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Monitoring Agricultural Expansion in Burkina Faso over 14 Years with 30 m Resolution Time Series: The Role of Population Growth and Implications for the Environment

Kim Knauer [1,2,*], Ursula Gessner [1], Rasmus Fensholt [3], Gerald Forkuor [4] and Claudia Kuenzer [1]

1. German Remote Sensing Data Center (DFD), German Aerospace Center (DLR), 82234 Wessling, Germany; ursula.gessner@dlr.de (U.G.); claudia.kuenzer@dlr.de (C.K.)
2. Department of Remote Sensing, University of Wuerzburg, 97074 Wuerzburg, Germany
3. Department of Geosciences and Natural Resource Management, University of Copenhagen, 1350 Copenhagen, Denmark; rf@ign.ku.dk
4. West African Science Service Center on Climate Change and Adapted Land Use (WASCAL), P.O. Box 9507, Ouagadougou 06, Burkina Faso; forkuor.g@wascal.org

* Correspondence: kimknauer85@gmail.com

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Abstract: Burkina Faso ranges amongst the fastest growing countries in the world with an annual population growth rate of more than three percent. This trend has consequences for food security since agricultural productivity is still on a comparatively low level in Burkina Faso. In order to compensate for the low productivity, the agricultural areas are expanding quickly. The mapping and monitoring of this expansion is difficult, even on the basis of remote sensing imagery, since the extensive farming practices and frequent cloud coverage in the area make the delineation of cultivated land from other land cover and land use types a challenging task. However, as the rapidly increasing population could have considerable effects on the natural resources and on the regional development of the country, methods for improved mapping of LULCC (land use and land cover change) are needed. For this study, we applied the newly developed ESTARFM (Enhanced Spatial and Temporal Adaptive Reflectance Fusion Model) framework to generate high temporal (8-day) and high spatial (30 m) resolution NDVI time series for all of Burkina Faso for the years 2001, 2007, and 2014. For this purpose, more than 500 Landsat scenes and 3000 MODIS scenes were processed with this automated framework. The generated ESTARFM NDVI time series enabled extraction of per-pixel phenological features that all together served as input for the delineation of agricultural areas via random forest classification at 30 m spatial resolution for entire Burkina Faso and the three years. For training and validation, a randomly sampled reference dataset was generated from Google Earth images and based on expert knowledge. The overall accuracies of 92% (2001), 91% (2007), and 91% (2014) indicate the well-functioning of the applied methodology. The results show an expansion of agricultural area of 91% between 2001 and 2014 to a total of 116,900 km^2. While rainfed agricultural areas account for the major part of this trend, irrigated areas and plantations also increased considerably, primarily promoted by specific development projects. This expansion goes in line with the rapid population growth in most provinces of Burkina Faso where land was still available for an expansion of agricultural area. The analysis of agricultural encroachment into protected areas and their surroundings highlights the increased human pressure on these areas and the challenges of environmental protection for the future.

Keywords: Africa; agriculture; Burkina Faso; data fusion; ESTARFM framework; irrigation; land surface phenology; Landsat; MODIS; plantation; protected areas; TIMESAT

1. Introduction

Over the last decades, Burkina Faso has undergone considerable changes. Since the year 2000, the population grew by about 56% from 11.6 million to 18.1 million people in 2015 [1]. Burkina Faso still ranks among the least developed countries in the world (Human Development Index, HDR = 0.402, rank 183 of 188 countries, [2]), even though the gross domestic product (GDP) exhibited a sustained growth during recent years with a plus of 6.7% in 2013 [3,4]. Since the economy is relatively undiversified and relies heavily on rainfed agricultural production, the country is highly vulnerable to climatic and economic shocks such as droughts, international market price fluctuations or political instability [4,5]. Thus, poverty, especially in rural areas, still prevails, and with a rapidly growing population also the number of undernourished people increased in recent years [4]. Despite the fact that the country is said to have a high agricultural potential [6,7] and more than 90% of the country's labor force is working in the agricultural sector, the crop productivity per hectare did not rise considerably during the last 50 years [1]. Thus in order to improve the situation in Burkina Faso, amongst others agricultural systems food security must be further developed.

Agriculture in Burkina Faso is characterized by small-scale rainfed subsistence farming with average farm sizes of less than 5 ha [8]. The lack of own capital and access to credits results in extensive farming as characterized by a low level of agricultural inputs, mechanization, fertilizer application, as well as irrigation [4,5]. With a rapidly increasing population and little improvement in agricultural productivity, farmers compensate by expanding cultivated area. As a consequence, it is estimated that the country will reach its limits of arable land by the year 2030 [5]. Furthermore, this expansion also threatens natural resources, and the pressure on the last remnants of natural vegetation is increasing [9]. In order to capture the whole anthropogenic need of space for agricultural production, (rainfed) agricultural area is defined here as farmed land with partial tree cover (<10%, potentially fruit trees) including the prevailing crop-fallow rotation system of annual crops and intensive pasture, i.e., shrub-free, partially fenced areas frequently used for grazing.

Even though accurate spatial documentation of the past and current extent of agricultural areas is essential information for decision makers, such information is currently missing. For Burkina Faso, statistical data on cropped area exist which are derived from household surveys conducted by the National Ministry of Agriculture, Water and Fishery Resources but these are of varying quality and only available at province level [10]. Agricultural extent can be deduced from global land cover maps such as the 500 m MODIS (Moderate Resolution Imaging Spectroradiometer) product MCD12Q1 [11], the 300 m ESA CCI (European Space Agency, Climate Change Initiative) land cover product [12] or the Chinese 30 m products FROM-GLC (Finer Resolution Observation and Monitoring of Global Land Cover) and GLOBELAND30 [13,14]. However, the usability of this data is often limited for detailed regional scale applications due to low spatial resolution, missing thematic complexity, temporal availability or regional accuracy [15–17]. Regionally optimized land cover information for West Africa based on moderate resolution (250 m) remote sensing data [15] give a good overview of the distribution of agriculture in Burkina Faso. Nonetheless, they face difficulties in the discrimination of small-scale agriculture from natural vegetation classes and are so far not available for recent years. Lambert et al. [18] derived croplands from 100 m PROBA-V data for the Sudanian and Sahelian region of West Africa for the year 2014. This interesting approach however is also struggling with some spatial resolution based errors in heterogeneous areas. Furthermore, high to medium resolution (5–30 m) remote sensing based land cover maps exist which are regionally optimized but they only cover small parts of the country [9,19–21].

In general, remote sensing is a highly suitable tool for large scale and cost efficient mapping of agricultural area. However, remote sensing based monitoring of the spatio-temporal development of agriculture in Burkina Faso and Africa in general is a challenging task. The above described small-scale extensive farming systems require high temporal and spatial resolution data for an accurate delineation. Landsat data may have a sufficient spatial resolution (30 m) to capture single fields but due to frequent cloud cover [22] and limited data availability for West Africa during the past decades

(Landsat-5 and Landsat-7), gap-free coverage of the country is mainly limited to the dry season when the agricultural area is difficult to delineate from other natural land cover types. Because of its high temporal resolution and its globally uniform acquisition scheme, the MODIS sensors deliver data more continuously but the spatial resolution of 250 m or less is not satisfactory to delimit small-scale agricultural areas [23]. Thus, in this study, a data fusion approach was chosen to combine the strengths of the two sensor systems (MODIS and Landsat) and to generate a high temporal (8-day) and high spatial (30 m) resolution time series for a better delineation of agricultural area in Burkina Faso. For this purpose, the ESTARFM (Enhanced Spatial and Temporal Adaptive Reflectance Fusion Model) framework for large- and cloud-prone area processing was employed [24,25].

The goals of this study are to derive high spatial (30 m) resolution information of agricultural area for entire Burkina Faso for the years 2001, 2007, and 2014. Based on these maps, the spatio-temporal development of the major food-producing land use types (rainfed agricultural area, irrigated agricultural area and plantations) is identified. Furthermore, the connection between agricultural expansion and population growth and the regional differences within Burkina Faso are outlined. Finally, the influence of agricultural expansion on natural reserves with different protection status is examined with a buffer analysis for selected protected areas and their surroundings.

2. Study Area

Burkina Faso is a landlocked country in the center of West Africa with a size of approx. 274,000 km^2 (Figure 1). The climate is characterized by a North-South moisture gradient and mainly influenced by the interaction between the West African Monsoon bringing rainfalls from the Southwest during the rainy season and the Harmattan blowing hot winds from the North during the dry season. The annual rainfall ranges from less than 300 mm in the North to more than 1100 mm in the South with distinct rainy and dry seasons. The rainy season occurs between May and October for four to five months with shorter duration in the North [26,27]. The mean monthly temperatures range between 23 °C and 34 °C in the North and 25–31 °C in the South [28].

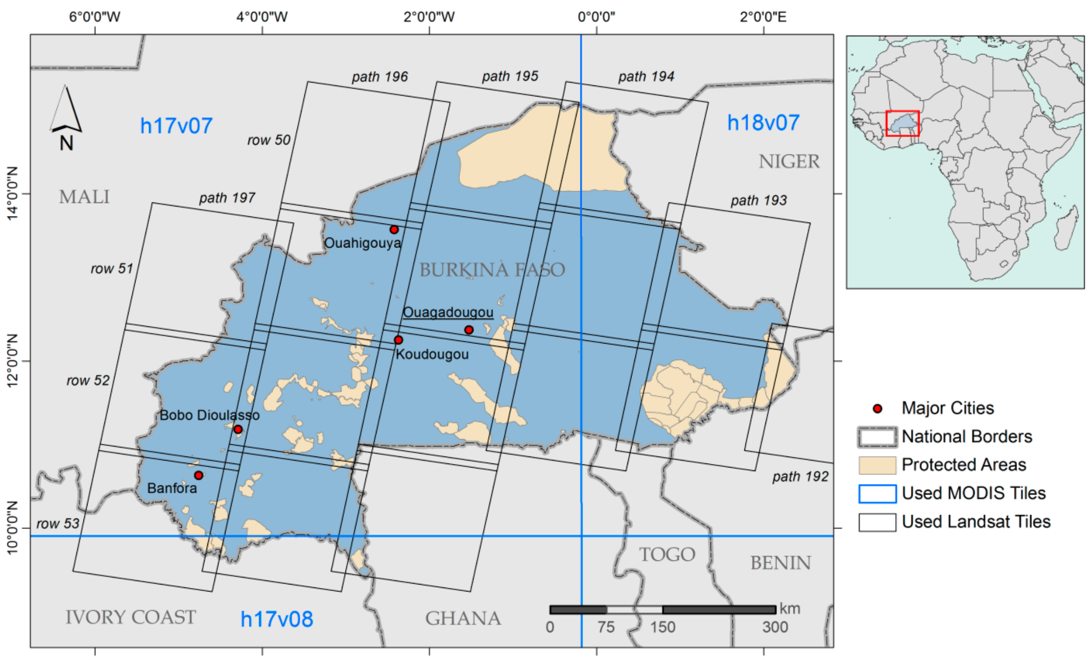

Figure 1. Study area of Burkina Faso showing the position of the used Landsat and MODIS tiles.

