Supplement of

Observed evidences of shallow groundwater resources threatened by multi-decadal re-greening practices in the Sahel

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S1. Comparison between automatic and manual classification methods

In order to assess accuracy between automatic and manual classification methods, training polygons were randomly defined over an area of 25 km^2 for each image in 1956, 1983, and 2014, for the same area (Figure S1). It was determined whether or not they represented the vegetation cover in 1956/1983/2014. This was then compared with the vegetation cover polygons detected by automatic methods (COO and unsupervised ISODATA). The intersection over union (IoU) was used to evaluate the performance of the two classification methods. According to the results of the analysis, both classification methods proved to be effective with an average IoU of 0.963. This indicates that the performance of automatic classification is comparable to that of manual classification.

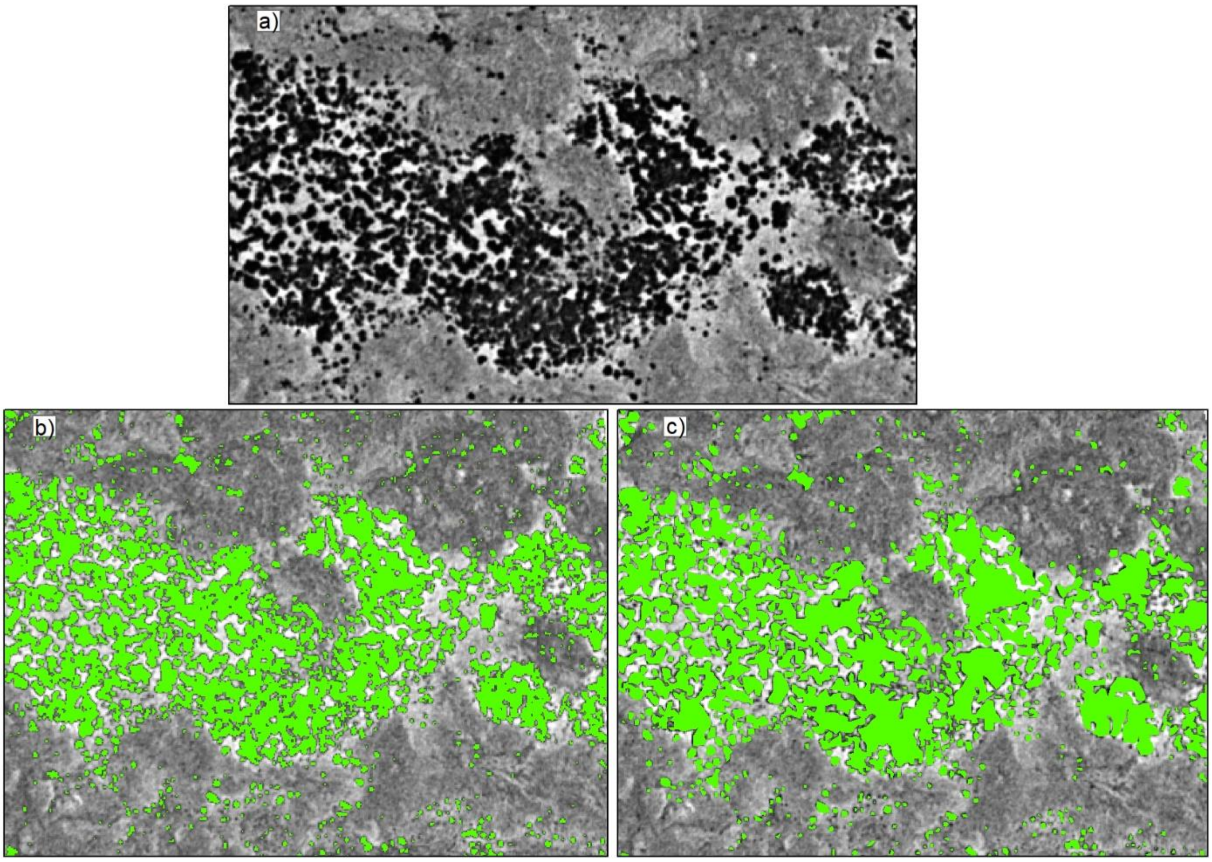

Figure S1. Example of vegetation detection comparison between: (b) unsupervised ISODATA classification, (c) manual classification method on the 1956 aerial photograph. Vegetation cover is mapped on an area of 25 km^2 for each method on the same area for comparison purposes.

