African & Mediterranean AGRICULTURAL JOURNAL AL AWAMIA

Balaghi R. et al. (2024). AFRIMED AJ –Al Awamia (143). p. 09-33

Climate change impact assessment on agriculture

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Executive summary - This document provides a comprehensive review of climate change impact studies on Moroccan agriculture, conducted by the National Institute of Agricultural Research (INRA). The studies reveal that climate change poses significant challenges to the agricultural sector, with projections indicating declining rainfall, rising temperatures, and increasing drought frequency throughout the 21st century.

Key findings:

1. Rainfall has decreased by approximately 25% since 1980, while temperatures have increased, leading to a higher probability of drought occurrence.
2. Climate projections based on IPCC scenarios suggest that by the end of the century, temperatures will continue to rise, and precipitation will decrease, resulting in a shorter cereal growing period and reduced yields.
3. Land suitability for cereal cultivation is expected to decline, particularly in the Atlantic plains, with a shift towards the north and mountainous regions.
4. The impact studies highlight the vulnerability of Moroccan agriculture to climate change and the urgent need for adaptation measures.

Implications:

1. Policy: The findings emphasize the need for policymakers to prioritize the development and implementation of comprehensive adaptation strategies, allocate resources for research and development, provide incentives for farmers to adopt sustainable practices, and foster collaboration among stakeholders.
2. Practice: Farmers and agricultural extension services must adapt their practices to cope with the changing climate by adopting drought-resistant crop varieties, implementing water-saving irrigation techniques, embracing conservation agriculture practices, and diversifying crop portfolios.
3. Research: Future research should focus on conducting site-specific impact assessments, developing adapted crop varieties and management practices, exploring innovative technologies, investigating socio-economic dimensions of adaptation, and assessing the effectiveness of adaptation strategies.

Recommendations:

1. Prioritize the development and dissemination of drought-resistant crop varieties and water-efficient irrigation technologies.
2. Promote the widespread adoption of conservation agriculture practices.
3. Strengthen the capacity of agricultural extension services to provide farmers with knowledge and resources for implementing climate-smart practices.
4. Invest in the expansion and improvement of early warning systems and climate information ervices.

5. Conduct further research on the socio-economic dimensions of climate change adaptation in Moroccan agriculture

6. Develop and implement monitoring and evaluation frameworks to assess the effectiveness and scalability of adaptation strategies.

Morocco has the potential to become a leader in developing and implementing effective adaptation strategies that can be replicated in similar geographic regions across Africa and the Mediterranean. By leveraging its expertise in climate change impact assessment and adaptation in the agricultural sector, Morocco can contribute to global efforts to address the challenges posed by climate change and promote sustainable agricultural development for future generations.

Résumé - Cet article présente une revue des études d'impact des changements climatiques sur l'agriculture au Maroc, réalisées à l'INRA. Il montre que la pluviométrie a diminué d'environ 25% depuis 1980 et que les températures ont augmenté. Des analyses fréquentielles ont été réalisées pour évaluer les changements climatiques passés et les probabilités d'occurrence de la sécheresse. Des projections climatiques basées sur les scénarios du GIEC montrent que les températures augmenteront et les précipitations diminueront au 21ème siècle, réduisant la longueur de la période de croissance des céréales et les rendements. L'étude de l'impact sur l'aptitude des terres à la céréaliculture prévoit aussi une réduction des zones aptes, notamment dans les plaines atlantiques.

L'article décrit ensuite les mesures d'adaptation, telles que les Mesures d'Atténuation Appropriée au niveau National, l'agriculture climato-intelligente et des projets prioritaires identifiés dans ce cadre comme le soutien à l'agriculture de conservation. L'agriculture de conservation et la réintroduction des légumineuses alimentaires dans les rotations sont des pratiques clés pour renforcer la résilience. La gestion des risques climatiques est également cruciale, d'où le développement par l'INRA du système CGMS-Maroc de prévision des récoltes. Ces résultats soulignent la vulnérabilité de l'agriculture marocaine et la nécessité de renforcer l'adaptation.

Mots clés : *Changement climatique, Agriculture marocaine, Études d'impact, Adaptation, Sécurité alimentaire, Gestion des risques climatiques, Agriculture de conservation.*

رياض بلغي وحسن بنعودة وحميد محيو ووديع السنيبي

الملخص التنفيذي - تقدم هذه الوثيقة مراجعة شاملة لدراسات تأثير تغير المناخ على الزراعة المغربية، التي أجراها المعهد الوطني للبحث الزراعي .تكشف الدراسات أن تغير المناخ يشكل تحديات كبيرة للقطاع الزراعي، مع توقعات تشير إلى تناقص هطول الأمطار وارتفاع درجات الحرارة وزيادة تواتر الجفاف خلال القرن الحادي والعشرين.

النتائج الرئيسية:

1. **انخفضت كمية هطول الأمطار بنسبة 25٪ تقريبًا منذ عام 1980، بينما ارتفعت درجات الحرارة، مما أدى إلى زيادة احتمالية حدوث الجفاف.**
2. **تشير التوقعات المناخية المستندة إلى سيناريوهات الهيئة الحكومية الدولية المعنية بتغير المناخ (IPCC)إلى أنه بحلول نهاية القرن، ستستمر درجات الحرارة في الارتفاع، وستنخفض كمية الأمطار، مما يؤدي إلى فترة نمو أقصر للحبوب وانخفاض الغلة.**
3. **من المتوقع أن تنخفض ملاءمة الأراضي لزراعة الحبوب، لا سيما في السهول الأطلسية، مع تحول نحو المناطق الشمالية والجبلية.**
4. **تسلط الدراسات الضوء على ضعف الزراعة المغربية أمام تغير المناخ والحاجة الملحة لاتخاذ تدابير التكيف.**

الآثار المترتبة:

1. **السياسة :تؤكد النتائج على الحاجة إلى أن يعطي صانعو السياسات الأولوية لتطوير وتنفيذ استراتيجيات تكيف شاملة، وتخصيص الموارد للبحث والتطوير، وتقديم حوافز للمزارعين لتبني ممارسات مستدامة، وتعزيز التعاون بين أصحاب المصلحة.**
2. **الممارسة :يجب على المزارعين وخدمات الإرشاد الزراعي تكييف ممارساتهم للتعامل مع تغير المناخ من خلال اعتماد أصناف المحاصيل المقاومة للجفاف، وتنفيذ تقنيات الري الموفرة للمياه، واعتماد ممارسات الزراعة الحافظة، وتنويع محافظ المحاصيل.**
3. **البحث :يجب أن تركز البحوث المستقبلية على إجراء تقييمات التأثير الخاصة بالموقع، وتطوير أصناف المحاصيل والممارسات الإدارية المكيفة، واستكشاف التقنيات المبتكرة، والتحقيق في الأبعاد الاجتماعية والاقتصادية للتكيف، وتقييم فعالية استراتيجيات التكيف.**

التوصيات:

1. **إعطاء الأولوية لتطوير ونشر أصناف المحاصيل المقاومة للجفاف وتقنيات الري الفعالة في استخدام المياه.**
2. **تشجيع التبني الواسع النطاق لممارسات الزراعة الحافظة.**
3. **تعزيز قدرة خدمات الإرشاد الزراعي على تزويد المزارعين بالمعرفة والموارد لتنفيذ الممارسات الذكية مناخيًا.**
4. **الاستثمار في توسيع وتحسين أنظمة الإنذار المبكر وخدمات معلومات المناخ.**

5. **إجراء المزيد من البحوث حول الأبعاد الاجتماعية والاقتصادية للتكيف مع تغير المناخ في الزراعة المغربية.**
6. **تطوير وتنفيذ أطر للمراقبة والتقييم لتقدير فعالية وقابلية تطبيق استراتيجيات التكيف.**

لدى المغرب القدرة على أن يصبح رائدًا في تطوير وتنفيذ استراتيجيات التكيف الفعالة التي يمكن تكرارها في مناطق جغرافية مماثلة في جميع أنحاء إفريقيا والبحر الأبيض المتوسط .من خلال الاستفادة من خبرته في تقييم آثار تغير المناخ والتكيف في القطاع الزراعي، يمكن للمغرب المساهمة في الجهود العالمية لمعالجة التحديات التي يفرضها تغير المناخ وتعزيز التنمية الزراعية المستدامة للأجيال القادمة.

الكلمات المفتاحية: *تغير المناخ، الزراعة المغربية، دراسات التأثير، التكيف، الامن الغذائي، إدارة المخاطر المناخية، الزراعة الحافظة.*

Introduction

Impact studies on Moroccan agriculture commenced at the Regional Center for Agronomic Research in Settat in the early 1980s, within the framework of the "aridoculture" research program, which focused on arid and semi-arid regions. Aridoculture is as a set of agricultural practices and techniques specifically adapted to arid and semi-arid regions, aimed at optimizing water use efficiency and improving crop productivity in water-scarce environments This collaborative effort involved the Mid-America International Agricultural Consortium (MIAC), Morocco. For example, in Meknes and Oujda, annual precipitation dropped by 151 mm, while in Fez, it decreased by 82 mm, representing a reduction of over 25%. These findings highlight the substantial changes in precipitation patterns experienced in Morocco over the past few decades. This change in precipitation patterns coincided with the rapid increase in global air temperatures (Brohan et al., 2006). The critical consisting of five American universities from the Midwest. The term "aridoculture," derived from the English term "dry farming," has historical roots dating back to the 1950s (Varaldi-Conia, 1953) and was advocated for North African agricultural practices as early as the early twentieth century (Augustin, 1911).

These groundbreaking studies continued at the Regional Center for Agronomic Research in Meknes in 1992 under the "Favorable Bour Program" before expanding to other INRA Regional Centers. Initially, the studies aimed to characterize the Moroccan climate and its relationship with cereal and pastoral production. Later, the scope broadened to include frequency analyses of climate patterns, assessing historical climate variations and the probability of drought occurrences in various locations.

To assess the historical changes in rainfall patterns across Morocco, breakpoint analyses of chronological series were conducted for several provinces (Table 1) and rainfall stations in the Oriental region (Table 2). These analyses identify significant shifts in precipitation levels and help understand the magnitude of change in different areas.

The breakpoint analyses reveal a significant decline in rainfall around 1980 across multiple stations in

breakpoint and subsequent drought years catalyzed INRA's aridoculture research efforts, which later encompassed programs on breeding drought-resistant cereals, promoting direct seeding techniques, advancing operational agrometeorology, and establishing the CGMS-Maroc program for crop monitoring and yield forecasting.

Table 1. Breakpoint analysis of chronological series for rainfall during the agricultural season (September to May) for several provinces of Morocco (Balaghi, 2006).

