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4 **Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa**

5 **Authors:**

6 **Martin Brandt,** Department of Geosciences and Natural Resource Management, University of Copenhagen,

7 1350 Copenhagen, Denmark, mabr@ign.ku.dk.

8 **Kjeld Rasmussen,** Department of Geosciences and Natural Resource Management, University of Copenhagen,

9 1350 Copenhagen, Denmark, kr@ign.ku.dk.

10 **Josep Peñuelas,** CSIC, Global Ecology Unit CREAF-CSIC-UAB, Bellaterra, 08193 Catalonia, Spain and

11 CREAF, Cerdanyola del Vallès, 08193 Catalonia, Spain, josep.penuelas@uab.cat.

12 **Feng Tian,** Department of Geosciences and Natural Resource Management, University of Copenhagen, 1350

13 Copenhagen, Denmark, feng.tian@ign.ku.dk.

14 **Guy Schurgers,** Department of Geosciences and Natural Resource Management, University of Copenhagen,

15 1350 Copenhagen, Denmark, gusc@ign.ku.dk.

16 **Aleixandre Verger,** CSIC, Global Ecology Unit CREAF-CSIC-UAB, Bellaterra, 08193 Catalonia, Spain and

17 CREAF, Cerdanyola del Vallès, 08193 Catalonia, Spain, verger@creaf.uab.cat.

18 **Ole Mertz**, Department of Geosciences and Natural Resource Management, University of Copenhagen, 1350

19 Copenhagen, Denmark, om@ign.ku.dk.

20 **John R.B. Palmer,** Interdisciplinary Research Group on Immigration, Pompeu Fabra University, Barcelona,

21 Spain, john.palmer@upf.edu.

22 **Rasmus Fensholt,** Department of Geosciences and Natural Resource Management, University of Copenhagen,

23   1350 Copenhagen, Denmark, rf@ign.ku.dk.

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Abstract

27   The rapidly growing human population in sub-Saharan Africa generates increasing demand for agricultural land

28   and forest products which presumably leads to deforestation. Conversely, a greening of African drylands has

29   been reported, but this has been difficult to associate with changes in woody vegetation. There is thus an incom-

30   plete understanding of how woody vegetation responds to socio-economic and environmental change. Here we

31   used a passive microwave Earth Observation data set to document two different trends in woody cover land area

32   for 1992-2011: an 36% increase (6,870,000 km²), largely in drylands, and an 11% decrease (2,150,000 km²),

33   mostly in humid zones. Increases in woody cover were associated with low population growth and driven by

34   increases in CO_2 in the humid zones and by increases in precipitation in drylands, whereas decreases in woody

35   cover were associated with high population growth. The spatially distinct pattern of these opposing trends re-

36   flects (1) the natural response of vegetation to precipitation and atmospheric CO_2 and (2) deforestation in humid

37   areas, minor in size but important for ecosystem services, such as biodiversity and carbon stocks. This nuanced

38   picture of changes in woody cover challenges widely held views of a general and ongoing reduction of the

39   woody vegetation in Africa.

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Introduction

41   Africa's human population has increased from about 230 million in 1950 to over 1000 million in 2010 and is

42   expected to grow to as high as 5700 million by the end of the 21st century[1]. This growth has led to the expansion

43   of agricultural land and the reduction of natural forests and other woody vegetation[2,3,4], affecting biodiversity and

44   carbon storage[3]. Severe droughts in recent decades have also had an adverse impact on humid and sub-humid

45   forested areas[5]. In contrast, studies of drylands have shown an increase in vegetation productivity over the last

46   30 years[6,7,8], also highlighting the importance of drylands for global carbon variability and as land CO_2 sink[9].

47   Whether this increase in vegetation productivity is driven by the growth of woody vegetation and/or by an in-

48   crease in productivity of herbaceous vegetation is not clear[6,7,8]. This is because the scattered nature of woody

49   plants in drylands is very different from forests with closed canopies and challenging to detect with optical satel-

50   lite imagery at regional to continental scales[10,11]. Previous studies have used vegetation indices as proxies for net

51   primary productivity, but these indices measure the photosynthetically active part of the vegetation and most

52   studies do not distinguish between woody and herbaceous vegetation[12,13]. Furthermore, studies of deforestation

53   in humid areas traditionally report the presence or absence of forests[3] and do not assess gradual changes in forest

54   biomass within existing forests (e.g., forest degradation). They are also based on temporal snapshots of satellite

55   imagery at a higher spatial resolution and only capture forests based on given definitions, e.g. tree height and

56   canopy cover percentage[3,14], which substantially underestimate shrubs and scattered trees in drylands[10]. Conse-

57   quently, little quantitative information is available about the state, rate, and drivers of change in the cover of

58   woody vegetation at the scale of the African continent. This information is crucial for ensuring that the design of

59   natural resource management in relation to deforestation and desertification is based on observations rather than

60   those based on narratives.

