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Reduction of tree cover in West African woodlands and promotion in semi-arid farmlands

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Woody vegetation in farmland acts as a carbon sink and provides ecosystem services for local people, but no macroscale assessments of the impact of management and climate on woody cover exist for drylands. Here we make use of very high spatial resolution satellite imagery to derive wall-to-wall woody cover patterns in tropical West African drylands. Our study reveals that mean woody cover in farmlands along all semi-arid and sub-humid rainfall zones is 16%, on average only 6% lower than in savannahs. In semi-arid Sahel, farmland management promotes woody cover around villages (11%), while neighbouring savannahs had on average less woody cover. However, farmlands in sub-humid zones have a greatly reduced woody cover (21%) as compared with savannahs (33%). In the region as a whole, rainfall, terrain and soil are the most important (80%) determinants of woody cover, while management factors play a smaller (20%) role. We conclude that agricultural expansion causes a considerable reduction of trees in woodlands, but observations in Sahel indicate that villagers safeguard trees on nearby farmlands which contradicts simplistic ideas of a high negative correlation between population density and woody cover.

Concerns about declining woody cover in West Africa have been raised since the early twentieth century[1,2]. In the 1970s and 80s, negative trends in woody vegetation, presumably associated with the 'Sahel drought' and agricultural expansion, were observed and became part of the desertification/land degradation discourse, later termed the 'Sahel syndrome'[3]. Rapidly growing settlements and urban markets demanded large amounts of firewood and charcoal, and concerns about an upcoming fuelwood crisis were widespread[4]. Certain parts of the Sahel experienced an increase in export-oriented agriculture (for example, groundnut production in Senegal and cotton production in Mali), which was understood to have contributed to a downward trend in woody cover as well[5]. All these concerns had substantial impact on natural resource policies of the Sahelian countries and the donors supporting them: new forests were planted (for example, 'shelterbelts' in northern Nigeria, village woodlots in Mali and Burkina Faso) and new attempts were made to regulate firewood harvesting and charcoal production[6]. Grand schemes of 'green belts' across the Sahel, already suggested before the Second World War[1], were taken up again. However, from the 1980s onwards, research by botanists[7], foresters[8], geographers[9–12] and anthropologists[13] painted a more complex picture of the relationship between humans and woody vegetation: studies at village and landscape scales showed that increase and decrease in woody cover occurred simultaneously in different parts of the Sahel[7,11,14]. The 'case study' character of this research, however, made it difficult to generalize findings, because the representativeness for the larger region was difficult to establish[15].

The idea of a progressing land degradation in arid and semi-arid West Africa was also challenged from another side: regional-scale analyses of time series of vegetation indices derived from different satellite systems showed that fluctuations of the Sahara Desert boundary are common[16] and that the Sahel was experiencing a 're-greening' after the drought years of the 1970s and 1980s[17]. These studies did not, however, allow separation of the contributions from the herbaceous and woody vegetation components. Only recently has this been achieved[18,19] revealing that the greening may be partly attributed to an increase in woody cover. The coarse spatial and limited temporal resolution of the satellite images used and the complexities of the methods applied imply that such assessments of vegetation change in the Sahel do not necessarily form a robust basis for estimating trends in woody cover locally, and leave considerable room for speculations regarding the nature of the woody vegetation changes. Attempts to produce global maps[20,21] of tree cover focus mainly on forests in humid areas and yield unrealistically low canopy cover estimates in drylands, which are thus commonly ignored neglected in woody vegetation assessments[22]. These obstacles have made it difficult to study linkages between woody vegetation, rainfall and humans for West African farmlands and savannahs—knowledge that is essential in the face of demographic and climatic change.

The recent access to large volumes of DigitalGlobe commercial satellite images with a spatial resolution as low as 0.3 m in the panchromatic band marks a technical tipping point in dryland research[23] and allows us to produce a reliable, fine-scaled assessment of woody cover[24]. Although the short period for which these data have been available does not allow estimation of long-term trends, the high level of detail of such maps makes it possible to analyse how woody cover is spatially correlated with the above-mentioned causal factors, from which explanations for changes in woody cover over time can be inferred: if woody cover is threatened by the expansion of cultiva-

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tion, we would expect woody cover to be substantially lower in farmlands than in the adjacent uncultivated savannahs. If local harvesting of firewood is a cause of loss of woody cover, we would expect woody cover to be lowest close to settlements. Here we test these hypotheses in order to obtain a complete understanding of the distribution of woody cover in relation to human presence and thus provide a valuable reference for individual case studies that generate in-depth contextual knowledge but have a limited scope for generalization.