The northern part of Burkina Faso is located in the Sahel zone or Sahelian Acacia Savanna. The natural vegetation of this area predominantly consists of wooded grassland and deciduous shrubland with a sparse tree layer [29]. The southern part of the country is located in the West Sudanian savanna; its natural vegetation is characterized by a more dense deciduous shrubland and woodland and is known for its high agricultural potential [7,30,31].

The major staple crops in Burkina Faso are maize, millet and sorghum while cotton is the most important agricultural export commodity [1,4]. Some irrigated areas of minor extent can be found mainly in the direct vicinity of dammed lakes. In the southwest of Burkina Faso, especially around the city of Banfora, plantations of fruit trees such as mango and citrus fruits as well as nut trees (e.g., cashew and shea nuts) are located [32,33]. In recent years, these plantation products experienced a considerable rise in production and export value (compare Section 4.1.1) [34].

The overall number of inhabitants in Burkina Faso has increased significantly during recent years, from about 12 million in 2001 to more than 17 million people in 2014 [1]. The rural population, which predominantly works in the agricultural sector, is concentrated in the central provinces around the capital of Ouagadougou (Figure 2). Since 2001, the rural population increased in most parts of the country, even in the remote, northern provinces bordering the Sahara [35].

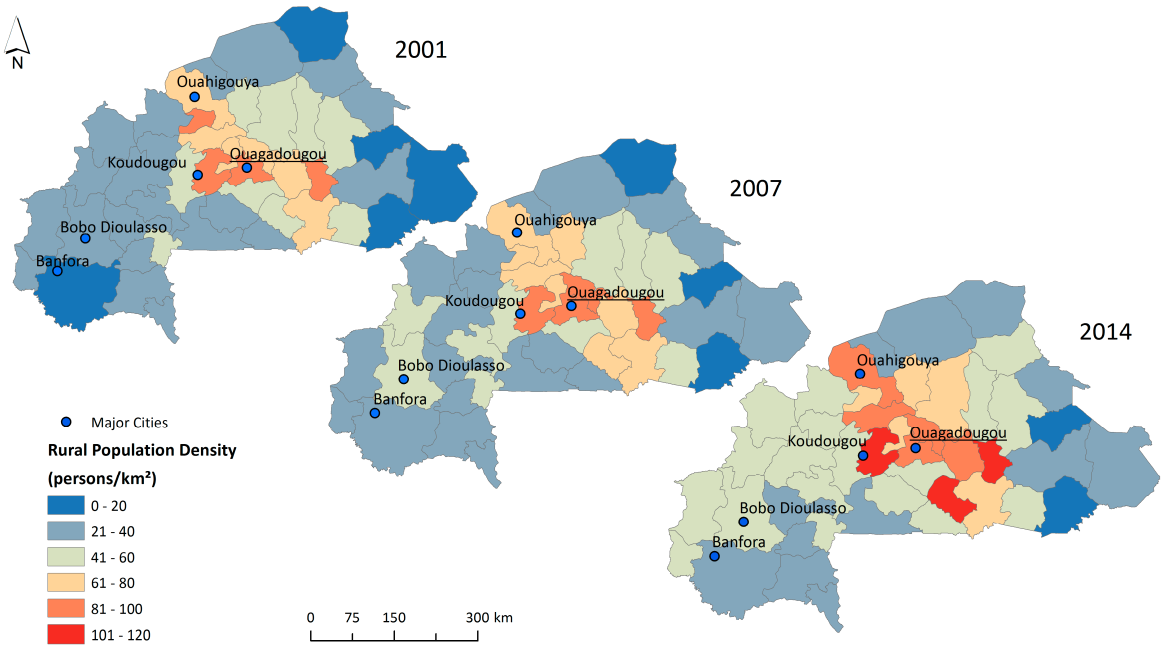

Figure 2. Development of rural population density in the provinces of Burkina Faso between 2001 and 2014 [35].

3. Materials and Methods

3.1. Landsat Data and Preprocessing

A total number of 504 surface reflectance scenes from Landsat sensors 5, 7, and 8 were obtained for a total of 17 tiles (Figure 1) from the USGS Landsat Archive [36]. The data covers the periods December 2000–January 2002 (Landsat-7), December 2006–October 2007 (Landsat-5) and December 2013–January 2015 (Landsat-8). For the year 2007, no Landsat-5 data were available after October and generally no images were available in 2007 for the two southwestern tiles (path/row: 193/52, 192/52). The surface reflectance datasets are atmospherically corrected with the L8SR algorithm [37] and include cloud and cloud shadow masks derived with the CFmask algorithm [37,38]. These masks were applied to the red and near infrared (NIR) bands of the scenes and from these, the NDVI was calculated.

3.2. MODIS Data and Preprocessing

Daily 500 m MODIS nadir bidirectional reflectance distribution function (BRDF) adjusted reflectance datasets (MCD43A4, Col. 6) were obtained for the tiles h17v07, h17v08, and h18v07 (Figure 1), and for the same periods as the Landsat data. MCD43A4 is a 16-day rolling composite product with the center date of this period associated to the daily dataset [39]. On the basis of the data in this compositing period, the best possible BRDF is derived for the correction of the reflectances [24,39].

From the red and NIR bands of the MODIS datasets, daily NDVI was calculated and further processed with the software TIMESAT [40]. First, outliers that deviate more than 0.2 times from the standard deviation in a moving window (width = 104 days) were removed from the time series [40]. For the interpolation of the resulting gaps and in order to reduce residual noise, the adaptive Savitzky-Golay filter [41] implemented in TIMESAT was then applied to the time series. For this purpose, a filter window size of 30 days and an adaptation strength of 2 were selected. The values of the filter as well as the factor of 0.2 for outlier removal were determined based on a visual analysis of their effects in the TIMESAT graphical user interface [40]. Detailed information on the time series filtering can be found in [40].

After filtering, the MODIS datasets were reprojected to UTM zone 30°N, automatically co-registered and resampled to Landsat 30 m spatial resolution with nearest neighbor method (Figure 3).

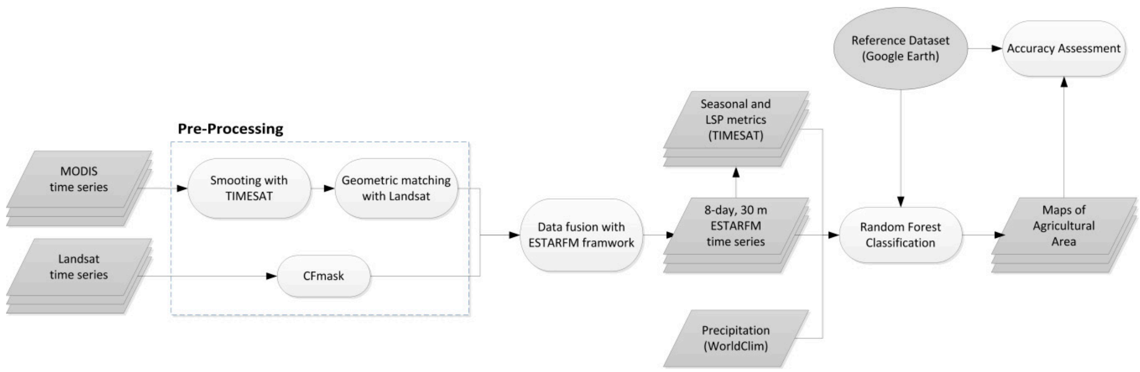

Figure 3. Workflow of pre-processing, data fusion, and classification for the generation of maps of agricultural area for entire Burkina Faso.

3.3. Reference Data Collection

In order to generate an accurate remote sensing based land cover and land use (LULC) classification a high quality reference database for training and validation of the classifier is required. However, such a database is not readily available for entire Burkina Faso. From several field trips within the scope of the WASCAL (West African Science Service Center on Climate Change and Adapted Land Use) [42] project during recent years, a range of LULC ground sampling points are available. Nonetheless, these do not cover the whole country and are not available for all focus years. However, the field data and the gathered field trip knowledge were used for the interpretation of very high resolution (VHR) imagery as provided by Google Earth. In this way, a comprehensive reference dataset for training and validation was generated. Such an approach was conducted previously by various authors for large-scale remote sensing based studies [15,43,44].

Samples were selected for eight general thematic LULC classes with a focus on agriculture. These classes were defined based on existing regional LULC descriptions [45] and expert knowledge of the region (Table 1). A *Simple Random Sampling* set [46,47] of 700 locations was generated in order to ensure an unbiased distribution of reference points across the study area. As suggested by Congalton and Green [47], at least 100 samples were collected for phenologically heterogeneous classes (e.g., rainfed agricultural area) and a minimum of 50 samples were assembled for temporally stable classes (e.g., water). In Google Earth, the closest spatially homogeneous area (of at least nine Landsat pixels) to the respective random point was delineated by a polygon and the class was identified for each of the three focus years (2001, 2007, 2014) with available Google Earth data for interpretation. Even though an unbiased distribution of ground truth data is important for an accurate classification, the *Simple Random Sampling* results in a low number of samples for less frequent LULC classes. Thus, additional reference data was collected for these classes to fulfill the above-mentioned minimum number of samples by directly targeting known areas of the respective class. The final reference dataset for training and validation contained 771, 836, and 1147 polygons for the years 2001, 2007, and 2014, respectively.

