



United Nations
Convention to Combat
Desertification

DROUGHT, DESERTIFICATION, AND REGREENING IN THE SAHEL



United Nations
Convention to Combat
Desertification

© Luc Descroix and UNCCD, 2021 This article was prepared by Luc Descroix, French National Research Institute for Sustainable Development (IRD).

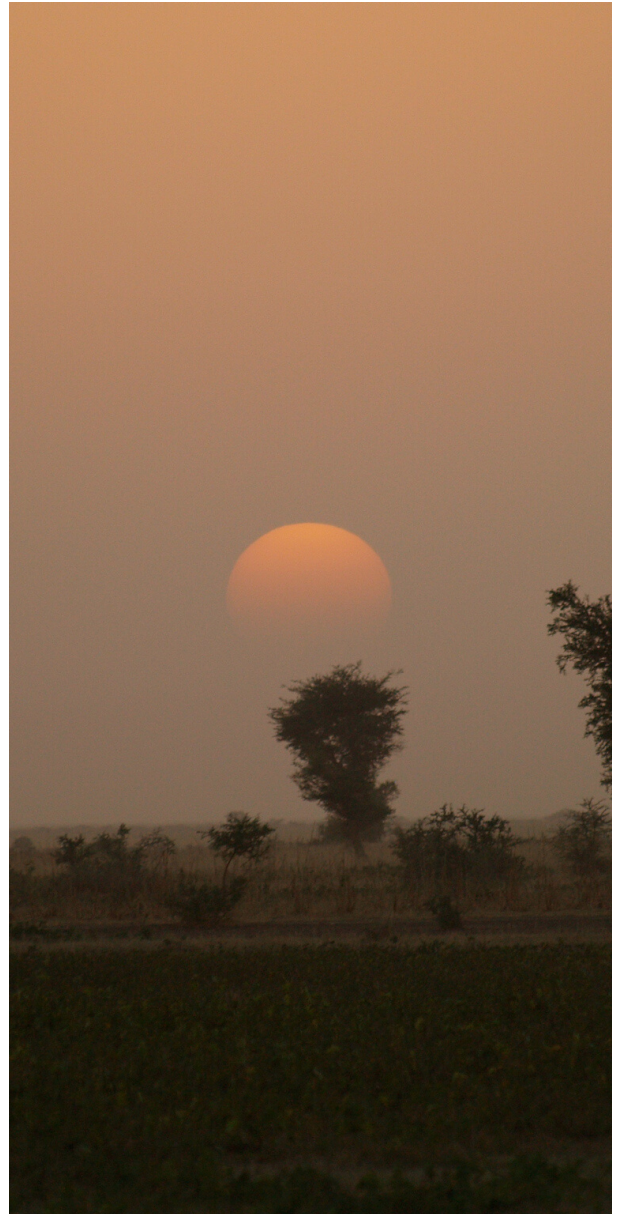
The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the United Nations Convention to Combat Desertification (UNCCD) concerning the legal or development status of any country, territory, city, or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

The views expressed in this information product are those of the author and do not necessarily reflect the views or policies of the UNCCD.

Cover photo: Sahel Sunset | Kenyon Gerbrandt

West Africa experienced severe drought from 1968 to 1993, which was all the more brutal as it followed a very wet period from 1950 to 1967. This drought was both exceptionally long, pronounced (a 15–25 percent rainfall deficit compared with the long-term average, and a 25–50 percent deficit compared with the previous wet period) and spatially extensive since the whole of West Africa was affected, i.e. more than 5 million km². As the deficit was increasingly pronounced towards the north, it was the naturally semi-arid Sahel zone that was most affected. Since the mid-1990s, rainfall has returned to its long-term average level. (Ali and Lebel, 2009; Nicholson, 2013; Descroix et al., 2015; Descroix et al., 2018)

Vegetation and soils were severely degraded. The length of the drought meant that even species adapted to aridity suffered, and sometimes dried out and perished, leaving large swathes without vegetation. Vegetation degradation resulted in degraded soils: large areas of bare soil were compacted and encrusted (Albergel, 1987; Ambouta, 1996; Cazenave and Valentin, 1992; Valentin and Bresson, 1992).



This can be the start of a vicious circle since water cannot infiltrate encrusted soil. The consequences are:

- Excess run-off: the term Sahelian hydrological paradox has been coined because, from the first years of the drought, small waterways that only ran through the Sahel saw their flows increase (Descroix et al., 2012; Mahé et al., 2013). This trend has continued and even increased with intensified rainfall and the higher frequency of extreme events. In the endorheic areas, which represent about 50 percent of the Sahel's surface area, an increase in the water table was observed during the drought. These areas are fed by the ponds formed by run-off, and their surface area, water volume, and water duration increased during the drought because of the increase in the run-off. This was one of the first times that the Sahelian paradox was observed (Leblanc et al., 2008).
- A water deficit in the soils in which water no longer infiltrates as this situation continued after the return of rainfall, it is said that the climatic drought was followed by an edaphic drought (soil drought) (Descroix, 2018).
- Aridification of the environment (with reference to desertification).

The population of West Africa is growing very rapidly (2.1 percent per year for Economic Community of West African States (ECOWAS) countries and 3 percent for landlocked countries without a coastline for 2005–2025, i.e. the inner Sahel). Over the past 30 or so years, the Sahel countries, in particular, have had the highest population growth rates in the world. It is estimated that the rural areas of the Sahel will be four times more populated in 2025 than in 1968 at the onset of the drought (Tables 1 and 2). This puts pressure on space, water resources, and plant resources, in connection with pastoral pressure, agribusiness, and land grabbing.

Table 1. Demographic data

Country	Pop. 2019 (millions)	Pop. 2050 (millions)	Pop. 2050 / pop. 2019	Fertility rate	Life expectancy	Infant mortality (‰)	Human Development Index (HDI) ranking	Rural pop. as a percentage	Percentage of population growth in years 2005–2025
Burkina Faso	20.3	43.4	2.1	5.23	60.9	84	183	60	2.84
Cabo Verde	0.55	0.68	1.2	2.29	72.7	20	125	34	1.98
The Gambia	2.35	4.88	2.1	5.25	61.5	68	174	35	2
Guinea-Bissau	1.92	3.56	1.9	4.51	57.8	82	177	56	3.02
Mali	19.7	43.6	2.2	5.92	58.7	105	182	52	2.92
Mauritania	4.53	9.03	2	4.59	64.6	79	159	25	2.44
Niger	23.3	65.6	2.8	6.95	61.8	102	189	75	3.23
Senegal	16.3	33.2	2	4.65	67.5	45	164	45	1.86

Source: Directorate General of the Treasury, France. The population growth column is based on the United Nations and Organisation for Economic Co-operation and Development (OECD)/Sahel and West African Club.