Province	Serie	Rainfall		Breakpoint test		
		Moy. (mm)	C.V. (%)	Mann and Pettitt[a]	Buishand[b]	Lee and Heghinian[b]
Tangier	1932-2004	770	32.3	1948 (0.0262)	(0.0001)	1948 (0.3214)
Tétouan	1938-2004	671	35.5	ns	ns	1971 (0.1669)
Kenitra	1951-2004	571	28.5	1972 (0.0375)	(0.1000)	1972 (0,1697)
Meknès	1932-2004	535	27.1	1980 (0.0009)	(0.0001)	1980 (0.2618)
Rabat	1931-2004	510	31.0	ns	ns	2002 (0.1435)
Fez	1915-2004	483	24.6	1978 (0.0846)	(0.1000)	1978 (0.0970)
Casablanca	1903-2004	399	29.8	ns	ns	1978 (0.0271)
El Jadida	1932-2004	371	34.2	ns	ns	2002 (0.0555)
Safi	1901-2004	353	37.4	ns	ns	2003 (0.0403)
Settat	1910-2004	353	35.1	1942 (0.0861)	(0.0500)	1980 (0.0781)
Essaouira	1894-2004	305	35.7	ns	(0.1000)	1898 (0.1362)
Oujda	1932-2004	297	33.0	1981 (0.0045)	(0.0001)	1981 (0.2376)
Agadir	1922-2004	232	49.1	ns	ns	ns
Marrakech	1919-2004	229	36.2	ns	ns	1919 (0.2433)
Ouarzazate	1932-2004	91	58.2	1950 (0.0842)	(0.1000)	1950 (0.1564)

ns: Non significant.

Table 2. Change point analysis of chronological series for rainfall from September to May for several rainfall stations in the Oriental region (Snaibi, unpublished).

Station	Period	Mann-Kendall Test		Test de de Pettitt			
		Tau-b de MK	*p*-value	Date of change	Avg. before 1976 (mm)	Avg. after 1976 (mm)	Difference in % (mm)
Oujda	1915-2020	-0,261	< 0,0001	1980	356,0	268,4	-24,6 (-87,6 mm)
Taourirt	1923-2020	-0,215	0,002	1976	265,0	185,7	-29,9 (-79,3 mm)
Bni Mathar	1932-2020	-0,240	< 0,0001	1979	239,4	186,1	-22,3 (-53,3 mm)
Tendrara	1932-2020	-0,055	0,329	-	201,8	193,0	-4,4 (-8,8 mm)
Bouaârfa	1970-2020	-0,066	0,500	-	167,6	146,8	-12,4 (-20,8 mm)
Figuig	1936-2020	-0,119	0,109	-	132,9	118,0	-11,2 (-14,9 mm)

To visualize the impact of climate variability on cereal production, the Agro-climatic Atlas of Morocco (Gobel et al., 2007) was developed using geographic information systems. Figure 1 presents maps of wheat yields derived from frequency studies on the length of the growing period for both dry and wet seasons. The maps in Figure 1 demonstrate the spatial variability of wheat yields across Morocco under different climatic conditions. By comparing the yields in dry and wet seasons, stakeholders can better understand the sensitivity of cereal production to rainfall and the potential implications of climate change for food security.

Building upon this foundation, various statistical studies were conducted to further investigate the effect of climatic hazards, particularly drought, on crops. These studies aimed to quantify the relationship between drought events and crop productivity, enabling researchers to develop a deeper understanding of the vulnerability of Moroccan agriculture to climate variability. By examining the statistical correlations between drought indices and crop yields, researchers could identify the most critical periods during the growing season when crops were most susceptible to water stress, informing strategies for drought mitigation and adaptation.

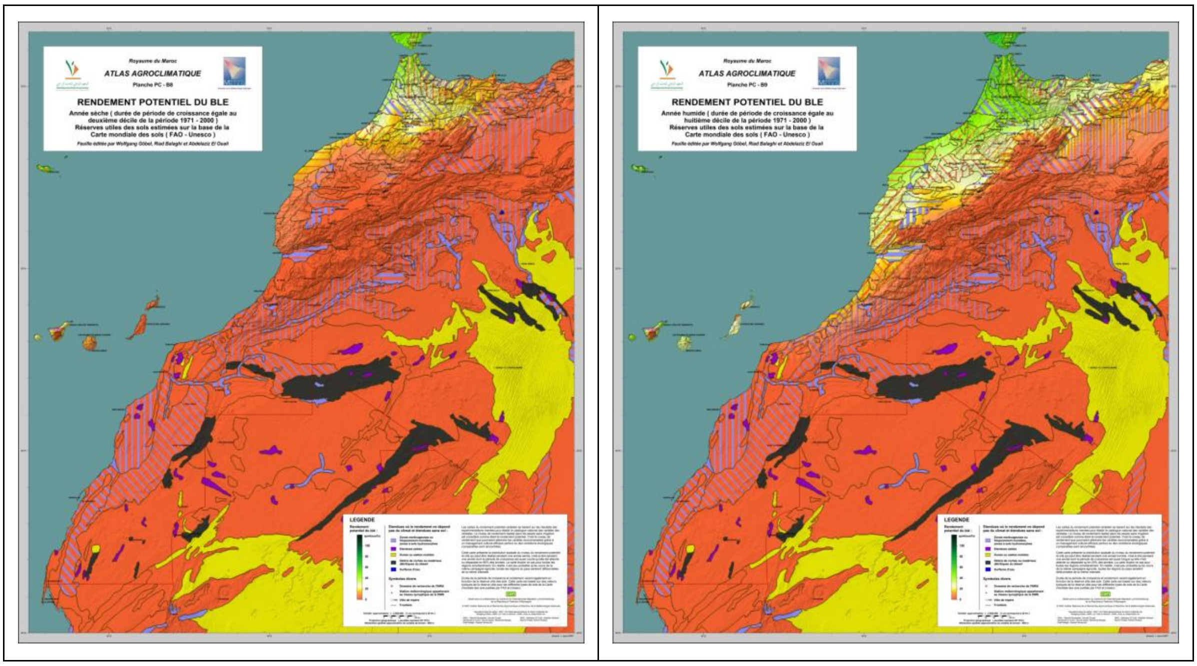

Figure 1. **Maps of wheat yields in dry (left) and in wet (right) seasons (Gobel et al., 2007).**

In 2007, INRA initiated impact studies of climate change on agriculture using scenarios from the Intergovernmental Panel on Climate Change (IPCC). These studies marked a significant milestone in understanding the potential consequences of climate change on Moroccan agriculture.

The first study, carried out in 2008 as part of the "ClimagriMed" project, was a collaborative effort with Italian partners (Istituto di Biometeorologia, Consiglio Nazionale delle Ricerche, Centro di ricerca di Bonassai) and supported by FAO (Motroni et al., 2008; Mereu et al., 2009; Bodini et al., 2011; Cesaraccio et al., 2011). This groundbreaking study produced the first maps depicting the impact of climate change on land suitability for cereal cultivation in Morocco, based on IPCC scenarios for the year 2100 (Figure 2).

A more comprehensive quantitative study followed, assessing the impacts on approximately fifty crops in Morocco using IPCC scenarios (A2 and B2) for the year 2100. Commissioned by the Ministry of Agriculture, Rural Development, and Maritime Fisheries (MPAM) just before the launch of the "Plan Maroc Vert" agricultural strategy (2008-2020), this study received support from the World Bank, FAO, the National Meteorological Directorate, and INRA (Gommes et al., 2009). The results suggested that agricultural yields would remain stable until 2030, followed by a significant decline, with scenario A2 showing a more pronounced decrease compared to scenario B2 (Figure 3).

Further studies were undertaken as part of the "Integration of Climate Change into the Implementation of the Plan Maroc Vert" project (Balaghi et al., 2011) between 2011 and 2012, the "Modelling System for Agricultural Impacts of Climate Change" project between 2011 and 2016 (Balaghi et al., 2016), and the "Adaptation to Climate Change in Agriculture in the Maghreb" project (Balaghi et al., 2017; Balaghi, 2017) between 2014 and 2016. The subsequent sections of this document will explore the findings of the latter two projects in detail.

From 2007 to 2016, INRA assumed a leading role in conducting most studies related to the impact of climate change on Moroccan agriculture, providing crucial insights for policymakers and stakeholders in the agricultural sector.

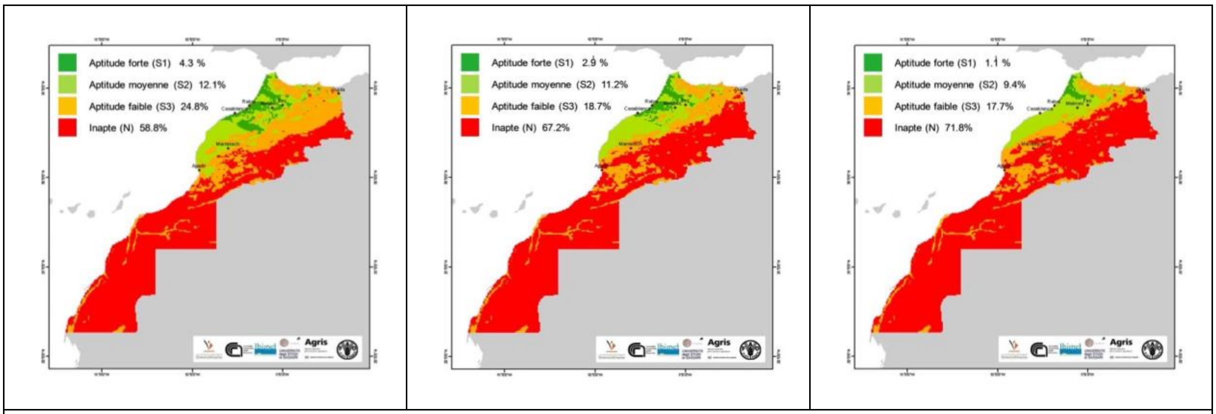

Figure 2. **Impact of climate change on the agricultural suitability of land, for the current period (left) and for the 2050 (middle) and 2100 (right) horizons according to scenario A1B (Motroni et al., 2008; Bodini et al., 2011; Cesaraccio et al., 2011).**

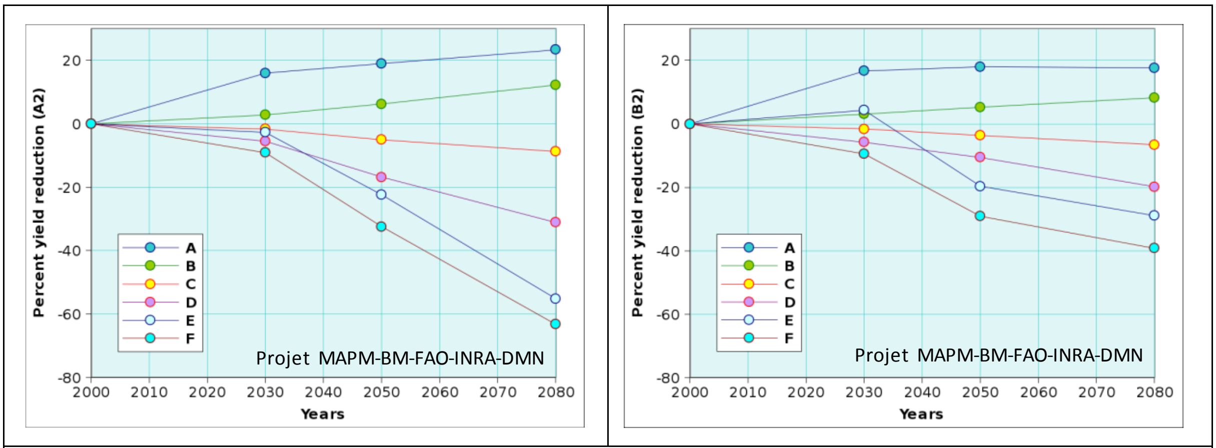

Figure 3. **Percentage reduction in agricultural yields according to scenarios A2 and B2, up to the horizon 2100. Adaptation through current technological progress is not considered. Crops are grouped into "impact groups" A to F, which can be characterized as follows: A: Irrigated legumes and forages - B: Irrigated fruit trees and vegetable crops - C: Forages and vegetable crops - D: Rainfed cereals and legumes - E: Rainfed winter cereals - F: Other rainfed crops.**

Navigating uncertainties in climate impact studies

Uncertainty is inherent in climate science due to the complex and interconnected nature of Earth's climate system. Assessing climate change involves a systematic progression through several stages, each introducing its own uncertainties.