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Results

Africa's changing woody cover

64   We used a new passive microwave Earth Observation (EO) data set (Vegetation Optical Depth, VOD) that cap-

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65 tures continuous changes in the coverage of canopies of all woody phanerophytes, regardless of size, in both

66 drylands and humid areas[15-17]. We applied VOD as a proxy for annual woody cover and documented changes in

67 Africa's woody vegetation between 1992 and 2011, with a special focus on the changes in drylands and humid

68 areas (defined by the ratio between annual precipitation and potential evapotranspiration, Supplementary Fig.

69 1a). Woody vegetation changed significantly (linear regression, $p<0.05$, n=20) during 1992–2011 in approxi-

70 mately half of sub-Saharan Africa (47% of land areas). A majority (77%) of the significant trends were positive,

71 covering 36% of sub-Saharan Africa and representing an overall increase of 2.1 woody cover (%) (Fig. 1a). Most

72 (70%) of the significant positive changes were in drylands covering approximately 4 900 000 km² (overall

73 change +2.9 woody cover (%)), mainly in the Sahel and southern Africa[18-20] (Fig. 2a). Positive trends are also

74 observed in the humid zones to a much smaller extent (2 100 000 km²), with an overall change of +0.8 woody

75 cover (%). Negative changes affected 11% of sub-Saharan Africa, of which 75% were in humid areas (approxi-

76 mately 1 600 000 km² in humid zones and 530 000 km² in drylands). The decline in woody cover primarily af-

77 fected areas that are also characterized by high carbon stocks (Supplementary Figs 2a, 2b), suggesting that areas

78 with the largest carbon sinks have been disturbed at the fastest rate. The classification of woody cover change

79 into bioclimate zones[21] confirms the overall tendency with larger increases in drier zones (except extremely hot

80 xeric) and lower increases and decreases in moister zones (Fig. 2d).

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82 **Drivers of woody cover changes**

83 The positive changes in woody cover in Africa's drylands are significantly related to precipitation (Fig. 1a). In

84 contrast to herbaceous vegetation, woody plants can benefit from a higher variability and intensity of precipita-

85 tion[22], as in southern Africa and the Sahel (Supplementary Fig. 1c). The dependence on precipitation was cor-

86 roborated with simulations of the vegetation using the dynamic vegetation model LPJ-GUESS[23], which simulat-

87 ed an increase in woody biomass for 1992-2011, consistent with the satellite estimates of woody cover (Fig. 3).

88 The relative increase of both woody cover and biomass was largest in drylands, and factorial simulations of the

89 individual driving variables indicated that precipitation accounted for most of the simulated increase in woody

90 biomass in drylands such as the Sahel and southern Africa (Fig. 3, Supplementary Fig. 3). Increasing concentra-

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91   tions of atmospheric CO_2 was a minor contributor to these dryland trends yet was the main variable driving the

92   growth of woody vegetation in humid areas, enhancing primary production[24] (Fig. 3, Supplementary Figs. 2, 3).

93   The absolute increase in woody biomass was largest in humid areas (mean increase of 0.04 kg C m^{-2} y^{-1} near the

94   equator, Supplementary Fig. 2), coinciding with overall large stocks of woody biomass. Solar radiation, nitrogen

95   deposition and temperature had minor impacts on the changes in woody biomass (Supplementary Fig. 2).

96   This overall increase in woody vegetation driven by climate and CO_2, however, was offset by anthropogenic

97   impacts, especially in humid areas. The increase in woody cover in the VOD analysis was thus most pronounced

98   in areas of low human population density and change (Fig. 4). Areas and countries with a higher population den-

99   sity and growth (Fig. 1b, Supplementary Fig. 1d) had decreases in VOD-based woody cover (Figs. 1a, 4, Sup-

100   plementary Fig. 4), offsetting the climate-driven increases in other parts of the humid zones (Figs. 2c, 3). This

101   separation in areas of high and low human pressure applied to both drylands and humid tropics. The average

102   trend, however, remained positive in drylands, even in areas with strong population growth, but was negative in