High-resolution woody cover mapping

The assessment of woody vegetation at hectare level requires high spatial resolution satellite data in order to highlight nuanced spatial differences (Supplementary Fig. 1). Here we derived canopy cover from multispectral DigitalGlobe QuickBird-2, GeoEye-1 and WorldView-2 satellite images at 1.7 m resolution without using the panchromatic band (Fig. 1, Supplementary Figs. 2,3) to train synthetic aperture radar (SAR) and normalized difference vegetation index (NDVI) imagery and predict continuous woody cover from 0 to 100% at 100 m resolution for the arid (150–300 mm rainfall), semi-arid (300–600 mm) and sub-humid (600–1,000 mm) zones of West Africa. The validation pixels are fairly in line with the prediction (mean absolute error (MAE) of 3.7, $r = 0.69$, slope = 0.84, $n = 661{,}708$; Supplementary Figs. 4,5), which also agrees well with independent in situ data (Fig. 1b,c). The woody cover maps shown in Fig. 2 reveal a broad scale pattern following the biogeographical regions but also a high level of detail showing differences at hectare scale. Woody cover is on average 3% in the arid zone, increases to 9% in the semi-arid, and exceeds 20% in the sub-humid zone (Fig. 2).

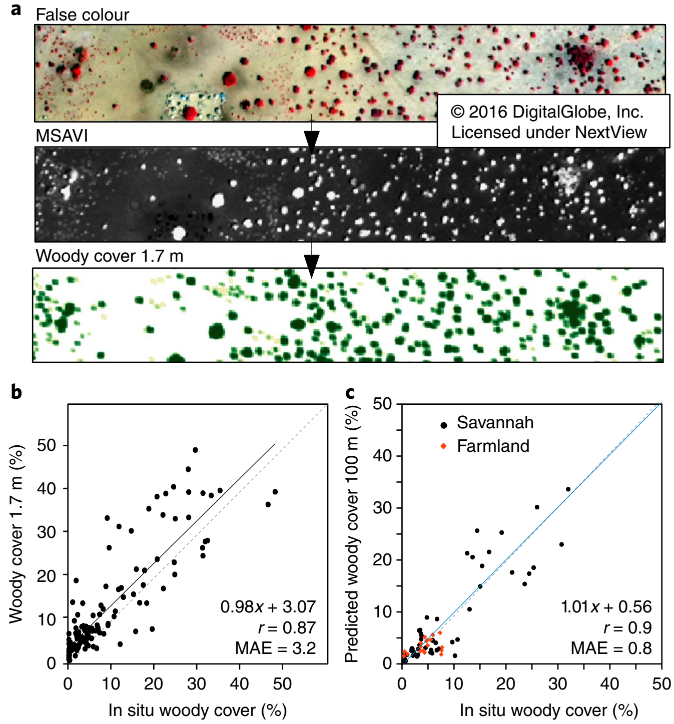

Fig. 1 | High-resolution woody cover mapping and validation with field data. a, Woody cover (colour scale) derived from MSAVI at 1.7 m resolution (Supplementary Figs. 2–5). **b**, The woody cover map at 1.7 m resolution was validated with in situ data from northern Senegal (MAE of 3.2, $r = 0.87$, slope = 0.98, $n = 144$). Woody cover >10% ($r = 0.76$); woody cover <10% ($r = 0.77$). **c**, The predicted woody cover map (100 m) was validated with independent in situ data from Senegal ($n = 24$), Mali ($n = 23$) and Niger ($n = 25$) (MAE = 0.8, $r = 0.9$, slope = 1.01) both for woody cover >10% ($r = 0.75$) and woody cover <10% ($r = 0.86$).

Determinants of woody vegetation cover

The coexistence of herbaceous and woody plants in savannahs is governed by rainfall regime (mediated by run-off and water table), soil, human management (including cutting, clearing for cropping, crop-fallow management, fire and grazing)[25]. These factors are interlinked and vary both spatially and temporally with available rainfall (Fig. 3a). Here we tested environmental variables in a decision tree ensemble model, which explained in total 67% of the predicted woody cover at 100 m resolution (Fig. 3b). Out of these, mean annual rainfall[26] is the major factor limiting woody cover (32%). It is followed by terrain (elevation, 23%) and human population density[27] is ranked third (13%), shortly before soil[28] (sand fraction, 12%) and inter-annual rainfall variability (12%). Distance to villages (6%) and fire frequency (2%) have a rather low relative weight. Taken together, climatic (44%) and edaphic (35%) factors are more important than management factors (21%) (Fig. 3b). Elevation here is used to represent the terrain morphology including dune structures, depressions, plateaux, valleys and so on. Already a moderate topography can have significant impact on rainfall run off/on and soil texture, explaining the high percentage explained by terrain. A land use and rainfall zone grouping is conducted to further explore the relationships between humans and woody cover and to rule out a bias by the rainfall gradient (Fig. 3c).

Rural management impacts on woody cover

We applied a new farmland mask at 100 m resolution[29] to separate the study area in uncultivated savannahs and farmland (Fig. 4a–c). For savannahs, there is a high positive correlation between woody cover and rainfall ($r = 0.75$, $P < 0.05$) with saturation around 30% canopy cover in the sub-humid zone, and with considerable spatial variations (Fig. 4b). The pattern is strikingly different for farmlands (Fig. 4c): although woody cover increases with increasing rainfall ($r = 0.45$, $P < 0.05$), the majority of the cultivated areas have a canopy cover exceeding 12%, independent of mean annual rainfall (> 300 mm), and variability is much lower than in savannahs (Fig. 4a–c). Average woody cover in arid and semi-arid Sahel is slightly higher and less variable in farmlands (arid: 3%, semi-arid: 11%) than in savannahs (arid: 2%, semi-arid: 8%). Sub-humid savannahs on average have a higher woody cover (33%) and wider range than woody cover in farmlands (21%) (Figs. 3c, 4a). More precisely, the median/mean of farmland woody cover is slightly higher as compared with savannahs below 680 mm annual rainfall but lower from 680 to 1,000 mm (Fig. 4a–c).

