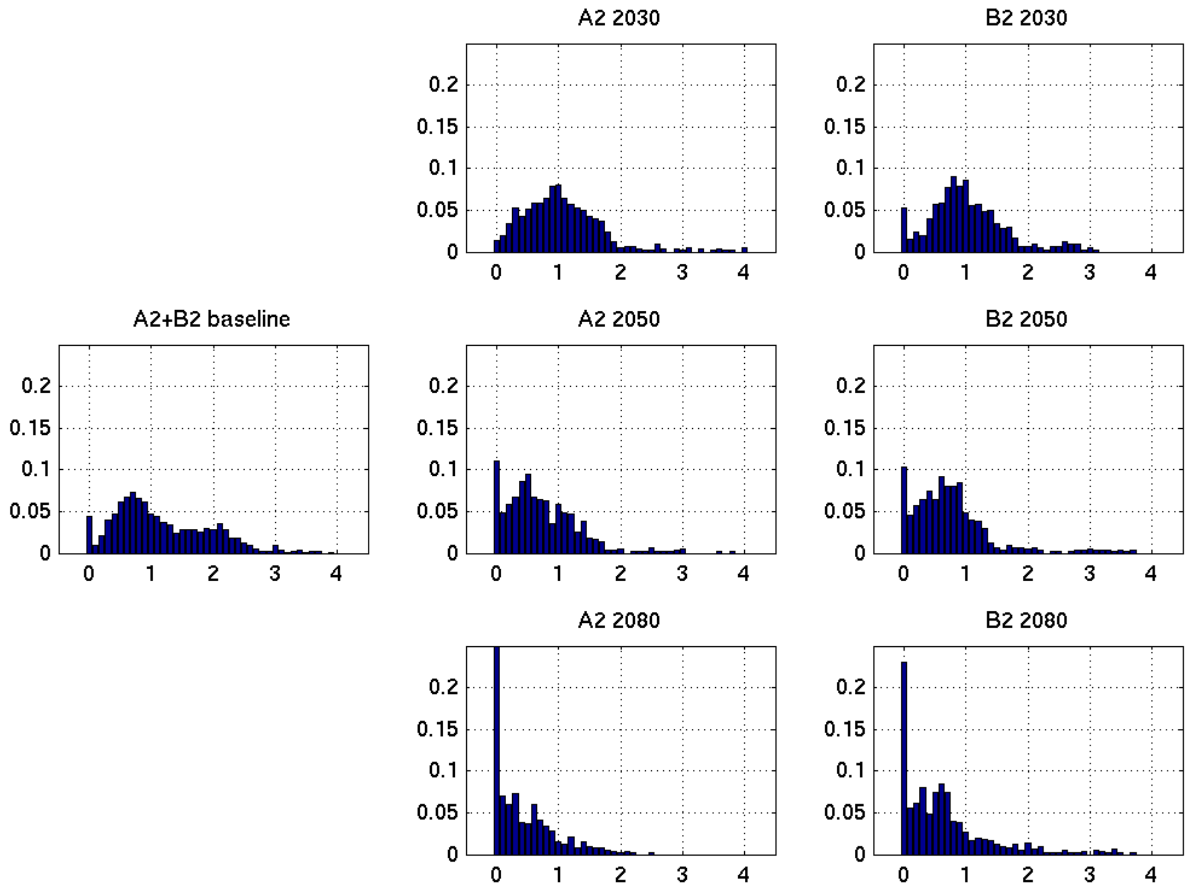
The major crops in this class include the following:

- cereals: barley (INT and DEF-sud agro-ecological zones) and oats (DEF and FAV);
- legumes: dry peas in FAV and INT, and dry beans in FAV;
- oil crops: olives in DEF-or and DEF-sud (the only irrigated crop in this class)
- sugar crop: sugar beet in FAV.

The frequency of low yields is everywhere close to or above 20%, and reaches about 60% in DEF-OR and FAV for both scenarios. The changes in low and high deciles indicate a marked accumulation of low values and a decrease of high values. This is clearly illustrated in the Figure 3.04 for barley in the INT agro-ecological zone.

Average yields are still close to 1 ton/Ha in 2030, but they decrease to 0.5 tons in 2050, while zero values increase in frequency and actually exceed average values. In 2080, the distribution assumes a J-shape, characterised by a high frequency (about one year out of four) of complete crop failures. This type of curve (Pearson III type statistical distribution) is well known to climatologist and is typical of rainfall in semi-arid and arid areas.

Figure 3.04: Frequency distribution (ordinate) **of barley yields** (rainfed) **in the INT agro-ecological zone under current conditions** (A2 and B2 data combined)**, 2030, 2050 and 2080, for scenarios A2 and B2.**
The abscissa is in tons/Ha



3.2. Effects of CO_2 and technology trend

3.2.1. Overview

Up to now, the report has examined the effects of changing climatic conditions assuming that CO_2 concentrations are constant at current levels, and that no improvements of crop production systems are taking place.

As described in the methodological section (§ 2.8.) past improvements are assigned to the technology trend which, however, is a complex mix of adaptations at various levels, from genetic plant improvements to use of inputs (fertiliser, pesticides) and farm management, including water management at field and regional level.

Without entering into details, Figure 3.05 illustrates the yield of a typical class E crop that is projected to undergo a decrease of about 20 % by 2050 and 50% by 2080 according to the scenario A2 based projections (refer to Table 3.01). The figure also shows the relative importance of CO_2 effects and trend and the fact that the inclusion of technology trend in yield projections can significantly modify the projections obtained for current technology conditions.

It is a common practice of operational crop yield forecasting to take trends into account and to project them into the near future, one or two years ahead. The technology trend is derived from recent historical yields and basically constitutes the most significant way in which we can assess the potential role of adaptation[42].

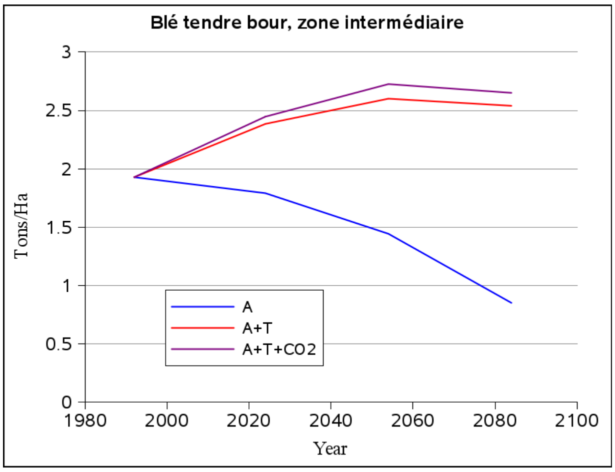


Figure 3.05: Sample output showing the effect on rainfed soft wheat in the INT agro-ecological zone of climate only (scenario A2), scenario with technology trend extrapolated from recent statistical series (A + T) and the combined effect of the three factors (climate + technology trend + CO_2 effects)

The question about how long the recent past trends can be sustained in the future cannot be answered easily, as the only known limit is the biological production potential that can be determined based on available solar radiation and water (refer, for instance to Gommes et al., 2009).

The highest future yields listed in this study by including a technology trend only very rarely exceed the best yields obtainable today for the respective crops, anywhere in the world. Current Moroccan yields are generally low, certainly so for field crops. For instance, average national wheat yields in France and the Netherlands easily reach 7 tons/Ha and 9 tons/Ha (resp.) under considerably less favourable radiation conditions than those prevailing in Morocco, but with abundant water supply.

The most spectacular increases are those projected for various crops are the following: tomatoes (502 T/Ha, to be compared to 1997 yields of 445 in the Netherlands), alfalfa (80 T/Ha, to be compared to 1997 yields of 80 in Jordan and 77 in Mexico), banana (56 T/Ha, to be compared to 1997 yields of 53 in Nicaragua), potato (79 T/Ha, to be compared to 1997 yields of 50 in New Zealand and 42 in the Netherlands), sugar cane (87 T/Ha, to be compared to 1997 yields of 122 in Peru and 120 in Tanzania and Egypt), sugar beet (150, to be compared with 82 for 1997 in France) and fodder (180 T/Ha).

The only value that may be unrealistically high is that of sugar beet. Yields as high as 150 T/Ha can be achieved in individual fields, but such a high value is unlikely for regional yields. The fundamental question, however, is whether water supply will actually be sufficient to

42 The statement refers to a static study like the present one. For a dynamic study taking into account future yields, available land and labour and assuming, for instance, that the objective of farming is to stabilise production, or maximise calorie production, or optimise water use, more "rational" adaptation options are available even without building in economic constraints.

cover the projected yields. Section 3.3. addresses the specific issue of future water use that will be required to achieve the projected yields. It seems obvious that water, and not crop physiology will set the limit, so that high values given above are not critical in the present context.

3.2.2. Moroccan technology trends

Trends observed for the main cereals between 1980 and 2006 in Morocco are given in Table 3.17, while the trend components of the yields between 2000 and 2050 in various impact groups and agro-ecological zones are shown in Table 3.17. Some crops display no trend, and this can be due to a number of factors, but mostly because many crops are traditional low technology productions, for instance some legumes.

Non-technology factors do sometimes significantly affect trends, for which barley provides a perfect example, for a number of economic and other reasons, but mostly because barley is valued as much (or more) for the straw as for grain. The use of barley is complex[43], as it is sometimes used for grazing during winter, fed to animals as straw, grain or silage, and because it occurs in all agro-ecological zones, including oasis. Only a fraction is irrigated. In addition, during dry years, grain production drops, but some straw is still available. Finally, barley straw cannot be imported, resulting in the Moroccan agriculture being very dependent on barley as a mainstay of feed security.

Table 3.17: trends in main cereals together with their coefficients of determination between 1980 and 2006.