Table 1. Classification scheme.

ID	Class Name	Description
1	Rainfed Agricultural Area	Farmed land with partial tree cover (<10%, potentially fruit trees) including annual crops, fallow and intensive pasture
2	Irrigated Agricultural Area	Croplands irrigated from water bodies (potentially 2 seasons)
3	Grassland	Herbaceous vegetation with less than 10% woody vegetation
4	Woody Vegetation (deciduous)	Areas with deciduous woody vegetation coverage of at least 10%
5	Plantation (evergreen)	Areas of evergreen broadleaved tree crops (mostly fruit & nut trees)
6	Water Bodies	Areas permanently covered with water
7	Temporarily Flooded	Temporarily flooded herbaceous or woody vegetation
8	Forest (evergreen)	Areas of dense evergreen broadleaved trees

3.4. Generation of High Spatial and Temporal Resolution Time Series and Classification Features

The ESTARFM framework was designed by Knauer et al. [24] as a further development to ESTARFM [25] in order to generate high temporal and spatial resolution time series in an automated and time-efficient way for large-scale, cloud-prone and heterogeneous areas. For this purpose, a filling of cloud-gaps prior to the time series generation was included to make best use of partly cloud-covered Landsat input images. Further enhancements of the original ESTARFM method focus on the user-friendly, consistent, and accurate application of the algorithm for large areas.

In this study, the ESTARFM framework was applied to generate 30 m, 8-day NDVI time series from the MODIS and Landsat input data for the years 2001, 2007, and 2014 for entire Burkina Faso based on the procedure generally described in Knauer et al. [24]. On the basis of these time series, a number of temporal features such as land surface phenology (LSP) metrics of the different LULC types of Burkina Faso can be delineated (compare Figure 3). This is valuable information for the discrimination of classes which are spectrally similar but show a different phenological development, e.g., agricultural area, grassland, and savanna. As previous studies in the same latitudes of West Africa have shown, the differentiation of such classes is highly challenging when using only mono-temporal remote sensing data [18,19,48].

In total, 57 features were generated for the classification of 2001 and 2014 (Table 2). For the classification of the year 2007, only 41 features were used since not the whole annual time series could be generated due to a lack of Landsat input data towards the end of the year. The NDVI of all available 8-day time steps was used as classification features (45 layers for 2001 and 2014 and 33 layers for 2007). In addition, eight phenological metrics for 2001 and 2014 (four for the year 2007) were derived with the TIMESAT software [40]. Furthermore, the mean NDVI, the maximum NDVI as well as a seasonal sum of NDVI (DOY 119-263) were calculated for each of the three annual time series. An additional 1 km WorldClim precipitation dataset [28] of annual long-term average rainfalls (1960–1990) was resampled to 30 m and included as input for the classification. The precipitation dataset represents the North-South moisture gradient of Burkina Faso and the changing phenology of different LULC types along this gradient which has been demonstrated in previous studies [23,48–50].

Table 2. Features used for the classification. The top eight features were generated with TIMESAT [40]. Features marked with an * could not be generated from the Landsat data available for 2007.

Feature	Description
Start of Season	Time for which the left part of the NDVI curve has increased to 30% of the seasonal amplitude measured from the left minimum level
End of Season *	Time for which the right part of the NDVI curve has decreased to 50% of the seasonal amplitude measured from the right minimum level
Length of Season *	Time from the start to the end of the season
Seasonal Amplitude	Difference between the peak value and the base level
Base Level	Average of the left and right minimum values
Middle of Season *	Mean value of the times for which the left part of the NDVI curve has increased to the 80% level and the right part has decreased to the 80% level
Rate of Increase at the Beginning of Season	Ratio of the difference between the left 20% and 80% levels and the corresponding time difference
Rate of Decrease at the End of the Season *	Ratio of the difference between the right 20% and 80% levels and the corresponding time difference
Maximum of NDVI	Annual maximum NDVI of the ESTARFM time series
Mean of NDVI	Annual mean NDVI of the ESTARFM time series
Seasonal Sum of NDVI	Sum of NDVI values (DOY 119 to DOY 263) of the ESTARFM time series
Mono-temporal NDVI	Single time steps of NDVI of the ESTAFM time series (45 scenes used for 2001 and 2014 and 33 scenes for 2007)
Precipitation	Long-term average of annual precipitation sums (WorldClim) [28]

3.5. Classification Approach and Accuracy Assessment

In this study, the random forest classification approach (RF) was applied for the delineation of LULC classes from the fused earth observation time series [51]. The classifier has been frequently used during the recent decade due to its strong and quick performance, its robustness to noise and overfitting, as well as its user-friendliness, since it does not require extensive tuning of its parameters [15,43,51]. The RF classifications in this study were conducted using the *randomForest* package implemented in the programming language R [52] and based on Breiman's random forest algorithm [51]. The final RF models, which were built independently for the three years, were based on a sufficiently high number of 500 decision trees and a default *mtry* value of 12, which is the number of randomly sampled variables at each split of a decision tree.

The reference database was split randomly into sets of 70% and 30% of the sample polygons as commonly recommended [43,53]. The 70% reference set was used for the training of the classifier and the 30% reference set was applied for the validation of its performance. The accuracy of the classifications was analyzed on the basis of confusion matrices, which highlight the separate user's and producer's accuracies for each class as well as the overall accuracy and indicate which classes are over- or underrepresented in the result [47].

In order to increase the accuracy of the classification as well as to sharpen the focus on agricultural areas several post-classification rules were applied. First, the classes *Woody Vegetation, Grassland, Temporarily Flooded*, and *Forest* were merged into one *Savanna* class, since they are not in the focus of this study but were classified separately due to their different spectral characteristics. Furthermore, areas with an annual mean NDVI of less than 0.2 were excluded from the *Irrigated Agricultural Area* class. The extent of lentic waterbodies varies significantly with the seasons in Burkina Faso. Since some of these temporarily flooded shore areas were misclassified as *Irrigated Agricultural Area*, but are clearly not cultivated (due to low NDVI and confirmed by visual inspection), they were reclassified as *Temporarily Flooded*. In addition, *Rainfed Agricultural Area* was overestimated in protected areas where frequent fires during the dry season seriously influence the phenology of vegetation and lead to misclassifications. In order to overcome this, the MODIS burned area product MCD45A1 [54] was applied for such regions to identify affected areas and reclassify them as *Woody Vegetation*.

3.6. Analyzing Connections to Population and Natural Reserves

The relationship between agricultural expansion and rural population growth was investigated by highlighting the changes of the two variables on a provincial level. Furthermore, per province agricultural area and rural population were correlated for the years 2001, 2014 and the respective change between those years and the dependency was assessed with the Pearson product-moment correlation coefficient [55]. In addition, the change in agricultural area per rural person between 2001 and 2014 was determined to examine the development of available farmland for self-subsistence.

In order to analyze the influence of agricultural expansion on natural reserves, two focus areas were selected and the development of agricultural area in their vicinity was monitored over the three years. This was done by a buffer analysis measuring the density of agriculture in the reserve itself and in five 2 km distance zones (0–2 km, 2–4 km, 4–6 km, 6–8 km, 8–10 km) surrounding the reserve.

3.7. Ancillary Data

Several supplementary datasets were used for the analyses in this study. The shapefile of protected areas (Figure 1) was acquired from the Institut Géographique du Burkina Faso (IGB) [56]. It contains natural reserves of different protection categories and represents the status of the year 2005. Furthermore, the rural population numbers of the provinces (Figure 2) were derived from census data obtained from the Institut National de la Statistique et de la Démographie (INSD) [35]. In addition, information about national harvested area of primary crops and estimations of agricultural area for the years 2001 and 2013 were downloaded from FAOSTAT [1]. For the direct comparison with the classification results of 2014, agricultural statistics are so far unavailable in the FAO database.

4. Results

The results are presented in three major sections: first, the novel Burkina Faso wide high resolution agricultural classifications are shown and regional differences and developments of agricultural patterns are highlighted giving examples of plantations, as well as rainfed and irrigated agricultural area. Then, the implications of agricultural expansion for protected areas are exemplarily analyzed and outlined based on two focus regions. Lastly, the link between agricultural area expansion and rural population increase is highlighted. In the following sections, the agricultural classification of 2007 is only used and presented for focus regions since it does not cover the whole country due to a lack of Landsat input data as described in Section 3.1.

4.1. Agricultural Area in Burkina Faso between 2001 and 2014

The extent of agricultural area at a 30 m spatial resolution for the years 2001 and 2014 can be seen in Figure 4. In 2001, rainfed agricultural area covers about 60,441 km^2 which corresponds to 22% of Burkina Faso's land surface (Table 3). It is mainly accumulated in the central area around the capital Ouagadougou and in the regions southeast of it. The more remote areas such as the northern Sahel region, the East bordering Nigeria and Niger as well as the moist southwestern regions were for the major part not cultivated in 2001. With an approximate extent of 561 km^2 in 2001, almost all of the plantations are established in these southwestern regions where the climate is more humid and the rainfalls are highest. In terms of size, the irrigated areas only play a minor role (about 78 km^2) and are mainly located around the water reservoirs in the same regions as the rainfed agricultural areas.