Table 2. Changes in the rural population in the Sahel

Year	Total pop.	Rural pop.	Rural pop. as a percentage
1968	16.9	15	88.8
1980	29.1	24	82.5
2000	55	35.9	65.3
2010	72.5	44	60.7
2019	89	50.5	56.7
2050*	204	76.1	37.3

Table 2 shows that the rural population is growing strongly in the Sahel, even if at a slower rate than the urban population. The rural population is more than three times higher than in 1968, the beginning of the drought.

* projections

There are also two major trends:

- A widespread and spontaneous greening of the Sahel, as if, 25 years after “normal” rainfall returned (in terms of quantity of rainfall, while its intensity has increased significantly), vegetation has managed to regain its place and reassert its rights. Attested mainly by remote sensing, this greening was mainly due to herbaceous plants between 1990 and 2010. Since then, it has been driven by trees (which take longer to grow and therefore to be seen from satellites) and can be seen in areas both with and without Farmer Managed Natural Regeneration (FMNR) or non-governmental organization (NGO) actions. It is therefore essentially spontaneous. Advocates of the FMNR method show that it is very effective and that it is behind greening in certain regions (Larwanou et al., 2006; Reij et al., 2009), which is very likely, albeit debated (Crawford et al., 2016). Nevertheless, density is increasing almost everywhere. Rain use efficiency, defined as net primary productivity (NPP) divided by rainfall (R), is also increasing, but at a slower rate. An overview of the areas where vegetation density has increased the most and where it has decreased the most has been mapped in Descroix (2018).
- The undeniable emergence of dense and perennial agrosystems and the spread of highly tree-filled agrosystems is being seen throughout the Sahel, often, but not exclusively, dominated by an increasingly dense network of *Faidherbia albida*. The acacia (a legume) is a somewhat “magical” tree in the Sahel as, besides its high capacity to store nitrogen from the air in the soil (which fertilizes soil), its staggered phenology allows it to offer welcome shade during the long and hot dry season and to lose its leaves during wintering, making agriculture possible under its crown. In addition, its branches and leaves make excellent fodder. NGO activities have had a very significant impact on this greening locally, such as in the Maradi Region of Niger. However, as they have above all promoted an ancestral practice, perhaps these NGOs have only accelerated a pre-existing very positive trend. In Senegal, in the heart of the groundnut basin or in the rice fields of northern Casamance, everything is done to preserve the ancestral presence of “cades” (*Faidherbia albida*). This is likely also the case elsewhere, although NGOs have undeniably played a role in disseminating this ancestral practice, which is rooted in local knowledge.

There are certainly still manifestations of desertification, which are lasting consequences of the 1968–1993 dry period, with (1) Areas where water continues to run off the crusted soils: for example, on some hardened plateaux in the “halo” of deforestation around the city of Niamey. These sparsely populated areas are overexploited to supply Niamey with charcoal and wood (98 percent of households cook with these two types of fuel). (2) Degraded areas can also be observed around some boreholes, due to the high density of livestock. (3) Areas that are being abandoned by rice growers in the rainy areas that have a long dry season (eight months) in Casamance and Guinea-Bissau. (4) Areas of ‘new land’ offered to Senegalese groundnut growers in the 1970s to compensate for losses in groundnut yields due to the ongoing drop in rainfall. In these areas, which have between 50 and 70 inhabitants per km², there are no trees.

In contrast, the heart of the Senegalese groundnut basin, 50 or 100 km further north and west, has 250–400 inhabitants per km² and is one of the most beautiful acacia parks in the Sahel strip, along with those of southern Zinder and South Maradi in Niger, regions which themselves have much higher population densities than the plateaux near Niamey.

Perception of desertification and regreening

Desertification, and the “sahelisation” of Sudanese areas, was the subject of numerous studies in the 1970s and 1980s (Olivry, 1982; Pouyaud, 1987; Albergel and Valentin, 1988; Luxereau and Roussel, 1997) and a terrible fate for the inhabitants that lost herds and crops. How are these trends perceived by:

a. The population?

Despite the work of Luxereau and Roussel (1997), among others, on the role of trees, population surveys are yet to be carried out. Most likely, the population’s perception is very much defined by the “single mindset” of governments, NGOs, local politicians, and leaders of agricultural networks. However, there is a general sense of an imbalance between the population and resources, a “desertification” characterized by a decrease in biomass and agricultural yields.



b. Scientists?

From the onset of the drought, most researchers noted a drastic reduction in plant cover, linked to both the drought and the need for farmers to greatly increase cultivated areas due to the drop in yields caused by reduced rainfall. This reduction in plant cover became even more marked when moving northwards towards the aridest areas and around the scarce water points. The exposed soils were weakened, eroded, and washed away by wind and water erosion. Soil crusting can be a lasting effect that prevents infiltration and continues to make the soil impermeable even after a drought ends.

Today, the regreening of the Sahel is indisputable and no longer the subject of much debate, having been confirmed year after year since the 1990s. Until the early 2000s, the trend was still uncertain, and debates were lively, but since about 2005, the trend has been confirmed year after year. This trend is linked to the return of around-average annual rains but also owes much to progress in the governance of natural resource management at the local level.

It does not extend to certain areas where soils have not recovered their water-retention capacity, such as the Middle Niger Basin (Descroix et al., 2012; Descroix et al., 2018), where the run-offs that led to the record black (Guinean) then red (Sahelian) floods of 2019 and 2020 were formed. The latter had dramatic consequences for the city of Niamey (Tarchiani et al., in press). Regreening has been found to be linked to the growth of woody plants (Brandt et al., 2018; Brandt et al., 2019; Brandt et al., 2020). Dryland desertification, and even the desert, shows a surprisingly high tree density (Brandt et al., 2020).