	Soft wheat		Durum wheat		Barley		Maize	
	Trend (T/Ha)/Year	R^2	Trend (T/Ha)/Year	R^2	Trend (T/Ha)/Year	R^2	Trend (T/Ha)/Year	R^2
FAV	0.0242	0.793	0.0189	0.711	−0.0153	0.118	0.0084	0.235
INT	0.0223	0.731	0.0255	0.850	0.0010	0.001	0.0154	0.692
DEF-or	0.0064	0.200	0.0076	0.371	−0.0086	0.076	0.0056	0.303
DEF-sud	0.0111	0.475	0.0148	0.704	−0.0009	0.004	0.0094	0.636
MONT	0.0168	0.601	0.0133	0.703	−0.0322	0.023	0.0105	0.279
SAH	0.0054	0.079	0.0126	0.201	−0.0037	0.027	0.0053	0.089
National	0.0189	0.872	0.0176	0.862	−0.0033	0.033	0.0112	0.699

As a result, barley has been expanding into marginal areas, which led to decreasing yields due to, mainly, poor soil conditions (low natural fertility and limited soil water holding capacity). The overall outcome is that no yield trends are present in production statistics even if varietal improvements have actually been taking places (Table 3.17). The trends are evident only in FAV and in favourable areas inside the modelling regions, at a micro scale not covered by the present study.

It is worth observing in Table 3.17 that there is little homogeneity in trends: with few exceptions, the trend varies from 0, or even negative values, to values as high as 250%, while the averages are usually below 50%. Also note that trends tend to be very low in B, D and F impact classes.

43 http://www.fao.org/ag/AGP/AGPC/doc/Counprof/frenchtrad/morocco_fr/Morocco_fr.htm; MADRPM, 2005.

Table 3.18: Order of magnitude (%) **of technology impact on future yields between the current period** (2000) **and 2050.**

	DEF-or	DEF-sud	FAV	INT	MONT	SAH
A	0	n.a.	240 (193 to 296)	n.a.	n.a.	n.a.
B	18 (0 to 329)	18 (0 to 326)	15 (0 to 320)	19 (0 to 328)	28 (0 to 317)	20 (0 to 334)
C	72 (0 to 221)	13 (0 to 56)	33 (0 to 223)	44 (0 to 215)	10 (0 to 49)	0
D	4 (0 to 46)	23 (0 to 211)	4 (0 to 30)	4 (0 to 45)	21 (0 to 219)	46 (0 to 211)
E	136 (127 to 139)	53 (0 to 107)	246 (0 to 1141)	46 (0 to 78)	80 (66 to 92)	n.a.
F	0	58 (0 to 117)	0	0	n.a.	344 (0 to 620)

3.2.3. Impacts in class A

The most interesting observation is that, while class A will benefit from improved yields even at current technology level (Table 3.19), the tree crops in the class are also characterised, at least locally, by high trends but minor CO_2 effects.

Table 3.19: Percent yield change above "current technology" due to CO_2 effects and technology trend for the crops in class A, by 2050. Line (1) corresponds to the percent increase due to "climate change only".

Scenario		DEF-or	DEF-sud	FAV	INT	MONT	SAH
A2	(1)	8	n.a.	25 (20 to 29)	n.a.	n.a.	n.a.
	(2)	14	n.a.	34 (33 to 35)	n.a.	n.a.	n.a.
	(3)	8	n.a.	271 (216 to 325)	n.a.	n.a.	n.a.
	(4)	14	n.a.	280 (231 to 329)	n.a.	n.a.	n.a.
B2	(1)	20	n.a.	17 (16 to 18)	n.a.	n.a.	n.a.
	(2)	25	n.a.	23 (18 to 28)	n.a.	n.a.	n.a.
	(3)	20	n.a.	251 (211 to 290)	n.a.	n.a.	n.a.
	(4)	25	n.a.	257 (221 to 292)	n.a.	n.a.	n.a.

(1) CC: current technology level impact
(2) CC+CO2: current technology with CO2 effects
(3) CC + T: current technology with trend
(4) CC + T + CO2: current technology with trend and CO2

3.2.4. Impacts in class B

Since the crops in class B suffer little water stress, certainly by comparison with other impact classes, it is relatively obvious that CO_2 effects are well marked, since water stress tends to reduce their effectiveness.

Roughly 15% of yield increase can be assigned to CO_2 effects, while trend accounts for slightly more (about 20%) for scenario A2. Increases under B2 are usually less well marked. The fact that the most "severe" scenario will improve yields of B-class crops more that the "milder" scenario B2 is easily explained by the fact that the B class suffers no or little water stress, so that higher potential evapotranspiration values translate directly into higher crop evapotranspiration and rates of photosynthesis (refer to § 2.2. for the links between water balance and energy balance of crops).

Table 3.20: Percent yield change above "current technology" due to CO_2 effects and technology trend for the crops in class B, by 2050. Line (1) corresponds to the percent increase due to "climate change only".

Scenario		DEF-or	DEF-sud	FAV	INT	MONT	SAH
A2	(1)	8 (7 to 8)	5 (4 to 7)	6 (5 to 6)	5 (1 to 6)	7 (4 to 8)	7 (0 to 8)
	(2)	22 (12 to 24)	19 (11 to 20)	20 (9 to 21)	19 (15 to 20)	22 (17 to 24)	21 (12 to 22)
	(3)	25 (7 to 335)	22 (4 to 333)	20 (5 to 323)	24 (1 to 333)	35 (4 to 321)	27 (3 to 342)
	(4)	39 (12 to 347)	37 (11 to 345)	34 (10 to 335)	39 (15 to 345)	50 (19 to 333)	41 (13 to 354)
B2	(1)	7 (6 to 11)	4 (4 to 7)	5 (-3 to 6)	4 (1 to 7)	6 (-6 to 7)	6 (0 to 8)
	(2)	16 (10 to 17)	14 (8 to 15)	14 (7 to 15)	14 (11 to 15)	16 (3 to 17)	15 (8 to 16)
	(3)	24 (6 to 336)	22 (4 to 333)	20 (-3 to 326)	24 (1 to 335)	34 (-6 to 323)	26 (4 to 341)
	(4)	34 (10 to 344)	31 (8 to 341)	29 (7 to 334)	34 (11 to 343)	44 (3 to 331)	36 (9 to 349)

(1) CC: current technology level impact
(2) CC+CO2: current technology with CO2 effects
(3) CC + T: current technology with trend
(4) CC + T + CO2: current technology with trend and CO2

3.2.5. Impacts in class C

In class C, yield reductions at current technology level are just under 2% in 2030, and should reach about 5% in 2050 (see Table 3.21). The effect of CO_2 turns this into a slightly positive impact, while trend has a much more marked effect that may reach 68% in DEF-or under A2 conditions. As already observed under class B, the higher temperatures and the resulting higher evapotranspirations under A2 lead to a slight advantage of A2 over B2, except in the less favourable agro-ecological zone, i.e. SAH.

Table 3.21: Percent yield change above "current technology" due to CO_2 effects and technology trend for the crops in class C, by 2050. Line (1) corresponds to the percent increase due to "climate change only".

Scenario		DEF-or	DEF-sud	FAV	INT	MONT	SAH
A2	(1)	-4 (-7 to -2)	-4 (-7 to 0)	-7 (-11 to -2)	-5 (-11 to 0)	-5 (-8 to -1)	-4 (-10 to -1)
	(2)	5 (-4 to 11)	6 (0 to 14)	3 (-4 to 11)	7 (0 to 14)	3 (-3 to 11)	2 (-8 to 13)
	(3)	68 (-7 to 215)	10 (-7 to 52)	26 (-11 to 217)	38 (-8 to 209)	5 (-8 to 48)	-4 (-10 to -1)
	(4)	78 (-4 to 227)	20 (0 to 64)	36 (-4 to 230)	50 (0 to 222)	13 (-3 to 60)	2 (-8 to 13)
B2	(1)	-5 (-11 to -1)	-3 (-9 to 1)	-5 (-8 to 2)	-5 (-11 to 0)	-2 (-7 to 3)	0 (-2 to 3)
	(2)	1 (-8 to 8)	4 (-6 to 9)	2 (-3 to 10)	2 (-7 to 10)	2 (-4 to 8)	4 (0 to 8)
	(3)	67 (-11 to 217)	10 (-9 to 50)	28 (-8 to 217)	38 (-11 to 209)	7 (-7 to 47)	0 (-2 to 8)
	(4)	73 (-8 to 220)	17 (-6 to 58)	34 (-3 to 221)	45 (-7 to 212)	12 (-4 to 55)	4 (0 to 3)

(1) CC: current technology level impact
(2) CC+CO2: current technology with CO2 effects
(3) CC + T: current technology with trend
(4) CC + T + CO2: current technology with trend and CO2

3.2.6. Impacts in class D

In impact class D, trend and CO_2 play a comparable but minor role, usually not exceeding a combined positive effect of about 10% (except in MONT agro-ecological zone, where the combined effect reaches about 30%, and SAH, where it is close to 60&). Class D is also the first one that suffers more under A2 than under B2.

Table 3.22: Percent yield change above "current technology" due to CO_2 effects and technology trend for the crops in class D, by 2050. Line (1) corresponds to the percent increase due to "climate change only".