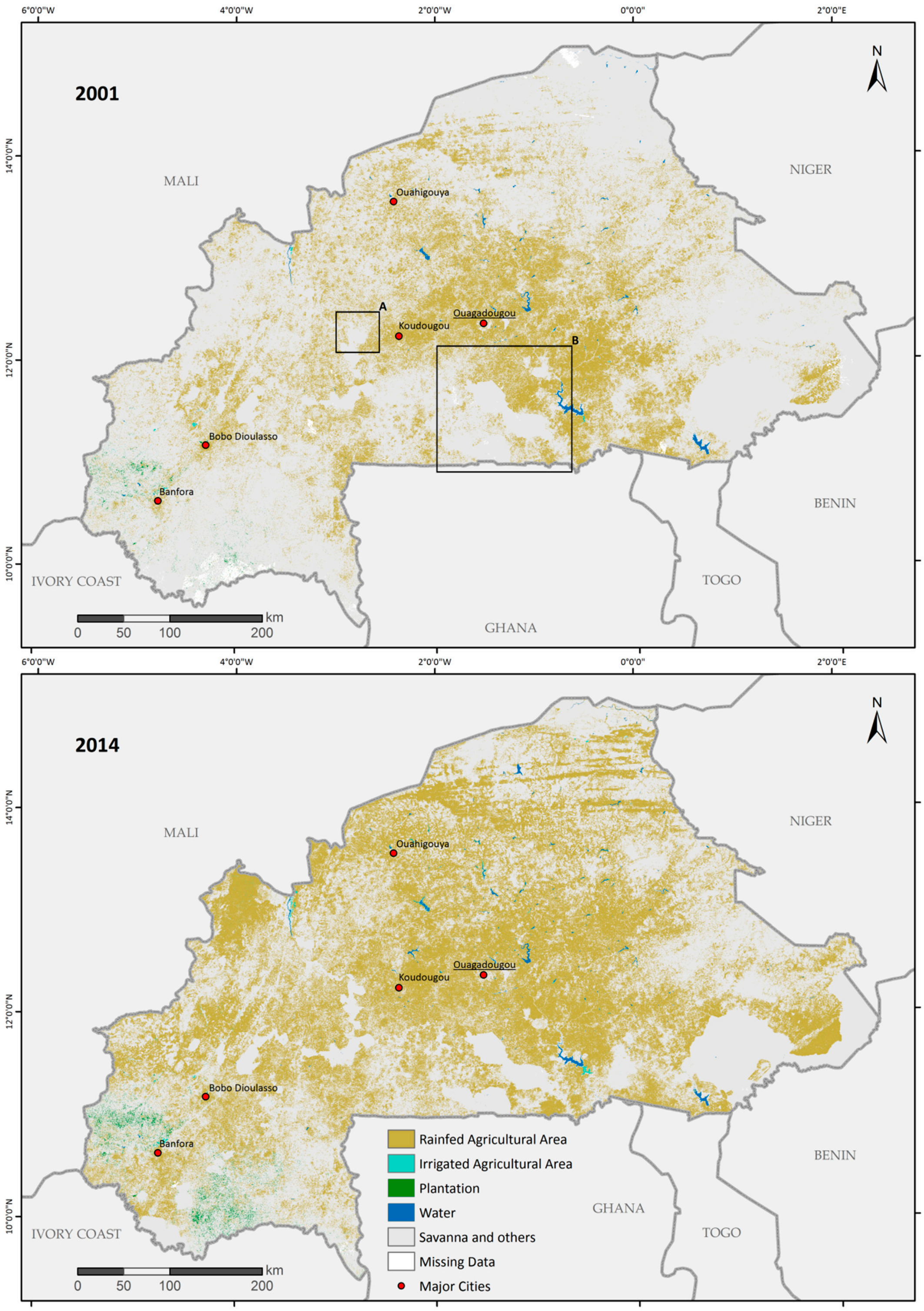

Figure 4. Extent of agricultural area of Burkina Faso for the years 2001 (**top**) and 2014 (**bottom**). Framed areas mark the locations of the focus sites of Section 4.4, the Tiogo classified forest (A) and the Kaboré Tambi National Park (B).

Between 2001 and 2014, the rainfed agricultural area increased by about 90% to 114,994 km^2 and now covers about 42% of the country area. While the already densely cultivated central region of Burkina Faso only marginally expanded its rainfed agricultural area, it spread into all parts of the country, also into the above mentioned remote areas. The plantation area in 2014 almost tripled to

1568 km^2 and two main regions are clearly visible: one is located in the northwest of the city of Banfora, mostly in the provinces Kénédougou and Léraba, and one is situated in the southeast of Banfora, in the provinces Comoé and Poni. With an increasing number of water reservoirs, also the irrigated area expanded significantly by about 340% although the total number of 345 km^2 is still low in comparison to the other forms of agriculture.

Table 3. Agricultural area in km^2 and percentage change for the years 2001 and 2014.

Class	2001 (km^2)	2014 (km^2)	Change
Rainfed Agricultural Area	60,441	114,994	+90%
Irrigated Agricultural Area	78	345	+344%
Plantation	561	1568	+179%

The overall accuracies for the three classified years are 92% for 2001, 91% for 2007, and 91% for 2014, and can be investigated in Table 4 including class-specific user's and producer's accuracies. While rainfed agricultural area displays user's and producer's accuracies of more than 80% for all three years, irrigated agriculture shows some underestimation and thus lower producer's accuracies for the years 2007 and 2014 due to some confusion with temporarily flooded vegetation. For plantation areas, the user's and producer's accuracies range between 77% and 97%. Some overestimations occur along rivers confusing plantation with gallery forests.

Table 4. Confusion matrices indicating overall accuracies as well as user's (UA) and producer's accuracies (PA) for each agricultural class in percent for the years 2001 (**top**), 2007 (**middle**), and 2014 (**bottom**).

		Reference				
Classification	**2001**	*Rainfed*	*Irrigated*	*Plantation*	*No Agriculture*	**UA**
	Rainfed	1300	22	0	204	85.19%
	Irrigated	0	406	1	41	90.63%
	Plantation	0	2	288	8	96.64%
	No Agriculture	242	36	13	4969	94.47%
	PA	84.31%	87.12%	95.36%	95.16%	92.45%

		Reference				
Classification	**2007**	*Rainfed*	*Irrigated*	*Plantation*	*No Agriculture*	**UA**
	Rainfed	2146	40	0	262	87.66%
	Irrigated	18	244	0	37	81.61%
	Plantation	6	0	275	70	78.35%
	No Agriculture	210	116	17	5234	93.85%
	PA	90.17%	61.00%	94.18%	93.41%	91.05%

		Reference				
Classification	**2014**	*Rainfed*	*Irrigated*	*Plantation*	*No Agriculture*	**UA**
	Rainfed	3486	17	0	566	85.67%
	Irrigated	0	424	2	2	99.07%
	Plantation	0	0	57	17	77.03%
	No Agriculture	299	164	8	7237	93.89%
	PA	92.10%	70.08%	85.07%	92.52%	91.25%

4.1.1. Development of Plantation Area

Between 2001 and 2014, a significant increase in plantation area of 179% from approximately 56,000 ha to 157,000 ha can be observed (compare Table 3). The six southwestern provinces of Comoé, Kénédougou, Léraba, Poni, Houet, and Noumbiel (Figure 5 left) make up 99% of Burkina Faso's plantation area. The Comoé province alone contains about 71,000 ha of plantation in 2014, which corresponds to 46% of the total plantation area of Burkina Faso. Figure 5 right reflects this development in detail, exemplarily for a focus site in the Kénédougou province, one of the major plantation regions of Burkina Faso. While the plantations in 2001 (light green) are rather small, scattered, and have undefined outlines, they increased considerably in size and numbers towards 2014 (dark green). Also the shapes of the plantations are much more distinct in 2014.

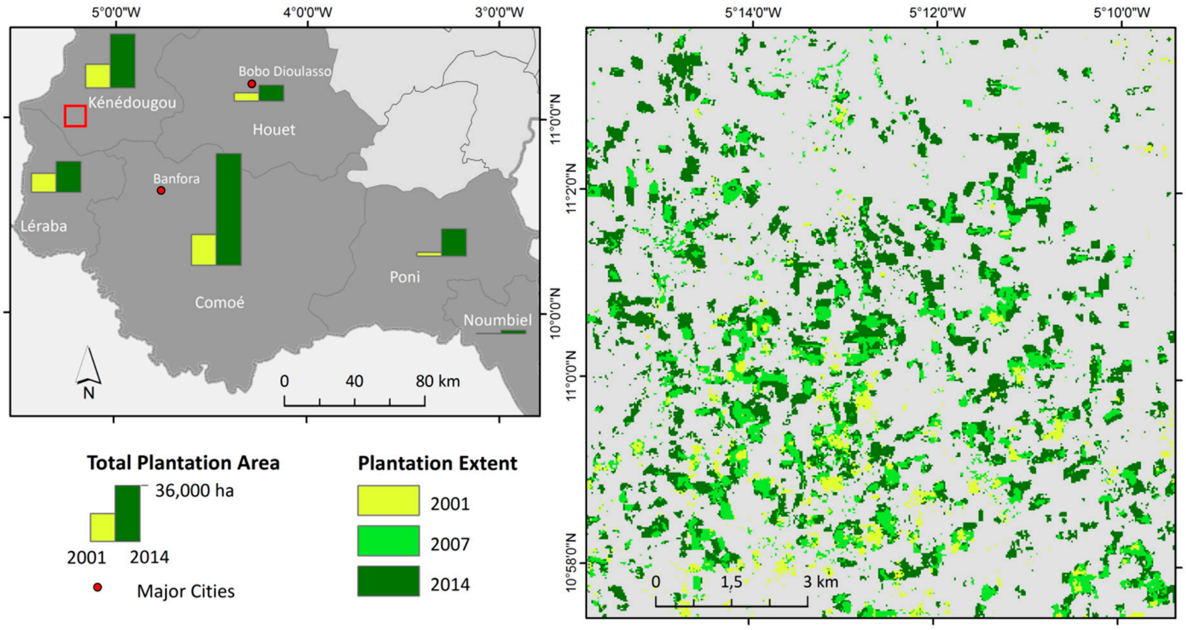

Figure 5. Major plantation provinces and their plantation coverage for 2001 and 2014 (**left**) and development of a plantation area in the province of Kénédougou between 2001 and 2014 (**right**); position marked by red rectangle in the left figure.