The process begins with the development of greenhouse gas (GHG) and aerosol emission scenarios based on assumptions about future socio-economic and technological trends. These emission scenarios are then converted into GHG concentration scenarios using sophisticated biogeochemical models.

The resulting GHG/aerosol concentration scenarios form the basis for generating global-scale climate projections. These global projections are subsequently downscaled to regional or local levels using either dynamic methods, such as regional climate models, or statistical approaches.

The downscaled data is then employed in impact studies using various models, including agricultural yield models, hydrological models, and vulnerability analyses.

It is crucial to recognize and account for the uncertainties present at each stage of this process. As uncertainties propagate through the modeling chain, they accumulate, resulting in what is known as the 'uncertainty cascade.' To effectively address these uncertainties, a thorough understanding of each modeling phase is essential.

Researchers must employ appropriate strategies to assess and mitigate uncertainties at each stage. This may involve using multiple emission scenarios, comparing results from different climate models, and employing ensemble approaches to capture the range of possible outcomes. Sensitivity analyses can help identify the most influential sources of uncertainty, guiding efforts to reduce them.

Communicating these uncertainties to stakeholders and decision-makers is equally important. Transparently conveying the limitations and potential ranges of outcomes enables informed decision-making and the development of robust adaptation strategies.

By acknowledging and effectively managing uncertainties, researchers can enhance the reliability and usefulness of climate impact studies, ultimately supporting more effective climate change adaptation and mitigation efforts.

The impact studies discussed in this document reveal the significant challenges Moroccan agriculture faces due to climate change. These challenges include reduced crop growing seasons, decreased cereal yields, and changes in land suitability for cultivation. In the following sections, we will explore these impacts in detail and discuss potential adaptation strategies to mitigate the effects of climate change on Moroccan agriculture.

Impact on the length of the crop growing season

Climate change projections for Morocco indicate a gradual increase in temperatures and a corresponding decrease in precipitation. Across all models and scenarios, temperatures are expected to rise by 1.3°C (± 0.2°C) by 2050 and by 2.3°C (± 0.9°C) by 2090, compared to the 2001-2010 period. Simultaneously, precipitation is projected to decline by 11% (± 0.5%) by 2050 and by 16% (± 1.3%) by 2090 (Balaghi et al., 2017).

The Length of the Crop Growing Period (LCGP), a concept introduced by the FAO in 1978, is a critical tool for assessing agricultural resources and potential. It defines the period during the year when the combination of humidity and temperature is most suitable for crop growth. The LCGP is an integral part of the FAO's "Global Agro-Ecological Zones" classification and represents an improved version of the Bagnouls and Gaussen ombrothermic diagram. It takes into account soil water retention capacity and provides a more accurate estimate of water evaporation. The LCGP is determined using the ombrothermic diagram, calculating the number of days when precipitation (mm) exceeds twice the temperature (°C). In Morocco, the LCGP is used to optimize crop cycles, minimizing risks associated with drought or excess water and improving agricultural productivity (Jlibene and Chafai, 2002; Jlibene and Balaghi, 2009).

The MOSAICC project utilized three different climate models—CanESM2, MIROC-ESM, and MPI-ESM-MR—to assess the impacts of climate change on cereal cultivation in Morocco (Table 3). These models were selected to provide a comprehensive and robust assessment of potential outcomes under RCP4.5 and RCP8.5 scenarios for the 2050 and 2090 time horizons. RCP4.5 assumes greenhouse gas emission mitigation efforts, while RCP8.5 is a more pessimistic scenario, projecting a continuous and rapid increase in emissions. By employing multiple climate models, the MOSAICC project accounts for the inherent uncertainties in climate change projections. The use of CanESM2, MIROC-ESM, and MPI-ESM-MR allows for a more reliable assessment of the potential impacts on cereal cultivation and helps identify areas of agreement and divergence among the models. Significant differences among model outcomes indicate higher uncertainty, reflecting variations in the interpretation and prediction of climate change impacts. Conversely, when model results show strong agreement, it suggests lower uncertainty and increases confidence in the accuracy of the assessments.

Table 3. Climate models used.

Model	Description
CanESM2	CanESM2 (Canadian Earth System Model version 2) is a global Earth system model developed by the Canadian Centre for Climate Modelling and Analysis. It encompasses components of the atmosphere, oceans, land, cryosphere, and biogeochemistry. Widely recognized for its application in future climate projections, it has been prominently featured in both the IPCC AR5 and CMIP5 reports.
MIROC-ESM	MIROC-ESM (Model for Interdisciplinary Research on Climate, Earth System Model) is a Japanese Earth system model. Developed through collaboration among various Japanese institutions, it offers detailed simulations of the atmosphere, oceans, land, cryosphere, carbon cycles, and other biogeochemical processes. It has also played a significant role in CMIP5 studies.
MPI-ESM-MR	MPI-ESM-MR (Max Planck Institute Earth System Model, Medium Resolution) is an Earth system model developed by the Max Planck Institute for Meteorology. It provides simulations of the atmosphere, oceans, land, and biogeochemical cycles. Distinguished by its medium resolution, enabling detailed representation of climatic processes, it has been employed in CMIP5 analyses.

To illustrate the projected changes in the length of the growing season under climate change, Figure 4 presents national ombrothermal diagrams for the current period and the 2090 horizon under the RCP8.5 scenario. These diagrams are based on the average output of the CanESM2, MIROC-ESM, and MPI-ESM-MR climate models. Table 4 provides a more detailed breakdown of the expected changes in the length of the wheat growing season for different time periods and climate scenarios.

The diagrams reveal a striking reduction in the length of the growing season, from seven months (October to April) in the current period to just two months (January and February) by 2090 under the RCP8.5 scenario. This drastic decrease is due to the simultaneous increase in temperatures and decrease in precipitation, which would make rainfed cereal cultivation largely unfeasible.

Examining the details further, the RCP8.5 scenario projects a reduction in the growing season duration by 30 days by 2050 and an alarming 90 days by 2090, compared to the 2010 decade (Table 4). In comparison, the RCP4.5 scenario forecasts a reduction of 60 days for both the 2050 and 2090 horizons. A shortened growing season for cereals would likely require adaptations in sowing and harvesting schedules, potentially affecting resource use efficiency and cereal productivity.

These findings underscore the severe consequences of climate change on cereal cultivation in Morocco, particularly under the high-emission RCP8.5 scenario. The projected reduction in the length of the growing season poses significant challenges for rainfed cereal production, necessitating the development and implementation of robust adaptation strategies. These may include adopting drought-resistant crop varieties, optimizing water management practices, and adjusting cropping calendars to align with the changing climatic conditions. Failure to adapt to these changes could lead to substantial declines in cereal yields and threaten food security in the region.

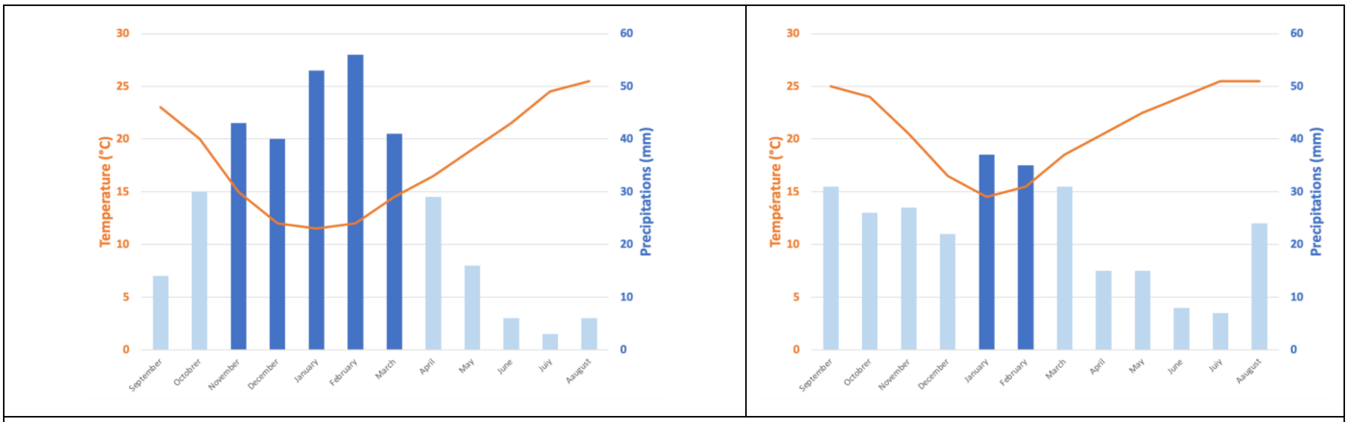

Figure 4. Ombrothermal diagram at the national scale for the current period (left) and the 2090 horizon under the RCP8.5 scenario (right), based on the average of the three climate models CanESM2, MIROC-ESM, and MPI-ESM-MR.

Table 4. Length of the wheat growing season, according to the average of the climate models CanESM2, MIROC-ESM, and MPI-ESM-MR. The table utilizes shades of green to indicate favorable periods for cereal growth, while shades of red designate unfavorable periods, with increasing intensity according to the degree of favorability or unfavorability respectively.

RCP 4.5	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.
2090												
2050												
2010												
RCP 8.5	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**March**	**April**	**May**	**June**	**July**	**Aug.**
2090												
2050												
2010												

Having examined the impact of climate change on the length of the crop growing season, it is crucial to also consider its effects on cereal yields. The following section will delve into the potential consequences of climate change for wheat and barley production in Morocco, as revealed by the MOSAICC project simulations.