In the sub-humid zone, woody cover reaches high values primarily in rural areas with low population density, and decreases in urban areas with >100 persons km^{-2} (Fig. 4d). Interestingly, a different pattern is observed in the arid and semi-arid Sahel, where both woody cover and population density are increasing along the rainfall gradient up to 160 persons km^{-2}. Woody cover decreases at higher population densities in and around larger cities. On average, areas with a higher population density also have a higher woody cover than sparsely populated areas in the arid (7/2%) and semi-arid (12/10%) Sahel, but the opposite is observed in the sub-humid zone (31/21%) (Figs. 3c, 4a–c).

Woody cover in conservation areas is generally higher (29%) in comparison to surrounding areas (5 km) (21%) (Fig. 3c). This difference is most pronounced in the semi-arid Sahel (conservation 16%; conservation surroundings 11%) and sub-humid zone (conservation 34%; conservation surroundings 23%). Differences between farmland (typically occupying sandy soils) and savannahs (including vast areas of non-arable soils) become more comparable and exclude a bias by environmental pre-conditions when studying woody vegetation on sandy soils only[28]. Sandy soils used for cultivation have remarkably higher woody cover than comparable sandy soils that are uncultivated (Fig. 4e). Buffer zones were drawn around

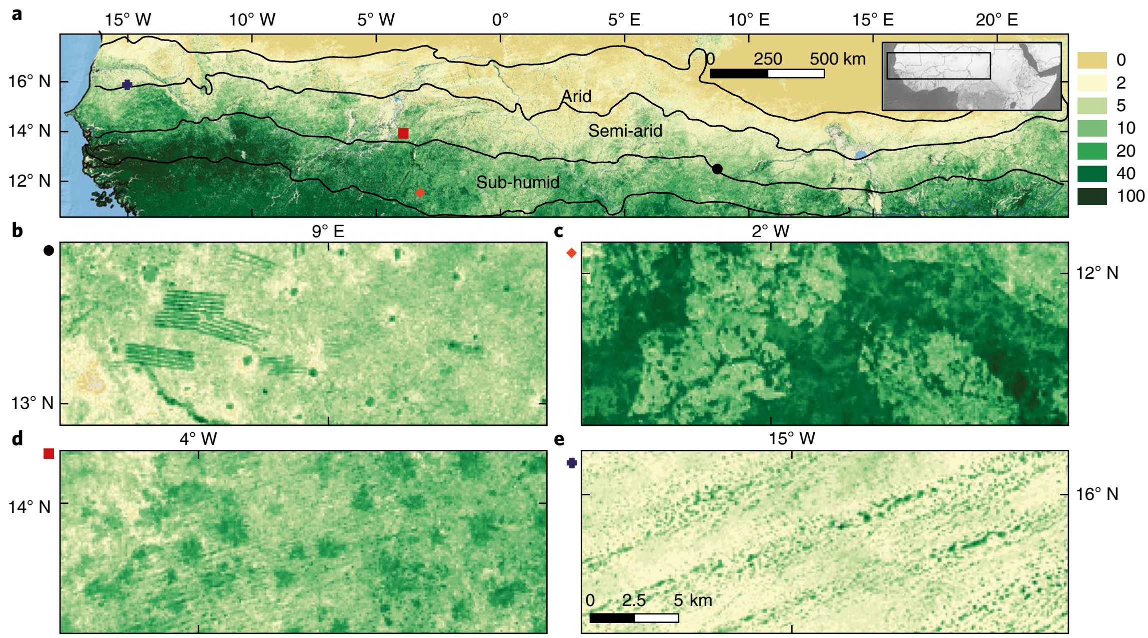

Fig. 2 | Predicting woody cover. a, Predicted woody cover at 100 m resolution with locations of the close-up views (**b**–**e**) indicated. **b**, Woody cover in farmlands at the semi-arid Nigeria/Niger border. The presence of trees within villages makes them stand out as green clusters. Woody corridors (shelterbelts) can be identified. **c**, Farmlands in sub-humid Burkina Faso are expanding into remnants of forest reserves. **d**, The villages in the Malian Seno Plain are surrounded by a well-managed woody vegetation. **e**, The sandy pastoral zone of arid Senegal has locally high concentrations of woody plants on fine-textured soils of inter-dunes.

37,294 villages on sandy soils (Supplementary Fig. 6). Shade trees are responsible for a high canopy cover in the village centres (~12%), and areas surrounding villages within a distance up to 1.5 km have a moderately high woody cover (7–9%) which decreases gradually further away (<5%).