4.1.2. Development of Irrigation Area

Efficient irrigated agriculture could be a key to improving food security in Burkina Faso and mitigating the negative effects of the varying timing and length of the rainy season for cultivation [57]. The country has an estimated potential of about 233,500 ha irrigable land but as highlighted above only a small fraction of this area is currently under irrigation (34,500 ha in 2014) [57–59]. The main areas of irrigation lie in the central, northern, and westernmost provinces of Burkina Faso (Figure 6). Especially in the central and northern regions of Burkina Faso, the irrigation areas are mainly located around natural lakes or small water reservoirs established through the damming of rivers. Although, the smaller reservoirs are often used for household water supply and livestock than for irrigation, the distribution of reservoirs derived from the classification results partially reflects the provinces with higher irrigation area.

However, the highest values of irrigation area per province can be attributed to respective single major irrigation systems (confirmed by visual inspection). These areas receive their water supply directly from the major rivers of Burkina Faso and their tributary streams and not from reservoirs. One exception is the irrigation area at the Lake Bagré (Figure 7 and white rectangle in Figure 6), which developed with the construction of a hydropower dam retaining the water of the White Volta river in 1994. In 2001, the area under irrigation at the Lake Bagré covered approximately 9.26 km^2. In 2007 and 2014, it increased to 21.67 km^2 and to 37.28 km^2 respectively which equals an expansion of about 300% over the 14 years. Today, Lake Bagré is one of the biggest connected irrigation systems in Burkina Faso.

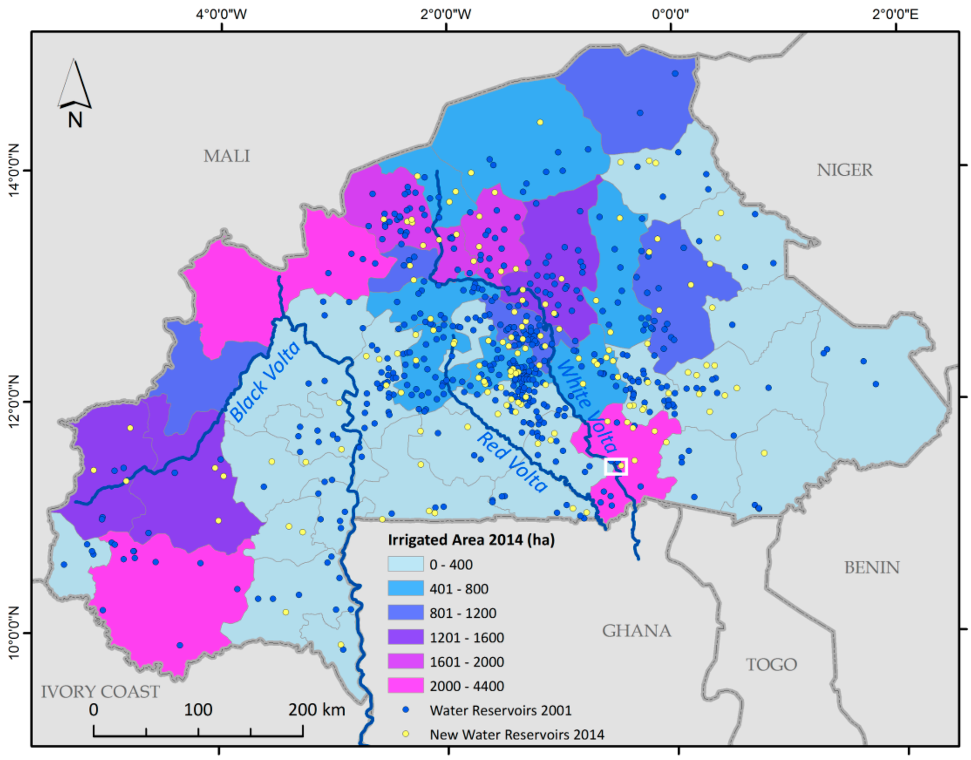

Figure 6. Irrigated area per province for the year 2014 and locations of artificial water reservoirs for the years 2001 and 2014 derived by digitization from the classification results; the white rectangle marks the location of Figure 7.

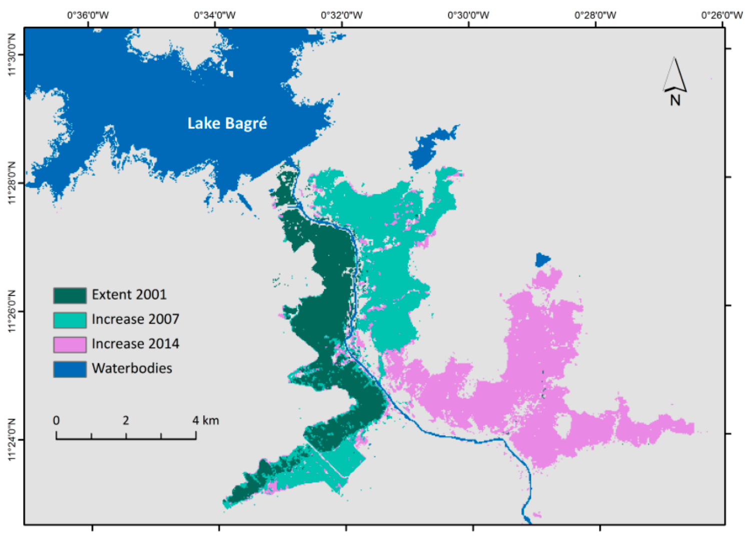

Figure 7. Development of an irrigation area at the Bagré dam in southern Burkina Faso between 2001 and 2014; Location of focus area within Burkina Faso is marked in Figure 6.

4.2. Feature Importance

The respective importance of input features for the discrimination of different classes in the study area is shown in Figure 8. Precipitation is the most important feature representing the North-South moisture gradient of Burkina Faso and the general occurrence of classes along this gradient. In general, wetlands and forests are more frequent in Burkina Faso's southern regions. The Start of Season (SOS) shows early dates for the irrigated agricultural areas which are more independent of the onset of rainfalls, while rainfed agricultural areas generally show later SOS than the natural vegetation classes. This can be explained by the reaction of natural vegetation to the first rainfalls while rainfed agricultural areas are commonly sown later. The NDVI of DOY 271 (end of September) represents the peak of rainy season, similar to the Middle of Season (MOS) feature. For dense vegetation classes such as forests and plantation, the NDVI of DOY 271 is generally higher and the MOS tends to be later.

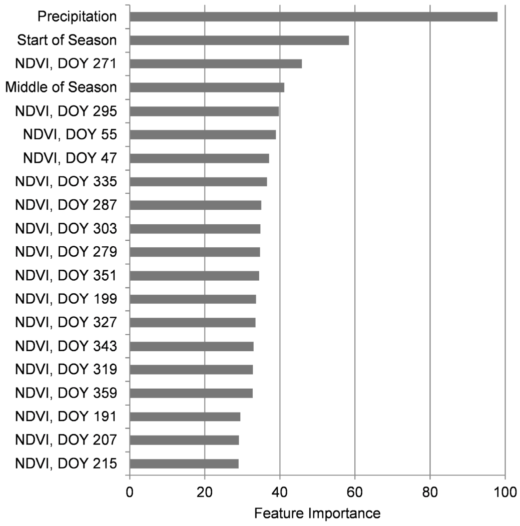

Figure 8. Mean feature importance of the 20 most important features for the years 2001–2014 scaled between 0 and 100.

4.3. Relationship between Agricultural Expansion and Population Growth

The total population of Burkina Faso grew rapidly during the period of investigation from approx. 12 million in 2001 to more than 17 million people in 2014 [1]. As outlined in Section 2, also the rural population increased in almost all provinces during that time. Especially the more remote provinces like Tapoa (TAP), Comoé (COM) or Houet (HOU) increased in rural population by up to 244,000 people (Figure 9 left) [35]. The central provinces with an already high population density in 2001 as well as the central southern provinces only increased moderately in population numbers. The only province with a negative rural population development is the province of Zondoma (ZON) decreasing by about 58,000 rural inhabitants.

Similar patterns as for the rural population growth can be observed for the expansion of agricultural area in the provinces between 2001 and 2014 (Figure 9 right). Agriculture spread into all remote and so far rather uncultivated regions of Burkina Faso. The above mentioned provinces Tapoa (TAP) and Comoé (COM) are among the provinces with the biggest agricultural expansion with an increase of about 323,000 ha and 315,000 ha, respectively. However, the highest numbers of expansion are observed for the two Northern provinces Kossi (KOS) with a plus of 392,000 ha and Soum (SOM) with an increase of 386,000 ha between 2001 and 2014. Similar to the changes in population growth, the central provinces show only moderate levels of agricultural expansion between 600 ha for the Koulpélogo province (KOP) and 60,000 ha for the Bazèga province (BAZ).

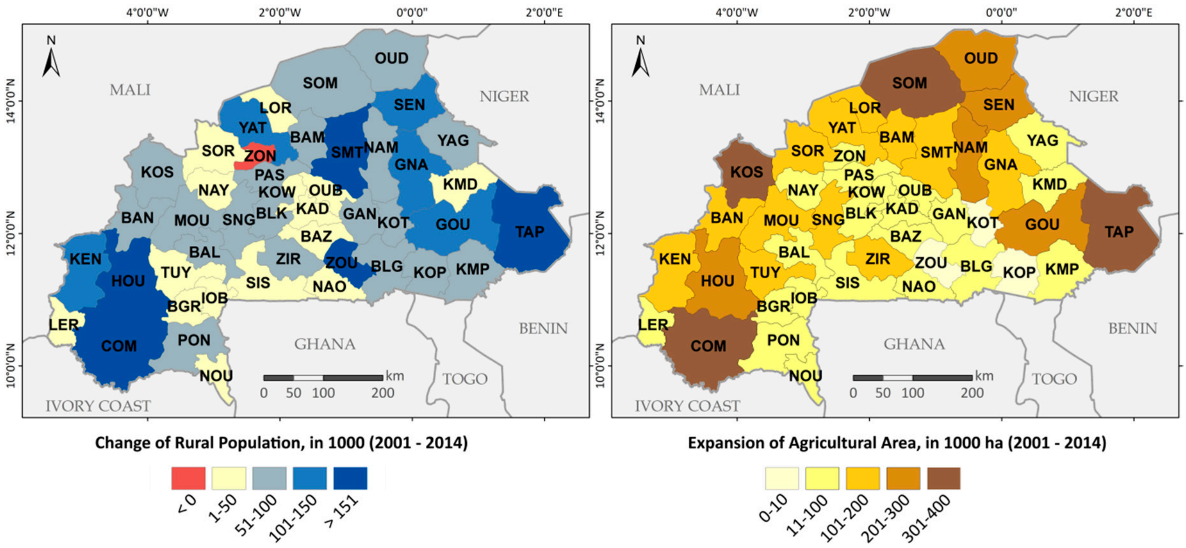

Figure 9. Change of rural population in the provinces of Burkina Faso between 2001 and 2014 (**left**) [35] and expansion of agricultural area in the provinces derived from the classification results (**right**); the province names are abbreviated by three letters.