S2. Quantifying land clearance and re-greening practices

The woody vegetation changes on the various landscape units of the study area were computed from 1956 to 2014 (Table S1 and Table S2). The most noticeable land-use change has taken place on the plateaus, where deforestation is perceptible everywhere, according to aerial and satellite imagery (Figure S2). The woody vegetation on plateaus has become sparser. In 1956, woody vegetation covered 30 % of plateaus; by 1983, that number had dropped to 4 % (87 % decline), and by 2014, it had dropped to just 2 % (93 % decrease) (Table S1). Clearing areas on slopes is also obvious. On the slopes, vegetation had fallen from 20 % in 1956 to 18 % in 1966. Most clearing took place in the 1980s as a result of population expansion. At that time, 65 % of the vegetation was cleared to open up new farmland.

In contrast to the plateaus and slopes areas, valley bottoms show an increase in woody vegetation, caused by programs to protect and restore degraded land, mainly tree plantations, during the intervention of large-scale programs of windbreak tree plantations (*Azadirachta indica*, a non-indigenous tree species). In the 1980s, following recurrent droughts, the region was identified as one of the main national targets for soil and water control practices (SWC). As a result, a large number of large-scale planting and windbreak projects were launched by the government with donor support towards the end of the second half of the 20th century (1980-2000). Before the large-scale integrated reforestation in the 1980s, the vegetation cover in the valleys was only 13 % (Table S1). By the end of the reforestation phase in 2001, this vegetation cover had risen to 40 %. A total reversal of land and tree cover thus occurred within 20 years. However, due to a lack of tree protection regulations and awareness-raising, the resumption of land clearing led to a reduction in vegetation cover of over 27 % in just 12 years (2002-2014).

Table S1. Change in vegetation cover between 1956 and 2014 in the upstream part.

Date	Vegetation cover			Changes/1956			Changes/1983		
	Plateaus	Valley	Slopes	Plateaus	Valley	Slopes	Plateaus	Valley	Slopes
1956	30%	14%	20%	−	−	−	−	−	−
1966	28%	14%	18%	- 6%	−	- 10%	−	−	−
1983	4%	13%	7%	- 87%	- 7%	- 65%	−	−	−
2002	3%	40%	−	- 90%	+186%	−	- 17%	+207%	−
2014	2%	29%	2%	- 93%	+107%	- 90%	- 42%	+123%	- 71%

Changes in land use are also perceptible in the different landscape units of the downstream part. Most valley bottoms appeared as dark, densely wooded areas on aerial photographs in 1956.

By 2014, some of these areas had already been completely cleared for agricultural purposes, as shown in Figure S2**.** During this period, the land required for agriculture increased considerably, so that vast areas of natural bush were cleared. By this time, 72 % of the valley bottom vegetation had been lost (Table S2). What was once dense vegetation is now completely cleared and represents a form of barren land with no vegetation, sometimes replaced by new ponds. Clearing on the plateaus and slopes is also evident and has been more noticeable since the 1950s. It resulted in a rapid increase in the number and extent of cultivated fields from the 1950s onwards.