Trees are reduced in woodlands but promoted in farmlands

The traditional assumption that human presence has an exclusively adverse impact on West Africa's woody vegetation has been challenged by local studies showing that human presence can also have positive impacts on tree cover[13], as in the case of agroforestry

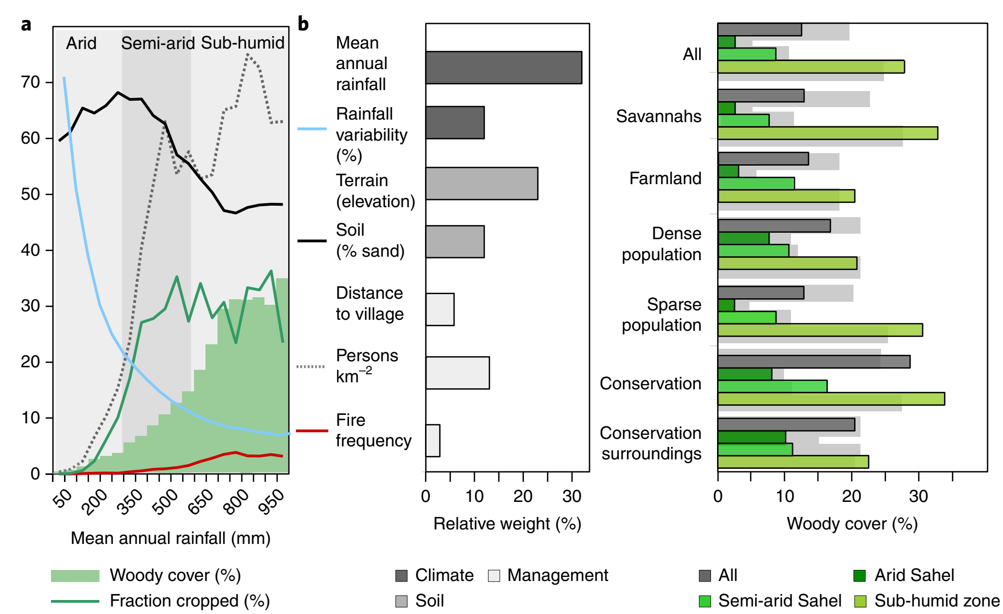

Fig. 3 | Determinants and patterns of woody cover. a, Factors potentially impacting woody cover are averaged along the rainfall gradient (50 mm steps). Fire frequency shows the number of fires (2000–2015). **b**, The relative weight of variables in a decision tree model explaining predicted woody cover (150–1,000 mm) with an overall explaining power of 67%. **c**, Woody cover averaged by groups: savannahs (n = 148,286,890), farmland (n = 43,374,091), areas of dense (>50 persons km^{-2}; n = 23,127,786) and sparse (<50 persons km^{-2}; n = 167,752,160) population densities, as well as conservation areas (n = 8,902,702) and their surroundings (5 km) (n = 6,040,825). Standard deviations (grey background bars) reflect the variability. Total pixels: 191,660,981.