103   humid areas with strong population growth, regardless of the trends in precipitation and CO_2 (Fig. 2b, c). Popu-

104   lations increased by an average of 40 persons km^{-2} over 20 years in areas where woody cover decreased suppos-

105   edly due to agricultural expansion, logging, and other uses of woody products. In contrast, populations increased

106   by an average of only 6 persons km^{-2} in areas where woody cover increased. Human population increase was

107   highest in moist and mesic bioclimate zones and woody cover changes were accordingly negative or low, where-

108   as population growth was lower in xeric areas and woody cover increases were higher (Fig. 2d). At the continen-

109   tal scale, a simultaneous autoregressive model (SAR) explained nearly half of the spatial pattern of changes in

110   woody cover in terms of changes in population and precipitation (r^2=0.46), with population being more im-

111   portant than precipitation (standardized slopes of -0.27 and 0.08, respectively) (Supplementary Table 1).

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113   **Discussion**

114   The opposing trends in dry and humid zones have implications for our understanding of environmental change in

115   sub-Saharan Africa. While areas of high population growth, mostly in humid zones, on average experience a

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116   decrease in woody vegetation, areas with low population growth on average experience an increase in woody

117   vegetation, mainly driven by changes in precipitation and CO_2 concentrations. This latter increase is not captured

118   in official forest statistics, since much of it takes place outside of humid forests.

119   This implies that the 'problem' of woody cover loss - and thus carbon stocks decreases - in the humid forest

120   zones is at least partly balanced by an increase in drylands. 'Bush encroachment' in savannas of southern Africa,

121   however, has traditionally been considered an undesired effect[14,25]. Since the VOD data used to estimate woody

122   cover does not allow a direct estimation of carbon stocks, the exact balance between gains and losses in carbon

123   cannot be directly assessed in this study. Further work combining field measurements, ecosystem modelling and

124   new satellite-based passive microwave sensors is required to further understand these linkages. In humid areas,

125   woody biomass may actually increase without any change in woody cover.

126   The close relationship between population growth and decreased woody cover suggests that agricultural expan-

127   sion, urbanization and wood fuel harvest were the main causes of the decrease in woody cover, as also found in

128   studies of tropical deforestation[3,26]. The reduction in woody cover tends to primarily affect areas with high car-

129   bon stocks and other studies suggest that these are also areas characterized by the highest biological diversity[27].

130   There is, however, no simple relation between losses and gains in woody cover and biodiversity. While diversity

131   and productivity of natural vegetation are generally positively correlated[28], this does not exclude the possibility

132   that great losses may be experienced in areas of deforestation, while only smaller gains are seen in drylands with

133   increasing woody cover.

134   Due to the impact on land surface albedo, woody cover changes in dryland areas may trigger climate feed-backs.

135   Since the hypothesized existence of a 'biogeophysical feed-back'[29], many studies have attempted to model such

136   effects[30,31], with some research claiming that man-made afforestation efforts would give rise to increased precipi-

137   tation[32]. The extent of the observed increase in woody cover in African drylands may impact climate if the in-

138   crease continues in the coming decades, and this altered feed-back should preferably be implemented in regional

139   climate or Earth system models, with the observed increase in woody vegetation providing a test case for these

140   models.

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Methods

VOD data and calibration to woody cover. We define woody cover as the percentage of a given area covered by woody vegetation, including both leaf and woody components of woody plant canopies. The unit is woody cover (%). The VOD data was retrieved from satellite passive microwave observations quantified as brightness temperature based on the NASA-VU Land Parameter Retrieval Model (LPRM)[33]. Three passive microwave sensors, i.e. the Special Sensor Microwave Imager, the Advanced Microwave Scanning Radiometer – Earth Observing System, and the radiometer of WindSat are used to form the long-term data set by applying a trend-preserving cumulative distribution function matching without changing the inter-annual variations and long-term trends of the original retrievals[34,35]. The merged long-term VOD data set was gridded at a 0.25° spatial resolution and monthly interval from 1992 to 2011 and is consistent between different sensors[36]. VOD is sensitive to the total aboveground water content in both the photosynthetic (foliar) and non-photosynthetic (woody) components of the vegetation stratum[15,37]. Soil moisture conditions are retrieved simultaneously with the VOD information in LPRM and large variations in soil moisture can influence the accuracy of VOD, especially for dense rainforest regions[33]. Thus VOD values exceeding 1.2 are suggested to be excluded in vegetation studies[16]. The VOD signal has been separated from soil moisture and is used as a proxy for vegetation biomass globally[34]. The VOD seasonal variation is a combined effect of the seasonal dynamics of both herbaceous (including crops) and woody vegetation[15]. We used the annual minimum VOD values as a proxy for woody vegetation cover to minimize the influence of annual herbaceous vegetation[10] and avoided values exceeding 1.2 (Supplementary Fig. 5). Areas with perennial herbaceous vegetation may lead to an over-estimation of woody cover; however, the woody cover in % is usually higher in these areas concealing the influence from the herbaceous plant understory. Also, VOD data have been used to estimate forest change in South America by limiting the range of VOD values to 0.6-1.2[16]. We did not restrict the VOD range to also include young trees and shrubs, which form an important part of the community of woody vegetation. Minimum VOD agrees well with a field data based map of woody cover for Sahel (r^2=0.80)[10] (Supplementary Fig. 5). A global map calibrated with optical high spatial resolution images and also assessing smaller trees produced similar results[38] and was thus used to transform the annual minimum VOD to the unit woody cover (%) for further analyses (r^2=0.85, slope=0.86) (Supplementary Fig. 5). A third-