In a quantitative comparison of agricultural area and rural population in the provinces, a direct relationship becomes evident. For 2001, the numbers of rural inhabitants correlate with the extent of agricultural areas (r = 0.84) with highest numbers primarily for the larger central provinces like Sanmatenga (SMT), Boulgou (BLG), and Yatenga (YAT) (Figure 10a). For 2014, the numbers for the two variables generally increase in the provinces but the relationship between them stays the same (r = 0.84) (Figure 10b). While the leading provinces of 2001 are still among the highest in 2014, the above mentioned remote provinces of Comoé (COM), Soum (SOM), and especially a group of provinces from the region Est, Tapoa (TAP), Gourma (GOU), and Gnagna (GNA), joined the provinces with highest population numbers and biggest agricultural area. Though there are various reasons and pathways for different developments of the two variables, it is obvious that agricultural expansion and rural population growth go in line for multiple provinces (Figure 10c). Besides some single provinces, the more remote regions of Est, Sahel and Boucle de Mouhoun exhibit the highest changes in both variables. The central and generally smaller provinces of the regions Centre-Est, Centre-Sud, and Plateau Central only increased in rural population numbers without considerable agricultural expansion.

The average agricultural area per rural inhabitant rose from 0.63 ha to 0.88 ha (Figure 11). Especially in the more remote provinces like Oudalan (OUD), Soum (SOM) or Kossi (KOS) the agricultural area grew considerably while there was only a moderate population growth resulting in increases of up to 1.24 ha/person. While most provinces registered a plus in agricultural area per person, some provinces in the central and southwest of Burkina Faso almost did not change or decreased. Especially the provinces Zoundwéogo (ZOU), Kouritenga (KOT), and Koulpélogo (KOP) lost up to 0.66 ha per person. These are also the provinces with the smallest agricultural expansion while still increasing their rural population numbers by up to 240,000 people (ZOU) over the considered 14 years.

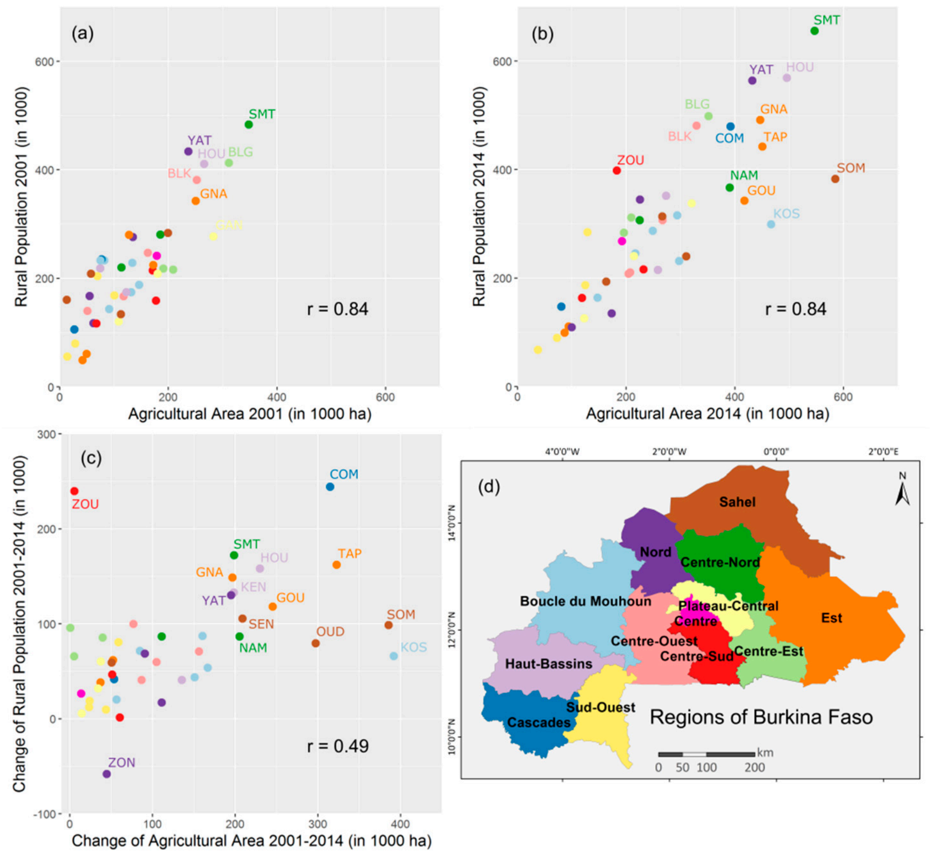

Figure 10. Scatterplots of agricultural area versus rural population in the provinces for the years 2001 (**a**) and 2014 (**b**) and the changes between the two years (**c**); the coloring of the points refers to the regions of Burkina Faso (**d**).

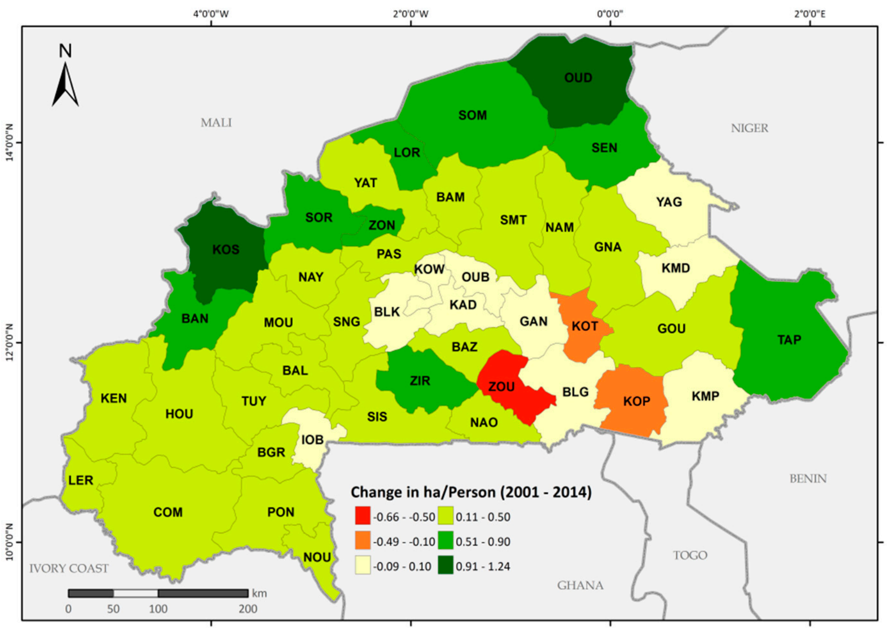

Figure 11. Change of agricultural area (in ha) per person (rural) in the provinces of Burkina Faso between 2001 and 2014; the province names are abbreviated by three letters.

4.4. Implications for Natural Reserves

In this section, an in-depth study of two protected areas (compare Figure 4) was conducted showing the development of agricultural area in their vicinity. The first one is the Kaboré Tambi National Park, which was founded in 1976 and directly adjacent in the Northwest, the classified forest Nazinon which lie about 60 km south of Ouagadougou (Figures 1 and 12). In 2001, the agricultural area inside the boundaries of the two protected areas was very low (3%) and was almost exclusively found in the Nazinon forest. Also the direct surroundings of the Kaboré Tambi are only marginally cultivated because of an apparent buffer zone around parts of the park borders.

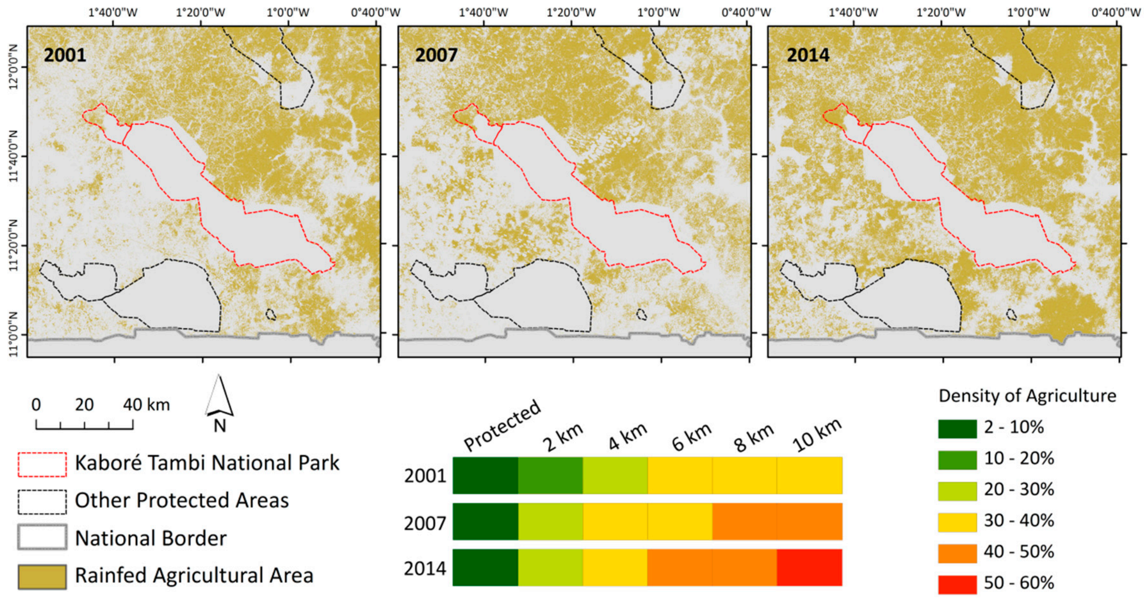

Figure 12. Maps of agricultural area in the Kaboré Tambi National Park and its surroundings for 2001, 2007, and 2014 (**top**) and plot of the development of agricultural area in the protected area and in 2 km distance zones around it between 2001 and 2014 (**bottom**); Location of focus area within Burkina Faso is marked in Figure 4.