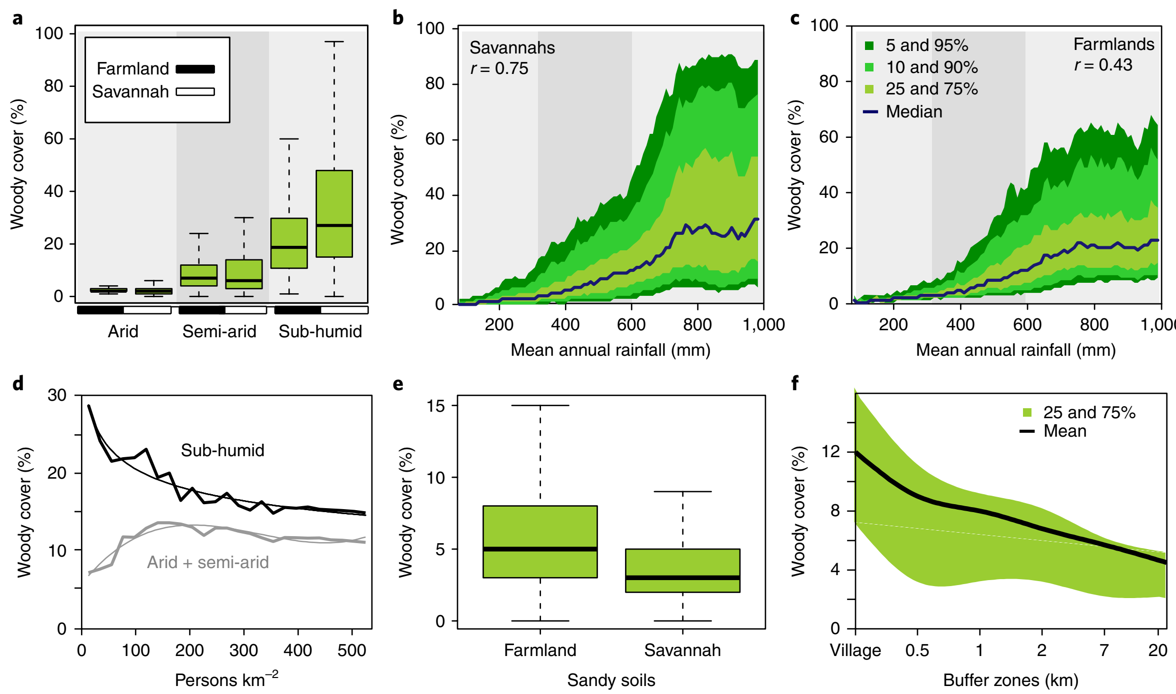

Fig. 4 | Land management impacts on woody cover. a, Spatial variations of woody cover grouped into farmland and savannah for each bioclimate zone. **b**,**c**, Median and quantiles of woody cover (a random sample of 1%; $n = 2,812,563$) are shown along the rainfall gradient (10 mm steps) for savannahs (**b**) and for farmlands (**c**). **d**, Woody cover is averaged within intervals of population density showing opposing patterns for arid/semi-arid (150–600 mm) and sub-humid (600–1,000 mm) zones. **e**, Comparison between woody cover on farmland and on savannahs, both on sandy soils only (entire region; $n = 73,848,805$). **f**, Woody cover as a function of distance to the village centre (entire region; average for 37,294 villages on sandy soils). In panels **a** and **e**, lines from top to bottom represent the maximum, third quartile, median, first quartile and minimum values.

systems encouraging and maintaining high tree densities[30]. Farmers' awareness of reforestation as a climate change adaptation measure has been shown[31], and farmer managed natural regeneration or tree planting programmes are common throughout West Africa. However, regional assessments of their success are rare, and our study shows that farmlands indeed support significant woody vegetation densities, supporting the results of ref. [32]. However, this is not the case in all landscapes and under all agricultural management regimes. The expansion of farmland leads to an initial reduction of woody vegetation, especially in higher rainfall zones with dense human population where savannah and woodland woody cover is dense[10]. If the rural population is dense, this expansion is ongoing, and forest reserves and savannahs-woodlands are being progressively reduced and converted into farmland with a considerably lower woody cover, and woodland vegetation remains only in protected areas. It has also been proposed that the recent increase in woody vegetation, which is a global phenomenon in semi-arid lands supposedly driven by climate and altered atmospheric CO_2 (refs [33,34]), often takes place in sparsely populated regions whereas high population growth decreases woody cover[35]. However, our current study shows that this is not always the case, and once savannahs and woodlands are transformed into farmland, management often aims at promoting and protecting valuable species (for example, *Faidherbia albida*, *Vitellaria paradoxa*) by clearing/coppicing other species which also favours the growth of a few tall trees. Additionally, shade trees in village areas (for example, *Azadirachta indica*) provide numerous ecosystem services that are more valuable for the local people[36] than those of typical savannah species (for example, *Combretum glutinosum*, *Guiera senegalensis*) and also contribute to carbon storage at landscape scales.

The results presented allow a robust generalization concerning woody cover and the relationships between woody cover and various explanatory factors. First of all, we describe rainfall as the main determinant of woody cover. We confirm increases in woody cover in arid and semi-arid Sahel with rainfall up to ~650–700 mm (ref. [37]). The median woody cover stabilizes in the sub-humid zone (650–1,000 mm) around 30% woody cover.

Secondly, and most importantly, we show that the role of climate is modified by humans. The way management affects woody cover relates to the amount of annual rainfall and livelihood strategy: the median woody cover in arid and semi-arid zones is equal and partially higher in farmlands than in savannahs up to an average annual rainfall of around 650 mm year^{-1}. In sub-humid zones, this difference is reversed, with median woody cover being lower in farmlands than in savannahs, indicating a pronounced human-induced reduction of woodland's woody cover. Unlike the rainfall driven gradient of woody cover found in savannahs, the woody cover in farmlands is spatially homogeneous (constant median, narrow range) across all rainfall zones. Local studies are likely to show considerable differences between countries and eco-regions, but on average the claim that cultivated areas in the arid and semi-arid Sahel have a relatively high woody cover is robust. Two possible explanations may be suggested: (1) farmers protect or plant trees due to a strong interest in the ecological services they provide[36]. Harvesting of wood for fuel and building material mostly takes place further away from the village areas in savannahs (thus accelerating the reduction of savannah's woody cover), and in fallows (which are here classified as farmland). (2) Farmland is generally located on the most suitable and fertile soils, whereas savannahs also include soil conditions less favourable for vegetation growth. Both explanations are likely to be concurrent, explaining our results of a high woody cover around villages and a reduced woody cover in neighbouring savannahs, both being largely impacted by human management. The generally higher woody cover in protected areas further indicates the exploitation of unprotected savannahs' wood resources by farmers and pastoralists, these numbers are however biased by the edaphic differences of conservation areas.

Thirdly, analysis of the effect of proximity to villages on woody cover discloses that woody cover is, on average, densest within village areas and decreases with distance. This is based on a great number of villages that are very different in size and structure and this distance–function may differ depending on village size, rainfall level, agricultural practices and ethnicity of the population. Yet, at the regional scale it is clearly demonstrated that the general idea that high local population pressure causes woody cover to decrease around villages does not always hold true. Rather, the alternative notion that farmers protect or plant trees in and around villages[13] is supported. The cause of a dense woody cover around villages is related to the above-mentioned finding that farmlands have a relatively high woody cover. Fields are often located close to villages, whereas more-distant savannahs are mainly exploited for fuelwood. Our results showing a positive relationship between population density and woody cover seem to support the 'more people, less erosion' argument[38] of environmental recovery and sustainability associated with agricultural intensification. However, this only holds true in semi-arid areas and only up to a certain threshold of population agglomeration, that is, at rural village level but not for larger urban settlements.