Impact on cereal yields

As part of the MOSAICC project, simulations were conducted to evaluate the yields of key autumn cereals in Morocco, specifically wheat and barley, up to the end of the century. The simulations considered the RCP4.5 and RCP8.5 climate scenarios, using the CanESM2, MIROC-ESM, and MPI-ESM-MR climate models, and encompassed all agricultural zones in Morocco.

The analysis of the results reveals potential negative impacts on both wheat and barley yields, especially under the RCP8.5 scenario, when compared to the reference period of 2010 to 2016. Under the RCP8.5 scenario, an average annual decrease of 6% in wheat yields (Figure 5) and 10% in barley yields (Figure 6) is projected. This declining trend is marked by alternating dry and wet periods and significant uncertainties among the three climate models used. These uncertainties highlight the complex nature of climatic systems and the difficulties in accurately predicting future impacts. In contrast, the RCP4.5 scenario presents a more optimistic outlook, with yields expected to remain relatively stable.

The projected yield reductions, particularly under the RCP8.5 scenario, underscore the urgent need to develop adaptation strategies. This may involve researching and developing cereal varieties that are more resilient to drought and higher temperatures. Furthermore, promoting crop diversification to include species that can adapt to changing climatic conditions and implementing crop rotations could be promising strategies to enhance the resilience of the agricultural sector.

Given the increased frequency of droughts, the importance of more efficient water management cannot be overstated. This could involve adopting dry farming techniques, conservation agriculture practices, and broader agroecological approaches. These strategies aim to optimize water use, conserve soil fertility, and promote biodiversity, thereby strengthening agricultural systems against the challenges posed by climate change.

To effectively address the projected impacts on cereal yields, a multi-faceted approach is necessary. This should involve collaboration among researchers, policymakers, and farmers to develop and implement innovative adaptation measures. Investing in research and development, providing support for farmers to adopt climate-resilient practices, and promoting sustainable water management will be crucial in safeguarding cereal production and ensuring food security in the face of a changing climate.

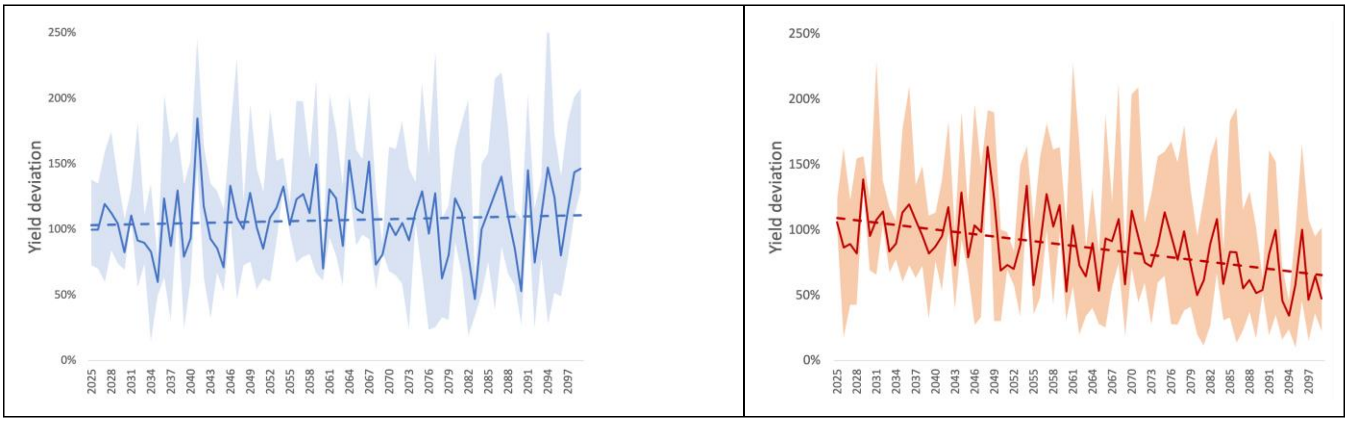

Figure 5. National wheat yield deviation, according to the RCP4.5 scenario (left figure) and RCP8.5 scenario (right figure), between 2017 and 2100, compared to the period 2010-2016. The average of the three models CanSEM2, MIROC-ESM, and MPI-ESM-MR is represented by the solid black line, the range of variation between the three models is shown shaded, and the trend is depicted by the dashed black line (data source: www.changementclimatique.ma).

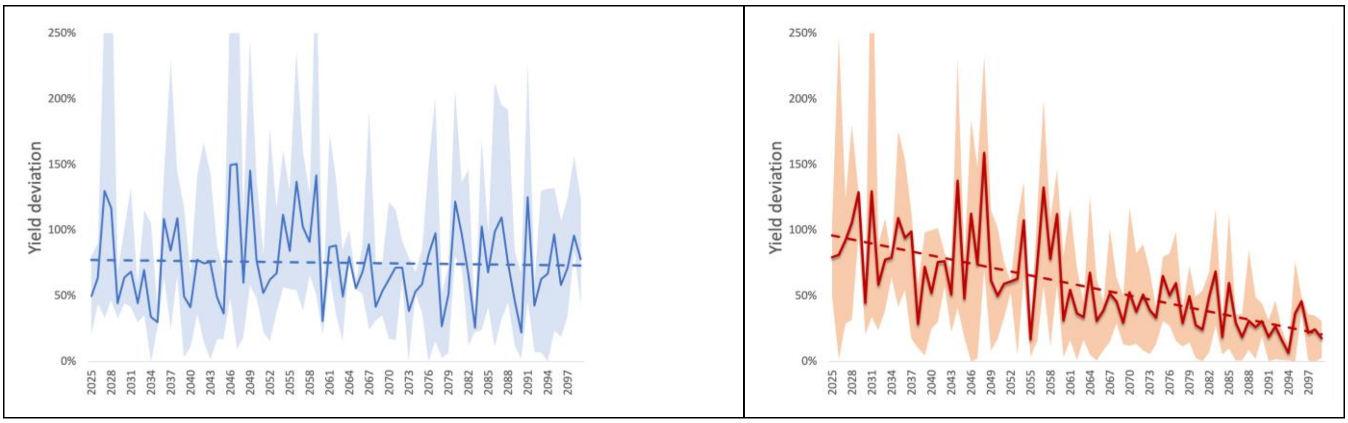

Figure 6. National barley yield deviation, according to the RCP4.5 scenario (left figure) and RCP8.5 scenario (right figure), between 2017 and 2100, compared to the period 2010-2016. The average of the three models CanSEM2, MIROC-ESM, and MPI-ESM-MR is represented by the solid black line, the range of variation between the three models is shown shaded, and the trend is depicted by the dashed black line (data source: www.changementclimatique.ma).

In addition to the direct impacts on crop growing seasons and cereal yields, climate change also has significant implications for land suitability for cereal cultivation in Morocco. The next section will explore how shifting temperature and precipitation patterns are expected to alter the geographic distribution of areas suitable for growing wheat, barley, and other key crops.

Impact of climate change on land suitability for cereal cultivation

The impact of climate change on potential areas for rainfed cereal cultivation in Morocco was assessed using the DIVA-GIS software (Diversity Analysis and Visualization for GIS, version 7, Hijmans et al., 2012). DIVA-GIS is a tool for mapping the spatial distribution of cultivated species based on their temperature and precipitation requirements. Precipitation and temperature data were extracted in raster format from the WorldClim database (Hijmans et al., 2005) at a spatial resolution of 30 arc-seconds (~1 km) for the RCP4.5 and RCP8.5 scenarios, using the MIROC-ESM climate model for the 2050 horizon. It is important to note that DIVA-GIS does not account for factors such as soil type and disease sensitivity. For olive trees, air humidity during pollination, a crucial factor, is not integrated into the DIVA-GIS software.

DIVA-GIS compares the length of the growing season for each pixel on a raster map with the specific requirements for each species, as defined in the FAO's ECOCROP database (Crop Ecological Requirements Database). ECOCROP is an FAO tool that identifies plant species suitable for different environments and uses, providing a library of environmental requirements for various crops, including minimum and maximum temperature, precipitation, altitude, soil pH, and salinity. The length of the growing season, as defined by DIVA-GIS, is the number of days between the start and end of growth. If this duration is greater than or equal to the minimum requirement for a particular species, as indicated in the ECOCROP database, DIVA-GIS labels the pixel as suitable for that species. The suitability of each pixel is scored from 0% (marginal suitability) to 100% (very favorable suitability), and these scores are then grouped into five suitability classes for simplified interpretation of the map (Table 5). This process is repeated for all pixels on the raster map to produce a comprehensive map of land suitability for cereal cultivation. Non-agricultural lands, such as deserts, uncultivated lands, urban areas, and water bodies, are excluded from the final maps to focus specifically on climatic suitability for cereal and olive cultivation.

The results of the DIVA-GIS analysis indicate that climate change will lead to a reduction in areas suitable for cereal cultivation, particularly for barley and wheat, primarily in the Atlantic plains. There will be a noticeable shift in suitable areas towards the north and mountainous regions, where conditions become more favorable due to temperature changes. However, the movement of cereal crops towards mountainous areas will require the reinforcement of agroforestry systems to mitigate erosion risks.

These findings emphasize the vulnerability of Moroccan agriculture to climate change and the urgent need for international support, despite Morocco's significant efforts to enhance the resilience of small-scale farmers. The results affirm the strategic decisions made by Morocco in the 1960s to address climatic challenges, particularly drought, and highlight the importance of strengthening the capacity of smallholder farmers, promoting climate risk management tools like the CGMS-Maroc crop forecasting systems and multi-risk agricultural climate insurance, and advocating for conservation agriculture and the cultivation of high-value fruit trees in areas unsuitable for annual crops, such as arid and mountainous regions.

Table 5. Description des classes d'aptitude climatique.

Class	Suitability	Description
Very unsuitable	0%	Areas unsuitable for cultivation, typically desertic, uncultivated, or heavily degraded, only allowing species survival with costly and specialized interventions. This may include the creation of oases, groundwater pumping, or specific protective measures.
Highly unsuitable	1 to 20%	Areas with very low potential, heavily constrained by unfavorable climatic conditions. Biomass production is very low, except in very rainy years or with major interventions (basins, terracing, localized irrigation, etc.).
Unsuitable	21 to 40%	Areas with limited potential, presenting more challenging conditions, with biomass production lower than what the species could achieve under optimal conditions. Arid farming practices, such as direct seeding, localized irrigation, and selection of drought-resistant species, are necessary.
Suitable	41 to 60%	Areas with good potential, allowing economically viable levels of biomass production, although optimized agricultural practices or interventions to improve soil or water conditions may be necessary.
Highly suitable	61 to 80%	Areas with very good potential, offering a favorable environment for species growth, with biomass levels that enable economically optimal production, with minor or moderate interventions to overcome specific challenges.
Very highly suitable	>80%	Areas with high potential, presenting the most favorable climatic and environmental conditions for species growth and development, allowing for the highest yields without major interventions or modifications.

