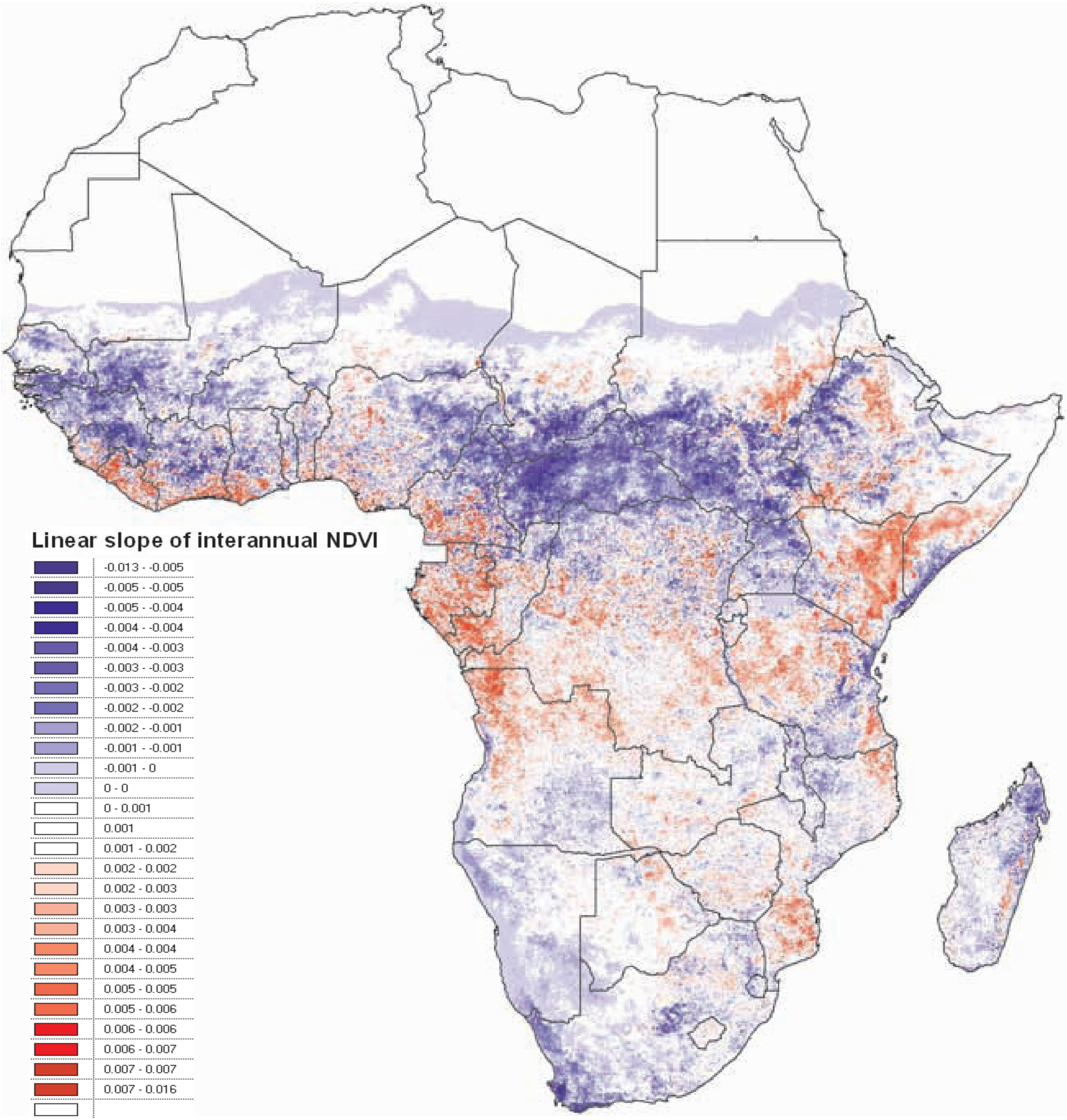