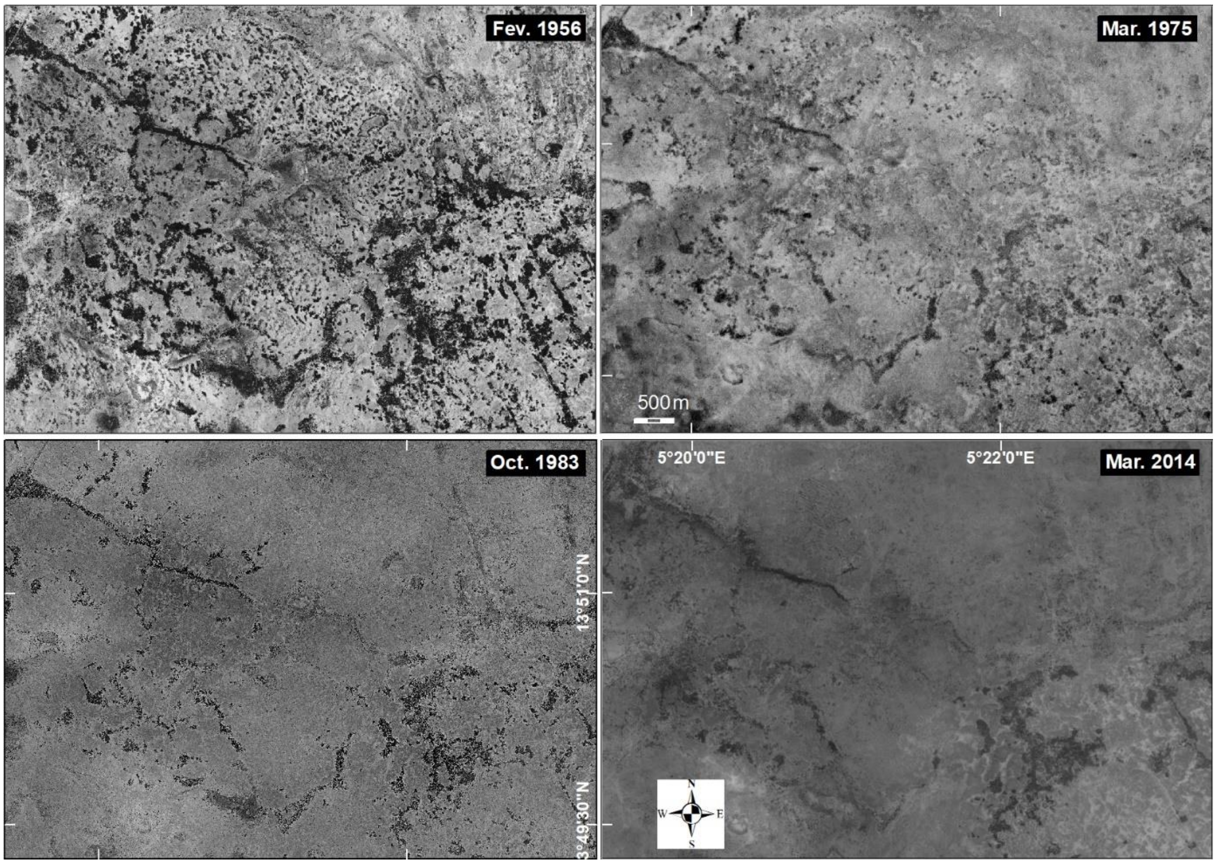

Figure S2. Evolution of vegetation on the plateau in the downstream part of the basin.

Field surveys and interviews with groups of farmers enabled us to describe the chronology of the changes observed. For most villagers, most of the less densely forested plateau had already been cleared by the early 1950s. The decline in soil fertility on the plateaus due to runoff, leaching, and the need to cultivate new fields subsequently led to the expansion of clearing on the sandy slopes. Densely wooded valley bottoms were flooded by runoff from the plateau, asphyxiating the dense woody vegetation. Peripheral areas with less dense vegetation were cleared to expand crop fields. Most of the area is now represented by vast arable fields, with a few new ponds appearing on the slopes and valley bottoms.

Table S2. Change in vegetation cover between 1956 and 2014 in the downstream part.

Date	Vegetation cover			Changes/1956			Changes/1983		
	Plateaus	Valley	Slopes	Plateaus	Valley	Slopes	Plateaus	Valley	Slopes
1956	37%	87%	67%	–	–	–	–	–	–
1983	14%	47%	27%	- 62%	- 46%	- 60%	–	–	–
2014	8%	24%	14%	- 78%	- 72%	- 79%	- 43%	- 49%	- 48%

S3. Increase and decrease in the density of the drainage system

The Analysis of aerial and satellite imagery, validated by fieldwork, showed that the drainage network experienced spectacular changes during the 1956-2014 period. The first major change was the increase in the drainage network in the upstream part between 1956 and 1983. Gullies drastically increased in number and length from 1956 to 1983, from 998 to 4830 and 1440 to 3534 km, respectively (Table S3), resulting in a more than 2.4-fold increase in drainage density. From 1983 onwards, gullies continuously decreased in number, from 21 % in 2002 to 39 % in 2014, resulting in a more than 1.6-fold decrease in drainage density.