The DIVA-GIS analysis reveals that climate change will lead to a contraction of cereal cultivation areas, with barley and wheat being particularly affected, especially in the Atlantic plains. As temperatures change, there will be a notable shift in suitable areas towards the north and mountainous regions, where conditions become more favorable for cereal cultivation. However, this shift of cereal crops towards mountainous areas will require the strengthening of agroforestry systems to mitigate the risks of soil erosion, which can be exacerbated by the cultivation of annual crops on steep slopes.

These findings underscore the vulnerability of Moroccan agriculture to the impacts of climate change and emphasize the urgent need for international support to build resilience, despite the significant efforts already made by Morocco to enhance the resilience of small-scale farmers. The results also validate the strategic decisions taken by Morocco in the 1960s to address climatic challenges, particularly drought, which has long been recognized as a major threat to agricultural productivity in the country.

Moreover, the findings highlight the importance of several key strategies for adapting to climate change, including:

1. Strengthening the capacity of smallholder farmers to adopt climate-resilient practices and technologies.
2. Promoting the use of climate risk management tools, such as the CGMS-Maroc crop forecasting system and multi-risk agricultural climate insurance, to help farmers mitigate the impacts of climate variability and extreme weather events.
3. Advocating for the widespread adoption of conservation agriculture practices, which can help to improve soil health, reduce erosion, and enhance the resilience of cropping systems to climate stress.
4. Encouraging the cultivation of high-value fruit trees in areas that are unsuitable for annual crops, such as arid and mountainous regions, as a means of diversifying agricultural production and improving the livelihoods of rural communities.

In terms of climate and agronomic research, these results highlight Morocco's significant expertise and global recognition in assessing the impacts of climate change on agriculture. This expertise has enabled Morocco to access international and bilateral climate finance and has strengthened collaboration with international development organizations. As a climate change hotspot, Morocco is increasingly being viewed as a testing ground for comprehensive scientific research on climate and innovative agricultural practices, with the potential to serve as a model for sustainable development in similar geographic regions, both in Africa and the northern Mediterranean.

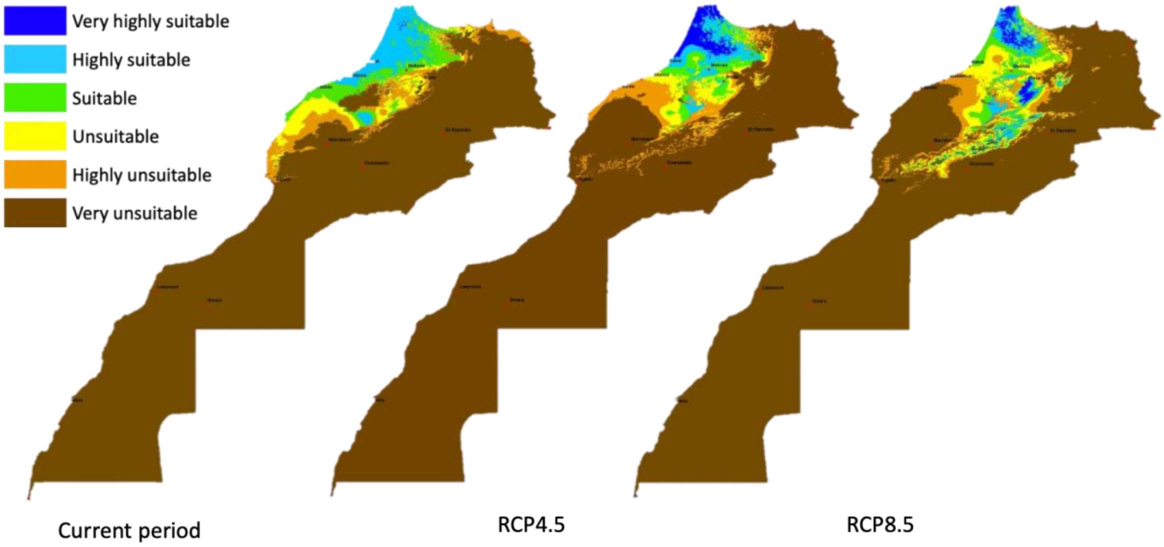

Figure 7. Land suitability for wheat cultivation under current climate conditions (1950-2000) and under the RCP4.5 and RCP8.5 scenarios, according to the MIROC-ESM model for the year 2050 (excerpt from Balaghi et al., 2016).

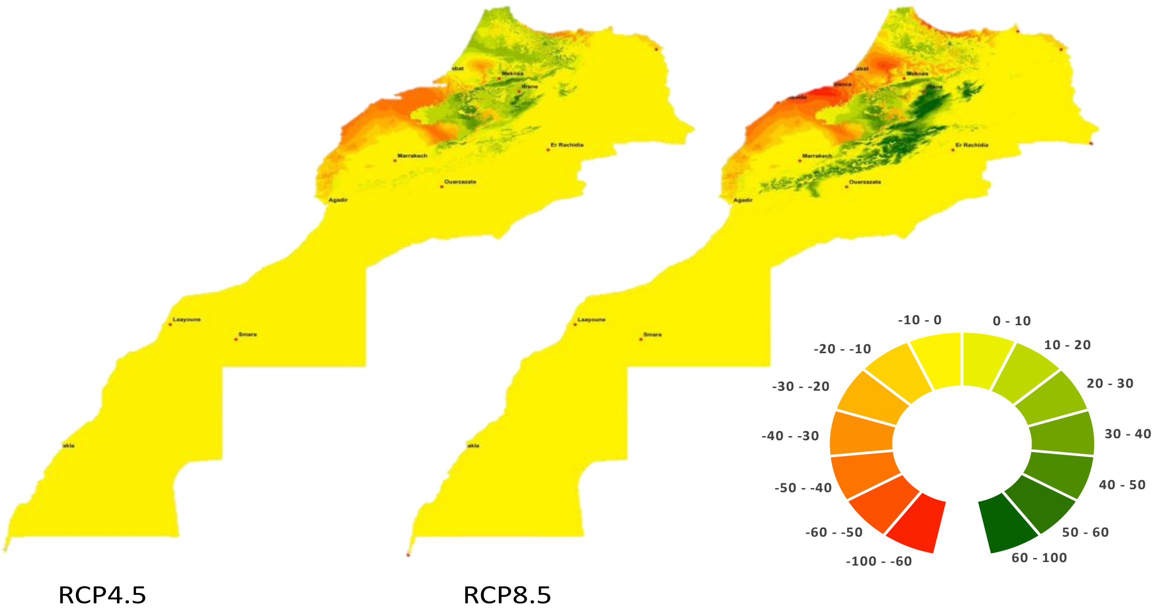

Figure 8. Change (%) in land suitability for wheat cultivation under the RCP4.5 and RCP8.5 scenarios, according to the MIROC-ESM model for the year 2050 (excerpt from Balaghi et al., 2016).

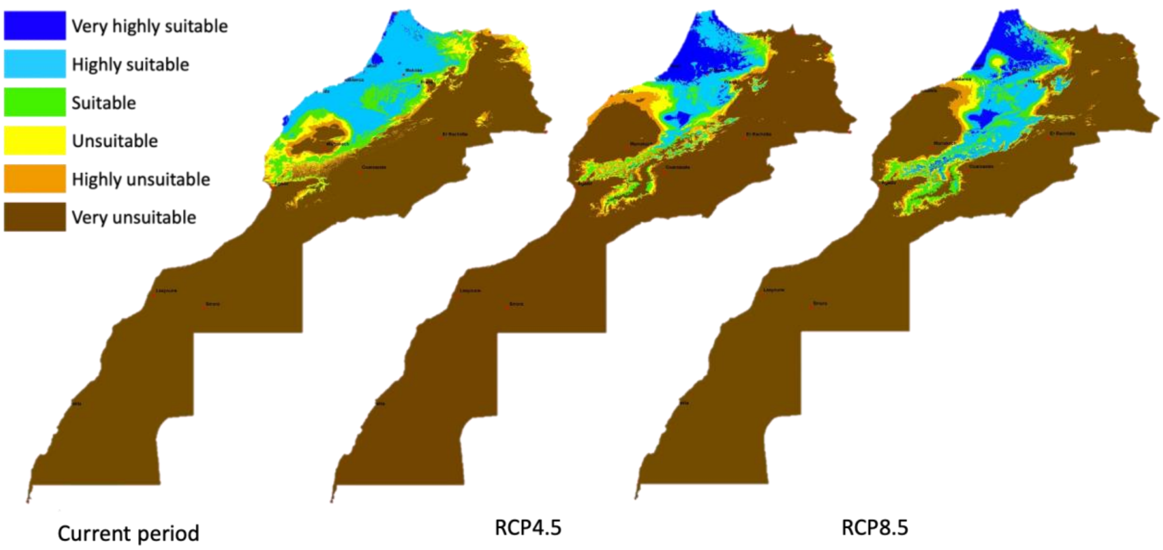

Figure 9. Land suitability for barley cultivation under current climate conditions (1950-2000) and under the RCP4.5 and RCP8.5 scenarios, according to the MIROC-ESM model for the year 2050 (excerpt from Balaghi et al., 2016).

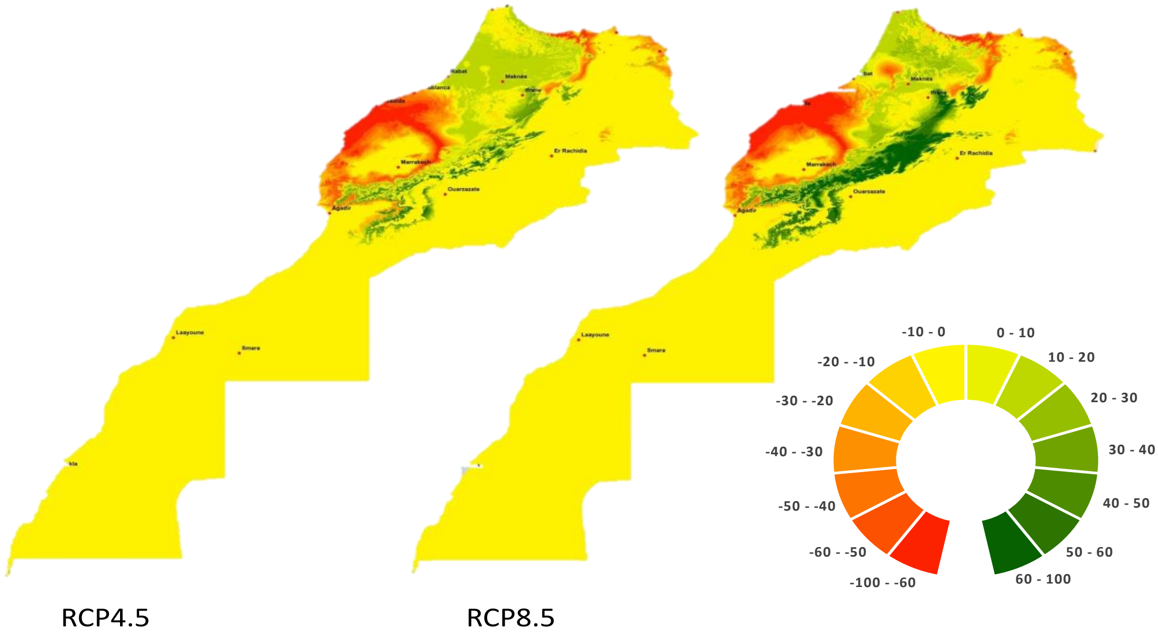

Figure 10. **Change (%) in land suitability for barley cultivation under the RCP4.5 and RCP8.5 scenarios, according to the MIROC-ESM model for the year 2050 (excerpt from Balaghi et al., 2016).**