With an average canopy cover of 13 ± 17%, we found substantially higher values (including larger variations) than other studies and data sets (for example 1.9 ± 3% in MODIS continuous fields[20]). It has to be taken into consideration that our definition of canopy cover is more inclusive, because we include scattered woody vegetation, whereas the MODIS product is limited to forests with large trees. Studies based on these data sets[22] are thus unable to provide detailed assessments of patterns and determinants of dryland woody cover.

The data and methods we used do not allow us to move beyond 'woody cover', which is the simple projected coverage of canopies. For many research applications additional variables would be of interest. From a botanical and ecological perspective, information on species would be desirable; from a climate change point of view, carbon stocks and transpiration may be in focus; foresters may require woody volume and quality; and from a pastoralist's perspective, the annual production of green foliage of fodder species is most important. Finally, from a socio-economic perspective, we would profit from estimating the amount of trees available for each person. Additional work, more fully exploiting very high resolution imagery (for example, mapping height and canopy size of individual trees), is likely to bring us further in these directions. This study was, however, able to demonstrate the potential of West African farmland and savannahs to provide a range of ecosystem services. Moreover, the wall-to-wall coverage and the high number of pixels in our analysis provide a solid basis for understanding woody cover in different landscapes at the regional West Africa drylands scale and this can be applied to other dryland regions globally. Case studies will still remain extremely valuable as a means of obtaining insights into the complex processes linking environmental factors and land management decisions to woody cover across the variety of local circumstances. By combining wall-to-wall analysis with process studies at local scale, a more robust basis for developing environmental policies may be established.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41561-018-0092-x.

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Author contributions
M.B., R.F., S.H., P.H. and K.R. designed the study. M.B., X.T. and F.T. conducted the analyses with support by L.K., O.M., K.R., R.F., S.H., M.D. and P.H. The data were provided by C.T., J.D., K.M., M.D., L.K., C.V. and P.H.; K.R. and M.B. drafted the manuscript with contributions by all authors.

Competing interests
The authors declare no competing interests.

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Methods

We define woody cover as the percentage of ground surface covered by the vertical projection of woody plant crowns. The technical framework of this study adapts local-scale approaches of modelling dryland woody cover[39,40] into reproducible regional/global scale assessments, as the unprecedented amount of very high spatial resolution (VHR) satellite images now available via the NextView license across the region allows for a new level of detail and larger geographic coverage. Most of the 2,006 available images are from November/December (2008–2015) when most of the evergreen and deciduous woody species have green leaves, whereas the herbaceous vegetation is senescent. If no images from these months were available, the period was extended to February. The modified soil-adjusted vegetation index (MSAVI) was calculated with a spatial resolution of 1.7 m, and woody cover was extracted by using a texture based feature extraction method. Field measurements (2000–2015) of woody cover at selected sites served as an independent validation of the remote sensing mapping approach. To achieve a woody cover map of the entire area, the spatially detailed woody cover data derived from VHR images were used to train a gradient boost decision tree regressor to predict woody cover from PROBA-V NDVI and PALSAR images at high resolution (100 m). For PROBA-V NDVI, we tested several filtering approaches and seasonal metrics derived with various methods[41,42] and decided to apply a moving median window for filtering the time series and filtered 10-day composites as input variables for the regressor to keep the process reproducible. A farmland map[29], satellite-based rainfall estimates[26] (CHIRPS), fire (MCD45A1) and population data[27] (Worldpop) were used for analysis of woody cover patterns in relation to climate and land management determinants (Supplementary Fig. 7).

Rainfall zones of the study area. We used rainfall isohyets derived from CHIRPS[26] mean annual rainfall (1981–2016) to divide the study area in arid Sahel (150–300 mm), semi-arid Sahel (300–600 mm) and sub-humid lands (600–1,000 mm) (Supplementary Fig. 8a). The zones correspond well with expected bioclimatic zones with different woody species[43]. Whereas *Acacia* ssp. and Capparidaceae are dominant in the arid and semi-arid, it is Combretaceae and Fabaceae in more sub-humid parts. In general, woody cover changes from sparsely scattered in the arid areas to closed canopies in the open woodland and riverine forest of the sub-humid zones.

Field data. Field data were available from extensive field work in the Ferlo in Senegal (144 sites surveyed in 2015), from the CSE (Centre de Suivi Ecologique) campaigns in Senegal (24 sites surveyed between 2000 and 2015 every other year)[18], from the Gourma region in Mali (23 sites)[44] and the Fakara in Niger (25 sites)[45]. All surveys measure the projected canopy cover[44] over plots of various areas (50 m to 1 km), and the data were recalculated in m^2 per ha and percentage canopy cover.