To study the changes, gully connectivity was assessed over the whole upstream part of the basin, using the Shreve (1966) order (SO) of the final collector. The results also show spectacular changes in the Shreve order of the drainage systems. The Shreve order for most gullies increased between 1956 and 1983 (mean SO of 0.70 and 1.45 in 1956 and 1983, respectively). Between 1983 and 2014, decreasing gully lengths resulted in a more than 1.8-fold decrease in gully connectivity (average SO of 0.78 in 2014). One of the most notable facts in the area is the development of large drainage systems between 1956 and 1983 and their decrease between 1983 and 2014. The maximum Shreve order for a drainage system in the upstream part of the study area was 13 in 1956, 23 in 1983, and 17 in 2014. The increase in gully connectivity between 1956 and 1983 can also be seen in the average length of all drainage systems, which increased by over 98 % between 1956 and 1983. The sharp decline in gully connectivity between 1983 and 2014 is also accompanied by a 66 % and 33 % decrease in the average lengths of all drainage systems between 1983 and 2002 and between 2002 and 2014, respectively. Systematic analysis of aerial and satellite imagery shows that most of these changes occurred in lower-order gullies. A redistribution of flows has taken place in a small catchment developed with stone bund lines, with the appearance and disappearance of some lower-order gullies. Fieldwork and interviews have largely confirmed that the disappearance of gullies on land developed with stone bund lines is a fairly widespread phenomenon in the upstream part of the study area. In most places, gullies have disappeared after the development of stone bund lines to limit runoff. As villagers recognize, stone bund lines have an immediate and substantial impact on gullies. They considerably reduce the flow rate and increase the sediment load in the gullies.

Table S3. Changes in the drainage network computed in the upstream part of the watershed from 1956 to 2014 over an area of 1727 km².

Date	Total drainage Length (km)	Mean length (km)/drainage system	Drainage density (km^{-1})	Changes /1956	Changes /1983
1956	1440	0.73	0.83	–	–
1983	3534	1.45	2.05	+147%	–
2002	2800	0.87	1.62	+95%	-21%
2014	2164	0.78	1.25	+50%	-39%

Significant changes have also taken place in the drainage system in the downstream part of the basin. The foremost change is the expansion of the drainage network. The number of drainage systems increased from 552 to 910, and then to 1937 in 1956, 1983, and 2014, respectively. The average length of gullies, which was 0.73 km in 1956, rose to 0.90 km in 1983 and approximately 0.94 km in 2014 (Table S4). This ongoing rise in the number and length of gullies has resulted in a more than 2.8-fold increase in drainage density from 1956 to 2014. The analysis of drainage systems according to their Shreve Order (SO) in 1956, 1983, and 2014 was also carried out in the downstream part of the basin. The results show that, throughout the period, most gullies remained with a small SO, with an average SO of 0.70, 0.90, and 0.94 in 1956, 1983, and 2014, respectively. There was a greater increase in drainage systems between 1983 and 2014, with the development of large and interconnected drainage networks. The maximum SO for a drainage system in the downstream part was 5, 13, and 18 in 1956, 1983, and 2014, respectively. The increase in drainage connectivity is also evident in the average length of all drainage systems, which increased by over 34 % from 1956 to 2014.

Table S4. Changes in the drainage network computed in the downstream part of the watershed from 1956 to 2014 over an area of 930 km².

Date	Total drainage Length (km)	Mean length (km)/drainage system	Drainage density (km^{-1})	Changes/1956
1956	502	0.73	0.54	–