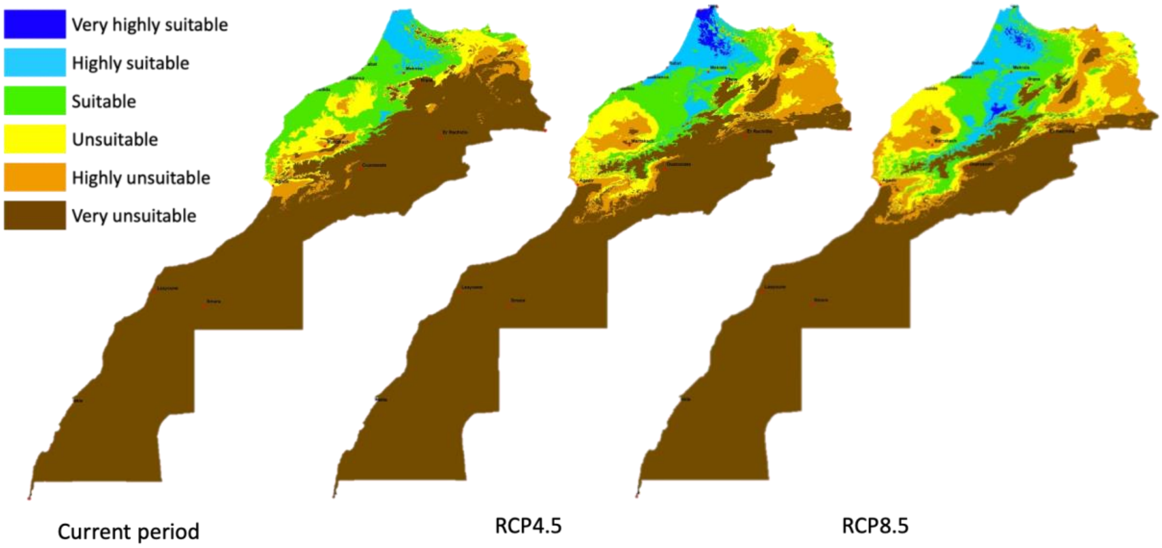

Figure 11. **Land suitability for olive cultivation under current climate conditions (1950-2000) and under the RCP4.5 and RCP8.5 scenarios, according to the MIROC-ESM model for the year 2050 (excerpt from Balaghi et al., 2016).**

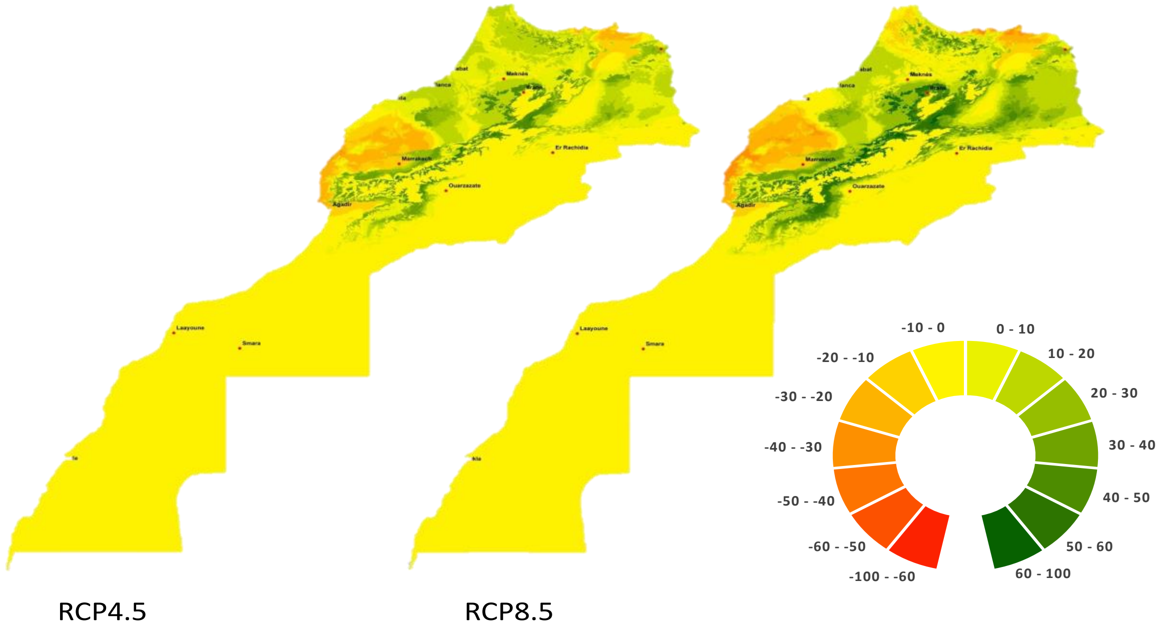

Figure 12. Change (%) in land suitability for olive cultivation under the RCP4.5 and RCP8.5 scenarios, according to the MIROC-ESM model for the year 2050 (excerpt from Balaghi et al., 2016)..

The findings discussed in the previous sections underscore the urgent need for adaptation strategies to address the impacts of climate change on Moroccan agriculture. In the following section, we will examine potential adaptation measures, including the adoption of drought-resistant crop varieties, improved water management practices, and the promotion of sustainable agricultural techniques like conservation agriculture.

Adaptation to climate change

Assessments of the impacts of climate change on Moroccan agriculture have yielded invaluable insights into the vulnerabilities of the agricultural sector. They have identified specific challenges that agriculture will confront in the coming years, including declining rainfall, rising temperatures, exacerbating drought, and resultant decreases in agricultural yields.

These vulnerability assessments underscore the imperative for proactive adaptation measures to mitigate the potential adverse effects of climate change on agricultural productivity and food security. These measures aim to bolster the resilience of agricultural systems, promote sustainable management of natural resources, and safeguard the livelihoods of rural communities reliant on agriculture.

The findings of these impact studies have laid the groundwork for the development and implementation of targeted adaptation strategies within Moroccan agriculture. These strategies encompass a diverse array of interventions, such as the adoption of drought-resistant crop varieties, improvement of irrigation water management practices, promotion of sustainable agricultural techniques like no-till farming, and strengthening of early warning systems for climate-related risks.

Nationally Determined Contributions

The Moroccan Nationally Determined Contribution (MEME, 2021) has underscored significant opportunities within agricultural policy for both climate change adaptation and the reduction of greenhouse gas (GHG) emissions, primarily through increased carbon storage in vegetation and soils. An investigation into the development of an expanded list of Potential Nationally Appropriate Mitigation Actions (NAMAs) identified eight NAMAs based on their potential for GHG sequestration (Balaghi et al., 2014). These eight NAMAs were also selected based on their alignment with climate change adaptation, food security, and poverty alleviation goals. The proposed actions include "renovation of agricultural landscape architecture," "restoration of degraded agricultural lands," "promotion of argan cultivation," "combatting desertification of Saharan pastoral spaces," "rehabilitation of pastoral lands," "conservation agriculture," "rainwater harvesting," and "rehabilitation of food legumes in crop rotation."

Of these eight NAMAs, only the "promotion of argan cultivation" has been implemented thus far, under the "Development of Argan Orchards in Degraded Environment" (DARED) project, co-financed by the Green Climate Fund. "Conservation Agriculture" and "rehabilitation of food legumes in crop rotation" stand out as promising measures for promoting agro-ecological agriculture.

Climate-smart agriculture

As part of the Initiative for African Agriculture Adaptation to Climate Change, a climate-smart investment plan was developed to enhance the resilience of the Moroccan agricultural sector to climate change (Bromhead et al., 2018). Climate-smart agriculture is an integrated approach to managing landscapes, including cropland, livestock, forests, and fisheries, that addresses the interlinked challenges of food security and climate change. This plan, structured into projects for the period 2020-2030, was crafted in partnership with the NDC Partnership, the World Bank, the International Center for Tropical Agriculture (CIAT), the Food and Agriculture Organization of the United Nations (FAO), as well as local experts. The aim is to support priority investments in agricultural systems to improve productivity, adaptation, and/or mitigation of climate change impacts. The Moroccan investment plan drew on the Green Morocco Plan strategy, the Moroccan Nationally Determined Contribution, the aforementioned eight NAMAs, the Low Emission Development Strategy (LEDS), and research conducted at the National Institute of Agricultural Research in Morocco.

The seven priority projects identified within this climate-smart investment plan are:

Category 1: Scaling up ongoing climate-smart projects

- Direct seeding support: Supporting the large-scale adoption of no-till agriculture, contributing to climate change resilience and food security while increasing carbon sequestration. The direct seeding project aims to extend no-till seeding over 700,000 hectares within five years - 806 million MAD.
- Irrigation modernization: Providing improved irrigation services to farmers in targeted areas, facilitating the adoption of technologies for more efficient water use - 1,400 million MAD.

Category 2: New projects focusing on climate-smart agriculture

- Rehabilitation of khettaras in the Draa-Tafilalet oases: For the Regional Offices for Agricultural Development (ORMVA) of Tafilalet and Ouarzazate, the goal is to provide farmers in selected areas with increased groundwater supply by improving the performance of khettaras. For farmers in these areas, the focus is on ensuring their commitment to the sustainability of investments and water resources - 355 million MAD.
- Water and soil conservation, and rainwater harvesting in the Massa Basin: Reducing soil erosion and improving water resource availability for the population in targeted areas, supporting the development of more resilient agricultural production systems and increasing local incomes - 180 million MAD.

Category 3: Capacity-building projects

- Pasture monitoring: Establishing an operational monitoring system for pastures using meteorological data collected in the field and from satellite images, facilitating the development of sustainable management strategies - 13.7 million MAD.
- Agrometeorological risk management: Strengthening the agrometeorological and biological risk management system to enhance decision-making in the agricultural sector and real-time disaster prevention - 85 million MAD.
- Capacity-building in CSA in areas with modernized irrigation systems: Assisting producers in targeted modernized irrigation systems with improved water management and agriculture practices, contributing to more efficient and sustainable water and land management, aquifer replenishment, GHG emissions reduction, and poverty alleviation - 50 million MAD.