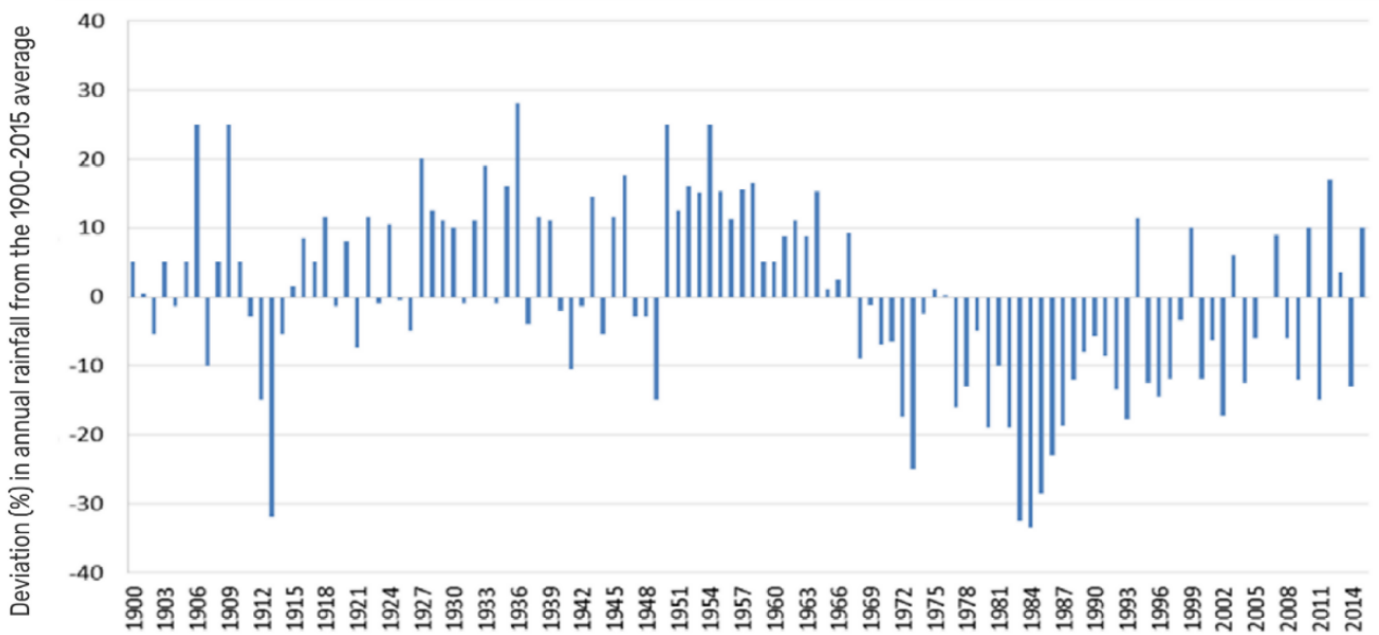


Figure 1. Percentage change compared with rainfall average from 1900 to 2015 (Descroix et al., 2018)

Because of the strong correlation between regreening and the return of rainfall, researchers had to use new indexes to show that the soils had also been able to recover their structural quality and, in particular, their water-retention capacity. The ratio of net primary productivity (NPP) to rainfall (R), called rain use efficiency, is used to better account for the conservation or restoration of vegetation and soil properties in semi-arid areas. Fensholt and Rasmussen (2013) calculated and mapped the evolution of this index between 1982 and 2010 over the Sahel, showing a robust, positive evolution. To obtain an even less questionable trend on a trend measured using satellite data, Dardel et al. (2014) used the residuals of the NPP/R ratio regressions.

The linearity of the NPP/R ratio was analyzed and shown to have no impact on rain use efficiency and the interpretation of residuals. In some areas of the Sahel, an increase in the run-off was observed while rain use efficiency values remained stable. The divergence of these two indicators of ecosystem resilience (stability of rain use efficiency) and land degradation (increase in run-off) has been described as “the second Sahelian paradox” (Dardel et al., 2014; Descroix, 2018; Descroix et al., 2018). Dardel et al. (2014) showed that, in the Malian Gourma, it is the areas of shallow soils that are characterized by declining vegetation and increasing run-off.

At the same time, the optimistic hypothesis of an increase in agrosystems' resilience is also advancing. This hypothesis, which is close to Boserupian thinking (Boserup, 1965), is advancing in scientific circles, but not yet at the political or community levels, inducing a certain degree of pessimism that persists in the corresponding networks. Boserup's theory considers population growth as an independent variable that is a major factor in agricultural development. It, therefore, opposes the Malthusian reasoning that food supply has no elasticity, making it the factor governing population growth. This implies that higher population densities spontaneously encourage rural activities to intensify.

In fact, FMNR – which is estimated to be practiced by half of the farmers in Niger (Larwanou et al., 2006; World Resources Institute (WRI), 2008; Reij et al., 2009) – and the actions of NGOs have only accelerated this natural trend, which is in fact not so natural, as farmers and rural stakeholders are involved in creating and extending these savannah parks. These agrosystems are becoming increasingly common in the most populated areas of the Sahel. The extension of the *Faidherbia albida* parks can be observed, for example, in the south of the Maradi and Zinder regions in Niger. Such parks are already established in the central part of the Senegalese groundnut basin.

Other types of very dense and highly vegetated agrosystems are also expanding, such as:

- West African mangroves (but where populations tend to be declining)
- orchard areas (mango, citrus, cashew, and others), around Niamey (Niger), in northern Benin, or in the Saloum area in Senegal
- market gardening, for example in the Niayes area in Senegal, around Niamey in Niger, or in the far north of Benin (for the Nigerian market)
- the "tapades", the highly intensified gardens of Fouta Djallon (Guinea).

This expansion, which follows and accompanies the increase in population density and urban demand follows a Boserupian (anti-Malthusian) pattern.

Strengthening agrosystems: what about production?