1983	815	0.90	0.88	+ 63%
2014	1434	0.94	1.54	+ 185%

S4. Evolution of the area developed with SWC

In the 1970s and 1980s, following recurring droughts, the region was identified as one of the main national priorities of SWC practices. Consequently, a large number of projects were launched by the government with donor support towards the end of the second half of the 20th century (1980-2000). They currently cover a large portion of the MRW and fall into two types: slopes and plateau management, consisting mainly of stone bund lines, half-moons, and contour ridges; and river network management, mainly re-greening, dams, and weirs. We do not have a precise chronology of the implementation of these structures, but we are able to map the area controlled by them using satellite images, aerial photographs, and SWC national archives. Figure S3 shows that they occupied a small part of the MRW until the early 1950s. Most of the work was carried out in the early 1980s and 2000s. Thus, the area controlled with SWC practices, which was just 1 % in 1956, rose to 10 % in 1983 and to around 28 % in 2014. Stone bund lines occupy most of the MRW. The surface area covered by these rose from 18 km^2 in 1956 to 137 km^2 in 1983 and over 350 km^2 in 2014. The second most common type of development is contour ridges, located in the upper part of the basin (Figure S3). The re-greened area increased from 29 km^2 in 1983 to 93 km^2 in 2014. In 2014, the cumulative area of SWC in the upstream part reached 670 km^2, i.e., around 40 % of the MRW.

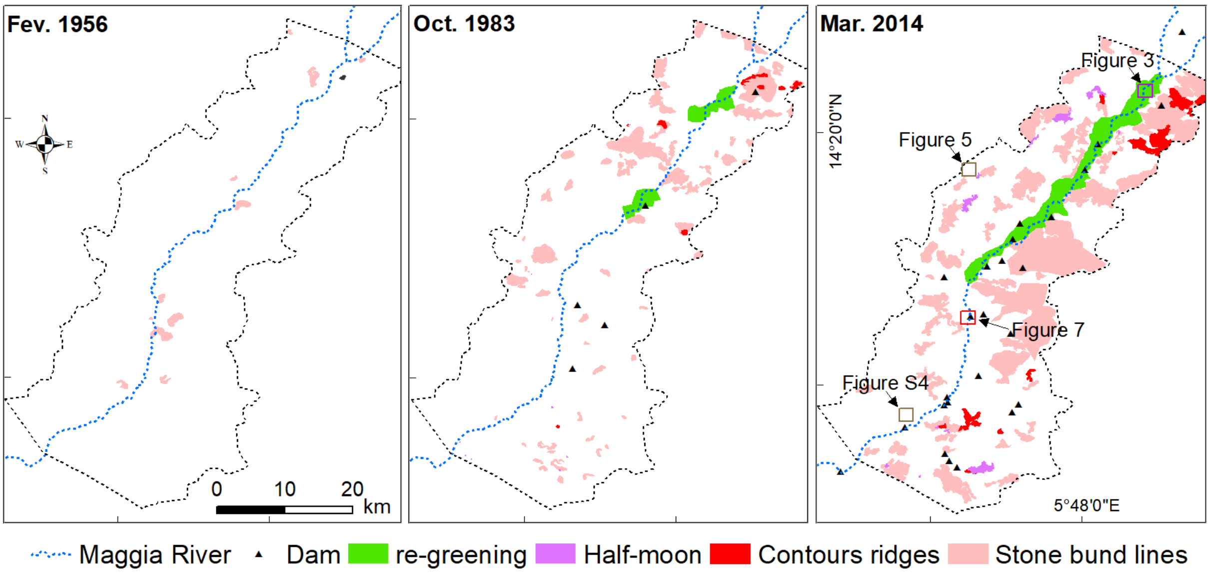

Figure S3. Evolution of re-greening and soil and water control practices in the upstream part of the study area.

S5. Changes in the pond system in the upstream part

Another type of change observed in the upstream part of the MRW is the appearance of ponds between 1956 and 1983 and their disappearance between 1983 and 2014. In most places, ponds appeared before the 1980s. The appearance of new ponds is a well-known and widespread phenomenon in the Sahel. This phenomenon, reformulated as the "Sahelian paradox", has been widely observed and described in the Sahel. Field surveys and interviews also confirmed that the appearance of new ponds between the 1960s and 1980s and their disappearance afterward are widespread phenomena in the upstream part of the study area. Most villagers recognized the increase in the appearance of ponds in the landscape until the 1980s. From the 1990s onwards, a new dynamic began (reduced runoff, disappearance of ponds, etc.). Most inhabitants described events as follows: the need to cultivate new fields as a result of population growth and land degradation led to the conversion of plateaus into cultivated fields using various SWC practices. This has led to a gradual decrease in surface flows, feeding less and less of the ponds and the river. According to them, most of the disappearing ponds began to decrease in surface area as a result of the gradual reduction in runoff before their complete disappearance. Figure S4 illustrates this process in the upstream part of the MRW. The red circles highlight the location of ponds that appeared before the 1980s and disappeared before 2014. The larger pond at the bottom, referred to by villagers as "Tafkin Maman", was a permanent pond before the 1980s but disappeared around 30 years ago, according to interviews with farmer groups.