Scenario		DEF-or	DEF-sud	FAV	INT	MONT	SAH
A2	(1)	-17 (-26 to -10)	-16 (-31 to -9)	-16 (-31 to -16)	-15 (-30 to 26)	-17 (-29 to -8)	-15 (-21 to -15)
	(2)	-13 (-21 to -2)	-11 (-22 to -5)	-11 (-22 to -11)	-11 (-23 to 30)	-10 (-21 to 4)	-7 (-14 to -7)
	(3)	-13 (-23 to 15)	-12 (-22 to -5)	-12 (-22 to -12)	-12 (-25 to 26)	5 (-26 to 209)	40 (-16 to 40)
	(4)	-9 (-21 to 24)	-8 (-20 to 4)	-8 (-20 to -8)	-7 (-23 to 30)	12 (-21 to 221)	48 (-14 to 48)
B2	(1)	-12 (-21 to -3)	-10 (-18 to -7)	-10 (-18 to -10)	-12 (-26 to 9)	-9 (-18 to 2)	-9 (-13 to -9)
	(2)	-9 (-19 to 5)	-6 (-17 to 1)	-6 (-17 to -6)	-9 (-24 to 12)	-4 (-18 to 7)	-5 (-12 to -5)
	(3)	-8 (-21 to 43)	-6 (-18 to 23)	-6 (-18 to -6)	-8 (-26 to 30)	14 (-18 to 212)	47 (-13 to 47)
	(4)	-5 (-19 to 51)	-3 (-17 to 31)	-3 (-17 to -3)	-5 (-24 to 37)	18 (-18 to 215)	51 (-12 to 51)

(1) CC: current technology level impact
(2) CC+CO2: current technology with CO2 effects
(3) CC + T: current technology with trend
(4) CC + T + CO2: current technology with trend and CO2

3.2.7. Impacts in class E

Table 3.23: Percent yield change above "current technology" due to CO_2 effects and technology trend for the crops in class E, by 2050. Line (1) corresponds to the percent increase due to "climate change only".

Scenario		DEF-or	DEF-sud	FAV	INT	MONT	SAH
A2	(1)	-23	-17 (-22 to -11)	-22 (-31 to -14)	-31 (-40 to -25)	-16 (-19 to -12)	n.a.
	(2)	-20	-12 (-18 to -6)	-14 (-25 to -5)	-26 (-35 to -19)	-11 (-14 to -7)	n.a.
	(3)	109 (104 to 114)	35 (-11 to 81)	221 (-31 to 1104)	12 (-40 to 41)	64 (47 to 80)	n.a.
	(4)	112 (107 to 117)	40 (-6 to 85)	229 (-25 to 1112)	18 (-35 to 47)	69 (52 to 85)	n.a.
B2	(1)	-27 (-33 to -20)	-16 (-19 to -12)	-17 (-29 to -11)	-26 (-33 to -21)	-16 (-17 to -14)	n.a.
	(2)	-25 (-31 to -18)	-13 (-16 to -9)	-11 (-25 to -5)	-22 (-29 to -17)	-12 (-14 to -10)	n.a.
	(3)	113 (106 to 119)	38 (-12 to 88)	232 (-29 to 1130)	22 (-33 to 55)	65 (55 to 74)	n.a.
	(4)	115 (108 to 121)	41 (-9 to 91)	238 (-25 to 1136)	26 (-29 to 59)	68 (59 to 77)	n.a.

(1) CC: current technology level impact
(2) CC+CO2: current technology with CO2 effects
(3) CC + T: current technology with trend
(4) CC + T + CO2: current technology with trend and CO2

With class E (Table 3.23), the effect of the trend can exceed 100%, while CO_2 stays at a low 5 % impact. Clearly, this is a class of crops and locations where information about future water supply is most crucial to assess the final effect of climate change.

3.2.8 Impacts in class F

As already noted to some extent for D, but more clearly so for E, class F will suffer more under A2 than under B2. With the exception of DEF-sud and SAH, impacts should remain negative event if the technology trends are applied. Contrary to the previous group (class E), the behaviour of the crops in the class is much more homogeneous, as indicated by the limited spread of impact values.

Table 3.24: Percent yield change above "current technology" due to CO_2 effects and technology trend for the crops in class F, by 2050. Line (1) corresponds to the percent increase due to "climate change only".

Scenario		DEF-or	DEF-sud	FAV	INT	MONT	SAH
A2	(1)	-27 (-29 to -25)	-28 (-30 to -26)	-35 (-37 to -30)	-34 (-41 to -29)	n.a.	-40 (-50 to -33)
	(2)	-17 (-20 to -14)	-24 (-25 to -22)	-29 (-32 to -20)	-29 (-35 to -25)	n.a.	-42 (-57 to -31)
	(3)	-27 (-29 to -25)	29 (-30 to 88)	-35 (-37 to -30)	-34 (-41 to -29)	n.a.	296 (-33 to 528)
	(4)	-17 (-20 to -14)	34 (-25 to 92)	-29 (-32 to -20)	-29 (-35 to -25)	n.a.	294 (-31 to 521)
B2	(1)	-29 (-34 to -23)	-25 (-29 to -20)	-35 (-38 to -31)	-27 (-32 to -23)	n.a.	-34 (-50 to -26)
	(2)	-22 (-28 to -16)	-22 (-27 to -16)	-31 (-35 to -25)	-23 (-27 to -18)	n.a.	-35 (-55 to -24)
	(3)	-29 (-34 to -23)	34 (-20 to 88)	-35 (-38 to -31)	-27 (-32 to -23)	n.a.	319 (-26 to 570)
	(4)	-22 (-28 to -16)	37 (-16 to 90)	-31 (-35 to -25)	-23 (-27 to -18)	n.a.	317 (-24 to 565)

(1) CC: current technology level impact
(2) CC+CO2: current technology with CO2 effects
(3) CC + T: current technology with trend
(4) CC + T + CO2: current technology with trend and CO2

3.3. Changes in crop water use

As shown in Table 3.25, baseline water use follows a regular pattern with 25,000 m³ water use per hectare in class A, 10,000 m³ in B and C, 5,000 m³ in D and 2,500 m³ in E and F. If we consider the water use with technology trend in 2080, the values corresponding to the projected yields will approximately double over the century in classes C, D and E, remain stable in B and F (albeit for different reasons!) and increase fourfold in A. Although this is not shown in the table, water use for scenarios A2 and B2 is very similar (the difference does exceed 2%, rarely 3%) for most time horizons and classes in classes A, B and C. Differences are larger for classes D (4%), E (7%) and F (10%), with water use being higher under scenario B2. The highest differences occur in the relatively mild stresses foreseen for 2030 (30 to 35% in classes E and F).

The table contains several apparently paradoxical aspects. For instance water use will increase at current technology level between the baseline and 2080, even in the face of dropping yields. In fact, classes A and B will witness an increase of both yield and water use, while the less favourable classes will use less water because of lower yields brought about by increasing potential evapotranspirations.

Table 3.25: Projected future water use per crop classes between 2000 and 2080, average for scenarios A2 and B2. Baseline WU is in thousand m³ per hectare, while the other data are the factors by which the baseline has to be multiplied to achieve the projected yields.

		A	B	C	D	E	F
Baseline	2000	25.5	11	12	5	2.6	2.7
Without Techology trend and CO2 effects	2030	1.11	1.02	0.97	0.82	0.65	0.62
	2050	1.19	1.04	0.97	0.89	0.83	0.78
	2080	1.30	1.07	0.98	0.94	1.00	0.91
With technology trend	2030	2.09	1.12	1.28	1.27	1.40	0.80
	2050	3.10	1.23	1.65	1.68	1.69	0.90
	2080	4.15	1.34	2.03	2.09	1.95	0.98
With technology trend and CO2 effects	2030	2.13	1.15	1.31	1.30	1.43	0.85
	2050	3.21	1.32	1.74	1.74	1.73	0.95
	2080	4.37	1.52	2.18	2.16	2.00	1.00

3.4. Some details on major "pilot crops"

This section presents results that apply more specifically to some of the crops of major economic importance, such as the cereals barley and wheat, as well as citrus, tomatoes and vegetables, which are major export crops in Morocco.

Table 3.26: List of pilot crops with agro-ecological zones, baseline yield and EcoCrop profiles.

Crop	Class	Agroecological zone	Baseline yields Tons/Ha	EcoCrop profiles
Barley_rf	D	DEF-or, MONT, SAH	0.99	DDBB, EEDB, AAAA
Barley_rf	E	FAV	1.51	EEBB
Barley_rf	F	DEF-sud,INTER	1.02	DBBB, BBBB
Citrus_irr	B	DEF-or, FAV, MONT	14.36	AEEE, AAEE, AAAE
Citrus_irr	C	DEF-sud, INTER, SAH	15.17	AAEE, AEEE, EEEE
Sugar_beet_irr	C	DEF-or, DEF-sud, FAV, INT	46.19	EEEC, EEEE
Sugar_beet_rf	F	FAV	20.19	DDAA
Tomato_gh (Early)	B	All	82.35	EEEE
Tomato_irr (Industrial)	B	All	40.20	EEEE
Tomato_irr (Seasonal)	B	All	26.18	EEEE
Vegetables_irr ("Other Seasonal")	A	FAV	19.65	GGGG
Vegetables_irr ("Other Seasonal")	B	INT, MONT, SAH	17.33	GGGC, EEEE, CCCA
Vegetables_irr ("Other Seasonal")	C	DEF-or, DEF-sud	19.69	GGGC
Wheat_irr (Durum)	D	All	3.11	EEEE, EEEA
Wheat_irr (Soft)	B	SAH	1.64	EEEA
Wheat_irr (Soft)	C	DEF-or, DEF-sud, FAV, INT, MONT	2.39	EEEE
Wheat_rf (Durum)	E	DEF-or, DEF-sud, FAV, INT, MONT	1.47	AAAA, DDAA, EEDA, DDAA
Wheat_rf (Durum)	F	SAH	0.24	AAAA
Wheat_rf (Soft)	E	DEF-or, FAV, INT, MONT	1.66	DDAA, DDDD
Wheat_rf (Soft)	F	DEF-sud, SAH	0.59	DDDA, AAAA

Table 3.26 lists the impact classes to which the crops belong, baseline yields as well as their EcoCrop profiles. The crops belong to all impact classes:

- A, irrigated seasonal vegetables in FAV agro-ecological zone;
- B, tomatoes and irrigated soft wheat in SAH AEZ, and citrus (always irrigated) in DEF-or, FAV and MONT;
- C, citrus in the less favourable ecological zones (DEF-sud, INT and SAH, seasonal vegetables), sugar beet in DEF-or, DEF-sud, FAV and INT and vegetables in the DEF AEZs;
- D, Barley (always rainfed) in the unfavourable AEZs and durum wheat in all AEZs;
- E, Barley in FAV, rainfed durum wheat in the DEF, FAV, INT, MONT agro-ecological zones and rainfed soft wheat in DEF-or, FAV, INT and MONT and, eventually,
- F, rainfed sugar beet in FAV and rainfed soft wheat in DEF-sud and SAH.