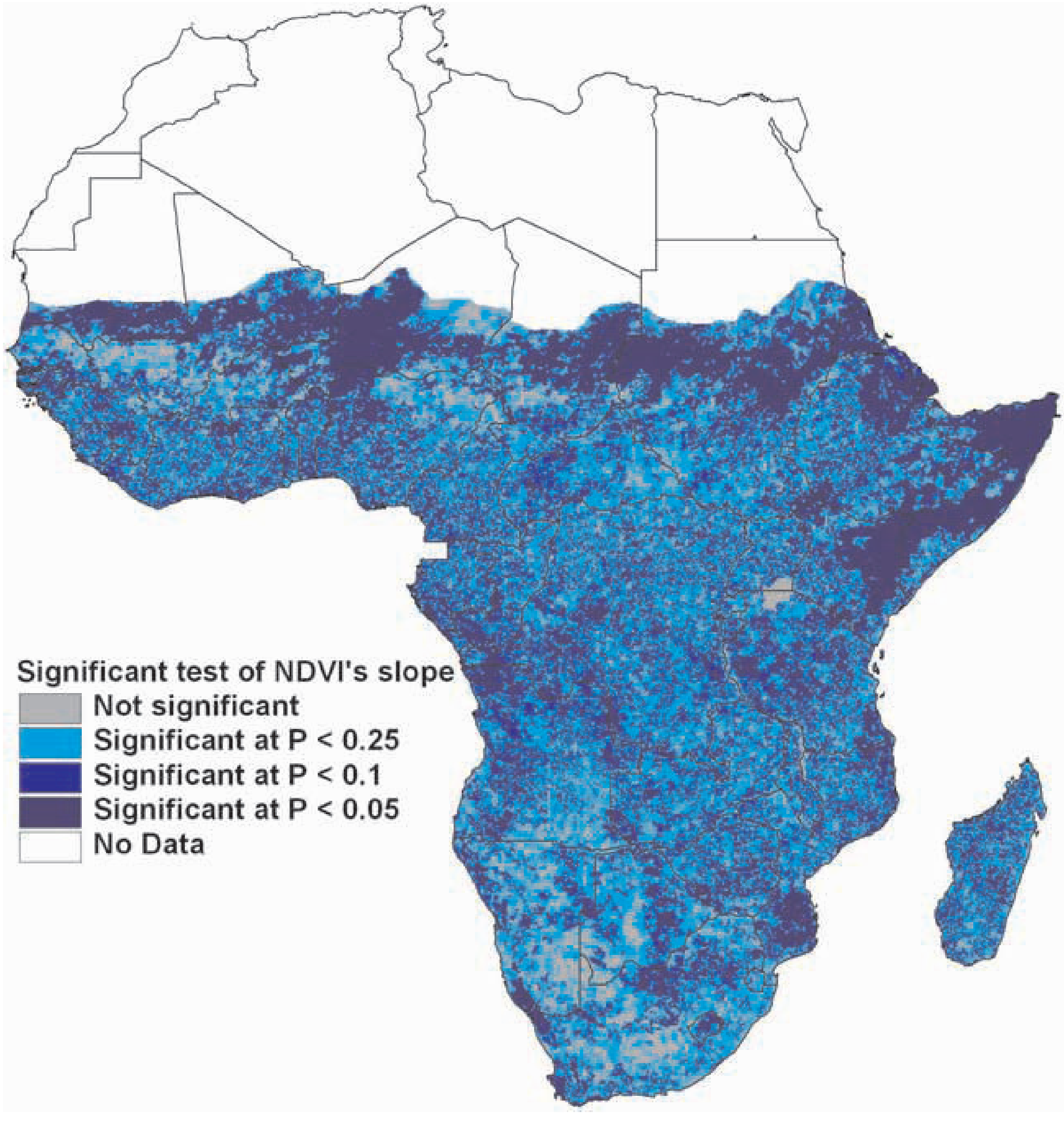