Conservation agriculture

Conservation agriculture is defined by the FAO as a farming system that helps prevent arable land losses while regenerating degraded land. It is a farming system that promotes minimal soil disturbance, permanent soil cover, and crop rotation to enhance soil health, reduce erosion, and improve water retention. The IPCC's Special Report on Climate Change and Land in 2019 includes conservation agriculture among the progressive adaptation options to address climate risks. Conservation agriculture, with no-till seeding as its core component, is a farming method aimed at promoting sustainable, cost-effective, and environmentally friendly agricultural systems beneficial for future generations. It advocates for maintaining permanent soil cover, minimal soil disturbance, and plant species diversification. Conservation agriculture enhances biodiversity and natural biological processes above and below the soil surface, contributing to more efficient water and nutrient use and improved and sustained crop production, enabling adaptation to climate change while reducing GHG emissions. Conservation agriculture is practiced in 79 countries, covering 12.5% (180 million hectares) of arable land worldwide in 2015/2016. The expansion of conservation agriculture is exponential, with areas exceeding 68% of what they were in 2008/2009 (Kassam et al., 2018).

The National Institute of Agricultural Research (INRA) of Morocco initiated a significant research program for arid and semi-arid zones (250 to 450 mm/year) called "Aridoculture" as early as 1981. This program aimed to increase and stabilize the production of cereals, food legumes, and forages, leading to high-efficiency rainwater use production systems. Experience in conservation agriculture began at INRA in the late 1980s as part of doctoral research (Bouzza, 1990). From 1990 onwards, INRA conducted direct seeding verification trials with cereal farmers in several regions of Morocco, including the Chaouia and Saiss regions. Starting from 2010, conservation agriculture was introduced to farmers in the Middle Atlas region (Had Bouhsoussen commune) and Chefchaouen (FERT annual reports 2010-2013) as part of the "Soil Conservation and Food Security" project, funded by the French Development Agency and implemented by FERT association, the Hassan II Agronomic and Veterinary Institute, the National School of Agriculture in Meknes (ENA), and the Provincial Directorates of Agriculture in Khénifra and Chefchaouen. Additionally, under German funding (GIZ), the Moroccan-German Agricultural Advisory Center, in partnership with ENA and the National Agricultural Advisory Office, introduced no-till seeding to farmers in the rural commune of Had Kourt.

Starting from 2011, conservation agriculture was disseminated to small cereal farmers on a relatively small area of 2,900 hectares, as part of the Climate Change Integration into the Green Morocco Plan Implementation Project (PICCPMV), covering the period 2011-2015, in the Rabat-Salé-Zemmour-Zaër and Chaouia-Ouardigha regions (Balaghi et al., 2011). In 2014, conservation agriculture was successfully promoted in northern regions of Morocco (Essahat et al., 2018) as part of the ACCAGRIMAG project. Under this project, eight direct seeding machines were distributed to professional organizations in the Fès-Meknès region to cover 150 hectares of conservation agriculture.

Since 2013, no-till seeding has been subsidized under Joint Order No. 3183-13 of November 13, 2013, amending and supplementing Joint Order No. 360-10 of January 26, 2010, setting the terms for granting state aid for the acquisition of agricultural equipment. The subsidy amounts to 50% of the seeding machine acquisition price, up to 90,000 dirhams.

Currently, Morocco has about 10,000 hectares of conservation agriculture, which is very low compared to the country's potential and to other countries with similar climates. Despite its proven benefits in Morocco, including improved yields in dry years, conservation agriculture must overcome certain challenges to expand further. Difficulties are related to the relatively high cost of no-till seeding machines, the challenge of maintaining crop residues on the soil surface due to grazing, the non-adaptation of seeders to different crop rotations, and probably also the mindset shift required at all levels of the cereal value chain (farmers, machine suppliers, input suppliers, technical support agents, and administrative and political leaders).

Indeed, conservation agriculture is estimated to have a potential area of between 1 million (NOVEC, 2016) to nearly 4 million hectares (Balaghi et al., 2014) in Morocco.

Rehabilitating food legumes in crop rotation

The area devoted to cultivating food legumes (such as broad beans, peas, chickpeas, and lentils) has witnessed a significant decline in Morocco since the launch of the Green Morocco Plan, dropping from 330,000 hectares in 2002 to 250,000 hectares in 2021, as per statistics from the National Interprofessional Cereal and Legume Office (ONICL) (Figure 13). The most notable reduction has been observed in broad beans, plummeting from 192,000 hectares in 2015 to 105,000 hectares in 2021. Broad beans constitute nearly half of the legume area (42%), with chickpeas (25%), lentils (17%), and peas (16%) making up the remainder. Several factors contribute to this decrease, including low yields, susceptibility to diseases, labor costs, and notably, competition from imported products.

The Moroccan agricultural landscape predominantly features cereal monoculture or cereal fallowing (Figure 14). Already historically low, the diminishing area allocated to food legumes in crop rotation has adverse implications for soil organic and chemical fertility, as well as soil erosion.

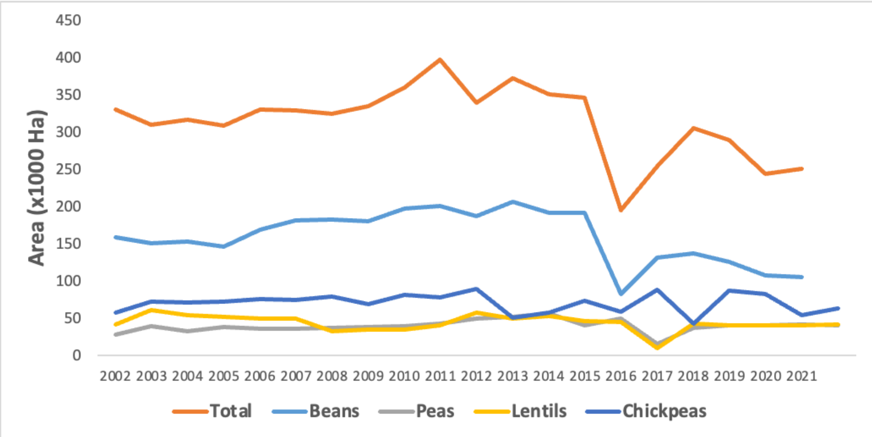

Figure 13. Evolution of the area dedicated to food legumes (Source: ONICL).

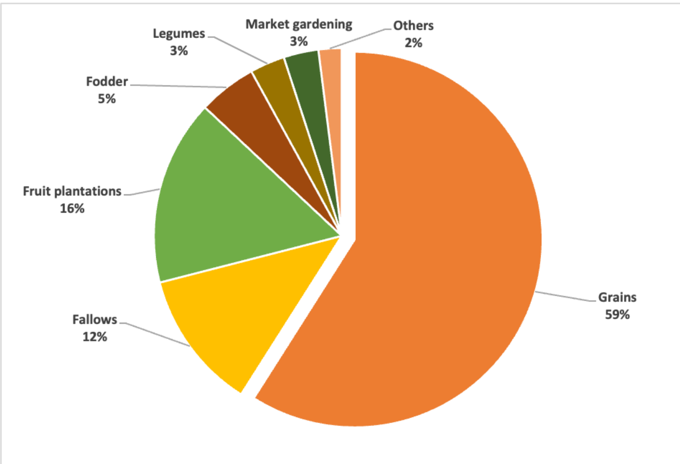

Figure 14. Occupation of agricultural land area (MAPMDREF, 2018).

Climate risk management

Effective management of climate risks is crucial in Morocco, especially given the characteristics of its climate that pose significant challenges for cereal cultivation. The climate in Morocco is primarily semi-arid, with an average rainfall of about 341 mm per growing season (from September to May of the following year), according to data from 2001 to 2017. However, variability between seasons is very high, with recorded precipitation ranging from a minimum of 198 mm in 1994-1995 to a maximum of 610 mm in 2009-2010 (Balaghi et al., 2012). The three main cereals in Morocco - durum wheat, soft wheat, and barley - are grown for grain, while their straw is used as fodder (Balaghi et al., 2012). Together, they cover an average cereal area of 4.96 million hectares, representing 55% of total agricultural land. Rainfed cereals represent 91% of this area and contribute to 81% of total cereal production. Soft wheat and barley each represent almost equal shares of rainfed cereal area, at 36% and 38%, respectively.

Despite the significant contribution of cereal farming to the national economy, cereal yields in Morocco remain relatively low compared to other countries with similar climates. Reasons include weaknesses in technology transfer, capacity building, climate information services, fertilizer use, and agricultural insurance. On average, from 2001 to 2017, national yields for rainfed cereals were 1.31, 1.41, and 0.96 tons per hectare (t/ha) respectively for durum wheat, soft wheat, and barley

(Balaghi, unpublished). These factors have a significant impact on food security in Morocco, which heavily relies on cereal production and is subject to fluctuations depending on the quantity and variability of precipitation in all regions of the country (Balaghi et al., 2012).

Morocco has seen a fivefold increase in the frequency of dry growing seasons in recent years, from one dry year out of 15 normal years in the 1930s-1970s to one dry year out of three in the last two decades. The severity of these droughts has had a significant impact on the country's economy and agricultural sector, highlighting the crucial need for effective climate risk management policies since the early 1980s. Consequently, managing climate hazards, especially drought risks, has become a major priority in Morocco's agricultural policy. This is evident in the Green Morocco Plan (2008-2020) and the current Generation Green plan (2020-2030), which integrate strategic guidelines aimed at controlling risks through the development of effective risk management tools and adaptation programs to mitigate the impacts of climate change.

Historically, INRA began developing its own crop monitoring and yield forecasting system in the early 2000s, first laying the scientific foundations (Balaghi, 2006), and then developing calculation tools in collaboration with the Joint Research Centre of the European Commission, as part of the Monitoring Agriculture ResourceS (MARS) project (El Aydam et al., 2010; El Aydam & Balaghi, 2011; Confalioneri et al., 2013; De Wit et al., 2013). Subsequently, INRA developed its own system, called CGMS-Maroc (Figures 16, 17), independently of the MARS system (Balaghi et al., 2014), under the European project E-AGRI, through technological collaboration with international research institutions, namely: the Flemish Institute for Research and Technology (VITO), the Joint Research Centre (JRC) of the European Commission, the Research Institute of the University of Wageningen (Alterra), and the University of Milan (UNIMI). Development continued under the ACCAGRIMAG project funded by the French Global Environment Fund until 2016. CGMS-Maroc was ranked by FAO (FAO, 2016) as one of the top five crop monitoring and forecasting systems in the world, alongside the United States, China, Belgium, and South Africa.

The CGMS-Maroc system was developed by INRA for the preventive management of drought risks and the prediction of cereal harvests under the direction of Riad Balaghi. CGMS-Maroc is an institutionalized crop forecasting system, involving multiple parties responsible for collecting meteorological data (General Directorate of Meteorology) and agricultural statistics (Ministry of Agriculture) as well as research and development (National Institute of Agronomic Research and Hassan II Agronomic and Veterinary Institute). Institutional arrangements are key to the success of CGMS-Maroc, as they ensure long-term development and sustainability of the system.