For all the crops, judging from the current mostly low baseline yields, there is still room to improve yields (see § 3.2.1.).

Table 3.27 shows the results of the projections for 2050. Low yield probabilities will, in general, change little for irrigated crops, while they will double for rainfed crops (Barley, durum wheat), and even be multiplied by three for wheat (soft wheat and durum) when the crop occurs in class F.

Table 3.27: overview of pilot crops in 2050, average of scenarios A2 and B2.

Crop	Class	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Barley_rf	D	0.20	−13.67	−15.33	−14.00	−14.00	−10.00	−10.00	14.67
Barley_rf	E	0.23	−23.00	−13.50	−7.50	−18.00	−10.00	−10.00	14.50
Barley_rf	F	0.20	−56.50	−32.00	−28.00	−30.75	−25.75	−25.75	20.00
Citrus_irr	B	0.11	−12.00	0.25	11.25	0.00	12.00	12.00	13.50
Citrus_irr	C	0.12	−2.25	−3.25	−5.13	−2.13	9.38	9.38	9.63
Sugar_beet_irr	C	0.06	9.88	−8.50	−51.00	−2.38	7.75	62.50	10.63
Sugar_beet_rf	F	0.84	−41.00	−23.50	25.00	−32.50	−29.50	−29.50	11.50
Tomato_gh (Early)	B	0.00	144.30	−29.30	−92.00	6.30	16.30	339.80	12.50
Tomato_irr (Industrial)	B	0.00	6.60	5.40	−13.40	5.90	18.40	21.90	9.70
Tomato_irr (Seasonal)	B	0.00	6.60	5.40	−11.40	5.90	18.50	21.20	9.70
Vegetables_irr ("Other Seasonal")	A	0.00	79.50	−11.50	−77.00	19.00	31.50	226.00	13.00
Vegetables_irr ("Other Seasonal")	B	0.05	10.17	−1.67	−18.00	3.67	15.83	55.50	9.83
Vegetables_irr ("Other Seasonal")	C	0.09	0.75	−3.00	−17.00	−1.00	10.50	40.25	9.50
Wheat_irr (Durum)	D	0.16	−11.42	−15.83	−17.25	−16.75	−8.08	32.33	16.42
Wheat_irr (Soft)	B	0.01	9.00	−6.50	−41.00	0.00	10.00	80.50	13.00
Wheat_irr (Soft)	C	0.11	−0.40	−7.30	−25.40	−5.40	4.50	53.70	17.10
Wheat_rf (Durum)	E	0.20	−42.50	−18.20	−9.80	−20.80	−16.30	69.70	17.10
Wheat_rf (Durum)	F	0.34	0.00	−27.00	−27.00	−32.00	−33.00	401.00	13.00
Wheat_rf (Soft)	E	0.22	−32.63	−14.38	−1.88	−19.75	−14.88	69.63	17.13
Wheat_rf (Soft)	F	0.39	−16.75	−35.50	−34.75	−38.75	−40.25	317.00	15.00

(1) Low yields probability - no Tech, no CO2
(2) % change of 1st yield decile - no Tech, no CO2
(3) % change of 9th yield decile - no Tech, no CO2
(4) % change of yield interdecile (1-9) - no Tech, no CO2
(5) % change of average yield - no Tech, no CO2
(6) % change of average yield - with CO2
(7) % change of average yield - with CO2 and Tech
(8) % change of average water requirement

The deciles are not specifically discussed, because of the inherent difficulty of interpretation of those variables. Regarding yield changes between now and 2050, and the effects of trend and CO_2, they are in line with the averages of the classes the crops belong to: marked yield increases are projected for vegetables and tomatoes in class B, but also wheat in class E (and especially F), while Barley, because of the absence of current trend, is projected to undergo a drop in yields.

Table 3.28, in addition to 2030, 2050 and 2080 yield projections, also lists projected water use, of which some spectacular increases are predicted for 2080, as for instance between 20,000 and 50,000 m³ per hectare for early greenhouse tomatoes and seasonal vegetables in classes B and C. The most extreme case corresponds to seasonal vegetables (one of the few A class crops) in FAV agro-ecological zone: 222,000 m³ per Ha. For the 2030 time horizon, water uses are projected to be about three times less for the same crops.

For cereals, when they do not decrease (e.g. barley), water uses for of 2030 are projected to remain relatively stable.

Table 3.28: Projected yields and additional water use of pilot crops.

Crop	WUE av. Kg/m3	Class	Average A2 and B2 yields, tons/Ha							(1)	Additional trend-based water use thousand m3/Ha		
			Baseline	without technology trend			with technology trend						
			2000	2030	2050	2080	2030	2050	2080		2030	2050	2080
Barley_rf	0.5	D	0.986	0.945	0.848	0.748	0.945	0.848	0.748	-3.2	-0.08	-0.28	-0.47
Barley_rf	0.5	E	1.512	1.482	1.24	0.968	1.482	1.24	0.968	-10.1	-0.07	-0.52	-1.04
Barley_rf	0.5	F	1.019	0.917	0.706	0.51	0.917	0.706	0.51	-9.7	-0.20	-0.62	-1.01
Citrus_irr	2.2	B	14.359	14.168	14.168	15.508	14.168	14.168	15.508	1.0	-0.08	-0.08	0.49
Citrus_irr	2.2	C	15.171	15.019	14.943	15.222	15.019	14.943	15.222	0.1	-0.06	-0.10	0.02
Sugar_beet_irr	9.7	C	46.185	46.07	45.088	43.818	58.944	70.374	81.459	-0.3	1.26	2.39	3.49
Sugar_beet_rf	9.7	F	20.191	17.263	13.629	8.379	17.263	13.629	8.379	-13.0	-0.30	-0.67	-1.21
Tomato_gh (Early)	9.2	B	82.346	88.11	87.767	87.287	225.285	355.529	485.636	-0.3	15.54	29.71	43.85
Tomato_irr (Industrial)	9.2	B	40.196	41.469	42.608	44.484	42.005	43.981	46.393	0.8	0.20	0.41	0.68
Tomato_irr (Seasonal)	9.2	B	26.177	27.006	27.748	28.969	27.29	28.446	29.973	0.8	0.12	0.25	0.41
Vegetables_irr ("Other Seasonal")	0.3	A	19.651	21.714	23.385	25.743	41.365	61.606	82.731	1.9	76.50	147.79	222.18
Vegetables_irr ("Other Seasonal")	0.3	B	17.327	17.847	17.962	18.511	21.37	24.835	28.763	-0.3	12.10	22.42	38.84
Vegetables_irr ("Other Seasonal")	0.3	C	19.69	19.739	19.493	19.542	22.742	25.351	28.255	0.0	10.00	18.50	28.11
Wheat_irr (Durum)	0.5	D	3.109	2.966	2.588	2.055	3.609	3.845	3.923	-9.4	0.89	1.21	1.22
Wheat_irr (Soft)	0.9	B	1.636	1.661	1.636	1.62	2.258	2.789	3.346	-0.2	0.73	1.36	2.01
Wheat_irr (Soft)	0.9	C	2.392	2.387	2.263	2.141	2.99	3.44	3.892	-0.8	0.69	1.20	1.71
Wheat_rf (Durum)	0.5	E	1.467	1.444	1.162	0.822	2.089	2.423	2.682	-9.6	1.13	1.70	2.10
Wheat_rf (Durum)	0.5	F	0.239	0.223	0.163	0.114	0.748	1.2	1.63	-9.1	1.10	2.07	3.00
Wheat_rf (Soft)	0.9	E	1.66	1.637	1.332	1.025	2.353	2.735	3.09	-6.5	0.67	1.01	1.31
Wheat_rf (Soft)	0.9	F	0.586	0.535	0.359	0.265	1.55	2.452	3.345	-10.7	0.58	1.04	1.48

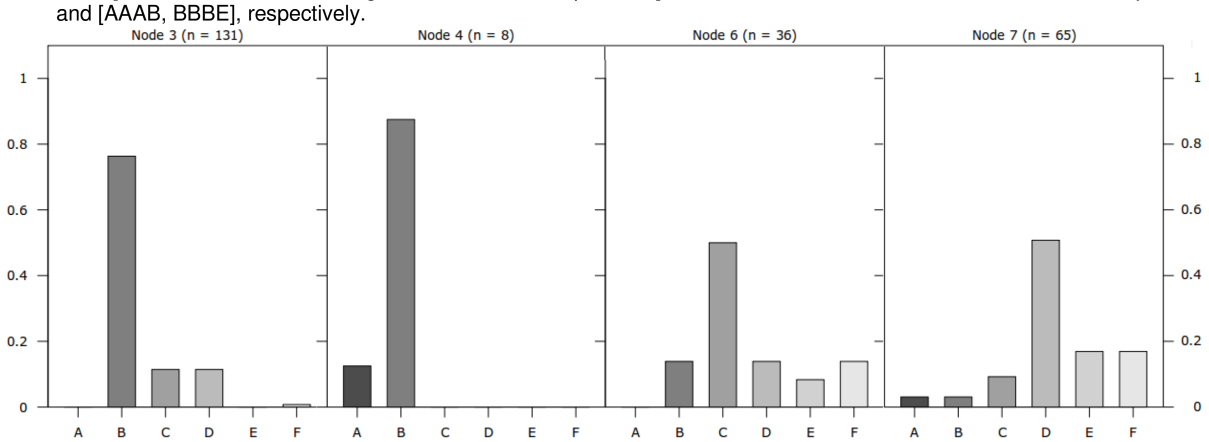
(1) Average % departure of A2 yields for the 2030, 2050 and 2080 averages; B2 and A2 values are symmetric. Example with yield=2 and -10%, A2=1.8 and B2=2.2.