The return of the rains during the 1990s was followed by a return to the inter-annual variability observed before 1950, along with very wet and very dry phases (Balme et al., 2005; Balme et al., 2006). For both agriculture and hydrology, the structure of the rainy season in terms of rainfall events is often more critical than the annual accumulation (Balme et al., 2006). Balme et al. (2005) were correct, showing that "in the Sahel, the food security of a majority of the population depends on the cultivation of food grains such as millet or sorghum" and that "population growth over the last 50 years has led to an increase in the proportion of cultivated land (fields, fallow land, pastures), threatening to saturate the exploitable land. This proportion rose from 30 percent in 1950 to 80 percent in 1992 in the Niamey region and from 28 percent in 1961 to 46 percent in 1996 across the Sahel strip (Guengant and Banoin, 2003). This situation is part of a difficult environment and climate, which has low-fertility soils and low and irregular rainfall, subject to great spatial and temporal variability."

These authors concluded that there was a need to better predict the start date of the rainy season (and thus to better study and understand the mechanisms of the monsoon), which was one of the justifications for the African Monsoon Multidisciplinary Analysis (AMMA) programme that was just starting out in 2003 (Balme, 2005). This refrain and the importance of ideal sowing dates were taken up and revisited more recently by Sultan (2012) and Sultan et al. (2015). But good farming know-how generally prevails and caution always guides farmers' choice of sowing dates. Farmers are always at the mercy of an early dry spell, and in any case, cannot plow (and seed) all their plots at the optimal time.

However, as shown in Figure 1, the large Sahelian countries have a high level of self-sufficiency in cereals, with the exception of those where rice is the main cereal consumed (Senegal, the Gambia) or countries with a Saharan climate (Mauritania, Cabo Verde). For the three inner Sahelian countries, rice accounts for the very small share not supplied by local agriculture, as it is the only cereal in which these countries are not self-sufficient. Mali, having significantly increased its rice production between 2008 and 2016, has become self-sufficient and virtually an exporter. Other interesting developments include the yields of all cereals, which have increased roughly in line with population growth since the end of the drought in 1994, particularly in Niger, where yields were very low and have more than doubled from 350 kg per hectare in 1995 (Guengant and Banoin, 2003) to over 800 kg per hectare in recent years (FAOSTAT, 2015). Apart from the Saharan states, Senegal is the only country that has not seen its self-sufficiency improve, due to the many difficulties affecting rice growing. Indeed, the cost price is much higher than the cost of imported rice. Rice cultivation is also hampered by the lack of drainage in the rice fields. This has led to the destruction of the highly productive flood-recession crop system, which has been replaced by rice fields built from nothing, an over-investment (dams, canals) for production that remains low due to socioeconomic and cultural factors, prices (comparative advantage of imported products near importing ports), the political over-representation of the importing class. The Gambia has unfortunately followed the Senegalese example. Rice cultivation in Guinea-Bissau is in competition with cashew cultivation, which does not use the same land but does monopolize labor. Rice, therefore, remains the "weak link" in Sahelian cereal farming, especially in coastal countries.



Cereal self sufficiency

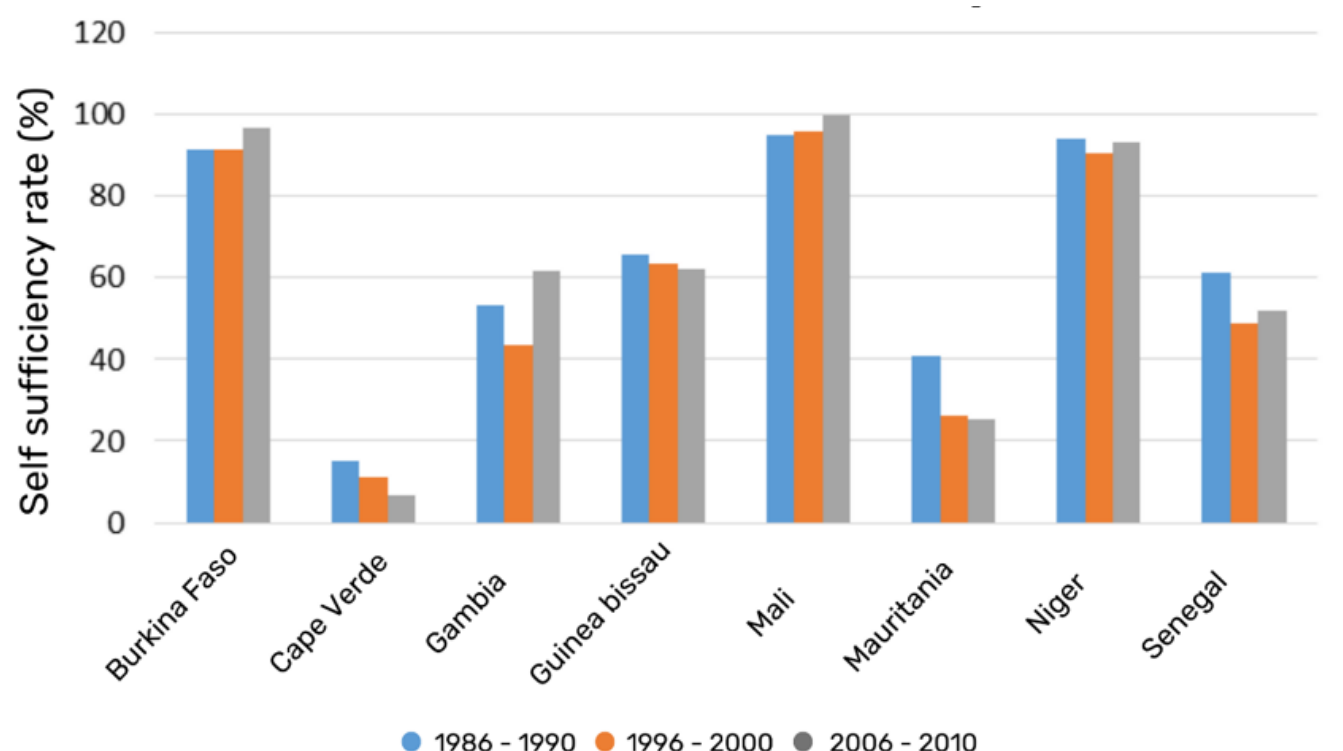
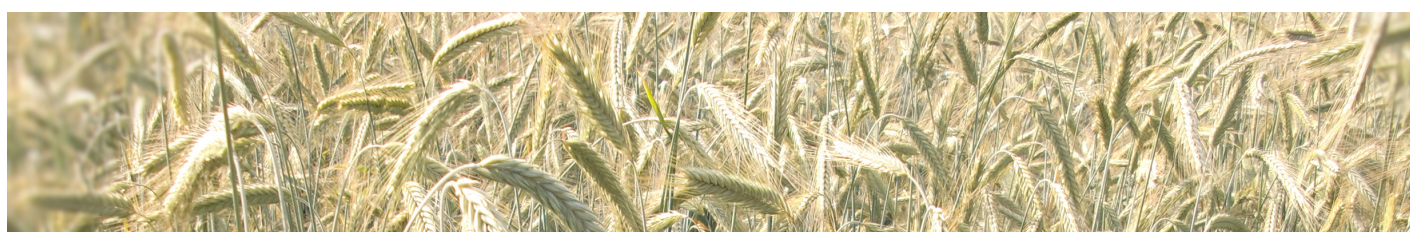