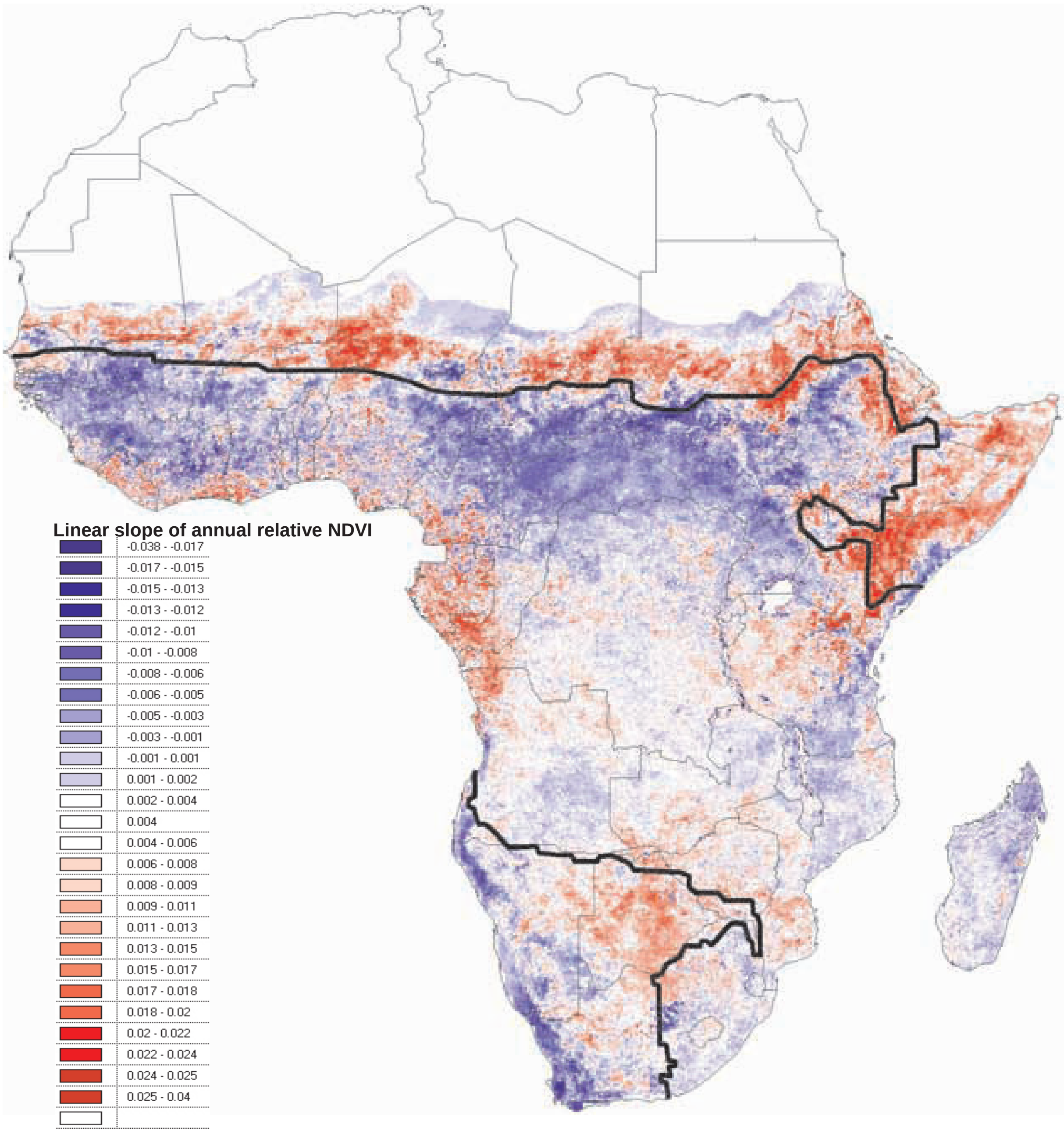