3.5. Future suitability according to EcoCrop

3.5.1. Comparison between impact classes and EcoCrop outputs

There is some statistical similarity between the six impact classes (A to F, see § 3.1.1.) and the EcoCrop suitability profiles defined under 2.12.2. As both CSSWB simulations (and the resulting A to F impact classes) and EcoCrop profiles are available for 240 couples of crop and ecological zone, the dataset could be used to statistically compare the outcome of the two approaches (Figure 3.06).

Figure 3.06: Conditional tree simulation of the A-F impact classes based on EcoCrop profiles. Nodes 3 and 4: A2 profiles [AAAA, AAAB, AABB, BBBB, BBBD, BBBE, BBEE]; node 6: A2 profiles [ABBB, BBBC, BBCC, DDDD, EEEC] ; node 7: A2 profiles [AAAD, AACC, AADD, ADDD, BBCD, BCCC, CCCC, CCCD, CCDD, CDDD, EEEE]. Nodes 3 and 4 are distinguished based on B2 profiles: [AAAA, AABB, ABBB, BBBB, BBBC, BBBD, BBEB} and [AAAB, BBBE], respectively.



It appears that class B is rather well identified using the much simpler EcoCrop approach: 108 out of 117 crops.AEZ, or 92%, are assigned correctly to classes A and B, while 72% (89 out of 123) are assigned correctly to classes C to F. About half the crops in C fall under node 6 (46%, or 18/39; Figure 3.07) and 62% of the crops under node 7 (33/53) belong to impact class D. Even if classes E and F are not well discriminated, it is nevertheless interesting to note that the results of the EcoCrop methodology are largely compatible with the more sophisticated CSSWB approach.

Table 3.29 shows the EcoCrop water requirements and the numbers of crop AEZ couples for the entire set of crops that are present in the EcoCrop database. Only one value is given for EcoCrop water requirements, covering 2000, 2030, 2050 and 2080. This is because the WR values are very highly correlated[44]. Compared with the baseline, increases are 6, 16 and 31% for A2 and 6, 12 and 17% for B2 in 2030, 2050 and 2080. In the Table 3.29, the water requirements for 2000, 2030, 2050 and 2080 can be obtained by multiplying the listed values by 0.89, 0.95, 1.04 and 1.17 (A2) and 0.91, 0.96,1.02 and 1.06 (B2).

44 The first principal component accounts for 99% of the variance of the 8 EcoCrop water requirements!

Node	Irrigated		Rainfed	
	WR	N	WR	N
3	630	7206	672	1461
4	685	440	0	32
5	376	798	677	4452
6	282	470	445	3090
other	300	482	110	361

Table 3.29: EcoCrop water requirements (WR) and number N of WR values corresponding to nodes and the "irrigated" and "rainfed" categories. The sum of N values is 9396 and corresponds to 1566 crops in 6 agro-ecological zones each.

300 irrigated crops/species and 110 rainfed crops/species do not fall into any of the nodes defined above (Figure 3.07). The bulk of the irrigated crops (7206+440, 81%) falls under nodes 3 and 4, which corresponds to most irrigated crops belonging to the impact class B. On the other hand, most rainfed crops (4452+3090, 80%) belong to nodes 5 and 6 which, again, underlines the overall agreement between the EcoCrop method and the CSSWB approach.

3.5.2. Results of EcoCrop analysis

The number of crops covered by the EcoCrop analysis is very large, and prevents the detailed description of the results.

Some results are shown below for specific crops, mostly for illustration purposes. The full set of data is available from the website given in the footnote[45] and should be consulted for specific crops.

Tables 3.30a and 3.30b represent two extremes of a crop that may become suitable (under irrigation) and a common current crop that may become unsuitable. The first is coffee (Arabica) and the second is a common strawberry cultivar (Fragaria x ananassa). Coffee will become "suitable" around 2050, when temperature will cross the Topmin limit and change from suitability class 22 to 30.

Strawberry will move from the current "optimal" conditions to less favourable suitability classes 22. Referring to Figure 2.13, it appears that 22 stands for "too cold" rather than "too warm". The explanation of this apparently counter-intuitive result is as follows: first consider that the best current suitability (30) corresponds to a cycle length of 270 days, while the best suitability class for 2030 and 2050 (still 30) are obtained for a 180 day cycle. In 2080, we have code 21 for a 180 days cycle, 22 for 240 and 1 for 270. Therefore we selected the value 22 as max (1, 21, 22).

45 ftp://ext-ftp.fao.org/SD/Reserved/Agromet/WB_FAO_morocco_CC_yield_ impact/EcoCrop_future_status.xls

Table 3.30a and 3.30b: Climatic suitability as determined by EcoCrop for various scenarios, agro-ecological zones and water control (irr: irrigated and rf: rainfed). a: Coffea arabica; b: Fragaria x ananassa.

AEZ	Scen.	irr/rf	2000	2030	2050	2080
DEF-or	A2	rf	3	3	3	3
		irr	22	22	21	22
	B2	rf	3	3	3	3
		irr	22	22	30	21
DEF-sud	A2	rf	3	3	3	3
		irr	22	22	22	30
	B2	rf	3	3	3	3
		irr	22	22	22	30
FAV	A2	rf	3	3	3	3
		irr	22	22	30	22
	B2	rf	3	3	3	3
		irr	22	22	22	30
INT	A2	rf	3	3	3	3
		irr	22	22	30	22
	B2	rf	3	3	3	3
		irr	22	22	30	22
MONT	A2	rf	3	3	3	3
		irr	22	22	22	21
	B2	rf	3	3	3	3
		irr	22	22	22	30
SAH	A2	rf	3	3	3	3
		irr	22	21	22	22
	B2	rf	3	3	3	3
		irr	22	21	21	22

Table 3.30a: Coffea arabica

AEZ	Scen.	irr/rf	2000	2030	2050	2080
DEF-or	A2	rf	13	13	3	3
		irr	22	22	22	22
	B2	rf	23	13	13	3
		irr	30	22	22	22
DEF-sud	A2	rf	23	23	13	3
		irr	30	30	22	22
	B2	rf	23	23	13	13
		irr	30	30	22	22
FAV	A2	rf	30	23	23	13
		irr	30	30	30	22
	B2	rf	30	23	23	13
		irr	30	30	30	22
INT	A2	rf	23	13	13	3
		irr	30	22	22	21
	B2	rf	23	13	13	13
		irr	30	22	22	22
MONT	A2	rf	13	13	13	13
		irr	22	22	22	22
	B2	rf	13	13	13	13
		irr	22	22	22	22
SAH	A2	rf	3	3	3	3
		irr	22	22	22	21
	B2	rf	3	3	3	3
		irr	22	22	22	22

Table 3.30b: Fragaria x ananassa

From a farmer's point of view, there are thus three options, of which the second is the most manageable:

- Option 1: cultivate from Feb. to Oct. (270 days) with a suitability of 1: the temperatures of this cycle are larger than Tmax, and therefore unsuitable;
- Option 2: grow the strawberries as winter crop from Oct. to May (240 days), with a suitability of 22. The average minimum temperature of the cycle are between Tmin et Topmin, i.e. they are sub-optimal because of the cold;
- Option 3: adopt the period from Feb. to July (180 days) with suitability 21. The average maximum temperatures of this cycle are between Topmax et Tmax and, therefore, sub-optimal because of heat.

Table 3.31 lists some plants/crops that are less than suitable in the current baseline period and in 2030, but change to suitable during the 2050 reference period. Note that the change specifically refers to 2050, i.e. plants that switch to suitable in 2030 are not included.

About half the plants in the list are woody, and a fair number are fodder crops (including legumes). While many of the crops do currently grow in Morocco, and even if the list includes some "trivial" crops (e.g. *Dactylis glomerata*), it is worth noting that crops of major economic importance such as Arabica coffee may become suitable under irrigated conditions in Morocco. Also note the Queensland nut (*Macadamia*) and Chinese cinnamon (currently cultivated commercially only in China and Vietnam). Even the above-mentioned *Dactylis* and several other fodder crops in the list point at the well know observation that the crop mix as we know it today is bound to undergo qualitative changes. For instance, almond is currently rainfed, but it may become necessary to irrigate it.

Table 3.31: List of plants that switch to "optimal" during the 2050 reference period, by agro-ecological zone, scenario and water control typology (irr and rf). Y and N after the name indicate whether the plant was covered in the CSSWB analyses, either directly or as part of a group (i.e. onion as part of "seasonal vegetables".