Figure 2. Change in food self-sufficiency (it is clear that the least outward-looking countries are self-sufficient over time). Source: FAOSTAT 2015

Table 3. Change in cereal production in the Sahelian countries. Source: Traoré, December 2020

Country	Expected production. 2020–2021	Percentage change in production 2015–2020	Expected production/capita 2020–2021	Percentage change in production/capita 2015–2020
Burkina Faso	5,331,073	+16.2	233	-4
Cabo Verde	3,500	+11.6	1	-85
The Gambia	120,721	-16.2	50	-47
Guinea-Bissau	257,504	+16.2	123	+4
Mali	10,233,207	+9.3	505	+32
Mauritania	478,584	+33.2	112	-44
Niger	5,312,500	-6.7	216	+12
Senegal	3,811,894	+53	214	+62
Chad	2,911,863	+4.1	175	-6
TOTAL SAHEL	28,460,747	+10.9	258	+5

Moreover, globalization has consequences for regional production as a result of comparative advantages, which negatively affect some local products (rice in particular, but also onions, palm oil, and sugar, among others).



Global warming will impact agricultural production

Given that rainfall has returned to its long-term average since the 1990s, as well as its inter-annual variability, warming is now the main factor affecting the climate vulnerability of Sahelian agriculture. West Africa is among those regions where global warming is happening fastest (+0.9°C between 1970 and 2010 compared with +0.7°C for the planet as a whole). Specifically, Guichard et al. (2015) have shown that minimum temperatures have risen much more than maximum temperatures, increasing by 3°C between 1970 and 2010 in the warmest months (March to June) over most of the Sudano-Sahelian zone. Heatwaves are also likely to become more frequent each year (Ringard et al., 2016; Diedhiou et al., 2018).

Projections show that due to increased atmospheric dynamics, the monsoon will bring increasing rainfall in West Africa (Biasutti, 2013). However, Biasutti (confirmed by IPCC 2014) predicts a disconnection between the western part of West Africa (Senegal, the Gambia, Mauritania, Guinea-Bissau, and western Mali), which after 2035 could experience a pronounced decline in rainfall, and the rest of West Africa, where rainfall is expected to continue to increase throughout the twenty-first century.

Sultan (in IPCC 2014) very clearly demonstrates the impact of global warming on yields (see annex 1), estimating that the temperature rise will more than compensate for the expected increase in rainfall and that cereal yields will fall by 7 percent by 2050 (Sultan et al., 2015, p. 220). This decline will be even more marked in the western Sahel, where rainfall is expected to decline from 2030 or 2035 onward (Sultan et al., 2015, p. 221). Sultan et al. note the statistical uncertainties in their estimates, linked to many factors, but conclude that we should not wait for greater certainty “to start thinking now about adaptation measures that are both scientifically relevant and socially acceptable, as today’s climate is already impacting the resources of rural populations” (Sultan et al., 2015). That said, a 7 percent decline is much smaller than the potential yield increases that could be achieved through simple soil fertility conservation practices, such as spreading manure (possibly compound fertilizers) or compost, mulching, selecting the best seeds, regenerating legume shoots, and, in the case of soil degradation, using zai, stone barrier and other techniques that prevent run-off and promote water infiltration.

It is also low compared with the doubling millet yields observed in the inner Sahel (Mali, Burkina Faso, and Niger) between 2000 and 2019. It is therefore likely that Sahelian farmers could well compensate for this fall in yields by continuing to adopt more intensive green and beneficial methods that will make productive agrosystems sustainable. On balance, this development also has the advantage of mitigating global warming, given the net increase in evapotranspiration. It could be said that the villages of the Sudano-Sahelian strip have long been “islands of village freshness”, thanks to their mangos, neem, acacia, cheese, cauliflowers, nere (locust bean), karite (shea tree), and other useful trees, while the towns, whose trees have been felled due to land speculation, have become “islands of urban heat”.



Conclusion

At present, despite past climatic shocks (drought) and ongoing changes, Sahelian countries are self-sufficient in cereals when there is no price distortion or distortion due to external geopolitical factors. Field research not only opened up the debate on regreening but also the debate on agrosystem resilience. Brandt et al. (2017) confirmed that agriculture and its expansion in the Sahel also promoted forestry and regreening, contradicting the widespread belief of the negative correlation between population density and forest cover. Indeed, at least 25 major papers were published between 1998 and 2010 showing the regreening of the Sahel before this point was accepted as fact.

Advancements in land governance have of course been supported by the return of the rains, though it should be noted that the Sahelian agrosystems, which are recovering fairly well (except in the middle Niger River Basin, where soil degradation seems to be ongoing*), suffered a terrible shock in the 1970s and 1980s when there was strong population growth. We must do all we can to make these agrosystems resilient to the coming shocks that are linked to the inevitable temperature increases.

As regards agrosystem resilience, the Boserupian hypotheses (Boserup, 1965), which predict better resilience in densely populated and occupied agrosystems, have been applied in Kenya (documented in the famous book *More People, Less Erosion* by Tiffen et al., 1994), in Niger (Luxereau and Roussel, 1997), in northern Côte d'Ivoire (Demont and Jouve, 2000), in north-eastern Nigeria (Mortimore and Adams, 2001), and across the entire Sudano-Sahelian strip (Descroix, 2018; Descroix et al., 2018). This point of view runs counter to the more common perception of widespread desertification linked to overpopulation, but needs to be qualified (Burger and Zaal, 2009).