Map 4a Linear slope of annual NDVI (the slope *A* in the equation *NDVI* = *A*×*year* + *B*) for the period of 1982 - 2003 shows long-term trends of green biomass change.

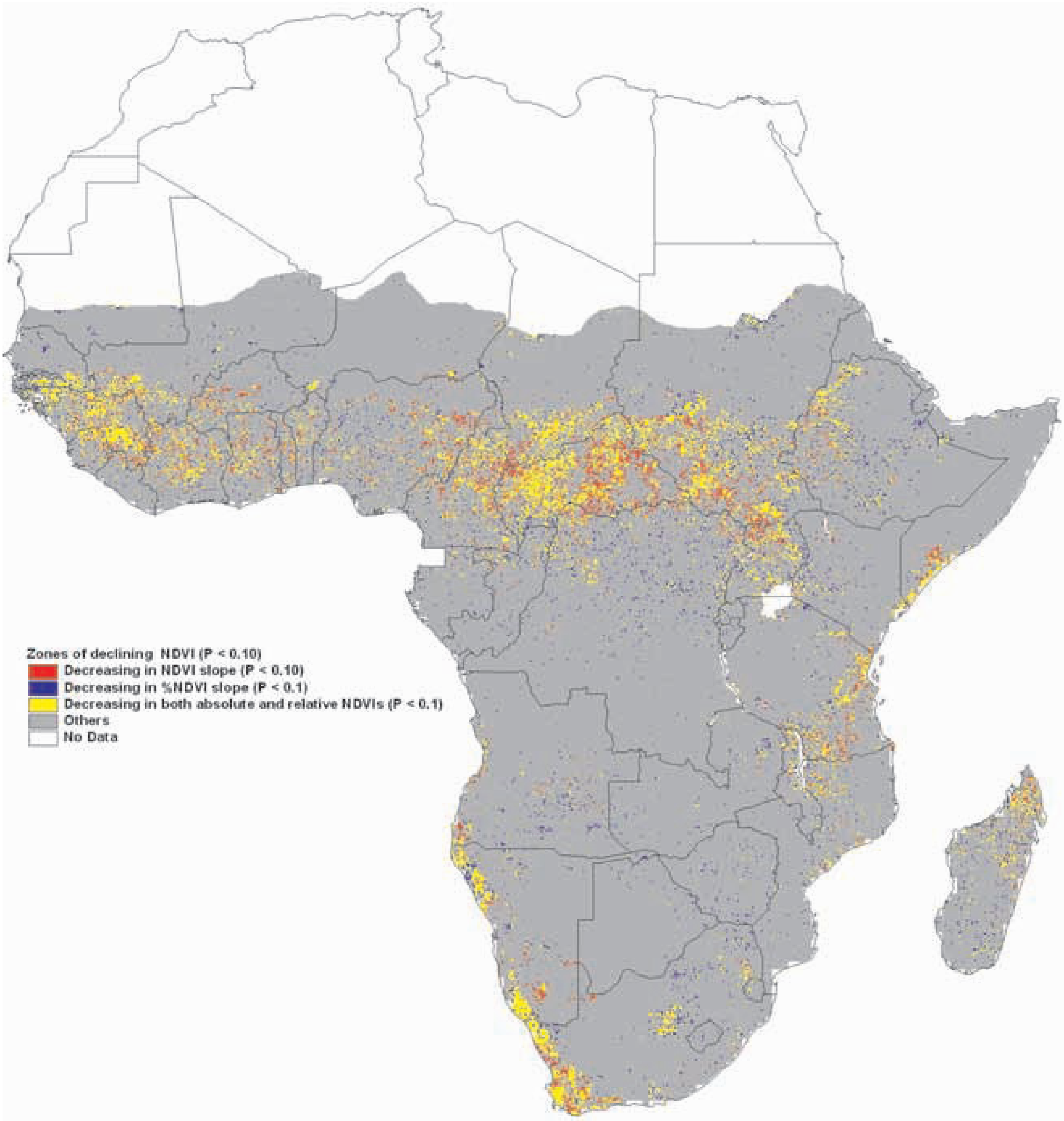


Map 4b Pixel-based significance of linear slope A (in the equation: *NDVI = A×Year + B*) over the period 1982 - 2002. (The same map for relative NDVI changes differs from this map in minor details only and is not reproduced here)



Map 4c Linear slope of annual relative NDVI (the slope coefficient A_r in the equation $\%NDVI = A_r \times year + B$) for the period of 1982 – 2003, showing long-term trends of green biomass change compared to the initial status (1982) at each pixel. Note: for each pixel, the relative NDVI of year *i* was calculated as: $\%NDVI_i = NDVI_i \times 100 / NDVI_{1982}$, where $NDVI_i$ and $NDVI_{1982}$ are the absolute NDVI values of years *i* and 1982, respectively. The bold black lines are the 500 mm yr^{-1} isohyets averaged for the same period.