AEZ	irr/rf	Species/crop
DEF-or	irr	Acacia jennerae Maiden (A2/N)
		Acacia jensenii Maiden (A2/N)
		Acacia murrayana F Muell (A2/N)
		Acacia pachyacra Maiden & B (A2/N)
		Allium cepa L v. cepa (B2/Y)
		Allium fistulosum L (B2/N)
		Atriplex hortensis L (A2-B2/N)
		Avena sterilis L (A2/N)
		Bouteloua gracilis (Willd) (A2/N)
		Coffea arabica L (B2/N)
		Dactylis glomerata L (A2/N)
		Hedysarum coronarium L (B2/N)
		Lolium multiflorum Lam (A2-B2/N)
		Macadamia tetraphylla (B2/N)
		Prunus amygdalus Batsch (A2/Y)
		Raphanus sativus L (A2-B2/N)
		Stripa glareosa Smirn (A2/N)
		Vigna parkeri Baker (A2/N)
	rf	Acacia jennerae Maiden (A2/N)
		Acacia murrayana F Muell (A2/N)
		Acacia pachyacra Maiden & B (A2/N)
		Stripa glareosa Smirn (A2/N)
DEF-sud	irr	Acacia jensenii Maiden (A2/N)
		Acacia murrayana F Muell (A2/N)
		Allium cepa L v. cepa (B2/Y)
		Allium fistulosum L (B2/N)
		Atriplex hortensis L (B2/N)
		Avena sterilis L (A2-B2/N)
		Bouteloua gracilis (Willd) (A2-B2/N)
		Bromus inermis Leyss (A2-B2/N)
		Capparis spinosa (A2/N)
		Coffea excelsa L (A2/N)
		Dactylis glomerata L (A2-B2/N)
		Eucalyptus pauciflora Sieb (B2/N)
		Melilotus officinalis Lam (B2/N)
		Prunus amygdalus Batsch (A2-B2/Y)
		Raphanus sativus L (L R) (A2-B2/N)
		Stripa glareosa Smirn (A2/N)
		Vigna parkeri Baker (A2-B2/N)
	rf	Acacia jensenii Maiden (A2/N)
		Acacia murrayana F Muell (A2/N)
		Allium cepa L v. cepa (B2/Y)
		Stripa glareosa Smirn (A2/N)
FAV	irr	Avena sterilis L (A2-B2/N)
		Bouteloua gracilis (Willd) (A2-B2/N)
		Bromus inermis Leyss (A2-B2/N)
		Capparis spinosa (A2/N)
		Coffea arabica L (A2/N)
		Coffea excelsa L (A2/N)
		Dactylis glomerata L (A2-B2/N)
		Eucalyptus pauciflora Sieb (A2-B2/N)
		Hedysarum coronarium L (A2/N)
		Lolium multiflorum Lam (A2/N)
		Lolium rigidum Gaud (A2-B2/N)
		Macadamia tetraphylla (A2/N)
		Malus domestica Borkh (A2/Y)
		Melilotus officinalis Lam (A2-B2/N)
		Prunus amygdalus Batsch (A2-B2/Y)
		Raphanus sativus L (R R) (A2-B2/N)
		Vicia sativa L s nigra (A2/N)
		Vigna parkeri Baker (A2-B2/N)
	rf	Lolium rigidum Gaud (A2-B2/N)
		Melilotus officinalis Lam (A2-B2/N)
INT	irr	Acacia jensenii Maiden (A2-B2/N)
		Acacia murrayana F Muell (A2-B2/N)
		Atriplex hortensis L (A2-B2/N)
		Coffea arabica L (A2-B2/N)
		Hedysarum coronarium L (A2-B2/N)
		Lolium multiflorum Lam (A2-B2/N)
		Macadamia tetraphylla (A2-B2/N)
		Stripa glareosa Smirn (A2-B2/N)
	rf	Acacia jensenii Maiden (A2-B2/N)
		Acacia murrayana F Muell (A2-B2/N)
		Stripa glareosa Smirn (A2-B2/N)
MONT	irr	Acacia victoriae Benth (A2-B2/N)
		Brassica nigra L (A2/N)
		Brassica oleracea L v botr (A2-B2/N)
		Lathyrus sativus L (A2/N)
		Lolium rigidum Gaud (A2-B2/N)
		Mentha rotundifolia (L)Huds (A2/N)
		Pisum sativum L (B2/Y)
		Sinapis alba L (A2/N)
		Vicia narbonensis L (B2/N)
		Vicia villosa Roth s dasy (B2/N)
	rf	Acacia victoriae Benth (A2-B2/N)
		Lolium rigidum Gaud (A2-B2/N)
		Vicia narbonensis L (B2/N)
SAH	irr	Acacia ampliceps B R Maslin (A2/N)
		Acacia glaucocaesia Domin (A2/N)
		Cinnamomum cassia Presl (A2-B2/N)
		Dalbergia latifolia Roxb (A2/N)
		Eucalyptus resinifera Smith (A2/N)
		Eucalyptus robusta Smith (A2/N)
		Eucalyptus saligna Smith (A2-B2/N)
		Hardwickia binata Roxb (A2-B2/N)
		Lotononis bainesii Baker (A2/N)
		Mentha arvensis v piperasc (A2/N)
		Pimenta dioica (L) Merr (A2-B2/N)
		Prunus armeniaca L (A2/Y)
		Quercus ilex L (A2/N)
		Xylia xylocarpa Roxb (A2/N)

4. Methodological issues

4.1. Introduction

It is extremely difficult to assess the actual level of confidence of the yield projections that have been developed in this report. As indicated above, the results should not be taken beyond the specific context for which they have been designed, in particular impacts should not be taken to a more detailed spatial scale than the six agro-ecological regions (AER). The same applies to the limitations introduced by the use of specific scenarios, groups of crops (e.g. "fodder"), time horizons, agricultural statistics, etc. For most of the statistical work, the statistical significance of the methods can be assessed, and this was done every time it was possible.

It is also stressed that the impacts we present are impacts on current agriculture: they are single-crop impacts on present-day crops. Some attempt was made to incorporate CO_2 effects and technology trend. While both effects are very conservative, in particular rather low technology trends, the future potential can be realised only if sufficient water is available. This is beyond the scope of this component of the WB_Morocco work. It will be covered in a separate study. The next critical issue is adaptation to climate change by the farming community[46]. As some adaptation, e.g. the selection of varieties suitable to future conditions depends on future climate; it was somehow taken into account through the determination of future phenology, such as shorter crop cycles and changing planting dates.

Since the yield projections presented in section 3 incorporate a number of raw and processed climatic data, agricultural statistics and others, it was found that the only way to assess the soundness of the whole procedure was in comparing the end products, i.e. estimated yield with observed yields. This was done in various sections of this report for instance in § 2.9.2. for the statistical distribution of yields.

4.2. Climate scenarios

The present study considers that scenarios are given. As far as possible, the present study adheres to climatological standards by considering 30-year periods in the presentation of results.

The location and the number of stations that were used for downscaling is the result of a compromise between availability of locations with adequate data, the need to cover the whole country and the main agro-ecological zones, and the amount of work required.

Based on processing of current data (e.g. computation of crop water requirements using a derived pseudo-Penman methodology and the spatialisation of climatic data using the AURELHY approach),

46 Other types of adaptation, i.e. those including institutional aspects, legislation and agricultural policy, markets etc. are, again, beyond the scope of the present component of the WB- Morocco study.

we consider that the scenarios and the data processing adequately represent current conditions.

Several problems were encountered during the processing of the scenario data, but they were mostly solved in consultation with the author of the downscaling methodology and DMN. Three points that certainly affect the results deserve mentioning:

- in about 0.7 % of the daily scenario outputs, minimum temperature (Tn) exceeds maximum temperature (Tx). It remains that daily thermal amplitude is usually underestimated, even if the effect tends to be less marked at the 10-day scale that was used for crop-weather simulations. Since the pseudo-Penman PET depends directly on the thermal amplitude, the actual crop water requirements are underestimated. Since this factor affects only the “future climate”, it leads to optimistic future yield assessments;

- the scenarios generate independent series of Tn, Tx and rainfall. In reality, however, temperatures and thermal amplitudes are both lower on rainy days than on rainless days. The result is an underestimation of crop water requirements on rainless days, and an overestimation of the same on rainy days. Again, this factor tends to underestimate future crop water stresses;

- for the period during which both actual data and scenario data are available, it was observed that, even considering that the scenarios were run 20 times while there is only one realisation of “actual data”, the variability of actual data exceeds that of scenarios. This is a third source of a too optimistic overall assessment, although this factor affects variability more than averages.

4.3. Agricultural statistics

A significant effort was made to assemble the agricultural statistics required to calibrate and to validate the yield simulations.

The level of significance of yield estimates for each individual crop is assessed by the strength of the correlation between agricultural statistics and simulations. In general, the correlations are good or excellent for main crops, for which statistics are usually deemed to be reliable. For instance, R2 reaches 0.9 for barley in the FAV agro-ecological zone. As a rule, for most crops, correlations are weaker in the DEF-sud and DEF-or zones. Altogether, a positive factor as correlations are strong in major producing areas and low in marginal ones which scarcely contribute to national production.

For some crops, correlations are weak or non-existent, in which case we have assumed that the “central dogma” of crop modelling applies, i.e. a direct linear relation between yield and actual evapotranspiration (refer to § 2.2.).

Several additional points deserve mentioning:

- Moroccan agricultural statistics do not distinguish between irrigated crops and non-irrigated ones. In almost all cases, it was possible to obtain sufficient data for irrigated and non-irrigated areas, whether at the level of provinces or ORMVA. In many cases, "mixed but predominantly irrigated" had to be taken as "irrigated" and "mixed but predominantly rainfed" had was considered as "rainfed";

- For irrigated areas, the simulation model was run in "automatic irrigation" mode, i.e. a mode in which water is automatically added (by the model) every time there is a water stress. For calibration of irrigated crops, both variables from rainfed and automatic irrigation simulations were used. For rainfed crops, however, only "rainfed simulations" variables were included;

- Crops for which no reference yields could be found were estimated in relative terms, i.e. expressed as the ratio between future yields and the base-line yield;

- Barley yields straw and grain. FAO colleagues from the Crops and Grassland Service (AGPC) provided the empirical information that was eventually used to estimate straw production.

4.4. Data processing

The present study was extremely heavy in data processing requirements as it covers 50 crops, 2 scenarios, 20 runs per scenario and 122 years (1979 to 2100). In addition, most simulation outputs had to be spatialised: about 20 water balance variables in calibration mode (1979 to 2006) and about 2 to 3 in simulation/projection mode (2011 to 2099). This required an "industrial" approach and a high degree of automation.

Most processing was done through batch command files running over night on several PCs, and resulting in millions of intermediate results and data files.

Although data manipulation and processing errors cannot be excluded, they are thought to be minimal, for the following reasons:

- Twelve people were involved, each working with inputs provided by the previous level. This ensures that data are cross-checked;

- All programmes performed internal and external consistency checks on inputs. Given the sequential nature of the processing, data errors have been gradually eliminated;

- The algorithms used in WABAL are those of the standard FAO AgroMetShell software[47]. This is suite of tools used in a number of countries and developed over the last thirty years. The algorithms are, therefore, reliable. The phenology tool (PLDEK) was developed for the current project. It was extensively tested against the calibration period (baseline period) before being applied to the climate projections. While the AURELHY tools were developed for this study, the method has a long history in agroclimatic applications in INRA (see § 2.10.). It was tested on standard climatic variables and compared with published climatic maps. While this is a rather qualitative approach, the method is deemed reliable.