Between 2001 and 2007, the agriculture in these protected areas did not change but it increased in all distance zones with a maximum of 43% within the 8–10 km zone. In 2014, the cultivated area in this zone increased by another 8% and values of dense agriculture are drawing closer to the park, but the protected area remains unaffected. This indicates a functioning protection of the park despite the concentration of agricultural area in its vicinity. However, this concentration also increases the isolation of the park and hinders animal movement to other habitat areas with a decreasing number of natural patches (stepstones) in between.

The second example, the classified forest of Tiogo is located about 130 km west of Ouagadougou and is a formally protected area adjacent to other areas with the same status (Figures 1 and 13). However, Tiogo does not underlie an exclusive park management as the Kaboré Tambi National Park [60].

In 2001, some croplands were detected in the northeastern part of Tiogo but so far they only cover 3% of the total area. The agricultural area in the surroundings of the park is moderately dense and reaches up to 36% in the 4–6 km distance zone. In 2007, the fields in the Northeast of Tiogo advance towards the center of the protected area and increased significantly to 13% of the total forest area. Also the surrounding agriculture increases in all distance zones with a maximum of 51% in the 8–10 km zone. Finally in 2014, the agriculture in the northeastern part of Tiogo intensifies (18% of total area) and dense agricultural area covering more than 50% starts right at the border of the Tiogo classified forest increasing the pressure on the remaining protected area.

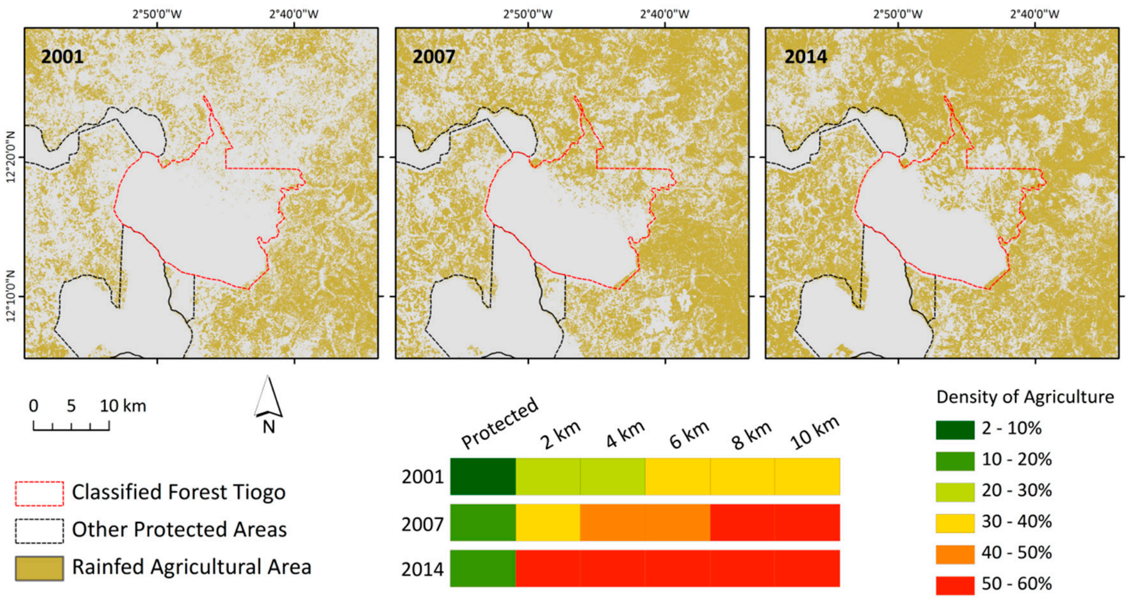

Figure 13. Maps of agricultural area in the classified forest Tiogo and its surroundings for 2001, 2007, and 2014 (**top**) and plot of the development of agricultural area in the protected area and in 2 km distance zones around it between 2001 and 2014 (**bottom**); Location of focus area within Burkina Faso is marked in Figure 4.

5. Discussion

5.1. Classification of Agricultural Area Based on Dense Time Series

In this study, a novel approach was applied for the derivation of countrywide agricultural classifications with a high spatial resolution (30 m) for entire Burkina Faso and three years. On the basis of the ESTARFM framework, an 8-day time series was generated and in combination with subsequently derived phenological metrics it was used to delineate different agricultural use types from savanna vegetation in Burkina Faso. The overall classification accuracies of 92% (2001), 91% (2007), and 91% (2014) show the suitability of this approach. The possibility to use a dense time series instead of single scenes with at the same time high spatial resolution is an important feature of this method. The frequent cloud coverage in West Africa decreases the data availability of common satellite sensors significantly [22] and often limits gap-free coverage of the country to the dry season when agricultural area is difficult to delineate. Furthermore, the small-scale extensive farming systems in Burkina Faso require a sufficiently high spatial resolution for the delineation of single fields. Thus, the sole use of high temporal (≤8 days) but lower spatial resolution time series (≥250 m, e.g., of MODIS or the Advanced Very-High-Resolution Radiometer, AVHRR) leads to high amounts of mixed pixels. To deal with this issue, alternative approaches such as fractional cover of agricultural area would have to be applied [19]. To our knowledge, there are so far no other products in this high spatial resolution and thematic complexity focusing on the accurate delineation of agricultural area in entire Burkina Faso for several years. For 2014, Lambert et al. [18] derived croplands from 100 m PROBA-V data for the Sudanian and Sahelian region of West Africa. The use of time series contributed to a suitable classification result but spatial resolution based errors still occurred in heterogeneous areas. Different global land cover maps like the MODIS MCD12Q1 [11] or GLOBELAND30 [13] also include agricultural area, but their usability for detailed regional scale applications is often limited due to spatial or temporal resolution as well as thematic complexity [15–17].

In our study, one limiting issue in the derivation of a multi-year countrywide agricultural classification was the data availability from the earlier Landsat generations 5 and 7. Though, the ESTARFM framework includes an automated filling of cloud gaps and can thus make use of also partially cloud covered scenes, for some tiles and years there was no or not enough data available. Especially for the year 2007, no Landsat-7 data were available for the southeast of the country and for several other areas the cloud coverage over the whole year was at exceptionally high levels. Thus, the classification of this year could only be used for local analyses. However, the classification of 2014 has shown that limited data availability should not be an issue for future applications of the developed methodology since the Landsat-8 sensor delivers sufficient amounts of input data. In addition, data from the Sentinel-2 satellites [61] will be an option enhancing future data availability for the presented methodology.

For a repeated application of the developed methodology for monitoring purposes, the automation of the classification procedure and the automated generation or update of the reference dataset would be desirable. Such an operational framework could significantly improve the overall processing time from data download to the final maps. However, this is beyond the scope of this study which aimed at the development of the general classification approach and the delineation of agricultural area for certain years.

A further challenge of the applied approach was the reference data collection. A reference dataset of land use for multiple years covering entire Burkina Faso is so far not available and thus, this information was collected from high resolution Google Earth images. Since in Google Earth there are often no multi temporal datasets available for a single year of interest, it can be difficult to visually distinguish active cropland from crop-fallow rotation systems or even recently abandoned land. The aim of this study was to delineate total agricultural area comprising fallow and intensive pasture and not strictly limit the classification to harvested crop area. The inclusion of these types of agricultural area provides a valuable picture on the overall need and expansion of land for agricultural production in Burkina Faso. However, the derived dense ESTARFM time series have the potential to also distinguish harvested crop area, if a suitable reference dataset would be available.

A comparison of classification results to official statistics of agricultural area is difficult since they are either so called 'manual estimations' or focus on only harvested area [1]. For the year 2001, the FAO estimates that 105,700 km^2 were used as agricultural area in Burkina Faso and 123,000 km^2 in 2013 while numbers for 2014 are currently unavailable [1]. However, in these values a constant number of 60,000 km^2 for 'permanent meadows and pastures' is included. Such a stable expanse of rangelands seems rather unrealistic since several processes like the conversion to cropland or the exploitation of new areas should alter this extent. According to the FAO, an area of 49,600 km^2 of primary crops was harvested in Burkina Faso in 2001 and 70,200 km^2 in 2013 with missing numbers for 2014 [1]. These values indicate the strong increase of agriculturally used area during the past years, which is also visible in the classification results of this study.

5.2. Land Cover Changes in the Context of Socio-Economic Development

While the rapid population growth in Burkina Faso seems to be the main driver for the expansion of rainfed agricultural area, the development of plantations and irrigation systems requires investments which are not feasible for the majority of Burkinabe. The considerable growth of plantation area and the formation of distinct plantation shapes (compare Section 4.1.1) indicate a substantial driving force of development and a professionalization of tree crop agriculture in the region. And indeed, this progress goes in line with the establishment of a predominantly Fairtrade business of cashew nuts and mangos in Burkina Faso during the past years. Since the beginning of the 21st century, several external organizations started to invest in and promote the development of plantations of cashew nuts and mangos. Amongst others, the German Society for International Cooperation (GIZ) initiated the African Cashew initiative (ACi) [32] optimizing the whole value chain of cashew production and distribution for several West African countries including Burkina Faso. Also in the mango production, professionalization was advanced by international projects as well as the implementation of local companies such as Fruiteq [33,62,63]. These promoted the establishment of farmer co-operatives, the training in mango cultivation, as well as the transport and Fairtrade marketing in Europe.

Though there are other tree crops in Burkina Faso, e.g., citrus fruits or other nuts, these are obviously not responsible for the significant growth of plantation area since their numbers rather stagnate or decrease over the period of investigation [1]. In contrast, the success of these international projects can be seen in the rise of trade values and amount of exported cashew nuts and mangos, a development which is well reflected in the observed expansion of plantation area (Figure 14).