The focal areas of long-term degradation in NDVI, whether in absolute or relative terms, are summarized in Map 5. Long-term degradation areas are pixels with a negative slope of either absolute or relative annual NDVI ($A < 0$ or $Ar < 0$), and a significance at 90% confidence ($P < 0.1$). Significant degradation pixels were identified by overlaying Maps 4a and 4c with their respective significance maps. It should be recognized, that although in the dry parts of Africa large regions are actually greening due to improving climate, parts of this region may suffer from human-induced degradation which is masked by this greening trend. Thus, the extent of degradation shown in Map 5 might be somewhat underestimated due to masking by climatic improvements or CO^2-or NOx-fertilization.



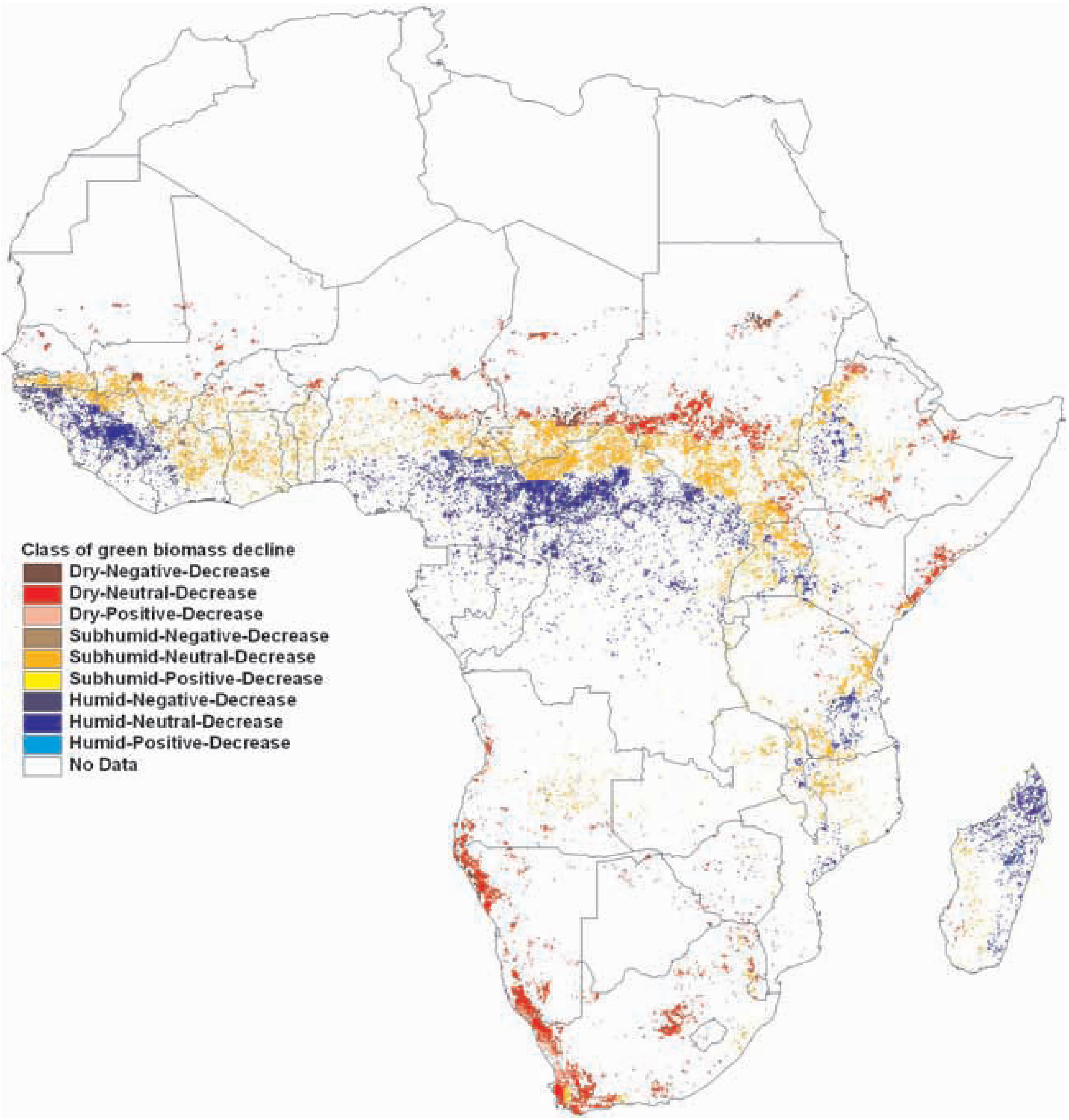
Map 5 Map showing areas of long-term degradation in green biomass. The significant degradation areas will be used as the boundary to formulate different degradation classes in the follow up steps.