47 http://www.fao.org/NR/climpag/pub/cm_box_4.pdf

4.5. Decreasing irrigated yields

4.5.1. Introduction

Next to the estimation of future water uses, the question of decreasing yields of irrigated crops is very visible from Table 3.04. It raised many questions and is, therefore, given a fair amount of attention below. The issue was examined from the double point of view of the eco-physiological reality of the phenomenon and the simulation procedure, and we conclude that the predicted decreases are not a methodological artefact.

4.5.2. Generic factors of yield decrease under projected climate change

The following factors contribute to decreasing future yields. They do not all apply to irrigated crops only, but they all apply to irrigated crops as well.

- **1.** Irrigated crops do not receive all the water they would optimally require. In other words, in order to save both water and to reduce irrigation costs, irrigated crops are maintained in a state of relative water stress. Using additional water could relieve the stress, at least partly, but would entail the risk of wasting water through "luxury consumption". It follows that, even for irrigated crops, rainfall constitutes a non-marginal water supplement, so that projected decreases in water supply through reduced rainfall and increased PET will be accompanied by a drop in yields.

  It is also in order to mention water requirements (refer to § 2.2.), especially the Box on "Water need (WN), requirement (WR) and use (WU)". WR is defined as the total water that has to be supplied in order to avoid water stress, in addition to rainfall. We have found that WR will increase for all crops (for instance, in 2050, the increase varies between 8% and 27%) and that yields of irrigated crops such as wheat, olive and early tomatoes will decrease[48]. The direct implication of those results is that "irrigation requirements" (or WR) we have estimated are insufficient to maintain current levels of water satisfaction.

  In fact, for wheat, the main yield predictor is average soil moisture (the variable is called "Smoist_cyc"), which is a clear indication that, even under irrigated conditions, the variable is not "saturated" (i.e. constant, in which case it would not have affected yield). The effect is more marked in the areas with high rainfall. For wheat, future Smoist_cyc will decrease compared with current conditions. It represents average soil moisture over the growing cycle. It is useful to quickly explain how the WABAL software manages "automatic irrigation": whenever a water stress occurs, i.e. soil moisture drops to 0 and water stresses equivalent to crop water requirement start accumulating, automatic irrigation supplies the amount of water that is required to prevent a stress. The result is that soil moisture stays usually close to 0, except during rainy periods. Therefore, Smoist_cyc reflects essentially the accumulated difference between rainfall and water requirements. Under equivalent conditions, soils with larger water storage capacities can continue supplying water longer than poor soils. Note, however (§ 2.2.) that 100 mm was adopted as a constant soil water holding capacity in this study, considering that a more detailed approach (variable soil moisture, shorter time steps, more complex "automatic irrigation") would not have substantially modified the above picture at the scale at which this study was done[49].

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48 For olives, the decrease is noted in the two DEF agro-ecological zones, but not in FAV and SAH.

49 These effects are well know in crop forecasting, and were discussed at length in the methodology development phase, where 100 mm was eventually agreed on as a "good" water holding capacity for Morocco because (1) other studies using the same CSSWB implemented in AMS and WABAL (Balaghi, 2006) have explicitly explored this issue and (2) local differences are "ironed out" by the statistical calibration of CSSWB outputs.

- **2.** Two factors will concur in the future to reducing cycle lengths: water balance conditions and temperature.

  2a. Due to deteriorating water balance conditions (period of effective climatic water availability), future growing periods will be shorter than the ones that occur today (refer to § 2.5. for details). This is due both to decreasing water supply and variability. This is well illustrated in Figure 2.08: cycles will get shorter particularly where conditions are currently favourable; the effect is least in the MONT agro-ecological zone, where temperature currently limits cycle lengths. In practice, it is particularly the onset of the growing period that will be occurring later and later in the season.

  2b. Increasing temperatures accelerate crop development and shorten growing cycles. The effect is well documented and the concept of Growing Degree-days (GDD) is a basic ingredient of the phenology module of most crop models (Gommes, 1999; Gommes et al., 2008). While (a) applies mostly to rainfed crops[50], (b) affects all crops. The present study did not undertake any systematic comparison between the water balance and temperature effects on the crop cycle, but since they vary in the same direction, they are completely compatible and by no means compensate each other. Since short cycles cannot possibly accumulate the same amounts of photosynthetates than longer ones, short cycles are by necessity associated with lower yields. This has been shown over and again using various approaches, for instance the standard method based on solar radiation developed by Kumar and Monteith (1981).

- **3.** Scenarios agree that the future temperature increases will not be achieved by a symmetric increase of minimum and maximum temperatures: minimum temperatures will increase more than maximum temperatures[51], which will result in respiration loss of photosynthetates during the night (Livingstone, 2003), leading, again, to lower production potentials in the affected areas.

- **4.** Indirect effects do exist as well along the whole production and processing chain, but in the absence of any precise simulation and empirical data, they are more difficult to assess. They include pests and diseases, weeds, soil and water pollution, salinisation, which are all enhanced by higher temperatures.

4.5.3. Specific aspects linked with the CSSWB and calibration

- **1. Introduction**

The calibration equations (yield functions) describe current agriculture. It is clear that agriculture will change, adapt etc., and that the crops grown in 2050 and 2080 will not be the same as those cultivated today. In addition, climate will not be the same, so that calibrations done for the climate conditions of the recent past will not, in all rigour, apply to drier and warmer future conditions[52]. These effects were well known when the methodology was developed but it was found that pros of the approach outweigh the cons.

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50 The same varieties are often used for irrigated and rainfed conditions, so that, to some extent, the temperatures also affect irrigated crops.

51 For instance: "Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range" (IPCC AR4: Meehl et al, 2007) and "Global mean temperatures are projected to increase by 1.4-5.8°C by 2100 AD (3), with decreases in diurnal and seasonal temperature ranges" (Williams et al., 2007).

52 To use an extreme image: assessing 2080 yields based on 1980-2000 data is like assessing current Moroccan yields based on Vietnamese yield functions.

If is also stressed that for several crops, a compromise had to be made between statistical significance and spatial scale. For instance, for early tomatoes, insufficient data were available to obtain any useful equations at the level of agro-ecological zones, but rather good coefficients were obtained at the national level (refer to Table 2.03). It is this national yield function that was used throughout the country, so that even projections at the agro-ecological zone level used yield functions validated at the national level. In some cases (sugar beet), calibrations at the ORMVA level were resorted to for agro-ecological zone-wide impact assessments. Finally, there are also cases where crops grown under rainfed conditions (yield functions calibrated with rainfed model data) were then simulated as rainfed. The rule has always been to use only statistically significant yield functions.

As already mentioned above for wheat, in spite of yield statistics that poorly differentiate between irrigated and rainfed conditions, there exist sufficient data at the national or sub-AEZ scale (e.g. ORMVA), or data where "almost all" wheat is rainfed or "almost all" wheat is irrigated to distinguish between rainfed and irrigated conditions and to indirectly confirm that yield functions are not very different: the most meaningful variables turn out to be the same, i.e. such variables as soil moisture and water excess. For some irrigated crops, data were insufficient to obtain significant yield functions. In this case, we resorted to assuming a direct link between total irrigated evapotranspiration (ETT_irr) and yield (refer to second paragraph of § 2.2.). It is noteworthy that for the crops where this was done (e.g. *rosaceae* fruit trees, rice and sugar cane), future irrigated yields do increase. The most typical result is probably that irrigated olive yield in SAH and FAV will witness an increase [based on yield = f (ETT_irr)], while other agro-ecological zones are projected to suffer a decrease. To what extent improved irrigation technology and practices can alter this behaviour would be worth exploring. It remains that the decrease of irrigated yields cannot be ascribed to methodological errors.

- **2. Calibration variables**

The following section looks specifically into variables used in the yield functions of crops that will undergo a decrease of yield under irrigated conditions:

- Wheat, durum, irrigated: Smoist_cyc_irr et EXCf_irr (excess water at the time of flowering, irrigated conditions), national calibration, r^2=0.623
- Wheat, durum, bour: ETf_rain et EXCf_rain (Evapotranspiration at the time of flowering, rainfed conditions and excess water at the time of flowering, rainfed conditions), national calibration, r^2=0.850
- Wheat, soft, irrigated: Smoist_cyc_irr, national calibration, r2=0.376
- Wheat, soft, bour: ETf_rain, WSI_rain (water satisfaction index, rainfed conditions), national, r^2=0.639
- Olive, INT agro-ecological zone: EXCi_irr (excess water in the initial phase, irrigated), r^2=0.828
- Olive, DEF-sud agro-ecological zone, E_Pres_irr (pre-season evaporation, with negative coefficient), r^2=0.385
- Olive, DEF-or, ETf_irr (evapotranspiration at the time of flowering, irrigated), r^2=0.336
- Early tomato, ETi_irr (ET during initial phenophase, negative) and EXCv_irr (excess water supply during the vegetative phase, negative), national calibration, r^2=0.518 and r^2=0.826
- Irrigated sugar beet, ORMVAD, E_cyc_irr (negative) and EXCi_irr (negative), calibrated at ORMVA level, r^2=0.332
- Irrigated sugar beet, ORMVAL, Smoist_pres_irr, calibrated at ORMVA level, r^2=0.315

- Irrigated sugar beet, ORMVAM, Smoist_pres_irr and EXCt_irr
- Irrigated sugar beet, ORMVATD, EXCt_rain and ETf_irr (negative), calibrated at ORMVA level, r^2=0.410

The case of wheat has already received a fair amount of attention above. It is just stressed that Smoist_cyc_irr does not depend much on cycle length, so that the shortening of the cycle cannot be responsible for yield decreases. On the other hand, we have a clear effect of deteriorating water balance conditions, and the presence of WSI definitely points in the same direction.