This beneficial intensification has not been studied enough and warrants serious research efforts across the entire Sahelian zone to determine its true scale, as well as the influence of climate, populations (and demography), and public policies. The population seems, ultimately, to be the best tool for agrosystem resilience; it is people who plant and conserve trees and it is people, more than ever, who has a key part in tackling global warming.

*This is difficult to determine other than by satellite imagery, given that insecurity in this "three-border" area (Mali-Burkina Faso-Niger) makes research work impossible.

References

- Ali, A. and Lebel, T. (2009) The Sahelian standardized rainfall index revisited. *Int.J. Climatol.*, 29, 1705-1714.doi: 10.1002/joc.1832.
- Albergel, J. (1987). Sécheresse, désertification et ressources en eau de surface : application aux petits bassins du Burkina Faso. In *The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources*; IAHS publication N° 168, Wallingford, UK; pp. 355-365.
- Albergel, J. et Valentin, C. (1988). « Sahélisation » d'un petit bassin versant soudanien : Kognéré-Boulsa au Burkina Faso. In : Bret, B., Ed. *Les hommes face aux sécheresses, Nordeste brésilien-Sahel Africain*. Paris : EST/IHEAL, coll. Travaux et Mémoires, 42 : 179-191.
- Ambouta, J.M.K., Valentin, C. et Laverdière, M.R. (1996). Jachères et croûtes d'érosion au Sahel ; *Sécheresse*, 7 : 269-275.
- Anchang, J.Y., Prihodko, L., Kaptué, A.T., Ross, C.W., Ji, W., Kumar, S.S., Lind, B., Sarr, M.A., Diouf, A.A., Hanan, N.P. (2019). Trends in Woody and Herbaceous Vegetation in the Savannas of West Africa. *Remote Sens. MDPI* 2019, 11, 576; doi:10.3390/rs11050576
- André, V. and Pestaña, G. (2002). Les visages du Fouta-Djalon. *Les Cahiers d'Outre-Mer*, 217: <http://com.revues.org/index1038.html>
- Balme, M., Galle, S. & Lebel, T. (2005) Démarrage de la saison des pluies au Sahel : variabilité aux échelles hydrologique et agronomique, analyse à partir des données EPSAT-Niger. *Sécheresse* 16 (1), 15-22.
- Balme, M., Lebel, T. Amani, A. (2006). Années sèches et années humides au Sahel : quo vadimus ? *Hydrological Sciences – Journal–des Sciences Hydrologiques*, 51 (2), 254-271.
- Biasutti, M. (2013). Forced Sahel rainfall trends in the CMIP5 archive. *Journal of Geophysical Research: Atmospheres*, 118: 1613–1623. doi:10.1002/jgrd.50206, 2013.
- Boserup, E. (1965). *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure*, Allen and Unwin, London (Republished 1993: Earthscan Publications, London).
- Boserup, E. 1981. *Population and Technological Change: A Study of Long Term Trends*. University of Chicago Press, Chicago, USA.
- Brandt, M.; Rasmussen, K.; Peñuelas, J.; Tian, F.; Schurgers, G.; Verger, A.; Mertz, O.; Palmer, J.R.B.; Fensholt, R. (2017). Human population growth offsets the climate-driven increase in woody vegetation in sub-Saharan Africa. *Nature Ecology and Evolution*, 1, 0081, | DOI: 10.1038/s41559-017-0081
- Brandt, M., Wigneron, J-P., Chave, J., Tagesson, T., Peñuelas, J., Ciais, P., Rasmussen, K., Tian, F., Mbow, C., Al-Yaari, A., Rodriguez-Fernandez, N. Schurgers, G., Zhang, W., Chang, J., Kerr, Y., Verger, A., Tucker, C.J., Mialon, A., Vang Rasmussen, L., Fan, L., Fensholt, R. (2018). Satellite passive microwaves reveal recent climate-induced carbon losses in African drylands. *Nature Ecology & Evolution* | <https://doi.org/10.1038/s41559-018-0530-6>

Brandt, M., Hiernaux, P., Rasmussen, K., Tucker, C.J., Wigneron, J-P., Diouf, A.A., Herrmann, S.M., Zhang, W., Kergoat, L., Mbow, C., Abel, C., Auda, Y., Fensholt, R. (2019). Changes in rainfall distribution promote woody foliage production in the Sahel. *Communications Biology* <https://doi.org/10.1038/s42003-019-0383-9>

Brandt, M., C.J. Tucker, A. Kariryaa, K. Rasmussen, C. Abel, J.L. Small, J. Chave, L.V. Rasmussen, P. Hiernaux, A.A. Diouf, L. Kergoat, O. Mertz, C. Igel, F. Gieseke, J. Schöning, S. Li, K.A. Melocik, J.R. Meyer, S. Sinno, E. Romero, E.N. Glennie, A. Montagu, M. Dendoncker, and R. Fensholt. 2020. An Unexpectedly Large Count of Trees in the West African Sahara and the Sahel. ORNL DAAC, Oak Ridge, Tennessee, USA <https://doi.org/10.3334/ORNLDAAC/1832>

Burger, K., et Zaal, F., Eds. (2009). *Sustainable land management in the Tropics: Explaining the Miracle*. Aldershot, Hants, UK: Ashgate Publishing Ltd, 226 p. ISBN 978 0 7546 4455 2.

Casenave A, Valentin C. (1992). A runoff capability classification system based on surface feature criteria in semiarid areas of West Africa. *J. Hydrol*, 130: 231 -49.

Crawford, A., Shteir, S., and Rojas Chaves, D. (2016). *Farmer Managed Natural Regeneration Evidence Gap Analysis*. World Vision Australia internal document, 69 p.

Dardel, C., Kergoat, L., Hiernaux, P. Grippa, M., Mougin, E., Ciais, P. et Nguyen, C-C. (2014). Rain-Use-Efficiency: What it tells us about the Conflicting Sahel Greening and Sahelian Paradox Remote Sens. 2014, 6, 3446-3474; doi:10.3390/rs6043446.

Demont, M. and Jouve, P. (2000). Evolution d'agro-systèmes villageois dans la région de Korhogo (Nord Côte d'Ivoire): Boserup vs Malthus, opposition ou complémentarité ? Dynamiques agraires et construction sociale du territoire. Séminaire CNEARC-UTM, Montpellier, France, pp. 93–108.