4.4 Mapping vegetation degradation

The area on Map 5 that is only discernable when looking at NDVI in relative terms comprises about 400.000 km^2 (shown in blue). The area that is significantly losing vegetation cover only in absolute NDVI terms is of similar magnitude (in red) whereas the area declining in both covers 1.4 million km^2 (yellow). The difference in the significant absolute or relative loss in NDVI is not obvious, so that for the purpose of identifying hot spots of degradation, all coloured areas on Map 5 are considered to be of equal importance. The analogue overlay of the thematic maps for climate zones (Map 1, with 3 classes), long-term vegetation response to rainfall (Map 2c, with 3 classes) and long-term vegetation degradation (Map 5, reconciled to 1 class) produces 9 composite classes of climate-vegetation change (Table 4) which are shown in Map 6.

We calculated the areas showing significant vegetation changes over time as represented in Table 7. Of the 2.18 million km^2 territory showing a significant (absolute or relative) decrease in NDVI, 94% is not affected by inter-annual changes in rainfall (shown in bold letters). This region does not appear to be affected by climate change and should be reflecting the human impact on vegetation. In addition, there are some areas that have a negative correlation with rainfall and are decreasing in NDVI in spite of an increase in rainfall, adding an additional 4% as degrading land that are of particular concern. The remaining 2 % (shown in lighter shaded colour) are areas with decreasing NDVIs but with NDVI positively correlated with rainfall). These are regions where the declining vegetation is likely due to reduced rainfall and in which any human induced causes may not be discernable.

For the remainder of this analysis we will focus on the region with declining NDVI (absolute or relative), with a neutral or negative response to annual rainfall representing the region that is subjected to human-induced vegetation degradation, an area of around 2.13 million km^2. Map 6 (the 2 darker shades of blue, yellow and red) shows the areas with long-term vegetation decline for different rainfall zones, indexed by categories (Dry, Subhumid and Humid). In these areas, annual NDVI was significantly decreasing over the last 22 years (1982-2003). Because the correlation coefficients between annual NDVI and precipitation are negative, poor (category Neutral: $|Rxy| < 0.45$) or not significant, there is no reason to assume that rainfall change was the cause of this long-term vegetation decline.



Map 6 Nine composite classes of vegetation degradation that combine climate (Map 1), vegetation response to rainfall (Map 2c) and long-term green biomass decline (Map 5). The lighter shades of color are likely reflecting decreasing vegetation in response to reduced rainfall and are eliminated from further analysis.

Table 7 Area (km²) of composite classes in Map 6. The areas with positive correlation between NDVI and rainfall (in gray) were considered not due to human activity (Map 2c).