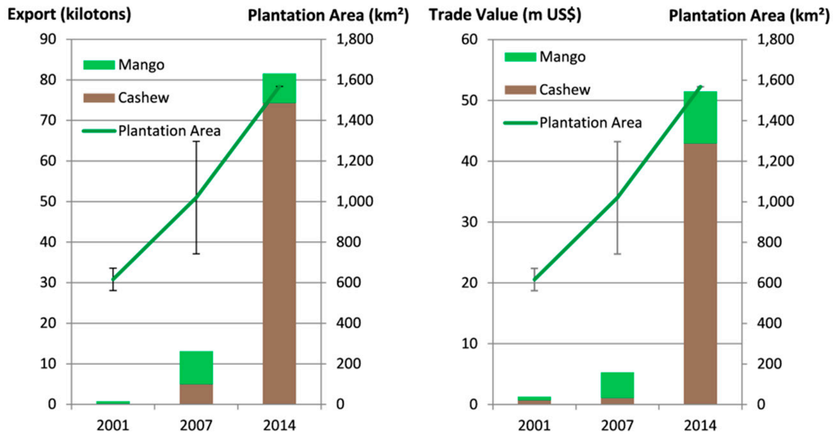

Figure 14. Amount (**left**) and trade value (**right**) of exported cashews and mangos from Burkina Faso as well as the total observed plantation area for the years 2001, 2007, and 2014; error bars describe the possible range of plantation area due to data gaps in the classifications [34].

While in 2001, the amount of exported cashews and mangos from Burkina Faso was at 224 and 580 tons, respectively, it rose rapidly to 74,303 and 7256 tons in 2014 [34]. Also the trade value of Burkinabe cashews and mangos increased considerably from 0.73 to 42.85 million US$ for cashews and from 0.56 million to 8.54 million US$ for mangos [34]. While the development of the cashew sector is even more remarkable than that of mangos, it can be noted that there has been a price increase (US$ per ton) for mangos from Burkina Faso. This could be attributed to rising world market prices but also to the improved quality of Burkinabe mangos and their Fairtrade marketing.

Besides the expansion of plantation area, also the increase in irrigated agricultural areas is remarkable (compare Section 4.1.2). In recent years, the government of Burkina Faso has been investing considerable amounts of money in the development of irrigation systems in the framework of their National Programme for the Rural Sector (PNSR) [64]. In addition, several international organizations are promoting irrigated agriculture within local projects in Burkina Faso. One example is the above mentioned Bagré dam located about 140 km southeast of Ouagadougou (Figure 7). Within the Bagré Growth Pole Project, the World Bank, the Global Water Initiative (GWI) and others are developing irrigation infrastructure and are advising and promoting smallholder farming in the region [58,59,65]. The success of these efforts can be seen in an expansion of irrigated areas by about 300% to 37.28 km^2 in 2014. However, this value is still far below the estimated potential irrigable area for the region of 299 km^2 [58].

5.3. Mapping of Agricultural Expansion for the Planning and Monitoring of Measures

The results of this study show links between agricultural expansion and the rapidly growing population of Burkina Faso. While the population increased by about 40% in almost all provinces between 2001 and 2014, the agricultural area nearly doubled and spread into all remote and previously almost unused regions. Until now, there has been an overall increase in agricultural area per person in the rural regions of Burkina Faso (from 0.63 ha to 0.88 ha during the period of investigation). However, some provinces which were already intensively cultivated in 2001 show a decrease in agricultural area per person. By the year 2030, it is estimated that Burkina Faso could reach its limit of arable land [5] and the population is expected to grow from 17 million people in 2014 to more than 26 million people in 2030 and even to about 41 million in 2050 [1]. Against this background, an overall positive trend in agricultural area per person cannot hold for a longer time. In addition, in the calculation of this factor, only the rural population was included since most of the smallholders cultivate for self-subsistence with only casual access to the market [4]. However, in order to improve food security and to avoid booming food prices during drought years, a self-sustaining agriculture would be desirable in Burkina Faso, meaning that also the increasing urban population would have to be taken into account in such a calculation. In this case, the agricultural area per person would be considerably lower. In combination with additional statistical data, the derived results could be valuable information for the analysis of regional migration and rural-urban development.

As highlighted by the analyses of Section 4.4, the pressure on protected areas has increased significantly in Burkina Faso during recent years. With population growth and agricultural expansion as the main drivers, some of the less guarded reserves have considerably decreased in size or even vanished completely. Because of an increase of agricultural area and rural settlements in the surroundings of the protected areas, the suitability of these areas as a habitat for a number of species is also decreasing. Maintaining a critical size and connectivity between natural habitats is important for many species to provide crucial habitat functions and to guarantee genetic exchange between populations and preserve biodiversity [66]. For the protection of the remaining natural reserves, the local communities have to be involved in order to prevent them from exploiting the forests for firewood or expansion of agricultural areas [60]. This is currently under development on the basis of funds from the Forest Investment Program (FIP) of the Climate Investment Funds financed by the World Bank [67]. Burkina Faso is one of eight pilot countries, given a 30 million US$ grant to reduce deforestation and promote sustainable forest management. The Tiogo classified forest, investigated in Section 4.4 is one of six focus reserves of this program within Burkina Faso.

Since the agricultural expansion will have to come to an end in the near future, there is a serious need to increase the efficient and sustainable use of existing agricultural areas. However, since the 1960s, the cereal productivity of Burkina Faso only rose very slowly from about 0.4 tons per hectare and year to approximately 1.16 t/ha/year [1]. Other developing and thresholding countries like e.g., Brazil improved their cereal productivity in the same time from 1.34 t/ha/year to about 4.8 t/ha/year while the productivity in Western Europe is already at more than 7 t/ha/year. Several international projects like the examples given in Section 5.2. promote the development of sustainable and more efficient agricultural areas. However, most of them are focusing on geographically small areas rather than targeting the majority of rainfed agricultural regions. For this purpose, a countrywide approach is necessary. During the past decade, the government of Burkina Faso made a considerable effort to support and develop the agricultural sector. More than 10% of the national budget was allocated to agriculture [4]. In the framework of the Rural Development Strategy (SDR), staple crop production was supported by subsidies on fertilizer, by distributing improved seeds and by supporting the improvement of irrigation systems [4]. These efforts will especially advance an intensification of existing agricultural areas and improve agricultural productivity. By promoting local focus areas such as the above mentioned Bagré Growth Pole Project, the government wants to attract private investment and initiate positive effects on the rest of the economy [4]. However, most of the national investments still focus on the production of cotton which is the major agricultural export commodity in Burkina Faso. It has to be awaited to see if these efforts have a considerable impact on the broad agricultural community and on the improvement of food security and sustainability in the country. The continuous application of the developed methodology could play a crucial role in the monitoring of Burkina Faso's efforts to develop a sustainable land management and to protect the remaining natural reserves. An annual or biennial mapping of Burkina Faso's focus areas and the development of the countrywide agricultural area in combination with regional population numbers could detect discrepancies between planning and implementation and identify potential hotspots of undesirable processes. In addition, the developed methodology could also improve the agricultural monitoring efforts planned by ESA's

S2-Agri project [68]. This project explores methods to generate cropland maps from Sentinel-2 time series on a frequent basis applicable for various regions on the globe. However, recent tests showed difficulties for their focus site in Burkina Faso due to the small-scale extensive farming practices as well as the persistent cloud coverage in the region [69,70]. The presented approach for the generation of a gap-free high temporal and spatial resolution time series with the ESTARFM framework could contribute to overcoming these issues and increase the classification accuracies in such difficult regions.

6. Conclusions

In this study, the ESTARFM framework was applied for the generation of a high temporal (8-day) and high spatial (30 m) resolution time series for the country of Burkina Faso, with an area of approx. 274.000 km^2. The fused time series were further used as a basis for the delineation of agricultural area in a spatial resolution of 30 m for entire Burkina Faso and for three years—2001, 2007, and 2014. To our knowledge, there is no other national product available at this spatial, temporal, and thematic resolution with an equal quality. Prior studies outline the challenges in the derivation of agricultural area from remote sensing data in West Africa [17–19,48]. The predominant small-scale rainfed subsistence farming and the low productivity of the fields complicates the separation of agricultural area from other land use and cover types. Despite these difficulties, the overall accuracies of 92% (2001), 91% (2007), and 91% (2014) of the presented results indicate the well-functioning of the method applied here. The possibility to use the whole phenological cycle of NDVI in a sufficiently high spatial resolution as input for the classification is a key factor for the delineation of agricultural area in the region.

Furthermore, the presented results give insight into the development of plantations, the establishment of irrigation systems, and the protection of natural reserves in Burkina Faso. This information can be important for decision makers in order to understand and quantify if recently initiated measures for the development of agricultural systems have the intended effects. For this purpose, the mapping and monitoring with the developed method could also be continued for subsequent years.

The results and analyses presented in this study highlight major challenges in terms of food production systems and food security Burkina Faso is facing and will face in the future. The massive expansion of agricultural area (from 61,100 km^2 in 2001 to 116,900 km^2 in 2014) is pushing towards the limit of available arable land and potentially more and more unsuitable regions will be used for cultivation. With a rapidly increasing population, this expansion is likely to continue if the productivity will not be improved significantly in the near future. These trends are also threatening the remnant natural reserves of Burkina Faso with illegal logging and cultivation on protected land. In future, the introduction of new satellite systems such as Sentinel-2 and -3 should improve the input data availability and facilitate subsequent applications of the developed approach for the delineation of agricultural area.

This study also highlights the great potential of the dense time series generated with the ESTARFM framework beyond its use for agricultural studies in Burkina Faso [24]. Further applications, where a combination of high temporal and spatial resolution would be essential, could be the analysis of land degradation or changes in the land surface phenology in Burkina Faso [24].

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Author Contributions: Kim Knauer conducted the processing of the time series and the classification of agricultural areas and together with Ursula Gessner conceived and conducted the analyses of the results;

Gerald Forkuor, Rasmus Fensholt, and Claudia Kuenzer guided the processing and interpretation. Kim Knauer wrote the first version of the manuscript and all authors jointly improved the version based on critical discussion.

Conflicts of Interest: The authors declare no conflict of interest.

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