Descroix, L., Genthon, P., Amogu, O., Rajot, J-L., Sighomnou, D., Vauclin, M. (2012). Change in Sahelian Rivers hydrograph: The case of recent red floods of the Niger River in the Niamey region. *Global Planetary Change*, 98-99, 18-30. [doi:10.1016/j.gloplacha.2012.07.009](https://doi.org/10.1016/j.gloplacha.2012.07.009).

Descroix, L.; Diongue Niang, A.; Panthou, G.; Bodian, A.; Sané, T.; Dacosta, H.; Malam Abdou, M.; Vandervaere, J.-P.; Quantin, G. (2015) Evolution Récente de la Mousson en Afrique de l'Ouest à Travers Deux Fenêtres (Sénégal et Bassin du Niger Moyen). *Climatologie*, 12, 25–43.

Descroix, L.; Guichard, F.; Grippa, M.; Lambert, L.A.; Panthou, G.; Gal, L.; Dardel, C.; Quantin, G.; Kergoat, L.; Bouaïta, Y.; et al. (2018). Evolution of surface hydrology in the Sahelo-Sudanian stripe: An updated synthesis. *Water*, 10, 748.

Descroix, L. (2018). *Processus et enjeux d'eau en Afrique de l'Ouest Sahélo-Soudanienne*. Editions des archives contemporaines, France, ISBN : 9782813003140, 320p., doi : 10.17184/eac.9782813003140.

Diedhiou, A.; Bichet, A.; Wartenburger, R.; Seneviratne, S.I.; Rowell, D.P.; Sylla, M.B.; Diallo, I.; Todzo, S.; Toure, N.E.; Camara, M.; Ngatchah, B.N.; Kane, N.A.; Tall, L.; Affholder, F. 2018. Changes in climate extremes over West and Central Africa at 1.5 °C and 2 °C global warming. *Environ. Res. Lett.* 13 065020.

Fensholt, R. & Rasmussen, K. (2011). Analysis of trends in the Sahelian 'rain-use efficiency' using GIMMS NDVI, RFE, and GPCP rainfall data. *Remote Sensing of Environment* 115, 438-451.

Fensholt, R., Rasmussen, K., Kaspersen, P., Huber, S., Horion, S., Swinnen, E., (2013). Assessing Land Degradation/Recovery in the African Sahel from Long-Term Earth Observation Based Primary Productivity and Precipitation Relationships. *Remote Sens.*, 5, 664-686; doi:10.3390/rs5020664 ISSN 2072-4292.

Guengant, J-P., Banoin, M. (2003). Dynamique des populations, disponibilités en terres et adaptation des régimes fonciers : le Niger. Pub. FAO-CICRED, 142 p.

Guichard, F., Kergoat, L., Hourdin, F., Léauthaud, C., Barbier, G., Mougin, E. et Diarra, B. (2015). Le réchauffement climatique observé depuis 1950 au Sahel. In Sultan, B., Lalou, R., Sanni, M.A., Oumarou, A. et Soumaré, M.A. (Eds) « Les sociétés rurales face aux changements climatiques et environnementaux en Afrique de l'Ouest ». Ed. IRD, pp. 23-42.

Intergovernmental Panel on Climate Change. (2014). Climate Change Synthesis report. 167 p.

Larwanou, M., Abdoulaye, M., Reij, C. (2006). Etude de la régénération naturelle assistée dans la région de Zinder (Niger). International Resources Group, USAID : Washington, DC, USA.

Leblanc, M., Favreau, G., Massuel, S., Tweed, S., Loireau, M., Cappelaere, B. (2008). Land clearance and hydrological change in the Sahel: SW Niger. *Glo Pla Cha*, 61, 49-62.

Luxereau, A. and Roussel, B. (1997). Changements écologiques et sociaux au Niger. *Etudes africaines*, L'Harmattan Ed, Paris, 239 p.

Mahé, G., Lienou, G. Descroix, L., Bamba, L., Paturel, J-E., Laraque, A., Meddi, M., Habaieb, M., Adeaga, O., Dieulin, C., Chahnez Kotti, F., and Khomsi, K. (2013). The rivers of Africa: witness of climate change and human impact on the environment; *Hydrol. Process.* 27, 2105–2114 (2013) DOI: 10.1002/hyp.9813.

Mortimore, M.J. and Adams, W.M. (2001). Farmer adaptation, change and 'crisis' in the Sahel. *Global Environmental Change*, 11, 49-57

Nicholson, S.E. (2013). The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. Hindawi Publishing Corporation ISRN Meteorology, Article ID 453521, 32 pages, <http://dx.doi.org/10.1155/2013/453521>.

Organisation de coopération et de développement économiques / Club du Sahel et de l'Afrique de l'Ouest. (2007). L'Afrique de l'Ouest : Une région en mouvement Une région en mutation Une région en voie d'intégration, document de travail n°1, 66 pages

Olivry, Jean-Claude (1982). Le point en 1982 sur l'évolution de la sécheresse en Sénégal et aux îles du Cap Vert. P.35 Rapport Orstom, éditions de l'Orstom, Dakar, 46 p. Panthou, G.; Viscel, T.; Lebel, T. (2014). Recent trends in the regime of extreme rainfall in the Central Sahel. *Int. J. Climatol.*, 34, 3998–4006.

Pouyaud, B. (1987). Variabilité spatiale et temporelle des bilans hydriques de quelques bassins versants d'Afrique de l'ouest en liaison avec les changements climatiques. The Influence of Climate Change and Climatic Variability on the Hydrological Regime and Water Resources. Proceedings of the Vancouver Symposium, August 1987. IAHS Publ. no. 168.

Reij, C.; Tappan, G.; Smale, M. (2009). Agroenvironmental Transformation in the Sahel, Another Kind of "Green Revolution"; IFPRI Discussion Paper 00914, 2020 vision initiative; IFPRI Pub, Washington, the USA.

Ringard, J., Dieppois B., Rome, S., Diedhiou, A., Pellarin, T., Konaré, A., Diawara, A., Konaté, D., Dje, B.K., Katiellou, G.L., Seidou Sanda, I., Hassane, B., Vischel, T., Garuma, G.F., Mengistu, G., Camara, M., Diongue, A., Gaye, A.T., Descroix, L. (2016). The intensification of thermal extremes in West Africa. *Global and Planetary Change*, 139, 66-77.