Comprising three interconnected subsystems - data collection and processing, statistical modeling of crop yields, and machine learning, as well as data visualization and dissemination - CGMS-Maroc harnesses a variety of data sources. These include interpolated meteorological data from synoptic stations as well as various satellite data with different spatial and temporal resolutions. CGMS-Maroc provides analysts with a comprehensive set of features to access and

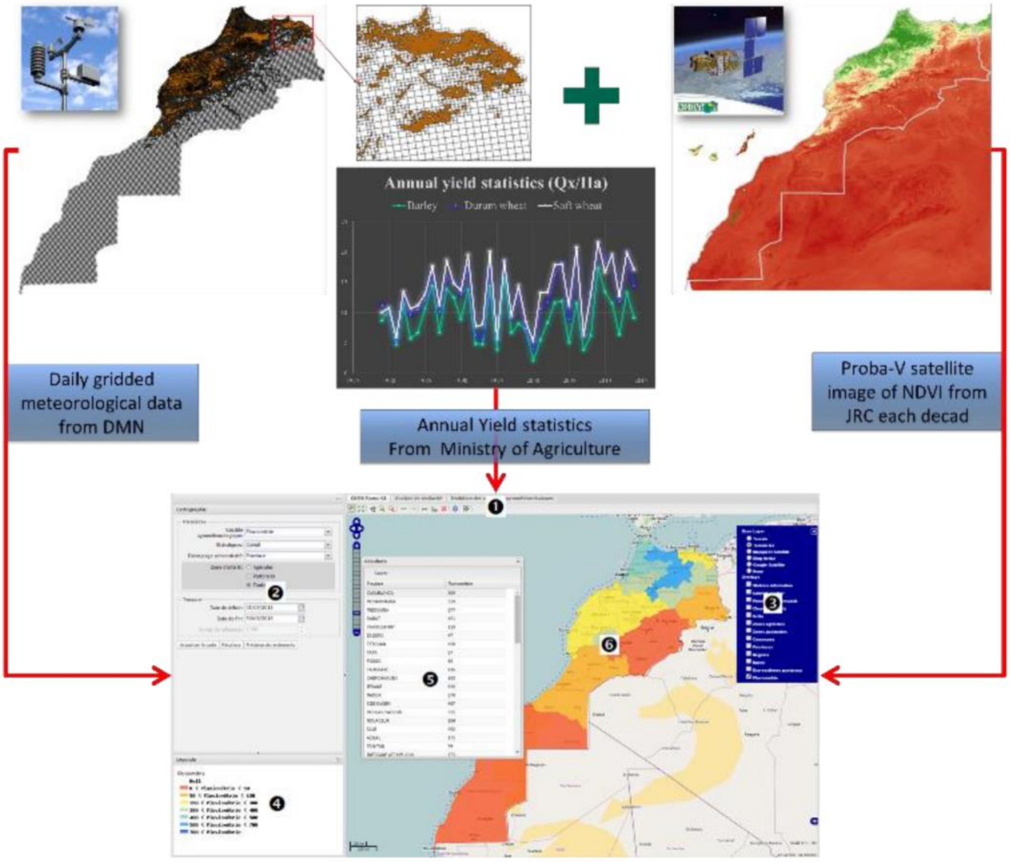

Figure 16. The CGMS-Maroc system for monitoring the agricultural season and forecasting cereal yields (Balaghi & Lahlou, 2016).

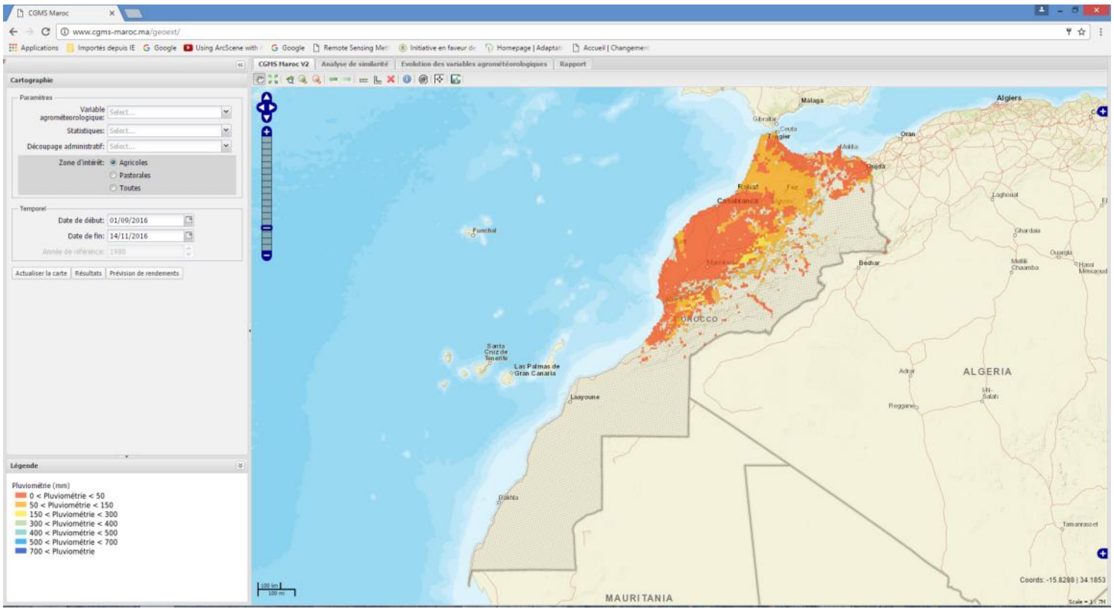

Figure 17. User interface of CGMS-Maroc.

In summary, the impact studies conducted by INRA have provided invaluable insights into the vulnerabilities of Moroccan agriculture to climate change. The projected reductions in crop growing seasons, cereal yields, and suitable cultivation areas highlight the pressing need for proactive adaptation strategies. By implementing targeted measures and leveraging its expertise in climate change impact assessment, Morocco can enhance the resilience of its agricultural sector and safeguard food security in the face of a changing climate.

Implications for Policy

The findings of the climate change impact studies have significant implications for agricultural policy in Morocco. To effectively address the challenges posed by climate change and support the implementation of adaptation strategies, policymakers must consider the following:

1. Allocating resources for research and development of drought-resistant crop varieties and improved water management technologies.
2. Providing incentives and support for farmers to adopt sustainable agricultural practices, such as conservation agriculture and agroforestry.
3. Strengthening early warning systems and disaster risk management frameworks to help farmers better prepare for and respond to climate-related risks.
4. Promoting policies that encourage crop diversification and the cultivation of high-value, climate-resilient crops in areas unsuitable for traditional cereal production.
5. Fostering collaboration between government agencies, research institutions, and international organizations to leverage expertise and resources in addressing climate change challenges.

Implications for practice

The impact studies also have important implications for agricultural practice in Morocco. Farmers and agricultural extension services must adapt their practices to cope with the changing climate and minimize the risks to crop productivity and food security. This may involve:

1. Adopting drought-resistant crop varieties and adjusting planting and harvesting schedules to align with changing temperature and precipitation patterns.
2. Implementing water-saving irrigation techniques, such as drip irrigation and deficit irrigation, to optimize water use efficiency.
3. Embracing conservation agriculture practices, such as minimum tillage, crop rotation, and permanent soil cover, to improve soil health and moisture retention.
4. Diversifying crop portfolios to spread risk and ensure income stability in the face of climate variability.
5. Participating in capacity-building programs to enhance knowledge and skills in climate-smart agricultural practices.

Implications for future research

The climate change impact studies conducted by INRA have laid a strong foundation for understanding the vulnerabilities of Moroccan agriculture to climate change. However, there is still a need for further research to refine our understanding of these impacts and develop more targeted adaptation strategies. Future research priorities may include:

1. Conducting fine-scale, site-specific impact assessments to capture the heterogeneity of climate change impacts across different agroecological zones and farming systems.
2. Developing and testing new crop varieties and management practices that are better adapted to future climate conditions.
3. Investigating the potential of innovative technologies, such as remote sensing and precision agriculture, to support climate change adaptation in the agricultural sector.
4. Exploring the socio-economic dimensions of climate change adaptation, including the barriers and enablers to the adoption of climate-smart agricultural practices by farmers.
5. Assessing the effectiveness and scalability of different adaptation strategies through monitoring and evaluation of pilot projects and case studies.

Conclusion

In conclusion, the comprehensive review of climate change impact studies on Moroccan agriculture, conducted by the National Institute of Agricultural Research (INRA), highlights the significant challenges that the agricultural sector will face in the coming years. The findings underscore the vulnerability of Moroccan agriculture to declining rainfall, rising temperatures, and increasing drought frequency, emphasizing the urgent need for proactive adaptation measures to mitigate potential adverse effects on agricultural productivity and food security.

To effectively address these challenges, a multi-faceted approach involving collaboration among researchers, policymakers, and farmers is necessary. Based on the findings presented in this document, the following specific recommendations for future actions and research directions are proposed:

1. Prioritize the development and dissemination of drought-resistant crop varieties and water-efficient irrigation technologies to enhance the resilience of Moroccan agriculture to climate change.
2. Promote the widespread adoption of conservation agriculture practices, such as minimum tillage, crop rotation, and permanent soil cover, to improve soil health, reduce erosion, and enhance moisture retention.
3. Strengthen the capacity of agricultural extension services to provide farmers with the knowledge, skills, and resources needed to implement climate-smart agricultural practices effectively.
4. Invest in the expansion and improvement of early warning systems and climate information services to help farmers better anticipate and prepare for climate-related risks.
5. Conduct further research on the socio-economic dimensions of climate change adaptation in Moroccan agriculture, including the identification of barriers and enablers to the adoption of climate-smart practices by farmers.
6. Develop and implement monitoring and evaluation frameworks to assess the effectiveness and scalability of different adaptation strategies, informing future policy decisions and investment priorities.

By prioritizing these actions and research directions, Morocco can build upon its existing expertise in climate change impact assessment and adaptation in the agricultural sector. Through sustained commitment and collaboration among stakeholders, the country can enhance the resilience of its agricultural systems, safeguard food security, and serve as a model for sustainable agricultural development in the face of climate change.

As a climate change hotspot and a testing ground for innovative agricultural practices, Morocco has the potential to lead the way in developing and implementing effective adaptation strategies that can be replicated in similar geographic regions across Africa and the Mediterranean. By leveraging its experience and expertise, Morocco can contribute to global efforts to address the challenges posed by climate change and promote sustainable agricultural development for future generations.

This strengthened conclusion not only summarizes the main points of the document but also provides specific recommendations for future actions and research directions based on the findings presented. It emphasizes the need for collaboration, investment, and sustained commitment to address the challenges posed by climate change in Moroccan agriculture, while also highlighting the potential for Morocco to serve as a leader and model for sustainable agricultural development in the region and beyond.

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