Extraction of canopy cover from very high spatial resolution data. The mapping technique was designed to be robust to the use of different sensor types, acquisition dates (that is, different leaf density), atmospheric conditions, as well as being applicable to various situations ranging from sparse shrub population in arid zones to closed canopy cover woodland in the sub-humid zone. The robustness was assessed by independent field data (Fig. 1b) and is demonstrated in Supplementary Fig. 5. DigitalGlobe QuickBird-2, GeoEye-1 and WorldView-2 were orthorectified and the scenes were screened for clouds and other disturbances. All selected multispectral images were resampled (nearest neighbour) to 1.7 m resolution matching GeoEye-1. MSAVI was calculated and rescaled from 0 to 100 (ref. [46]) to produce a quantitative base for estimation of canopy cover. Only if a pixel is fully covered with a green leaved canopy, the MSAVI will reach higher values, partly covered pixels (for example, parts of the crown area or small size shrubs and bushes) have relatively lower values. Visual screening of numerous images showed that most woody plants have MSAVI values above 50, which was robust across all rainfall zones and image acquisition dates. A texture-based Haralick feature extraction (eight bins) was then run considering all pixels with values between 50 and 100 (ref. [47]). The advanced texture filter can be parameterized to extract objects (in our case crown canopies) from their surroundings and from larger objects. The feature termed 'mean' was used—the objects have greyscale values depending on their distinctiveness—which was rescaled between 0 and 100, resulting in a quantitative estimate of the areas covered by canopies. Each image was visually screened and images dominated by obvious mis-estimations (strong under- or overestimation) were discarded. The final values represent the sub-pixel woody coverage, with 100 being fully covered and 0 free of any green leaved woody vegetation. The advantage of this weighted method over a binary tree/no tree classification is that a sub-pixel coverage (that is, small crowns and edge pixels) receives a lower weight, thus preventing overestimation (Supplementary Figs. 3,5). Moreover, using such weighting emphasizes larger canopies, which makes the product more robust against a rapidly changing (fire, field clearing and so on) bush layer, which receives a lower weight. Burned areas were manually clipped to keep only high-quality training images. In total, 219 images were used for the model (about 1% of the study area). The accuracy of the method was calibrated and tested with field data (144 plots) from Senegal. The square field plots are small (50 × 50 m) and include canopies of all size classes thereby being well suited to validate the VHR product. For the accuracy assessment, canopy cover surveyed for each field plot was compared with VHR imagery derived canopy cover averaged for polygons marking exactly the surveyed area.

Prediction of canopy cover at 100 m resolution. Advanced Land Observing Satellite (ALOS), Phased Arrayed L-band Synthetic Aperture Radar (PALSAR)[48] and PROBA-V NDVI[49] were used for a large scale assessment of woody vegetation (wall-to-wall coverage of West African drylands). For PALSAR, we used 100 m cross-polarized HV mosaics converted to gamma-naught values and averaged from 2009 and 2010 over the study area[48]. For PROBA-V, daily atmospherically corrected images at 100 m resolution were combined into 10-day maximum value composites to achieve full coverage in the lower latitudes, which are more frequently affected by cloud cover. Images are available from 2014 to 2016 and the maximum value for each 10-day composite over the three years was selected to avoid low values which can be caused by clouds and burned areas. To further filter out noise, a 30 day running median window was applied, choosing the median value of three images. This procedure does not only filter out low-value spikes caused by clouds, but also high-value spikes that can be caused by herbaceous vegetation (also dry season rainfall events can lead to a flush of herbaceous plants). Both possibilities potentially introduce noise in our analysis dedicated to woody vegetation and this filter is a simple way of reducing noise but keeping the original seasonality.

The woody cover derived from the VHR imagery was used to train the PALSAR and 36 (10-day frequency) PROBA-V NDVI images to obtain a regional-scale woody cover map at 100 m resolution. First, the canopy cover images at 1.7 m resolution were aggregated to 100 m by summing all values (respresenting sub-pixel canopy coverage), multiplying each pixel with the original pixel size (1.7 × 1.7 m) and dividing it by 100 so the derived map shows the projected area within the pixel covered by woody plants with the unit per cent woody cover. The data set was then split into training and validation sets by randomly dividing all pixels in two groups, each including 50% of the original pixels. A large number of pixels ($n = 1,323,416$) were available for training and for validation. The training set was then used to fit a non-parametric gradient boost regressor (GBR), which produces a prediction model by means of an ensemble of boosted decision trees[50]. The input data were the PALSAR and 36 filtered 10-day NDVI composites covering an entire year. The quality of the model was assessed by comparing the independent validation set with the predicted woody cover. Predicted values above 100 were masked out and below 0 set to 0. Due to the large amount of training and validation pixels and their spread and representation of different landscapes, over-fitting is not a concern and the model output is expected to be robust. It should be noted that the woody cover is predicted continuously from 0 to 100 (but rounded to 1% steps), leading to a lower statistical fit than similar approaches binning canopy cover into classes of, for example, 10% intervals.