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168 degree polynomial regression was used for the transformation. Woody cover <10% was predicted with an expo-

169 nential regression to avoid underestimation of very low values. The VOD is insensitive to the effects of atmos-

170 pheric and cloud contamination, ensuring reliable retrievals in cloudy regions e.g. central Africa.

171 **Correlation between the trends in woody cover and changes in human population and precipitation.** Pre-

172 cipitation data were derived from the Climate Research Unit (CRU) (data set version 3.23), which is globally

173 available for a 0.5° grid at monthly scale and is based on the upscaling of data from rain gauges[39]. CRU precipi-

174 tation data intrinsically includes some uncertainty, as the number of stations used for each grid cell varies con-

175 siderably between cells and years. Even though it is the most widely used precipitation data set in dynamic vege-

176 tation modelling[40] and consistency with other data sets has been shown[41], results have to be considered with cau-

177 tion[7]. We have tested the blended GPCP data set, without significant changes of the results, still it has to be not-

178 ed that a linear trend analysis on annually summed data includes uncertainties and simplification. We summed

179 the monthly observations to obtain annual sums from 1992 to 2011 and resampled the data to 0.25° using a bicu-

180 bic interpolation. Population data were acquired from Gridded Population of the World (GPW) v3[42], which in-

181 cludes estimates for 1990, 1995, 2000, 2005, and 2010, gridded with an output resolution of 2.5 arc-minutes,

182 resampled for this study to 0.25° (nearest neighbor). GPW population data were acquired from national statisti-

183 cal offices and gridded based on the proportional method, which allocates population counts to grid cells based

184 on the proportion of each administrative areal unit that overlaps the cell. The gridded counts for existing census

185 years are then projected to the set of output years based on a simple model of population growth. The modeling

186 was thus not based on any additional layers of data, such as land cover, avoiding potential problems of endoge-

187 neity between VOD and simulated population grids. A linear trend analysis was conducted for annual woody

188 cover and precipitation data, and the slope multiplied with the number of years to retrieve the absolute change

189 over time in the corresponding unit, facilitating the direct comparison with the human population data. We quan-

190 tified the relationships between the changes in woody cover (estimated by VOD), population increase (GPW),

191 and precipitation (CRU) by applying a simultaneous autoregressive model (SAR) (spatial error type[43]) to the

192 three gridded data sets. The SAR model accounts for spatial autocorrelation and uses change in woody cover as

193 response and log(change in population) and change in precipitation as explanatory variables. The logarithm of

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194 the human population data was applied since the relation between woody cover changes and human population is

195 non-linear at pixel scale, i.e. if a high number of population is reached (mostly in cities), the woody cover stops

196 to decrease further. Standardized variables were used to enable model coefficients inter-comparison (standard-

197 ized variable = (variable - mean) / standard deviation).

198 Fires frequently occur in most African ecosystems. However, at the spatial and temporal scale of our analysis,

199 we do not expect changes in fire regimes as a major cause of changes in woody cover in itself but rather as a

200 consequence of human induced deforestation and land use change[44].