Class	*Area (km²)*	*%*
Dry-Negative-Decrease	28,544	1
Dry-Neutral-Decrease	**528,443**	**24**
Dry-Positive-Decrease	35,078	2
Subhumid-Negative-Decrease	42,822	2
Subhumid -Neutral-Decrease	**854,333**	**39**
Subhumid -Positive-Decrease	8,954	0
Humid-Negative-Decrease	24,188	1
Humid-Neutral-Decrease	**654,332**	**30**
Humid-Positive-Decrease	6,014	0
Total degraded area	*2,182,707*	*100*

Note: Classes with grey boxes are likely losing vegetation due to change in rainfall and are eliminated from further analysis.

5 RELATIONAL ANALYSIS OF LAND ATTRIBUTES AND VEGETATION DECLINE

In the following section the results of the observations made from space and the monitoring of rainfall, culminating in Map 7, are related to some of the other attributes of the land, stored in databases held by different organizations. The expectation is that such an analysis may help set priorities on the territories that should be given research attention or that should be subjected to immediate remedial action, or, in extreme cases should be abandoned. It is recognized that the value of such analysis is directly related to the quality of the respective databases, which in some cases may be questioned. However, the analytical framework retains its validity and can be easily re-applied whenever better databases become available.

5.1 Population

The first question asked was whether the areas of degradation were associated with regions where population pressure is high, as suggested by the GLASOD analysis. The mean population densities for the 1980 – 2000 period (average of 1980, 1990, and 2000) were obtained from the Grid Population of the World Version 3 (GPWv3) dataset of the Center for International Earth Science Information Network (CIESIN) at Columbia University and Centro Internacional de Agricultura Tropical (CIAT) (CIESIN/CIAT, 2004).

The mean population densities for the three climatic zones are 14 pers/km² for the dry zone, and 31 and 28 pers/km² for the sub-humid and humid zone, respectively (Table 6). The pixels in these rainfall zones that are showing signs of vegetation degradation (declining NDVI) over the past 2 decades that can not be attributed to decline in rainfall have average population pressures of 15, 27, and 25 pers/km², respectively, very close to those for the rainfall zones as a whole. In order to see how the population is distributed within the degrading zones, each of the degrading pixels of the respective rainfall zones was differentiated according to three classes of population density (smaller than the mean, more than twice the mean and between these two) as shown in Table 8.

Table 8 Population density in main climate zones[1)] and in the areas with decreasing NDVI (biomass) not attributable to declining rainfall[2)] within them (see Table 7). Right hand column provides classification of population densities for further analysis[3)] (see text).

Climate[1)] zone	*Population density (pers/km²)*	*Zone with biomass decrease in relation to rainfall[2)] (Table 7)*	*Population density (pers/km²)*		
			Mean	*Population classes[3)]*	
Dry	14	*Dry-Negative and Neutral*	15	Low density:	< 15
				High density:	15 - 30
				Very high density:	> 30
Subhumid	31	*Subhumid- Negative and Neutral*	27	Low density:	< 27
				High density:	27 - 54
				Very high density:	> 54
Humid	28	*Humid- Negative and Neutral*	25	Low density:	< 25
				High density:	25 - 50
				Very high density:	> 50

A further stratification of the rainfall regions that are in vegetative decline (Map 6) based on population density is depicted in Map 7. This map clearly shows that most of the degrading areas are low-density in population for each of the respective rainfall zones. These regions possibly constitute marginal or fragile lands with limiting carrying capacities that are easily over-populated. However, there are some areas where vegetation decline is strong and population density is high, notably South Western Ethiopia, the Ugandan highlands, Northern Nigeria and South Eastern Sudan. The higher population densities are commonly found on the best and most resilient land, and these areas should be given high priority for restoration investments once the cause of degradation has been established. In case nutrient depletion is the cause, these areas could be targeted with fertilizer marketing schemes as such inputs are likely to be economical in such regions (Kaizzi et al., 2006). In the case of erosion, investments would be needed to slow run-off (Tamene, 2006). The more marginal areas where the carrying capacity is low to begin with are likely to suffer more as population density continues to increase unless (public) measures are taken to increase the carrying capacity of these regions and reverse or protect them from further degradation. There where