Even though all woody plants have a distinctively different phenological behaviour than herbaceous annuals, six different forms of evergreen and deciduous leaf phenologies exist, ranging from short deciduous plants shedding their leaves early in the dry season to evergreen species keeping their leaves throughout the year[51]. To avoid an underestimation of the crown cover of stands dominated by deciduous species, the median NDVI ratio between November (a period when all trees have leaves) and February–March (when most deciduous species are without leaves or have very few) was calculated. Field data from Senegal on species composition (ratio deciduous/evergreen per site) were compared with the NDVI ratio for corresponding sites (Supplementary Fig. 4b). The output of the GBR prediction was then multiplied with this ratio, enhancing the predicted cover of stands with deciduous species but keeping evergreen stands unchanged. The impact of fire is mitigated by the multi-year maximum and median value over several images. Finally, wetlands and irrigated areas were masked out by combining GlobeLand30[52] and ESA LC CCI (2010) land cover maps (https://www.esa-landcover-cci.org/). An independent accuracy assessment was conducted with field data from Senegal, Mali and Niger. These data are based on circular plots along 1 km transect lines (representing larger areas of homogeneous landscapes), spaced at 200 m intervals. The canopy cover of all woody plants was surveyed for these plots and averaged for each transect[51]. Polygons (3 × 3 km) covering the field sites were drawn and model-estimated woody cover extracted and averaged for each site giving valuable information on the overall fit of the predicted canopy cover.

Environmental data. Several data sets were used to analyse the relationship between woody cover, rainfall and management. CHIRPS rainfall was summed from 1981 to 2016 for each year and an average annual climatology was calculated (Supplementary Fig. 8a). The original CHIRPS resolution of 5 km was resampled (bilinear interpolation) to match the 100 m resolution of PROBA-V. A recently developed farmland map was used[29], which reflects the area under agriculture around 2014 (Supplementary Fig. 8b). The original resolution of the farmland map was 100 m and villages areas are masked out. Conservation areas were derived from the World Database on Protected Areas[53]. It includes national parks and protected forests of which most were established during colonial time by the administration in charge of forest and wild life. The conservation areas are found predominantly in low-populated regions characterized by poor soil fertility, but population growth and expansion of farmlands has often encroached into these areas. They are however edaphically different and the shrubland woody cover is therefore usually higher than in neighbouring savannahs and farmlands. Woody cover in the conservation areas was compared with woody cover in adjacent areas (within 5 km buffer around conservation area boundaries). We used WorldPop for the year 2010[27] as human population data set. The resolution of 1 km was resampled (bilinear interpolation) to 100 m for this study.

To improve the comparability between farmlands and savannahs, we used the newly developed African soil map at 250 m resolution[28] to extract sandy soils (from rock outcrops, shallow soils with dense shrubland, clayey valleys and so on) (Supplementary Fig. 8c). We used the soil texture fraction to calculate a mask leaving only areas with >70% sand in the depth 0–1 m.

To test the impact of rural population on woody vegetation, all settlements with a size smaller than 5 km^2 were extracted from the GlobeLand30 data set[52], resulting in 37,294 villages. The original resolution of 30 m was resampled to 100 m. We established buffer zones with 0.5, 1, 2, 5 and 20 km distance to the village areas (Supplementary Fig. 6).

A gradient boost classifier[50] was applied to test the determinants of predicted woody cover. Explanatory variables of this model based on an ensemble of decision trees were (1) mean annual rainfall, (2) fire frequency deriving the number of fires between 2000 and 2015 from MODIS burned area product MCD45A1 (Supplementary Fig. 8d), (3) rainfall variability (the coefficient of variation of annual sums between 1981 and 2016), (4) the sand fraction from the soil map, (5) the elevation derived from SRTM digital elevation model (90 m), (6) human population[27], and (7) distance from the villages (buffer zones). Predicted woody cover was grouped in classes (0–3%, 3–10%, 10–20% and >20%) to meet the requirements of the classifier and a random sample of 1% of the pixels was chosen (n = 2,812,563), which was used as response variable. The model was run with 10 different random sets of pixels to ensure that no bias emerges by the selection. Due to the decision tree structure of the model, correlations between the explanatory variables can be neglected. The accuracy of the model is calculated by setting aside 60% of the pixels, which are then used to test the predicted results.

Data availability. Commercial very-high-resolution satellite images were acquired within the NextView license program. The copyright remains at DigitalGlobe and a redistribution is not possible. PROBA-V NDVI data are freely available at VITO (http://proba-v.vgt.vito.be/). WorldPop population data are freely available from the University of Southhampton (http://www.worldpop.org.uk/). MODIS MCD45A1 burned area product can be freely obtained at http://modis-fire.umd.edu/pages/news.php. The soil map is freely available at ISRIC (http://www.isric.org/projects/soil-property-maps-africa-250-m-resolution). CHIRPS rainfall data are freely available at the Climate Hazard Group (http://chg.geog.ucsb.edu/data/chirps/). PALSAR mosaics are freely available from JAXA (http://www.eorc.jaxa.jp/ALOS/en/palsar_fnf/fnf_index.htm). The farmland mask is available from Marie-Julie Lambert upon request. The woody cover map at 100 m resolution is available from the corresponding author upon request.

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