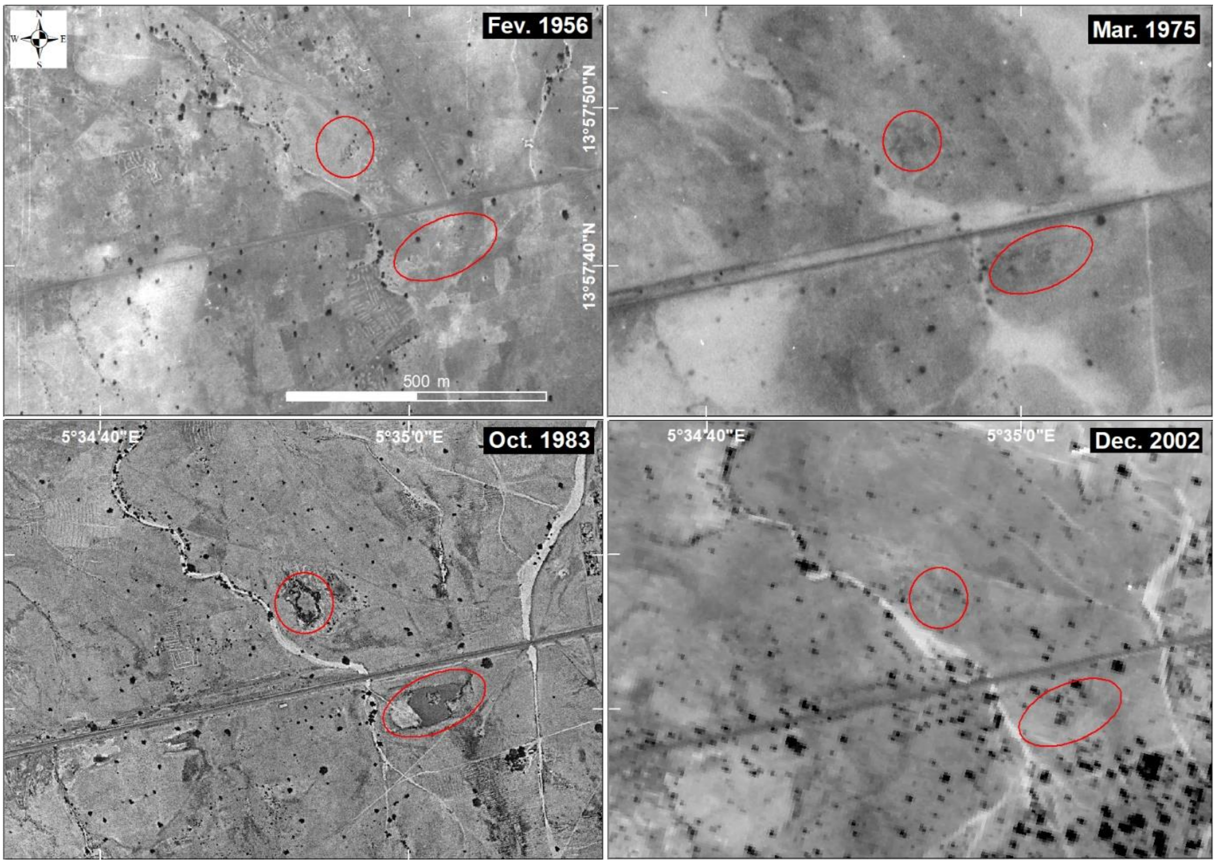

Figure S4. Example of changes in pond systems in the upstream part of the study area. The red circle delineates the location of the pond in 1956, 1975, 1983, and 2002. The location of the figure in the study area is reported in Fig. 1.

S6. References

Shreve, R.L., 1966. Statistical Law of Stream Numbers. J. Geol. 74, 17–37. https://doi.org/10.1086/627137