201 **Dynamic ecosystem model.** The dynamic ecosystem model LPJ-GUESS[23] was applied to simulate changes in

202 woody-biomass carbon in natural vegetation for 1992-2011. LPJ-GUESS simulates the distribution of plant

203 functional types, and each type is represented by four pools of biomass carbon: leaves, roots, sapwood, and

204 heartwood. The latter two were added to represent the amounts of stem (wood) carbon. This variable is closely

205 related to the woody cover estimated by VOD, but especially in tropical forests, differences are expected, as

206 VOD is not able to fully penetrate the tree crowns[45]. Simulations were run for 1992-2011, applying monthly

207 climate data (temperature, precipitation, sunshine duration) from meteorological stations, gridded to $0.5° \times 0.5°$

208 resolution (CRU TS 3.21[39]), monthly model-derived estimates for nitrogen deposition[46], and annual mean at-

209 mospheric CO_2 concentrations[47,48] based on ice-core data and atmospheric observations as forcing. Land use and

210 land use change were not accounted for in the simulations, which were only applied to quantify the changes in

211 natural vegetation. The simulations were preceded by a two-stage spinup: For the first stage, vegetation growth

212 starts from bare-ground conditions, using climatic data for 1901-1930, and CO_2 levels were kept constant at the

213 concentration for 1901. For the second stage, representing 1901-1991, the actual climate data, atmospheric CO_2

214 concentration and N deposition were used.

215 In addition to a full simulation with the forcing as described above, five factorial simulations were performed to

216 separate the impact of individual driving variables. Only one of the four parameters (temperature, precipitation,

217 radiation, or CO_2) was applied using the transient data as described above, whereas the other three parameters

218 used a climatology for 1992-2011, applying monthly means over this 20-year period for the climatic parameters

219 and an annual mean for CO_2. In the fifth factorial simulation, similar to the transient CO_2 simulation above, the

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220 changing CO_2 concentration was combined with a climatology for N deposition, to separate the impacts of at-

221 mospheric CO_2 and N deposition on the CO_2 fertilization. These simulations were applied to determine the im-

222 pact of the individual driving variables on the simulated trend.

223 **Data availability** CRU precipitation data are available from the University of East Anglia

224 (http://www.cru.uea.ac.uk/). The global tree cover map is available from the Geospatial Information Authority of

225 Japan, Chiba University (http://www.iscgm.org/gm/ptc.html#use). VOD raster data are developed by Yi Liu,

226 University of New South Wales. Gridded population maps are provided by CIESIN

227 (http://sedac.ciesin.columbia.edu/). Humidity zones are available from http://www.grid.unep.ch/index.php.

228 DGVM results are available from the corresponding author upon reasonable request.

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Figure legends:

245 **Figure 1 | Changes in woody vegetation and human population over two decades. a**, Significant trends of

246 woody cover (VOD) for 1992-2011, separated by the presence or absence of a significant ($p<0.05$, n=12845)

247 correlation with cumulative 2-year precipitation during this period. **b**, Changes in human populations for 1990-

248 2010. The maps in (**a**) and (**b**) share a clear pattern, especially areas with a decrease in woody cover, and no

249 relation to precipitation coincide with a high population pressure. **c**, SAR model of the changes between woody

250 cover, precipitation (both 1992-2011), and population (1990-2010). The units are expressed as change in the

251 corresponding unit over the period of analysis.

252 **Figure 2 | Changes in woody cover (VOD) in different humidity zones. a**, Areas with changes in woody cov-

253 er (linear regression of change in woody cover for 1992-2011). Annual profiles of woody cover for areas of sta-

254 tistically significant changes in woody cover in **b**, drylands and **c**, the humid areas of sub-Saharan Africa (Sup-

255 plementary Fig. 1a). Black lines characterize areas of high human population increase (>30 persons km^{-2}) and

256 grey lines areas of low human population increase (<10 persons km^{-2}) for 1990 to 2010. **d**, Woody cover and

257 human population changes are grouped according to bioclimatic zones[21].

258 **Figure 3 | Climatic drivers of changes in woody cover and biomass in sub-Saharan Africa.** Relative trends

259 (% of mean $year^{-1}$) for 1992-2011 in woody cover (estimated with VOD) and woody biomass (simulated with

260 LPJ-GUESS) had similar patterns of change from north to south. The trends of woody biomass were mainly

261 driven by CO_2 (humid areas) and precipitation (drylands) (Supplementary Figs. 2, 3).

262

263 **Figure 4 | Links between changes in woody cover and human population**. Intervals of mean population den-

264 sity (1990-2010, Supplementary Fig. 1d) were used to group the changes in woody cover (VOD) associated with

265 population increases and the number of pixels showing significant woody cover change. A Chi-squared test be-

266 tween woody cover and population change indicated the statistically significant dependency between the two

267 variables.

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