The interpretation of the EXC variables is not so straightforward. When the coefficients are positive, this is best interpreted as indication that the CSSWB probably underestimates water requirements, so that "excess" is really a useful water supply (possibly due to underestimated crop water requirements soil water holding capacity). This is a non-critical factor that is taken into account by the calibration.

On the other hand, the EXC predictors are very common (Table 2.01) for specific phenological phases of such crops as durum wheat, olive, early tomato and irrigated sugar cane. In many cases, the coefficients are negative, which points are a true excess with a negative impact. Again, this is relatively easy to understand in terms of irregular distribution of rainfall, leading to excess water supply at specific phenophases, particularly if such variability is expected to increase in the future.

The case of olive was discussed above too. For the INT agro-ecological zone, the above-mentioned underestimation of water requirements clearly plays a part. For DEF-sud and DEF-or, excessive water loss before the active vegetation phase and at the time of flowering can be suspected as the main factor. It is also stressed that, e.g. for the INT agro-ecological zone, regression coefficients are particularly good.

For early open field tomato and irrigated sugar beet (the latter crop calibrated based on ORMVA statistics), several variables occur with negative coefficients, but the yield functions have a high statistical reliability. Sugar beet is one of the crops with the weakest correlations, also considering that ORMVA statistics do not clearly distinguish between irrigated and rainfed conditions. It remains that the CSSWB yielded variables that were significantly correlated with yields.

5. Conclusions

The results of the present study include 68790 individual data items describing the impact of two scenarios on fifty crops in six agro-ecological zones and 3 time horizons. Most of the 68790 data items, especially those that refer to future risk, are the average of 600 repetitions (20 simulations over 30 years centred around 2030, 2050 and 2080). In addition, more than 1500 crops available in the EcoCrop database were screened against future climate conditions in the six agro-ecological zones, adding another set of just above 300,000 data items[53].

This is a huge "industrial" task and it could only be achieved through the collaboration of a number of institutions and scientists. The variety of projected impacts is huge as well, and the present report lost, by necessity, some information when attempting to structure the results into a logical and agronomically meaningful way. This is why a statistical approach was resorted to summarise the results.

The methodology was designed in such a way that it has the potential to realistically simulate present-day yields of major crops, within the limits of the data available for calibration. It bases on the experience of FAO in operational crop yield forecasting which was developed over the last twenty years and avoids many of the pitfalls encountered in climate change impact assessments, in particular those associated with up-scaling point data to regions.

Insofar as the same crops will be cultivated in the future, and insofar as the climate projections are reliable, the methodology that was applied in this study has the potential to assess impacts of climate change on crops, particularly for the near future, probably up to 2030 and hopefully to 2050 and beyond for most crops.

This comprehensive study was also a learning process for most participants. The tools and the software that was designed for the study remain valid, but additional factors should be considered. They include a more dynamic simulation of farming systems (to include several forms of spontaneous and controlled adaptation), the parallel modelling of crops and surface and groundwater availability, the dynamic downscaling of climate scenarios and a more explicit treatment of climate variability.

It was also discovered that the rather simple EcoCrop approach yields results that are compatible with the more complex Crop Specific Soil Water Balance (CSSWB) approach. This opens the door to simpler approaches which, however, need calibrating against more comprehensive ones such as the present CSSWB approach.

With few exceptions, the yield of the crops for which a detailed simulation was undertaken will decrease unless irrigated. As it is uncertain whether increased water demand for irrigated crops can be met under the drier climate predicted for climate change scenarios, this study invested a lot of time into exploring technology trends and water use.

Management of water, land and crops at the national, regional watershed and local (farm) level is the basis of "adaptation", driven by market, labour and food security constraints. More work is required to develop tools that can be used to realistically simulate adaptation.

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53 ftp://ext-ftp.fao.org/SD/Reserved/Agromet/WB_FAO_morocco_CC_yield_ impact/ has all the output data.

6. References

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Annexes

Annex 1 - list of meteorological stations

Rainfall, minimum and maximum temperature data were collected from 20 meteorological stations: 16 in Moroccan and 4 in Mauritania. The stations are listed from North to South.

Station name	Longitude (DD.dd)	Latitude (DD.dd)	Altitude (m)	Agrozone
Tangier	-5.90	35.72	15	FAV
Al Hoceima	-3.85	35.18	12	DEF-or
Oujda	-1.93	34.78	465	DEF-or
Taza	-4.00	34.22	509	FAV
Meknès	-5.53	33.88	548	FAV
Casa Anfa	-7.67	33.57	57	FAV
Ifrane	-5.17	33.50	1664	MONT
Settat	-7.58	33.03	375	INT
Midelt	-4.73	32.68	1508	MONT
Bouarfa	-1.95	32.57	1142	DEF-or
Beni Mellal	-6.40	32.37	468	MONT
Marrakech	-8.03	31.62	463	DEF-sud
Essaouira	-9.72	31.52	8	DEF-sud
Ouarzazate	-6.90	30.93	1136	SAH
Agadir Inezgane	-9.57	30.38	23	SAH
Laayoune	-13.22	27.17	64	SAH
Bir-Moghrein	-11.62	25.23	364	Mauritania
Zouerate	-12.48	22.75	343	Mauritania
Nouadhibou	-17.03	20.93	5	Mauritania
Atar	-13.07	20.52	226	Mauritania

Annex 2 - list of variables

- **1. CSSWB output variables**

The variables below were used as predictor variables for yield simulation and the development of the yield functions. For each variable, there is usually a "twin" variable corresponding to irrigated conditions, resulting in a total of 49 actual variables (as cycle length is always identical for both irrigated and rainfed crops).

	Short variable name	Definition: long variable name
1	Cycle	Cycle length
2	DEFf	Water deficit during flowering phase
3	DEFh	Water deficit during pre-harvest phase (yield formation)
4	DEFi	Water deficit during initial phase
5	DEFt	Water deficit over whole cycle
6	DEFv	Water deficit during vegetative phase
7	E_cyc	Evapotranspiration over whole crop cycle
8	E_pres	Evapotranspiration pre-season (100 days)
9	Etf	Evapotranspiration during flowering phase
10	Eth	Evapotranspiration during yield formation phase
11	Eti	Evapotranspiration during initial phase
12	Ett	Evapotranspiration over whole crop cycle
13	Etv	Evapotranspiration during vegetative phase
14	EXCf	Water Excess during flowering phase
15	EXCh	Water excess during pre-harvest period
16	EXCi	Water excess during the initial phase
17	EXCt	Water Excess over whole crop cycle
18	EXCv	Water excess during the vegetative phase
19	iPL	Planting dekad (1-36)
20	R_cyc	Average dekadal rainfall during the crop cycle
21	R_pres	Average dekadal rainfall during the pre-season period
22	Smoist_cyc	Soil moisture: average over the growing season
23	Smoist_pres	Soil moisture: average over pre-season dekads
24	WSI	Water satisfaction index
25	Totaut	Automatic irrigation amount

- **2. Model output variables**

The variables below are available for each crop, agro-ecological zone, reference period (one "current period", left, and three "future periods": 2030, 2050 and 2080), and two scenarios (A2 and B2).

Current period	Future periods
Baseline Low Yield Probability	Low Yields Probability (WITH tech trend)
	Low Yields probability (WITHOUT tech trend; CO_2 fertilization)
	Low Yields Probability (WITH tech trend; CO_2 fertilization)
Baseline 1st DECILE Water Requirement (mm)	Percent change in 1st DECILE Water Requirement
Baseline average Water Requirement (mm)	Percent change in average Water Requirement
Baseline 9th DECILE Water Requirement (mm)	Percent change in 9th DECILE Water Requirement
Baseline INTER DECILE Water Requirement (mm)	Percent change in INTER DECILE Water Requirement
	Percent change in 1st DECILE yield (WITH CO_2 fertilization)
	Percent change in average yield (WITH CO_2 fertilization)
	Percent change in 9th DECILE yield (WITH CO_2 fertilization)
	Percent change in INTER DECILE yield (WITH CO_2 fertilization)
	Percent change in 1st DECILE yield (WITH tech trend)
	Percent change in average yield (WITH tech trend)
	Percent change in 9th DECILE yield (WITH tech trend)
	Percent change in INTER DECILE yield (WITH tech trend)
Baseline 1st DECILE Yield (Ton/Ha)	Percent change in 1st DECILE yield (WITH tech trend; CO_2 fertilization)
Baseline average Yield (Ton/Ha)	Percent change in average yield (WITH tech trend; CO_2 fertilization)
Baseline 9th DECILE Yield (Ton/Ha)	Percent change in 9th DECILE yield (WITH tech trend; CO_2 fertilization)
Baseline INTER DECILE Yield (Ton/Ha)	Percent change in INTER DECILE yield (WITH tech trend; CO_2 fertilization)
	Percent change in 1st DECILE yield (WITH tech trend; WITHOUT climate change)
	Percent change in average yield (WITH tech trend; WITHOUT climate change)
	Percent change in 9th DECILE yield (WITH tech trend; WITHOUT climate change)
	Percent change in INTER DECILE yield (WITH tech trend; WITHOUT climate change)
	Percent change in 1st DECILE yield (WITHOUT tech trend; CO_2 fertilization)
	Percent change in average yield (WITHOUT tech trend; CO_2 fertilization)
	Percent change in 9th DECILE yield (WITHOUT tech trend; CO_2 fertilization)
	Percent change in INTER DECILE yield (WITHOUT tech trend; CO_2 fertilization)
	WU to achieve average Yield No Tec/No CO_2 (mm)
	WU to achieve average Yield with CO_2 (mm)
	WU to achieve average Yield with Tech trend (mm)
Baseline WU (mm)	WU to achieve average Yield with Tech trend and CO_2 fertilization (mm)