Sultan, B. (2012). Global warming threatens agricultural productivity in Africa and South Asia. *Environ. Res. Lett.*, 7, 041001.

Sultan, B., Lalou, R., Sanni, M.A., Oumarou, A. et Soumaré, M.A. (Eds) (2015). « Les sociétés rurales face aux changements climatiques et environnementaux en Afrique de l'Ouest » Ed IRD, 460 pages.

Tiffen, M.; Mortimore, M.; Gichuki, F. (1994). *More People, Less Erosion: Environmental Recovery in Kenya*. John Wiley & Sons, London. 311 pp.

Traoré, M. (2020). 2020/2021 season provisional figures and the regional market situation. Réseau de prévention des crises alimentaires (RPCA), CILSS, 36th RPCA annual meeting, 07/12/2020

Valentin, C. et Bresson, L-M. (1992). Morphology, genesis, and classification of surface crusts in loamy and sandy soils. *Geoderma*, 55, 225-245.

P.H. Verburg, G. Metternicht, C. Allen, N. Debonne, M. Akhtar-Schuster, M. Inácio da Cunha, Z. Karim, A. Pilon, O. Raja, M. Sánchez Santivañez, and A. Şenyaz. 2019. Creating an Enabling Environment for Land Degradation Neutrality and its Potential Contribution to Enhancing Well-being, Livelihoods and the Environment. A Report of the Science-Policy Interface. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany.

Verburg, P.H. , Metternicht, G., Allen, C. , Debonne, N., Akhtar-Schuster, M., Inácio da Cunha, M., Karim, Z., Pilon, A., Raja, O. , Sánchez Santivañez, M. and Şenyaz. , A. (2019) Creating an Enabling Environment for Land Degradation Neutrality and its Potential Contribution to Enhancing Well-being, Livelihoods and the Environment. A Report of the Science-Policy Interface. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany.

World Resources Institute (WRI) in collaboration with United Nations Development Programme, United Nations Environment Programme, and World Bank. 2008. Chapter 3: Roots to Resilience: Case Studies". In: *Roots of Resilience; Growing the Wealth of the Poor*. pp. 142–157 Washington, DC: WRI.

Annex 1: Impact of global warming on cereal yields in West Africa by Sultan (in IPCC, 2014)

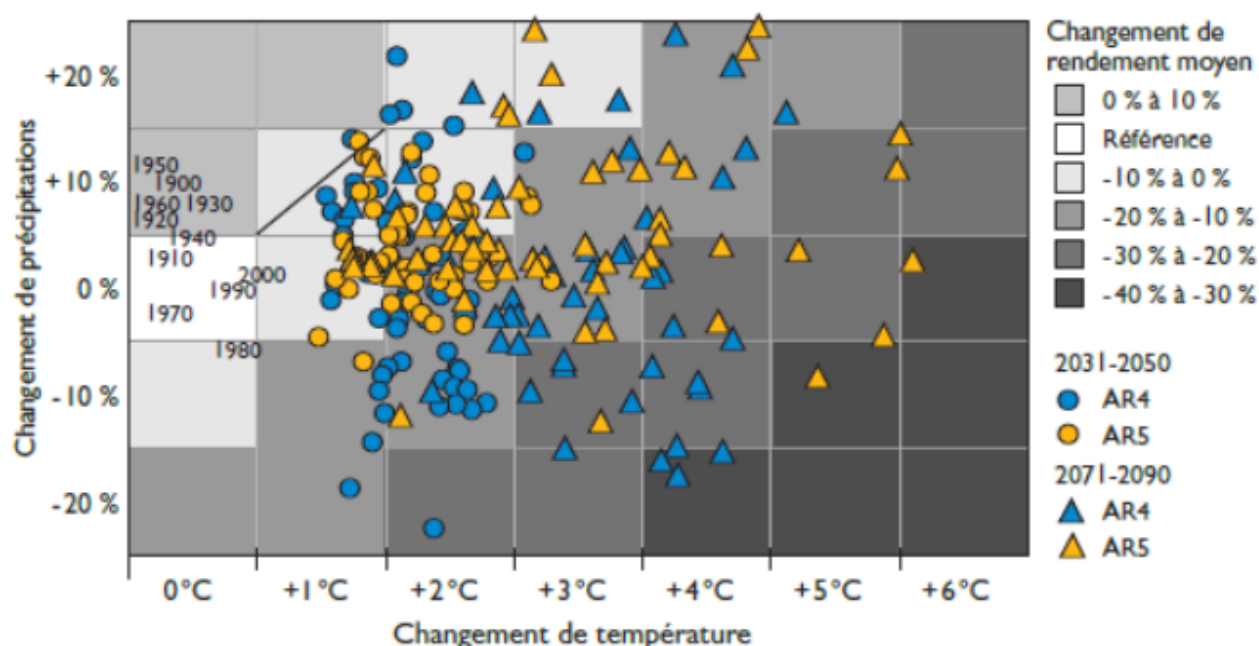


Figure 3.

L'effet des changements de températures et de précipitations sur le rendement moyen.
Changement relatif de rendement (%) par rapport à la période de référence 1961-1990
pour 7 scénarios de températures (abscisses) et 5 scénarios de pluies (ordonnées).

Les résultats sont montrés en moyenne pour 35 stations d'Afrique de l'Ouest
et 6 variétés de sorgho et de mil.

Les triangles et cercles bleus représentent les changements futurs
projetés par plusieurs GCM de CMIP3 (AR4 sur la figure) et trois scénarios du Giec (B1, A1B, A2)
respectivement pour les périodes 2071-2090 et 2031-2050.

Les projections des modèles de CMIP5 (AR5 sur la figure)
et de trois scénarios rcp (4.5, 6.0 et 8.5) sont représentées par des triangles et des cercles orange.

Les anomalies de températures et de précipitations observées depuis le début du siècle
à partir des données CRU sont aussi projetées par décades
(« 1940 » sur le graphique signifie l'anomalie 1941-1950 par rapport à 1961-1990).

Tous les changements de rendements sont significatifs au niveau de confiance 5 %,
sauf la case marquée d'une diagonale.

Source : IPCC (2014)



United Nations
Convention to Combat
Desertification